WCAP-17788-NP
Volume 3

December 2019
Revision 1

# Comprehensive Analysis and Test Program for GSI-191 Closure (PA-SEE-1090) – Cold Leg Break (CLB) Evaluation Method for GSI-191 Long-Term Cooling

Westinghouse

**WCAP-17788-NP**
**Volume 3, Revision 1**

# Comprehensive Analysis and Test Program for GSI-191 Closure (PA-SEE-1090) – Cold Leg Break (CLB) Evaluation Method for GSI-191 Long-Term Cooling

December 2019

Prepared by: Kevin F. McNamee*
Operating Plant Fluid Systems and Procedures

Reviewed by: Timothy S. Andreychek*
Operating Plant Fluid Systems and Procedures

Approved: Timothy D. Croyle*, Manager
Operating Plant Fluid Systems and Procedures

This work was performed under PWR Owners Group Project Number PA-SEE-1090.

*Electronically approved records are authenticated in the electronic document management system.

Westinghouse Electric Company LLC
1000 Westinghouse Drive
Cranberry Township, PA 16066, USA

## ACKNOWLEDGEMENTS

This report was developed and funded by the PWR Owners Group under the leadership of the participating utility representatives of the Systems & Equipment Engineering Committee. The authors thank the PWR Owners Group GSI-191 Technical Integration Group Engaged in Research (TIGER) Team for their support and contributions to this program; Mr. Jeffrey Brown, the late Mr. Phillip Grissom, Mr. Dana Knee, Mr. Ernie Kee, Mr. Kenneth Greenwood, Mr. Timothy Croyle, and associate members; Mr. Kurt Flaig and Mr. Paul Leonard. The authors also gratefully acknowledge and recognize Mr. Jay Boardman, PWR Owners Group Program Manager, and Mr. Paul Stevenson, Ms. Danielle Page Blair, Mr. John Maruschak and Mr. David C. Kovacic, Project Managers, for their guidance and encouragement throughout the process of developing this report.

The authors would also like to acknowledge Mr. Paul Leonard for his contribution of an alternate simplified method of determining the amount of fiber expected at the core following a large cold leg loss of coolant accident.

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## Foreword

USE OF TECHNICAL REPORT WCAP-17788
BY
MEMBERS OF THE PRESSURIZED WATER REACTOR OWNERS GROUP

This technical report is comprised of six volumes. All six volumes of Revision 0 of the technical report were submitted to the U.S. Nuclear Regulatory Commission (US NRC) with the objective of obtaining a Safety Evaluation (SE) on the complete report (all six volumes).

The US NRC initiated a review of the technical report and issued a number of Requests for Additional Information (RAIs). Responses to those RAIs were prepared and submitted to the US NRC to support their review. All RAIs and their responses are included in an appendix to the applicable volumes. It is noted that Volume 2 was not reviewed in detail by the US NRC, and as a result, no RAIs were provided for this volume of the technical report. It is also noted that sections of technical report PWROG-15091 Revision 0, "Subscale Brine Test Program Report" (Reference 1) were reviewed as supporting information to this technical report. The RAI and its response related to PWROG-15091 is included in the applicable Volume 1 appendix. Revision 1 of PWROG-15091 was also prepared and includes a modification committed to in the RAI response.

In the middle of 2019, the US NRC informed the PWROG that an SE would not be issued on this technical report. Rather, the US NRC would accept licensees referring to the technical report in their response submittals to Generic Letter (GL) 2004-02 (Reference 2), accompanied by a statement demonstrating the applicability of the referenced portion of the technical report to their specific PWR unit.

Additionally, the US NRC has used information contained in the technical report, along with other information, to prepare a Technical Evaluation Report (TER) that concludes in-vessel debris effects are of a low safety significance. The US NRC has used the TER to support closure of Generic Safety Issue (GSI) -191 (Reference 3). The TER is published in Volume 1 of this technical report revision.

To support this use of the technical report by PWROG members, Revision 1 of the technical report was prepared and includes all RAIs and their responses, as well as modifications committed to in the RAI responses. As noted previously, this technical report has not received an NRC SE. However, all six volumes of WCAP-17788 have been amended to Revision 1 and are made available to participating PWROG members for their use to respond to GL 2004-02 and close GSI-191 for the PWR units they operate.

REFERENCE

1. PWROG-15091-NP, Revision 1, "Subscale Brine Test Program Report," November 2019 (Non-proprietary).
2. NRC Generic Letter 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized-Water Reactors," ADAMS Accession Number ML042360586, September 13, 2004.
3. NRC Memorandum from R. V. Furstenau to H. K. Nieh, "Closure of Generic Issue GI-191, 'Assessment of Debris Accumulation on PWR Sump Performance,'" ADAMS Accession Number ML19203A303, July 23, 2019.

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| | |
|---|---|
| BWST | Borated Water Storage Tank |
| CL | Cold Leg(s) |
| CLB | Cold Leg Break |
| CSS | Containment Spray System |
| ECCS | Emergency Core Cooling System |
| FA | Fuel Assembly |
| GSI | Generic Safety Issue |
| GL | Generic Letter |
| HL | Hot Leg(s) |
| HLB | Hot Leg Break |
| HLSO | Hot Leg Switchover |
| LOCA | Loss-of-Coolant Accident |
| LTC | Long-term Cooling |
| NEI | Nuclear Energy Institute |
| NPSH | Net Positive Suction Head |
| NRC | Nuclear Regulatory Commission |
| PWR | Pressurized Water Reactor(s) |
| PWROG | Pressurized Water Reactor Owners Group |
| RCS | Reactor Coolant System |
| RV | Reactor Vessel |
| RWST | Refueling Water Storage Tank |
| SE | Safety Evaluation(s) |
| U.S. | United States |
| TIGER | Technical Integrated Group Engaged in Research |
| WCAP | Westinghouse Technical Report Number Preface (formerly Westinghouse Commercial Atomic Power) |

# 1 EXECUTIVE SUMMARY

On September 13, 2004, the Nuclear Regulatory Commission (NRC) issued Generic Letter (GL) 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized-Water Reactors (PWRs)," (Reference 1) as the primary vehicle for addressing and resolving concerns associated with Generic Safety Issue (GSI)-191. The GL requested that all PWR licensees use an NRC-approved method to:

1. Perform a mechanistic evaluation of the potential for post-accident debris blockage and operation with debris-laden fluids to impede or prevent the recirculation functions of the Emergency Core Cooling System (ECCS) and Containment Spray System (CSS) following all postulated accidents for which these recirculation functions are required.
2. Implement plant modifications or other corrective actions that the evaluation identifies as necessary to ensure system functionality.

Resolution of GSI-191 requires that every plant evaluate plant-specific debris generation and transport to their recirculation sump screen(s) for a variety of breaks and break locations. Coolant sources and their volumes are known and understood for every plant as are the piping, pumps and valves that move and direct these coolant sources. The transport of generated debris relies on these known and understood coolant sources and the flow rates associated with the ECCS and CSS to define that amount of debris that washed to the sump and eventually arrives and passes through the recirculation sump screen(s).

The PWR Owners Group (PWROG) has actively pursued closure of GSI-191 through its conduct of a number of programs. This included funding the development of the following documents:

1. Guidance for performing condition assessments of debris sources inside PWR containments (Reference 2).
2. Guidance for evaluating post-accident sump screen performance (Reference 3).
3. Guidance for evaluating ex-vessel downstream effects of debris-laden coolant on performance of ECCS and CSS (Reference 4).
4. Guidance for evaluating post-accident chemical effects in the containment sump (Reference 5).
5. Guidance for evaluating long-term cooling (LTC) of the reactor core considering the effects of debris-laden coolant (Reference 6).

The NRC staff has issued Safety Evaluations (SE) accepting the material and methods advanced in Reference 3 through Reference 6 as modified by conditions and limitations identified in the respective SE.

Reference 6 identifies that LTC of the core is not impeded if the plant-specific fibrous debris load is less than or equal to 15 grams of fiber per fuel assembly for all United States (U.S.) fuel and U.S. PWR designs. The NRC SE for Reference 6 accepts this 15 grams of fibrous debris per fuel assembly as a hot leg break (HLB) limit. The SE goes on to identify actions to be taken by licensees should they choose to increase their acceptable fiber limit above the 15 grams per fuel assembly limit. The PWROG has undertaken a comprehensive test and analysis program to increase the HLB fibrous debris limit above the currently accepted 15 grams per fuel assembly (g/FA). Volume 1 of WCAP-17788 summarizes the testing and analyses performed to support defining an increase in the debris limit for a HLB, as well as defining debris limits for both the HLB and the cold leg break (CLB).

As part of this comprehensive program, a method has been developed to assess the time-dependent collection of fibrous debris near the core inlet for CLB conditions. The method is based on the approach described in WCAP-16406-P-A (Reference 4) and tracks the depletion of fibrous debris concentration in the recirculating coolant due to capture of that debris on both recirculation sump screens and the delivery of fibrous debris to the reactor vessel and core. The method assumes that any debris delivered to the reactor vessel and core is captured near the core inlet.

A description of the method, the inputs required for the method to operate on a specific plant, and a description of how the method may be used are provided in this document.

# 2 INTRODUCTION

PWR containment buildings are designed to contain radioactive material releases and to facilitate core cooling during a postulated Loss Of Coolant Accident (LOCA) event. In some large LOCA scenarios, water discharged from the break and containment spray is collected in the containment sump for recirculation by the ECCS and CSS. The coolant in the sump will contain debris from insulation and protective coatings damaged by the jet formed by the release of coolant from the break and from the washdown of resident containment debris from upper containment regions into the sump. This debris will be in both particulate and fibrous form. Additionally, chemical products may form from the interaction of boric acid, buffering agents and other materials inside containment.

There is a concern that, following a LOCA, this debris mix could collect on the sump screen and create sufficient resistance to the recirculating flow such that long-term core cooling might be challenged. There is also concern about the consequences of the debris that may pass through the sump screen. This debris could be ingested into the ECCS and flow into the reactor coolant system (RCS) where it may collect on the fuel. These concerns have been broadly grouped under Generic Safety Issue 191 (GSI-191) (Reference 7).

Significant work has been performed by the nuclear industry to address the issues associated with GSI-191. Included within this body of work is a PWROG program in which testing was performed to assess the effect of the collection of debris and chemical precipitates on core components and on head loss across the core at flow rates representative of when the ECCS is realigned to recirculate coolant from the containment sump. The results of this program are documented in WCAP-16793-NP-A, Revision 2 (Reference 6) and support the overall evaluation of the GSI-191 issue. From the testing, a fibrous debris loading of 15 g/FA has been shown to provide for sufficient flow as to provide assurance that LTC of the core is not impeded for all United States (U.S.) fuel and U.S. PWR designs. The NRC SE for Reference 6 accepts the 15 g/FA loading of fibrous debris as a HLB limit. The SE also suggests that, for a maximum fibrous debris loading of 15g/FA at the core entrance, the maximum fibrous debris loading anticipated at the core entrance for a CLB scenario would be less than 7.5 g/FA. The SE goes on to identify actions to be taken by licensees should they choose to increase their acceptable fiber limit above the 15 g/FA limit.

The PWROG has undertaken a comprehensive test and analysis program to demonstrate that LTC is maintained with increased fibrous debris limits per fuel assembly. Described in Volume 1 of this technical report are the debris limits for both hot leg (HL) and cold leg (CL) breaks for PWR's. As part of this comprehensive program, a method has been developed to conservatively predict and assess the time-dependent delivery of fibrous debris to the reactor vessel and core for a CLB once the ECCS has been realigned to take suction from and recirculate the coolant in the containment recirculation sump. The method assumes that any fibrous debris delivered to the reactor vessel and core is captured near the core inlet.

The method is an extension of the approach described in Section 5.0 of WCAP-16406-P-A (Reference 4). The method applied to the CLB scenario tracks the depletion of fibrous debris concentration in the recirculating coolant due to capture of that debris on both recirculation sump screens and near the core inlet. The method uses plant specific values in the calculation method to track fibrous debris through the sump screen and through the ECCS, the CSS, and to the reactor vessel and core to make a determination of the

amount of fibrous debris that is delivered to the bottom entrance of the core for a CLB LOCA. Presented here is a description of the method and the inputs required for the method to operate upon.

This method is developed for use by utilities to evaluate plant-specific PWR CLB performance in the presence of post-LOCA debris.

1. The method provides a means for plants to calculate the plant-specific amount of fiber actually reaching the core in a large CLB scenario, which can then be compared to the at-core CLB fiber limit (see Volume 1 of this WCAP for the CLB fiber limit). A value lower than this defined fiber limit is interpreted as an acceptable condition to provide for LTC of the core.
2. Alternatively, a utility can use this methodology to develop a plant-specific limit on the amount of fiber that can bypass the recirculation sump screens in a CLB scenario and still stay beneath the at-core limit defined in Volume 1 of this WCAP. This limit can then be used in conjunction with HLB limits, also defined in Volume 1, to determine the overall plant-specific limit on fiber bypassing the sump screen.

A description of the method and the inputs required for the method to operate on a specific plant is provided in this document.

# 3 METHOD DISCUSSION

## 3.1 GENERAL DISCUSSION

For a large break LOCA, the ECCS and CSS flows are generally aligned to draw suction from the containment sump when the liquid inventory in the Refueling Water Storage Tank (RWST), Borated Water Storage Tank (BWST) is depleted to a predetermined level. The CSS supplies spray to the containment environment for control of pressure, temperature, and dose. The ECCS supplies water to the core via the RCS cold legs which then flows into the downcomer and through the lower plenum for long-term core cooling.

Containment recirculation sump screens are designed to act as filters to collect post-accident debris, thus preventing a wide range of debris from entering the ECC and CS systems. However, a portion of the debris may be sufficiently small or deformable to actually "pass through" the recirculation sump screen and enter the ECC and CS systems. This "pass through"' (also sometimes called "bypass") debris in the ECCS may then enter the RCS. For either a HL or a CL break the CSS flow is returned to the containment where it is ducted to the sump and again filtered by the recirculation sump screen before the coolant enters either the ECCS or the CSS.

During the recirculation phase for a CLB LOCA, coolant flow into the core region is driven by a balance between the available driving head of the water height in the downcomer and the rate of boil-off of liquid inventory due to removal of decay heat from the core. Therefore, the amount of "pass through" debris provided to the Reactor Vessel (RV) and the core is proportional to the amount of flow needed to satisfy core boil-off requirements. Decay heat will decrease following the initiating event, resulting in decreased flow into the core due to decreased boil-off. The calculation method uses the rated core power of the reactor, time of recirculation initiation, decay heat rate at the time of recirculation and fluid properties of the coolant to calculate the boil-off rate at the time of recirculation initiation and thereafter.

As described above, the operation of the CSS acts to "clean up" fibrous debris in the recirculation sump inventory without adding debris to the core. Thus CSS flow rates and time of CSS actuation and/or termination are parameters used to assess the time-dependent concentration of fibrous debris in the recirculation sump inventory.

As part of the resolution of GSI-191, many plants have performed debris capture testing of their replacement sump screen. The purpose of these tests was to determine the amount of debris that can accumulate on the screen while still maintaining sufficient net positive suction head (NPSH) to meet pump performance criteria and ensure long term core cooling. In some instances, plants have also performed bypass tests to determine the capture efficiency (debris retention as opposed to pass through) of their screen and use this information to estimate the amount of fiber that may accumulate in the core on a grams per assembly basis. The conservative default baseline bypass value used in this evaluation methodology is 45% (55% capture efficiency) and is based on the Nuclear Energy Institute (NEI) 'clean plant' criteria (Reference 8). For the plant-specific evaluations, plants should use their screen capture efficiencies when acceptable.

## 3.2 DESCRIPTION OF SYSTEM ALIGNMENTS

To evaluate the potential for accumulation of fiber at the core entrance, this evaluation method considers the complete system requirement for a cold leg break LOCA, including containment spray, CL safety injection, and core boil-off requirements. Figure 1, below, provides a general schematic of the flow paths for coolant when the ECCS and the CSS are realigned from drawing suction from the RWST (also called the Refueling Water Tank (RWT) or Borated Water Storage Tank (BWST) at some plants) to recirculating coolant from the reactor containment building recirculation sump. For a CLB scenario;

- The ECCS draws coolant from the sump through the recirculation sump screen and pumps it into the RCS. Coolant in excess of that needed to match boil-off spills from RV out the broken loop and back into the sump. Only the coolant that is needed to make up boil-off carries debris into the core.
- The CSS also draws coolant from the sump through the recirculation sump screen, pumps it to the CSS spray headers, where the coolant is released to the containment and is returned to the sump.

These two flow paths drawing from a common source suggest a simple model may be used to evaluate the total amount of fibrous debris delivered to the core while accounting for the depletion of fibrous debris in the sump coolant due to capture by the recirculation sump screen and the fibrous debris that is delivered to the RV and core. Plant-specific applications should confirm the applicability of these flow paths and model them as appropriate. See the next section for important assumptions, including debris concentration, incorporated into this model.

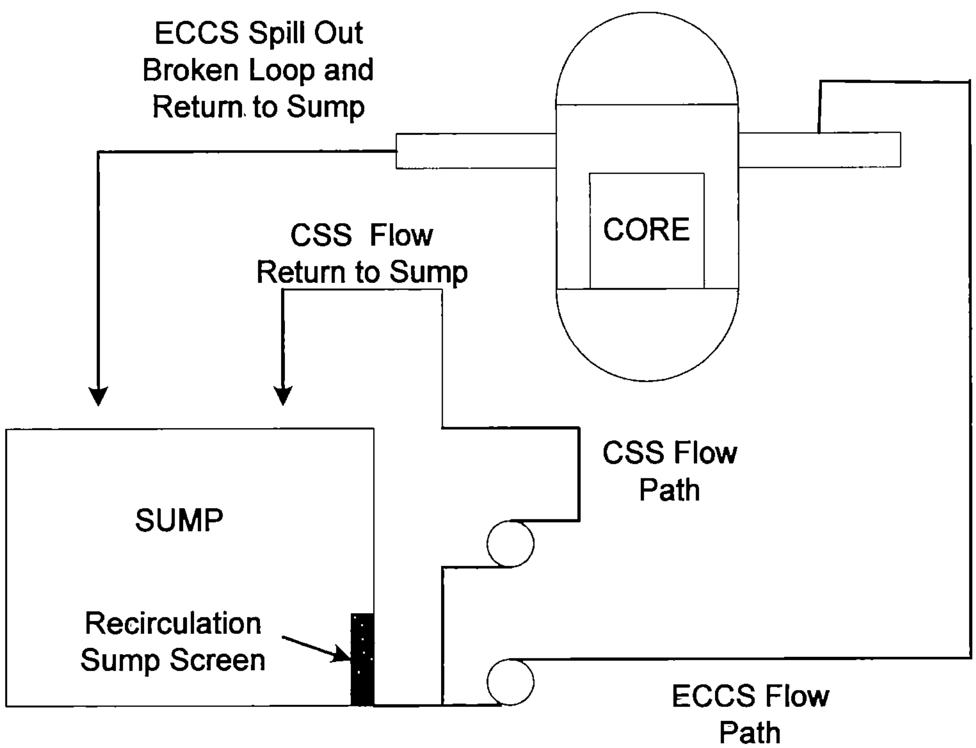


**Figure 1 - ECCS and CSS Flow Paths for a CLB**

## 3.3 ASSUMPTIONS OF THE METHOD

The following assumptions are made for the method to calculate fibrous debris deposition at the core entrance for a CLB.

1. The fiber is in its constituent form, i.e., individual fibers. This is consistent with maximum transport assumptions.
2. The fibrous debris remains suspended in the recirculating fluid and does not settle out. Suspended fibers are easily transported throughout containment, and assuming no settling is conservative.
3. The fiber in the sump pool is uniformly mixed at all times. Uniform mixing in the sump pool maintains a uniform fiber concentration as it transports throughout containment.
4. The fiber in the ECCS and CSS flow is uniformly mixed for each time step. Uniform mixing in the ECCS and CSS maintains a uniform fiber concentration as it transports to downstream locations.
5. To allow for uncertainties in the debris concentration of the coolant entering the core, the fluid volume entering the fuel is assumed to be 1.2 times the boil-off flow rate requirement based on the decay heat at any given time in the transient starting at recirculation initiation. Although the 1.2 multiplier on boil-off flow is consistent with the guidance of NSAL-95-001 (Reference 9) it is not related to the guidance of NSAL-95-001. As noted, the 20% increase in the amount of fiber laden fluid reaching the core accounts for uncertainties in the stepwise hand calculation.
6. The core entrance is assumed to capture 100% of the fibrous debris delivered in the boil-off mass.
7. The mass of coolant in the recirculation sump remains constant in time.
8. The concentration of fiber in the sump volume is reduced in each time step by the amount of fiber captured by the recirculation sump screen and at the core entrance. All fiber not captured by either the recirculation sump screen or the entrance to the core in a single time step is returned to the sump and accounted for in the sump fiber concentration for the next time step.
9. In the absence of plant specific recirculation screen performance, a recirculation screen bypass fraction of 45% is suggested (Reference 8). If a licensee has either a constant bypass fraction or time-dependent fiber bypass fraction for their recirculation sump screen(s) based on testing, the licensee may use that data in the calculation scheme. The licensee assumes the responsibility for justifying the use of the fiber bypass fraction with the NRC.

### 3.3.1 Conservatisms

Listed below are conservatisms of the method to calculate fibrous debris deposition at the core inlet for a CLB.

- The minimum sump water volume assumed in the input to provide the highest concentration of fiber.
- Earliest time of sump recirculation provides highest core decay heat.
- Earliest time of sump recirculation maximizes fiber capture in the core.
- Limiting single failure in the ECCS and CSS.
- Core power uncertainty: The prevailing core power uncertainty should be assumed.

- In the absence of data, use the NEI recommended recirculation sump strainer bypass value. This is considered a conservative value that maximizes sump strainer bypass.
- The maximum fiber load transported to the sump strainer is uniformly mixed in the sump volume, providing the highest concentration of fiber.
- The maximum LTC sump water temperature assumed in the input provides the highest mass to satisfy boil-off requirement and thereby provides for the highest fiber deposition rate in the core.
- The amount of fiber entering the core is increased by 20%.
- 100% of the fiber entering the core is captured in the core.
- The latest HL switchover time maximizes fiber capture in the core.

## 3.4 OVERVIEW OF THE METHOD LOGIC

The amount of fiber delivered to the core entrance between the initiation of sump recirculation and hot leg switchover (HLSO), or similar actions to prevent boric acid precipitation, may be determined by applying the following method with plant-specific parameter values. The method is applied on a time-wise basis between the initiation of recirculation and HLSO to provide the user with a conservative value of fiber delivered to the core entrance.

The following is a description of the calculation logic for the method.

- Determine the mass of transportable fiber in the sump due to the event.
- Determine the coolant volume in the sump.
- Calculate the initial mass concentration of fiber in the sump pool.
- Determine the sump filtering screen efficiency (fraction of fiber captured by the screen) to be used in the calculation.
- Determine the ECCS and CSS flow rates.
- Calculate the mass concentration of fiber in the downstream ECCS and CSS flows considering the sump screen filtering efficiency.
- Return CSS mass and its fiber concentration to the sump.
- Determine core boil-off requirement based on decay heat and sump fluid temperature (account for sensible heat and heat of vaporization).
- Determine the split of the ECCS flow between the amount needed to satisfy core cooling requirements with the remaining coolant spilling into the recirculation sump through the broken CL pipe.
- Using the fiber concentration in the ECCS flow required to match core boil-off, calculate the fiber mass delivered to the core entrance.
- Return the spilled ECCS mass and its fiber concentration to the sump inventory.
- Repeat with reduced ECCS fiber concentration due to fiber capture on the sump screen and in the core.

Using the flow schematic of Figure 1 and the general description given above, the calculation flow chart for the CLB method is shown in Figure 2.

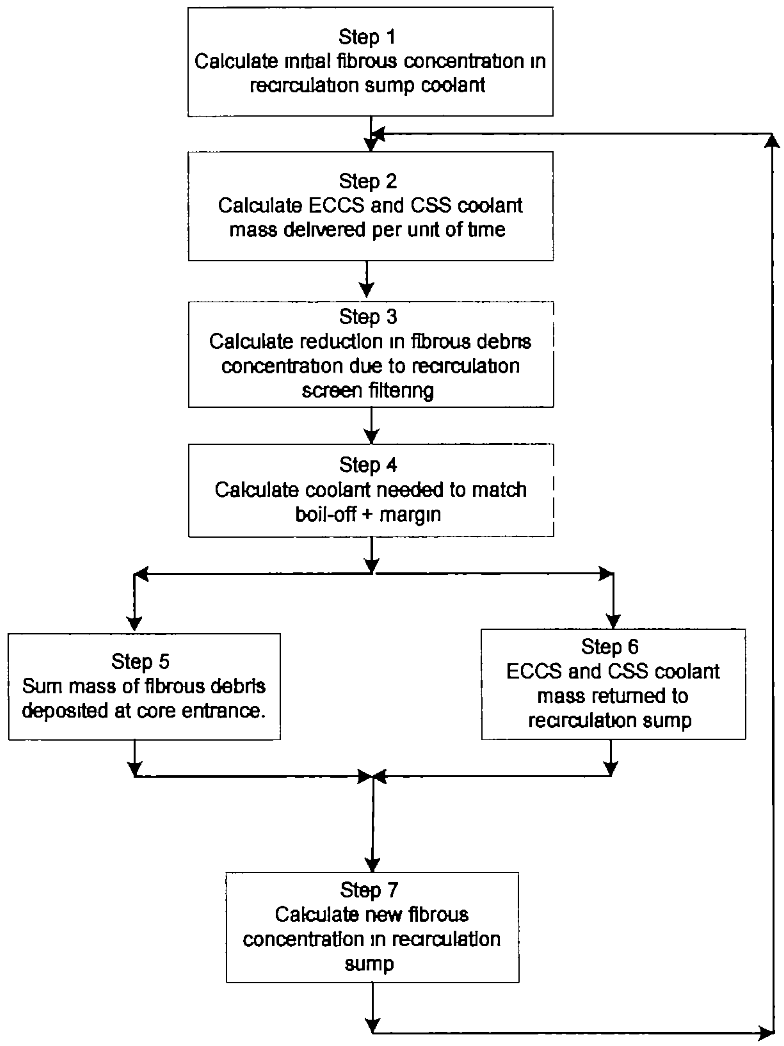


**Figure 2 - Flow Chart for CLB Method Calculations**

## 3.5 EQUATIONS

The mathematical equations needed to perform the calculations to support this evaluation are straightforward and follow those presented in Chapter 5 of Reference 4. As the equations are solved explicitly as a difference from time step to time step, they may be solved by hand using the appropriate thermodynamic properties of water. Alternatively, these equations can be readily solved using a spreadsheet formulation and an appropriate add-in set of equations to calculate thermodynamic properties of water.

Guidance on input parameter values is provided in Section 3.6, "Input Required," including the use of conservative design basis values.

### 3.5.1 Step 1: Calculate Initial Fibrous Concentration in Recirculation Sump Coolant

The initial concentration of fibrous debris in the recirculation sump coolant is calculated as:

$$C_i^* = \frac{M_{fiber,i}}{M_{Sump\ Coolant}}$$

Where the parameters are defined as:

| | | |
|---|---|---|
| $C^*$ | = | Mass concentration; ppm. |
| $M$ | = | Mass; $lb_M$. |

And the subscripts are defined as:

| | | |
|---|---|---|
| $fiber$ | = | Transportable fibrous debris in the form of fiber fines that is available to the coolant inventory; $lb_M$. |
| $Sump\ Coolant$ | = | Refers to mass of coolant in recirculation sump; $lb_M$. |
| $i$ | = | The index on time steps for the calculation scheme and is set to $i = 1$ for the first calculation. |

Note that the values for all time-dependent parameters such as time of switchover from ECCS injection to ECCS recirculation from the recirculation sump or the decay heat rate for an iteration, are based on time from the initiation of the event. The index, $i$, refers to the iteration sequence or number following switchover from ECCS injection to start of ECCS recirculation from the recirculation sump.

### 3.5.2 Step 2: Calculate ECCS and CSS Coolant Mass Delivered per Unit of Time

The mass of coolant delivered by the ECCS per unit time is calculated using the following equation;

$$M_{ECCS} = c_1 \times \dot{V}_{ECCS} \times \Delta t$$

Where the parameters are defined as:

| | | |
|---|---|---|
| $\dot{V}$ | = | Volumetric flow; gpm. |
| $c_1$ | = | Conversion factor; gpm to $lb_M$/minute; evaluate the density of water at the containment pressure and the sump fluid temperature (note that for water, the conversion from gallons to pounds is 8.329 $lb_M$/gal. at 70°F). |
| $\Delta t$ | = | Time interval for calculations; one minute is used for reference or base calculations. If a unit of time other than minutes is used (perhaps seconds), |

assure that an appropriate time conversion is applied to this and all other time-based equations employed by this method.

The subscripts are defined as:

| | | |
|---|---|---|
| $ECCS$ | = | Refers to the ECCS. |

The mass of coolant taken from the recirculation sump by the CSS per unit of time is calculated using the same equation, but substituting the volumetric flow of the CSS for that of the ECCS:

$$M_{CSS} = c_1 \times \dot{V}_{CSS} \times \Delta t$$

Where the subscript is defined as:

| | | |
|---|---|---|
| $CSS$ | = | Refers to the CSS. |

### 3.5.3 Step 3: Calculate Fibrous Debris Concentration Downstream of the Recirculation Sump Screen

The fibrous debris concentration downstream of the recirculation sump screen is reduced due to the filtering action of the recirculation sump screen. This reduction is calculated as:

$$\Delta C_i^* = C_i^* \times (1 - \varphi_{EFF})$$

Where the parameters are defined as:

| | | |
|---|---|---|
| $\Delta C^*$ | = | Remaining concentration of fibrous debris in coolant passing through the sump screen; ppm. |
| $\varphi_{EFF}$ | = | Filtration efficiency of the recirculation sump screen (percentage of fibrous debris filtered by the recirculation sump screen); dimensionless. |

### 3.5.4 Step 4: Calculate Coolant Needed to Match Boil-off plus Margin

First, the amount of decay heat to be removed in one time step is calculated. The amount of decay heat to be removed at a given time, t, is calculated as follows.

$$Q_i = \dot{Q}_{Rated\,Power} \times \theta_i \times \Delta t$$

Where the parameters are defined as:

| | | |
|---|---|---|
| $Q$ | = | Total thermal energy released during the time step, $\Delta t$: Btu. |
| $\dot{Q}$ | = | Rate of thermal power generation: Btu/min |

$\theta$ = Decay heat curve relative to time of reactor trip: dimensionless.

And the subscripts are defined as:

$Rated\ Power$ = Rated power of the reactor: Btu/min

This equation assumes that the decay heat remains constant over the time interval $\Delta t$. The amount of coolant needed to remove the decay heat by boiling is evaluated accounting for both sensible and latent heat. This is accomplished by evaluating the sensible heat needed to raise the temperature of the coolant from the sump temperature to the saturation temperature at the containment pressure. Expressed mathematically;

$$\Delta h_f = h_{f,T=Saturation,t} - h_{f,T=Sump,i}$$

Where the parameters are defined as:

$h_f$ = Enthalpy of the liquid coolant: Btu/lb$_M$.

$\Delta h_f$ = Change in enthalpy of the liquid coolant: Btu/lb$_M$.

And the subscripts are defined as:

$T$ = Temperature: °F.

$Saturation$ = Refers to saturation temperature at containment pressure.

$Sump$ = Refers to temperature of coolant in the recirculation sump.

Next, the latent heat of vaporization of the coolant, $h_{fg,i}$, is evaluated at the containment pressure. The units on the heat of vaporization are also Btu/lb$_M$.

The mass of coolant needed to remove the decay heat generated over one time step by boiling is now calculated as:

$$M_{Boil-off,i} = \frac{Q_t}{(\Delta h_f + h_{fg})}$$

Where the subscript is defined as:

$Boil - off$ = Refers to the mass of coolant needed to remove all of the decay heat generated in one time step by heating the coolant from sump temperature to saturation temperature at containment pressure and then boiling the coolant.

A 20% factor is added to $M_{Boil-off,t=0}$ to account for uncertainties in the amount of fibrous debris delivered to the core. Thus, the method increases the coolant mass, and therefore the amount of fibrous debris, delivered to the core at each time step by 20% as follows;

$$M_{Core,i} = 1.2 \times M_{Boil-off,i}$$

This is the value of the coolant mass that is used to calculate the amount of fibrous debris deposited at the core entrance for each time step. Note that the 1.2 multiplier is only used to increase the debris provided to the core; it does not affect the mass of coolant used for decay heat removal.

### 3.5.5 Step 5: Sum the Mass of Fibrous Debris Deposited at the Core Entrance

The mass of fiber deposited at the core entrance is calculated by multiplying the coolant mass delivered to the core by the fibrous debris concentration that was calculated in Step 3.

$$M_{Core\ Fiber,i} = c_2 \times \Delta C_i^* \times M_{Core,i}$$

Where the parameter is defined as:

| | | |
|---|---|---|
| $c_2$ | = | Is a constant for converting lbm to grams; 453.6 g/lbm. |

And the subscript is defined as:

| | | |
|---|---|---|
| $Core\ Fiber$ | = | Refers to the fiber delivered to the core with the coolant mass needed to removed decay heat + 20% to address uncertainties. |

The running total mass of fibrous debris delivered to the core is calculated by summing the fibrous debris delivered for each time step. This is calculated as follows.

$$M_{Total\ Core\ Fiber} = \sum_{i=0}^{i=N} M_{Core\ Fiber,i}$$

Where $M_{Total\ Core\ Fiber}$ is the running total of fibrous debris delivered to the core from time step $i = 1$ (switchover from ECCS injection from the RWST/BWST to recirculation from the recirculation sump) to time step $i = N$.

The running loading of fibrous debris per fuel assembly (F/A) is also readily calculated by dividing $M_{Total\ Core\ Fiber}$ by the number of fuel assemblies in the core.

$$M_{Fiber\ per\ F/A} = \frac{M_{Total\ Core\ Fiber}}{No.of\ F/A\ in\ core}$$

### 3.5.6 Step 6: ECCS and CSS Coolant Mass Returned to Recirculation Sump

As shown schematically in Figure 1 and stated in Assumption 7, the method maintains the mass of coolant in the recirculation sump constant at all times during the calculation. To accomplish this, and to prepare for calculating a reduced fibrous debris concentration in the recirculation sump inventory:

- All of the coolant taken by the CSS during a time step is returned to the coolant mass in the recirculation sump with the fibrous debris concentration reduced by the filtration efficiency of the recirculation sump screen.
- Similarly, the spilled ECCS flow is also returned to the coolant mass in the recirculation sump with the fibrous debris concentration reduced by the filtration efficiency of the recirculation sump screen.
- The mass directed to the core is also returned to the coolant mass in the recirculation sump, but with no fibrous debris as this debris is assumed to have been completely deposited near or at the core entrance.

The returned masses are used as inputs to the calculation of a reduced concentration of fibrous debris in the recirculation sump for the next time step. This is shown as Step 7 of Figure 1.

### 3.5.7 Step 7: Calculate New Fibrous Debris Concentration in Recirculation Sump Inventory

The filtering of fibrous debris by the recirculation sump screen and the deposition of fibrous debris at the core entrance reduces the available fibrous debris in the sump coolant and therefore reduces the concentration associated with that debris. This reduced concentration is calculated as follows.

The mass of fibrous debris filtered by the recirculation sump screen for any time step, $i$, is calculated as follows;

$$M_{Filtered,\ i} = (M_{ECCS} + M_{CSS}) \times C_i^* \times \varphi_{EFF}$$

The mass of fibrous debris deposited at the core entrance for time step $i$, $M_{Core\ Fiber,i}$, is calculated in Step 5. The remaining mass of fibrous debris is then calculated as:

$$M_{fiber,i+1} = M_{fiber,i} - M_{Filtered,i} - M_{Core\ Fiber,i}$$

Where the subscript are defined as:

| | | |
|---|---|---|
| $i+1$ | = | Refers to the next time step in the sequence of iterations of the calculations performed to determine the mass of fibrous debris deposited at the core inlet. |

Replacing $M_{fiber,i}$ with $M_{fiber,i+1}$, the calculations given in Step 1 through and including Step 6 are repeated to calculate the deposition of fibrous debris at the core entrance for time step $i+1$. In Step 7, the residual amount of fibrous debris remaining in the recirculation sump fluid at the beginning of the time step $i+2$ is calculated by repeating this process.

The calculations of Step 1 through and including Step 6 are then repeated for N time steps, or until a decision is made to terminate the calculation.

### 3.5.8 Suggested Time Step Interval

For this evaluation, a time step of one minute is suggested for the following reasons:

- The mass of fluid inventory in the recirculation sump is large compared to the mass of the ECCS and CSS over a one minute time step. The one minute time step provides for a relatively slow "clean up" of fibrous debris by both the recirculation sump screen and the core. The results of the calculations are therefore insensitive to variations in time step sizes about the one minute value.
- The use of a one minute time step provides for small changes in the decay heat curve from time step to time step in the time period of start of recirculation from the sump and beyond. This provides for an accurate calculation of core boil-off mass needed for long-term core cooling.
- The use of a one minute time step is convenient for the calculations as the ECCS and CSS flow rates are generally defined in units of gallons per minute.
- The use of time steps smaller than one minute have been evaluated and determined to have a negligible impact on the calculated results.

Thus, for the reasons noted above and from a practical consideration, a one minute time step for this calculation is suggested. This recommendation, however, does not preclude the use of a smaller time step.

### 3.5.9 Additional Discussion

It is important to note that this is a plant-specific calculation based on plant-specific parameters. The method provides for the calculation of both the mass of fibrous debris past sump screen, and the mass of fibrous debris delivered to the core inlet following a postulated CLB. The method also allows for the calculation of the maximum allowable fiber that may past through (bypass) the sump screen for a CLB at a plant and still meet the at-fuel fiber limit determined in Volume 1 of this WCAP.

## 3.6 INPUT REQUIRED

This section identified and discusses the input parameters needed for the calculations of this method.

### 3.6.1 Overview of Required Inputs

The inputs required for the method for calculating debris deposition at the core entrance are as follows. These inputs should be readily available in current plant documentation and the values should be consistent with the plant design basis. See Section 3.6.1, "Design Basis Inputs," for additional discussion regarding use of design basis and conservative inputs.

| PARAMETER | UNITS |
|---|---|
| 1. Earliest time of sump recirculation initiation after the LOCA | – minutes |
| 2. Minimum sump volume at recirculation initiation | – $ft^3$ |
| 3. Screen bypass fraction | – dimensionless |
| 4. Core power (thermal) plus uncertainty | – MWt |
| 5. Latest time of HL switch over (or the equivalent) following a LOCA | – hours |
| 6. ECCS flow at recirculation; design basis value* | – gpm |
| a. ECCS initiation and termination or flow reduction times following a LOCA | – minutes |
| 7. CSS flow at recirculation; design basis value* | – gpm |
| a. CSS initiation and termination or flow reduction times following a LOCA | – minutes |
| 8. Total volume of fiber fines transported to the sump screen** | – $ft^3$ |
| 9. Number of FAs | – dimensionless |
| 10. Decay heat curve, starting at recirculation initiation*** | – dimensionless |
| 11. Sump fluid temperature curve starting at recirculation initiation | – °F |
| 12. Containment pressure curve starting at recirculation initiation | – psia |

* ECCS and CSS flows should account for the limiting single failure in the ECC and CS system. Also, "flow reduction" refers to throttling as well as other means of flow reduction for both ECCS and CSS flows.

** When converting the volume of fiber fines transported to the sump screen to a mass value, care should be taken to use the appropriate density. A density of 2.4 $lb_M/ft^3$ may be used for low-density fiberglass and latent fibrous debris. An appropriate as-manufactured density value should be used for high-density fiberglass.

*** The use of the normalized ANSI/ANS 1971+20% decay heat curve is recommended as the default decay heat curve for use in this calculation. Note that a different decay heat curve, such as the ANSI/ANS 1979+2σ decay heat curve, may be used when accompanied with appropriate technical justification.

In addition to the input parameters listed above, the CLB methodology also requires access to thermodynamic properties for water and an approved decay heat curve.

1. If performing these calculations by hand, table lookup of thermodynamic properties is appropriate.
2. If automating the calculations using an automated tool such as Excel, steam table routines are commercially available and can be included as an 'Add In' in Excel.
3. The decay heat curve used should be an NRC-approved version that is consistent with the plant licensing basis. See Section 3.6.1, "Design Basis Inputs," for additional discussion regarding use of a decay heat curve.
4. A table lookup may be used if performing the calculations by hand, or if automating the calculations using a tool such as Excel, an automated routine that calculates the decay heat as a function of time may be used.

### 3.6.2 Design Basis Inputs

The use of design basis inputs are recommended for this calculation method as their use will predict a conservatively large collection of fibrous debris near or at the core entrance. Listed below are recommendations for use of design basis and conservative inputs to the method to calculate fibrous debris deposition at the core inlet for a CLB.

1. Use of minimum coolant mass or volume in the sump. The minimum sump coolant mass or volume used as an input provides the highest concentration of fiber in the recirculation coolant both initially and throughout the calculation.
2. Use the maximum fiber load that has been calculated to be transported to the sump strainer. This input, along with the use of the minimum coolant mass or volume in the sump, provides for a maximum concentration of fibrous debris throughout the calculation,
3. Use the limiting single failure in the ECC and CS system. This will result in a slower "clean-up" of the fibrous debris by the recirculation sump screen and maximize the concentration of the fibrous debris laden coolant delivered to the core.
4. Use of the latest HLSO time. This provides for a maximum time to provide debris laden coolant to the RV and core, maximizing the fibrous debris capture at and near the core.
5. Use the maximum LTC sump water temperature. Use of the maximum temperature of the recirculation sump inventory provides for maximum coolant mass to the core to satisfy boil-off requirement and thereby provides for the highest fiber deposition rate at the core.
6. Use the earliest time of start of recirculation from the recirculation sump consistent with design basis calculations. This provides for the use of the highest core decay heat throughout the calculation and maximizes the fibrous debris laden coolant delivered to the core.
7. Use the licensing basis core power uncertainty. This value will provide for maximum decay heat at any time in the calculation, thereby maximizing boil-off requirements and maximizing fibrous debris delivered to the RV and core.

8. Use the ANSI/ANS 1971+20% decay heat curve. This decay heat curve is conservatively large, will maximize fibrous debris laden coolant needed to match boil-off and therefore provide for the delivery of a conservatively large amount of fibrous debris to the RV and core.
9 In the absence of data, use the NEI-recommended recirculation sump strainer bypass value. This is considered a conservative value that maximizes sump strainer bypass. Using a fixed strainer bypass fraction maximizes accumulation in the core in the baseline calculation by providing the highest downstream concentration throughout the calculation. See Section 3.6.3, "Best Estimate Inputs," for additional discussion on use of plant specific recirculation sump strainer data.

### 3.6.3 Best Estimate Inputs

A licensee may choose to use best estimate but still conservative inputs. It is the responsibility of the licensee to justify and defend the use of such inputs to the regulator.

Possible best estimate input values include, but may not be limited to, the following.

1. Use a plant-specific average sump strainer bypass value or use a time-dependent strainer fiber capture curve (based on test data, the plant specific data may demonstrate a larger fibrous debris capture than the NEI "clean plant" value.

   **CAUTION:** The plant-specific bypass fraction is usually a single value but may be a time dependent curve. When using a plant-specific value, it is important to iterate on the assumed CLB method input value so that the resulting total bypass value over the transient is equal to the value resulting from plant-specific testing. See Section 3.7, "Other Considerations" for additional guidance on this item.

2. ECCS flow may be modeled as being best estimate flows; these flows provide a steady clean-up of fiber by the recirculation sump screen while providing fiber to the core.
3. CSS flow may also be modeled as being a best estimate; these flows provide a steady clean-up of fibrous debris by the recirculation sump screen.
4. The use of a decay heat curve other than 1971+20%.
   a. The decay heat curve identified in the explanation of the calculations of the method is the 1971 ANS Infinite Decay Heat + 20%.
   b. If already a part of their licensing basis, or if it is decided to defend its use, individual plants may choose another decay heat curve such as the ANS 1979 + 2σ decay heat curve.

Additional possible best estimate or realistic inputs (inputs with reduced uncertainty) include the following.

- Rated core power without uncertainty (reduces boil-off, thereby reducing fibrous debris laden coolant to the core).
- A best-estimate or average sump volume instead of the minimum sump volume (reduces fibrous debris concentration in the recirculating coolant for the calculation).
- A best-estimate initiation of recirculation time instead of earliest time (reduces decay heat at the initiation of recirculation, thereby reducing the need for debris laden coolant to remove decay heat from the core).

- A best-estimate HLSO time instead of the latest time (earlier termination of delivery of fibrous debris laden coolant to the bottom of the core).
- A best-estimate sump temperature curve (cooler coolant from the recirculation sump reduced steaming, thereby reducing delivery of debris laden coolant to the RV and the core).
- A fibrous debris capture efficiency of the core inlet that is less than 100% (assumes fibrous debris is either deposited elsewhere or is carried out of the core region by steam and coolant carry-over).
- Take credit for a fraction of the CSS fibrous debris concentration being unrecoverable (i.e., fiber that does not return to the sump).
- A plant-specific average sump strainer bypass value, or use a time-dependent strainer fiber capture curve.

  **Caution:** The plant-specific bypass fraction is usually a single value but may be a time-dependent curve. When using a plant-specific by-pass fraction, it is important to iterate on the assumed CLB method input value so that the resulting total bypass value over the transient is equal to the value resulting from plant-specific testing. See the explanation in Section 3.7, "Other Considerations."

## 3.7 OTHER CONSIDERATIONS

As noted previously, if the total fibrous debris that will pass through or "bypass" the sump has been determined by plant specific testing, the following ratio SHOULD NOT be used in the calculations described for this method of calculating fiber capture at or near the core for a CLB:

$$Bypass\ Ratio = \frac{Total\ Mass\ of\ Fibrous\ Debris\ Passed\ Through\ Sump\ Screen}{Total\ Fibrous\ Mass\ in\ Sump}$$

Using the bypass ratio above as a constant value in the calculations of the method will not correctly predict the mass of fiber collected by the sump screen. Rather, a strainer pass-through or "bypass" may be defined by selecting a value less than the ratio defined by the equation above, and then iterating on the value for that ratio until the total calculated mass of fibrous debris that passes through or bypasses the screen equals the total mass of fibrous debris that has been determined to pass through or bypass the sump screen. This is important to avoid being overly conservative, since this methodology returns any uncaptured fiber back to the sump again and uses the input bypass ratio on *each* iteration. Bypass ratios determined by many utilities represent the total bypass ratio (i.e. the total bypass integrated over multiple sump turnovers). The iteration technique allows a bypass ratio input to be developed that allows the total bypass to match utility data.

The CLB method can be used in a number of ways to provide the user with meaningful information regarding the accumulation of fiber at the core. The plant-specific input parameters can be manipulated by the user to run the calculation forward and backward to determine:

- The g/FA accumulated at the core at the time of HLSO (or the equivalent).
- The strainer bypass fraction that must be attained to meet a specified core accumulation (g/FA) prior to HLSO (or the equivalent) for a given debris load.
- How much fiber actually bypasses the sump strainer to arrive at a specific core accumulation (g/FA): this calculation is performed assuming a specified core accumulation (g/FA) at HLSO and working backward to determine the amount of fiber that bypassed the sump strainer to accumulate this specific amount in the core. This is done by increasing or decreasing the initial debris load in the sump until the specified core accumulation (g/FA) is reached at exactly the HLSO time (or at 24 hours if a plant does not go to HLSO).

Each of these calculations can be performed using the CLB method as discussed here.

# 4 EXAMPLE APPLICATION OF METHOD

This methodology may be used by licensees to derive a value of fiber bypassing the sump strainers and entering the core following a CLB. Licensees will be expected to provide both their plant specific inputs and the application of this methodology to their plant.

An example of the application of the CLB method described in Section 3 is provided below. Using the information in Section 3, plants can gather input as shown in Table 4-1 to implement the methodology and calculate the amount of fiber expected at the core following a large cold leg break LOCA.

## 4.1 EXAMPLE APPLICATION

The following list supports the implementation of the CLB methodology. The collected input values are listed in Table 4-1 to determine the amount of fiber expected at the core following a large cold leg break LOCA. Since this process takes place over a number of hours (typical) steps can be taken at specific time intervals. Since the ECCS and CSS flows are normally reported in gallons per minute (gpm), a time step of one minute is reasonable for this calculation.

- Determine the amount of fiber transported to the sump screen, 20.60 $ft^3$
- Define the sump volume, 47343.93 $ft^3$
- Define the concentration of fiber in the sump pool, 4.35E-04 $ft^3/ft^3$
- Define the sump screen efficiency (fraction of fiber captured by the screen), 55%
- Define the ECCS and CSS flows, 3800 gpm, 3000 gpm
- Define the concentration of fiber in the downstream ECCS and CSS flows, considering the sump screen efficiency 1.958E-04 $ft^3/ft^3$
- Determine core boil-off requirement based on sump fluid temperature and core decay heat, 2.507E+05 $lb_M/hr.$ @ 1500 seconds
- Split the ECCS flow between core requirements and CL spill from the break
- Deposit the fiber concentration in the ECCS flow required for boil-off in the core
- Return the CSS and spilled ECCS fiber concentration to the sump
- Repeat until HLSO (or the equivalent) with reduced ECCS fiber concentration due to fiber capture on the sump screen and in the core

Considering the values in Table 4-1 and the steps above, implementation of the methodology would provide a fiber quantity at the time of HLSO of 6.04 g/FA at the fuel based on a fiber load of 116.197 g/FA upstream of the sump screen and 45% fiber bypass (55% fiber capture).

**Table 4-1 – Input Collection**

Note that this table extends over pages 4-2 and 4-3

| Parameter | Units | Value | Comment |
|---|---|---|---|
| Active sump volume | $ft^3$ | 47343.93 | Minimum volume will result in the highest debris concentration throughout the calculation. If a time dependent sump volume is available, the plant could model the change in sump volume over time. |
| Volume of fibrous debris (transported) | $ft^3$ | 8.0, NUKON<br>0.1, E-glass<br>12.5, latent | Limiting transport value to strainers from the plant debris transport calculations and is used to establish sump fiber concentration (if in $lb_M$, convert to equivalent NUKON 2.4 $lb_M/ft^3$). |
| Recirculation initiation: time of switchover from RWST injection to sump recirculation | seconds | 1500 | Earliest time conservative for setting decay heat at the beginning of recirculation. |
| Bypass fraction | fraction | 0.45 | Default = 0.45 based on the NEI "clean plant" criteria (Reference 8). The default fraction may be reduced when a justified or defendable value is available. Alternate values have risk without bypass test acceptance. |
| Rated core power | MWt | 3500 | Rated core power includes power uncertainty. Uncertainty may be reduced when justified or defendable value is available. |
| Time of HL switch-over (CL injection to HL injection) | hours | 6.0 | Sets time to assess fibrous debris loading on fuel. |
| ECCS flow rate | gpm | 3800 | Design or licensing basis value for baseline calculation. |
| CSS flow rate | gpm | 3000 | Design or licensing basis value for baseline calculation. |
| Fraction of fiber concentration lost to CSS | fraction | 0.0 | Use a zero value (no fibrous debris depletion due to the Containment Spray System) unless plant-specific data or analyses support the use of a non-zero value. Note that technical justification must support the use of a non-zero value for this input parameter. |
| Number of fuel assemblies | N/A | 193 | Plant value. |
| Fiber capture rate of core | fraction | 1.0 | Current capture rate is 100% of fiber entering the core at 1.2 times boil-off. May be reduced when justified or defendable value is available. |
| Sump temperature transient curve (°F/min) | °F | 245°F to 165°F | This is used in conjunction with the time of recirculation initiation and the decay heat curve to determine the core boil-off requirements. |

| Parameter | Units | Value | Comment |
|---|---|---|---|
| Decay heat curve | NA | | ANSI/ANS 1971+20% for baseline calculation. |
| Access to referenceable steam tables | NA | | Used to determine latent heat of vaporization and sump water density using sump fluid temperature. |
| **Plant flow rates:** Because of the numerous ECCS/CSS configurations that currently exist, a single ECCS/CSS flow definition would not be appropriate for all plants. The following input collection scheme is intended to allow plants to capture their unique ECCS/CSS configuration as accurately as possible. | | | |
| ECCS recirculation total flow rate | gpm | 6800 | Total flow entering RCS assuming no failure. |
| ECCS recirculation flow rate with single failure | gpm | 3800 | Flow entering RCS with single failure assumption. |
| ECCS recirculation flow rate with no failure | gpm | | If limiting failure not a train of ECCS. |
| CSS recirculation total flow rate | gpm | | Total flow entering CSS assuming no failure. |
| CSS recirculation flow rate with single failure | gpm | | If limiting single failure is a train of spray. |
| CSS recirculation flow rate with no failure | gpm | 3000 | If limiting single failure is not a train of CSS. |
| CSS switchover time to recirculation | minutes | | If CSS does not coincide with ECCS recirculation. |
| CSS termination time | minutes | | If CSS are terminated prior to HLSO. |

Note that the values in Table 4-1 are for illustrative purposes and are not representative of any particular plant.

# 5 SIMPLIFIED ALTERNATE METHOD

## 5.1 METHOD DISCUSSION

As an alternative to the CLB method described Section 3, a simplified method is presented below. The input used in the simplified method is consistent with the input gathered for the CLB method described in Section 3 and is described as follows.

- The total quantity of fiber expected to bypass the strainer. This can be either the quantity determined from testing, or if testing was not performed, the quantity determined using the Clean Plant Criteria described in Reference 8.
- The earliest time a plant could transfer from injection to sump recirculation.
- The earliest time a plant could transfer from CL recirculation to HL recirculation.
- The expected flow rates for both the ECCS and CSS. The flow rates for these systems determined by the plant's hydraulic analysis should be used. The worst-case single failure that maximizes the flow rate to the core is the case that should be utilized. Typically this would be the case where a single containment spray pump is not operating but could be the case where an entire train of core cooling and spray flow is not available.
- The core boil-off expected at the time of transfer to sump recirculation and at the time of hot leg recirculation is calculated using the product of the value of the reactor full power, plus uncertainty, times the appropriate value of the normalized ANSI/ANS 1971+20% decay heat curve. Note that a different decay heat curve, such as the ANSI/ANS 1979+2σ decay heat curve, may be used when accompanied with appropriate technical justification.

The following calculation is performed to determine the quantity of fiber expected to be delivered to the core. This calculation determines the ratio of the average core boil-off from the initiation of cold leg recirculation to the transfer to HL recirculation, conservatively increased by 20% to the expected total flow through the strainer for the limiting plant configuration, multiplied by the quantity of fiber determined to bypass the strainer.

$$F_{CLB} = F_{BYPASS} \times \frac{ECCS}{STRN} \times \frac{CB_{AVG}}{ECCS} \times 1.2 = F_{BYPASS} \times \frac{CB_{AVG}}{STRN} \times 1.2$$

Where,

$F_{CLB}$ = Fiber expected at the core following a CLB

$F_{BYPASS}$ = Total quantity of fiber that bypasses the strainer

$ECCS$ = Total flow rate of emergency core cooling through the strainer

$STRN$ = Total flow rate through the strainer, which is the sum of emergency core cooling flow and containment spray flow

$CB_{AVG}$ = Average core boil-off flow, determined by summing the core boil-off flow at transfer to CL recirculation and the core boil-off flow at transfer to HL recirculation, and dividing by 2.

The acceptability of this approach is based on the following contributors:

1. The determination of the quantity of fiber that bypasses the strainer does not consider the agglomeration effects that would be prototypical in the plant environment. In other words, testing was performed to maximize the quantity of individual fibers that would reach the strainer, maximizing the quantity that would pass through or bypass the strainer.
2. The 30-day quantity of fiber that bypasses the strainer is used as the total quantity of fiber that is available for transport. Most plants will transfer to HL recirculation in the 4 to 12 hour time frame, which results in a significant reduction of fiber that would be expected to bypass the strainer and available for transport to the core.
3. That fraction of fiber that passes through the strainer and enters the containment spray system would result in a significant quantity of the fiber being dispersed throughout containment, allowing for significant holdup or capture by plant features. Some of the fiber would return to the strainer, where a majority would be expected to be captured by the strainer.
4. 100% of all fiber that enters the ECCS is assumed to be available for transport.
5. Use of the core boil-off values from the earliest time of transfer to CL recirculation and transfer to HL recirculation maximizes the core boil-off flow rate and thus the quantity of fiber delivered to the core.
6. The quantity of fiber expected to be transferred to the core is increased by 20% to provide additional margin to allow for uncertainties in the fibrous debris concentration provided to the core.

# 6 SUMMARY

A method utilizing various flow paths (splits) associated with the ECCS, the CSS, and spilling of excess flow out the broken loop has been developed to evaluate the time-dependent mass of fiber that may pass through the sump screen and time-dependent fiber collection in the core following a postulated cold leg break LOCA for a PWR. The constituent equations for the method are presented in Section 3 and are consistent with those used in prior debris depletion evaluations (Reference 4). Along with the method itself, assumptions and input parameters for the calculations have been identified. This method (or the alternate method in Section 5) is provided for use in performing plant-specific evaluations of the fibrous debris loading on that plant's fuel for a CLB LOCA.

As noted several times, this is a plant-specific methodology that operates on plant-specific parameters. The method provides for the calculation of both the mass of fibrous debris past sump screen, and the mass of fibrous debris delivered to the core inlet following a postulated CLB.

This calculation method can be used to determine the limit on both the maximum allowable fiber that may pass through the sump screen for a CLB at a plant and the maximum allowable fibrous debris loading on a fuel assembly and still meet the at-fuel fiber limit determined in Volume 1.

As an alternative, a simplified method of calculating the fibrous debris delivered to the core has been presented in this document.

# 7 REFERENCES


1. NRC Generic Letter 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized-Water Reactors," September 13, 2004. (U.S. NRC ADAMS Accession No. ML042360586)
2. NEI 02-01, Revision 1, "Condition Assessment Guidelines: Debris Sources Inside PWR Containments," September, 2002. (U.S. NRC ADAMS Accession No. ML030420318)
3. NEI 04-07, Revision 0, "Pressurized Water Reactor Sump Performance Evaluation Methodology," December 2004. (U.S. NRC ADAMS Accession Nos. ML050550138 (Vo. 1) & ML050550156 (Vol. 2))
4. WCAP-16406-P-A, Revision 1, "Evaluation of Downstream Sump Debris Effects in Support of GSI-191," Westinghouse Electric Co. LLC, March 2008.
5. WCAP-16530-NP-A, Revision 0, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," Westinghouse Electric Co. LLC, March 2008. (U.S. NRC ADAMS Accession No. ML060890509)
6. WCAP-16793-NP-A, Revision 2, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid," Westinghouse Electric Co. LLC, July 2013.
7. GSI-191, "Assessment of Debris Accumulation on PWR Sumps Performance," Footnotes 1691 and 1692 to NUREG-0933, 1998," Nuclear Regulatory Commission, May 14, 1997.
8. NRC Review Of Nuclear Energy Institute Clean Plant Acceptance Criteria For Emergency Core Cooling Systems, May 2, 2012. (Adams Accession Number: ML120730181)
9. NSAL-95-001, "Minimum Cold Leg Recirculation Flow," Westinghouse Electric Co. LLC, January 1995.

# APPENDIX A REQUESTS FOR ADDITIONAL INFORMATION (RAIs)

The RAIs addressed herein were provided to the Pressurized Water Reactor Owners Group (PWROG) via the following document. NRC Correspondence, "Request for Additional Information RE: Pressurized Water Reactor Owners Group Topical Report WCAP-17788, 'Comprehensive Analysis and Test Program for GSI-191 Closure,'" August 2016, ADAMS Accession No. ML16102A357

Attachment 1 to LTR-SEE-17-94 Revision 0
Responses to NRC RAIs Specific to WCAP-17788, Volume 3 Supporting the Closure of GSI-191 (PA-SEE-1090) and Mark-ups to WCAP-17788, Volume 3 NON-PROPRIETARY Attachment
(RAIs 3.1, 3.2, 3.22, 3.23, 3.24, 3.25)
(ML17293A218)

Attachment 1 to LTR-SEE-18-153, Revision 0
Revised Responses to NRC Requests for Additional Information (RAIs) Related to WCAP-17788-P/NP, Revision 0, "Comprehensive Analysis and Test Program for GSI-191 Closure (PA-SEE-1090)"
(RAIs 3.3, 3.26, 3.32)
(ML18285A019)

**RAI-3.1**

In Table 1 of Volume 3, the input for fraction of fiber concentration lost to Containment Spray System has a value of 0.0. The comment says "Use non-zero value when justified or defendable value is available." Would the non-zero value be a result of testing? How would a justifiable value be determined?

***Response***

As requested by licensees, the Cold Leg Break (CLB) method described in Volume 3 was developed to be generic with sufficient flexibility to allow for plant specific inputs, should licensees choose to develop them. This parameter is one such instance of the flexibility made available to licensees. A non-zero entry for this parameter is left to the licensee to develop and justify, should they chose to do so. Therefore, Volume 3 of WCAP-17788 does not and will not provide guidance as to how a non-zero value would be determined or justified.

***Proposed Revision to WCAP-17788, Volume 3:***

The WCAP-17788, Volume 3 text in question will be revised to clarify the input values to this parameter as follows:

*Use a zero value (no fibrous debris depletion due to the Containment Spray System) unless plant-specific data or analyses support the use of a non-zero value. Note that technical justification must support the use of a non-zero value for this input parameter.*

**RAI-3.2**

On page 3-9 of Volume 3, parameter $c_2$ is defined as 0.0022026 grams per pound mass (g/lbm). It appears to be the inverse of the intended value. Using this value will have a significantly non-conservative effect. The correct value should be 454 g/lbm (or 0.0022026 lbm/g). Clarify whether the value will be revised.

***Response***

The conversion factor, $c_2$, for converting pound mass to grams that is given on page 3-9 of Volume 3 of WCAP-17788 is the inverse of the correct conversion factor, which is $454\, grams/lbm$. This typographical error will be corrected in the –A version of WCAP-17788, Volume 3.

***Proposed Revision to WCAP-17788, Volume 3:***

The text of WCAP-17788, Volume 3 will be revised as follows:

*Where the parameter $c_2$ is defined as:*

$c_2$ = *Is a constant for converting lbm to grams;* $453.6\ g/lbm$.

**RAI-3.3**

The use of average core boil off values as discussed in Section 5.1 of Volume 3 may result in unrealistic values of fiber at the core inlet. Most of the fiber will penetrate the strainer early in the loss-of-coolant accident (LOCA) response. Using an average value when the actual flow rate decreases during the event can result in unrealistic values of debris transported to the core. Provide justification that the use of an average value results in realistic or conservative values for debris entering the core.

***Response***

While an initial "puff" of fibrous debris may or may not initially pass through the sump strainer, the following is noted:

1. Testing of scaled sump strainer screens at scaled volumetric flow yielding prototypic flow rates has demonstrated that fiber build-up on these screens is rapid with fibrous beds being formed within minutes of initiation of simulated recirculation operation.
2. For a Cold Leg Break, the break of interest in Volume 3 of WCAP-17788, the coolant flow to the core is small, essentially matching core boil-off in the core. For example;
    a. At the time of initiation of recirculation from the reactor containment building sump, about 97% of the coolant being recirculated from the reactor containment sump is either spilled out the break or is ducted to the containment spray system (CSS); only about 3% of the recirculation flow is ducted to the core.
    b. As the transient progresses and core decay heat continues to exponentially decrease, the flow rate to the core also exponentially decreases as core boil-off continues to decrease.
3. Figure RAI-3.3-1 displays a core boil-off curve for a typical Westinghouse 4-loop pressurized water reactor.
    a. The solid black line represents the calculated core boil-off rate as a function of time after the initiation of recirculation from the containment sump, which is taken to be at 30 minutes following the postulated accident. The total amount of debris-laden coolant provided to the core is calculated as the integral under the curve between the time that recirculation is initiated and the time of hot-leg switch-over.
    b. The solid red line connects the core boil-off rate at the start of recirculation from the sump, taken to be 30 minutes after the initiation of the accident, to boil-off rate at the start of hot-leg switch-over which is estimated to be at two hours after initiation of recirculation from the containment sump. The total amount of debris laden coolant provided to the core using the Alternate Simplified Method of WCAP-17788, Volume 3, Section 5.0 is calculated by the trapezoidal rule.
    c. Similarly, the blue dashed line connects the core boil-off rate at the start of recirculation from the sump, again taken to be 30 minutes after the initiation of the accident, to the core boil-off rate at the start of hot-leg switchover which is estimated to be at five hours after the event initiation. Again, the total amount of debris laden coolant provided to the core using the Alternate Simplified Method of WCAP-17788, Volume 3, Section 5.0 is calculated by the trapezoidal rule.

The area under the exponential core boil off (black) curve is less than the area under either the red solid line or the blue dashed line. This would be the case for all PWRs. It is further noted that this example

demonstrates that the greater the time span between start of recirculation from the sump to the start of hot-leg recirculation, the greater the conservatism in coolant mass evaluated using the Simplified Alternate Method (see the blue dashed line).

Thus, the use of the average core boil- off rates conservatively overestimates the total debris laden coolant provided to the core for the Simplified Alternate Method. Thus, the Simplified Alternate Method provides for a conservatively large amount of debris-laden coolant to the core compared to a computed exponential core boil-off curve.

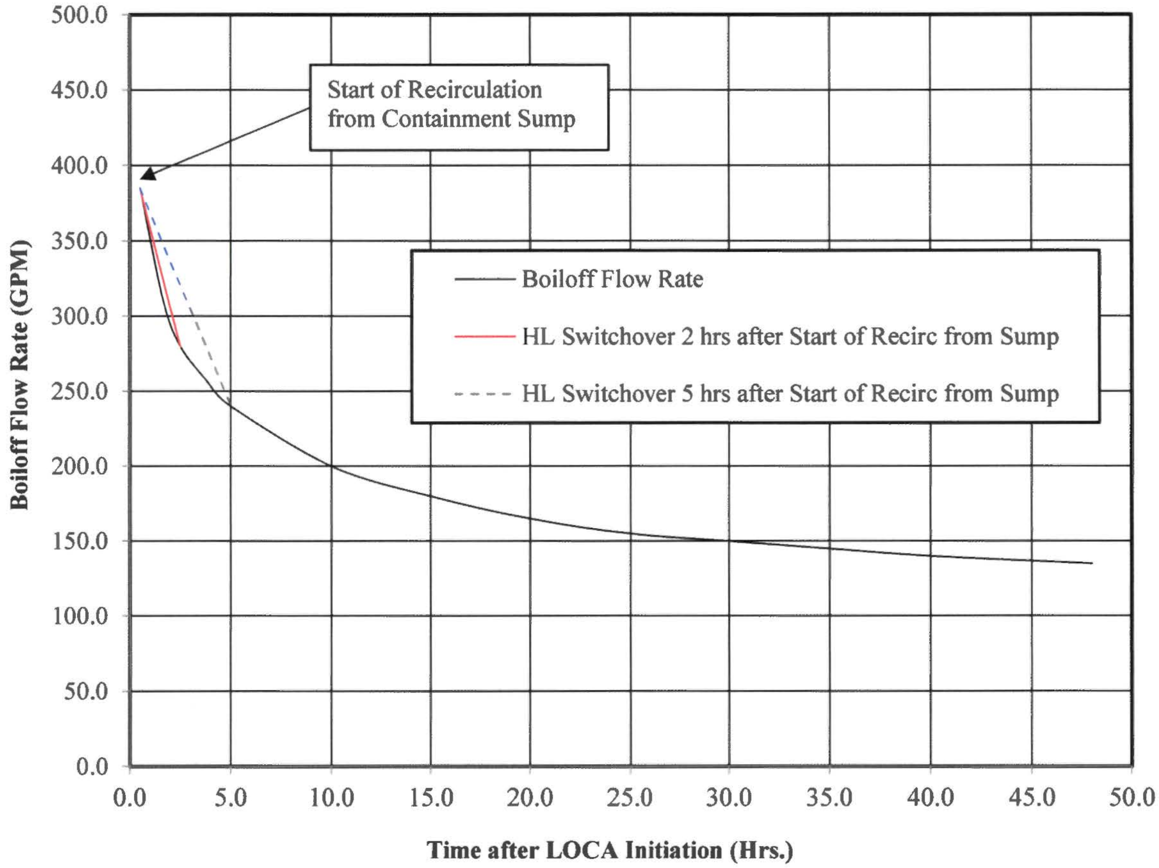


**Figure RAI-3.3-3 - Boil-off Curve for a Westinghouse 4-loop PWR**

Given the sum of the discussion above, the use of the average core boil-off flow rate is taken to be a reasonable approximation employed in the Simplified Alternate Method of Section 5.0 to assess the deposition of fibrous debris at the core inlet for a CLB loss-of-coolant-accident (LOCA).

**RAI-3.22**

Section 5.1 states that "the worst-case single failure that maximizes the flow rate to the core is the case that should be utilized." At the same time, the quantity is defined as "total flow rate of emergency core cooling through the strainer." This is not necessarily an accurate statement. Clarify that the STRN concept, defined as the total flow rate through the strainer, which is the sum of the emergency core cooling (ECC) flow and containment spray flow should be to minimize the flow through the strainer in relation to the flow that enters the core.

***Response***

The statement that, "the worst-case single failure that maximizes the flow rate to the core is the case that should be utilized" is correct as written. The effect of flow rate on the amount of fibrous debris that is passed by sump screens was experimentally studied by the US Nuclear Regulatory Commission and is reported in NUREG/CR-6885 (ML053000064). The parametric test data presented in Table 5-1 of NUREG/CR-6885 shows that the amount of fiber penetrating a sump screen with a given hole size increases with an increase in velocity of the fluid. As the amount of coolant going to the core is dependent upon decay heat, and not the flow rate of ECCS, maximizing the flow through the sump screen maximizes the concentration of fibrous debris, and therefore the mass of fibrous debris, to the core.

**RAI-3.23**

As described for the cold leg break (CLB) method in Section 3.5.4, Step 4 uses a dimensionless quantity, θ, which is identified as the decay heat (DH) curve.

In the simplified alternate CLB method described in Section 5, an average core boil-off flow is used to calculate the expected core fiber load.

Confirm that the quantity, θ, and the average core boil off flow will be calculated based on "the ANSI/ANS (American National Standards Institute/American Nuclear Society) 1971 + 20% decay heat curve" in accordance with Item 8 in Section 3.6.2, unless explicitly stated otherwise.

***Response***

The dimensionless quantity, θ, that is identified as the Decay Heat (DH) curve in WCAP-17788, Volume 3, Section 3.5.4, Step 4, represents a decay heat curve that has been normalized to full power. This was done to provide for the calculation method to be generically applicable to all plants by having the full-power thermal output of a given plant be an input parameter that is supplied by the licensee.

Both calculation methods, Section 3 "Method Discussion," and Section 5 "Simplified Alternate Method," of WCAP-17788-NP Volume 3, employ the ANSI/ANS 1971 + 20% decay heat curve as a default.

Both methods are sufficiently flexible as to allow licensees to employ an alternate decay heat curve. However, should a licensee choose to use a decay heat curve other than ANSI/ANS 1971 + 20%, the licensee is responsible for providing the justification for its use.

***Proposed Revision to Volume 3:***

The following text will be added to Section 3.6.1, "Overview of Required Inputs" of Volume 3 of WCAP-17788:

> 10. *Decay heat curve, starting at recirculation initiation****
>
> ****The use of the normalized ANSI/ANS 1971+20% decay heat curve is recommended as the default decay heat curve for use in this calculation. Note that a different decay heat curve, such as the ANSI/ANS 1979+2σ decay heat curve, may be used when accompanied with appropriate technical justification.*

Likewise, the following clarification will replace the last bulleted item of the first paragraph of Section 5.1:

> *The core boil-off expected at the time of transfer to sump recirculation and at the time of hot leg recirculation is calculated using the product of the value of the reactor full power, plus uncertainty, times the appropriate value of the normalized ANSI/ANS 1971+20% decay heat*

*curve. Note that a different decay heat curve, such as the ANSI/ANS 1979+2σ decay heat curve, may be used when accompanied with appropriate technical justification.*

**RAI-3.24**

As described for the base CLB method in Section 3.5.4, Step 4, a quantity representing the mass of coolant needed to remove the DH generated over one time step by boiling, $M_{Boil-off, i}$, is used to calculate the coolant mass delivered to the core at each time step, $M_{Core, i}$. Section 3.5.4 explains that the method increases the boil-off coolant mass by 20% to determine the coolant mass delivered to the core at each time step. Section 3.5.4 explains that the "20% factor is added" to the boil-off mass to "to account for uncertainties."

For the simplified alternate CLB method described in Section 5, a multiplication constant of 1.2 is used to calculate the expected core fiber load. Section 5.1 clarifies that it is "the average core boil-off from the initiation of cold leg recirculation to the transfer to hot leg (HL) recirculation," which is "conservatively increased by 20%" in the derived formula thus relating the 1.2 multiplier to the boil-off rate in a manner similar to the base CLB method.

a. Confirm that the multiplication factor of 1.2 used to calculate the amount of coolant "needed to match boil-off plus margin" for both the base and the simplified alternate CLB methods accounts for uncertainties other than the uncertainty related to the DH model, which is accounted for separately when calculating the applied DH generation rate.
b. Identify the major factors that contribute to uncertainty and explain how uncertainties associated with these factors were assessed and accounted for by application of the multiplication factor of 1.2.

***Response***

a. The method detailed in WCAP-17788, Volume 3, Section 3.5 does provide for the calculation of the amount of coolant needed to remove decay heat from the core at each time step.

   The multiplication factor of 1.2 is a conservative adder applied to the <u>fibrous</u> <u>debris</u> delivered to the core to ensure that the resultant accumulated fiber quantity is conservative, considering the step-wise hand calculation used to project fiber collection in the core.

   - To that end, the multiplication factor <u>does</u> <u>not</u> increase the flow into the core; rather, the 1.2 multiplier serves to <u>only</u> <u>increase</u> the <u>debris</u> <u>load</u> <u>entering</u> <u>the</u> <u>core</u> by 20%.
   - Therefore, the 1.2 multiplier identified in Section 3.5.4, Step 4, is intended to account for unknowns and uncertainties associated with the delivery of fibrous debris transported to the core independent of flow itself.
   - The 1.2 multiplier is not related to uncertainties in the decay heat model.

   To summarize, the 1.2 multiplier does not add additional flow to the core, only additional debris. Also, the 1.2 multiplier on debris delivered to the core is applied throughout the 30 day time period of interest, thereby providing for a conservatively large amount of fibrous debris to be captured by the core above that needed to match boil-off.

b. The same explanation of the 1.2 multiplier given in Part (a.), above, applies to the response to Part (b.). The unknowns and/or uncertainties associated with the 1.2 multiplier on debris added to the core for each time step are related to variations in the concentration of fibrous debris in the recirculating Emergency Core Coolant (ECC) flow. The selected value of 20%

was based on engineering judgement gained from observing testing of replacement sump screens and fuel assembly debris capture testing.

***Proposed Revision to Volume 3:***

To clarify that the 1.2 multiplier is to account for additional debris provided to the core without increasing the flow to the core, the text of Item 5 of WCAP-17788, Volume 3, Section 3.3, "Assumptions," will be amended as follows:

5. *To allow for uncertainties* ***in the debris concentration of the coolant entering the core****, the fluid volume entering the fuel is assumed to be 1.2 times the boil-off flow rate requirement based on the decay heat at any given time in the transient starting at recirculation initiation.* ***Although*** *the 1.2 multiplier on boil-off flow is consistent with the guidance of NSAL-95-001 (Reference 9),* ***it is not related to the guidance of NSAL-95-001.*** ~~***and accounts for both the possibility of extended boiling in both the downcomer and lower plenum during injection and CL recirculation, as well as the potential for insufficient ECCS flow to the RCS cold legs during CL recirculation for plants which use either residual heat removal, low head safety injection, low pressure safety injection, or recirculation pumps to supply both ECCS recirculation and containment spray flow.***~~ *As noted, the 20% increase in the amount of fiber laden fluid reaching the core accounts for uncertainties in the stepwise hand calculation.*

Also, the text of WCAP-17788, Volume 3, Section 3.5.4 will be amended as follows:

*A 20% factor is added to $M_{Boil-off,t=0}$ to account for uncertainties* ***in the amount of fibrous debris delivered to the core****. Thus, the method increases the coolant mass, and therefore the amount of fibrous debris, delivered to the core at each time step by 20% as follows:*

$$M_{Core,i} = 1.2 \times M_{Boil-off,i}$$

*This is the value of the coolant mass that is used to calculate the amount of fibrous debris deposited at the core entrance for each time step.* ***Note that the 1.2 multiplier is only used to increase the debris provided to the core; it does not affect the mass of coolant used for decay heat removal.***

Text of Item 6 of WCAP-17788, Volume 3, Section 5.1 will be amended as follows:

*The quantity of fiber expected to be transferred to the core is increased by 20% to provide additional margin to allow for uncertainties in the fibrous debris concentration provided to the core.*

## RAI-3.25

Section 3.3, "Assumptions of the Method," attempts to establish a basis to allow for uncertainties in calculating the amount of fibrous debris deposition at the core entrance. The uncertainty in the debris load is based on the uncertainty in the rate at which the coolant enters the core region. The proposed margin in the assessed debris load is introduced by assuming that the rate at which coolant enters the core can be calculated from the current core boil-off rate multiplied by a constant.

Nuclear Safety Advisory Letter (NSAL) 95-001 (Reference 9) considered criteria for minimum ECC System (ECCS) flow during cold leg recirculation, which if met or exceeded, ensures compliance with Title 10 of the Code of Federal Regulations (10 CFR) Section 50.46, "Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors." It was determined that it should be ensured that ECCS flow during cold leg recirculation is at least equivalent to 1.2 times the DH boil-off at the time cold leg recirculation is initiated. As such, Reference 9 does not justify the application of a multiplier of 1.2, or any other value (e.g, 1.5 as recommended in NSAL 92-010), when it comes to describing the rate at which coolant is delivered to the core following recirculation initiation and during the period for which the CLB methods in Volume 3 will be applied.

Verify that the flow assumed to reach the core inlet accounts for phenomena and uncertainties such as those discussed in NSAL 95-001 and 92-010. Provide a justification that the margin added to the calculation by using the multiplier of 1.2 is adequate to account for uncertainties in all plant designs covered by the TR. The methodology assumes that the flow into the core is solely based on fluid boil-off. However, there is likely to be liquid exiting the core. How is the additional flow from any liquid phase accounted for?

***Response***

As noted in the response to RAI #3.24, the method detailed in WCAP-17788, Volume 3, Section 3.5 provides for the calculation of the amount of coolant needed to remove decay heat from the core at each time step.

However, the multiplication factor of 1.2 is a conservative adder applied to the fibrous debris delivered to the core to ensure that the resultant accumulated fiber quantity is conservative, considering the step-wise hand calculation used to project fiber collection in the core, and not an adder to the flow provided to the core.

- To that end, the multiplication factor does not increase the flow into the core; rather, the 1.2 multiplier serves to only increase the debris load entering the core by 20%.
- Therefore, the 1.2 multiplier identified in Section 3.5.4, Step 4, is intended to account for unknowns and uncertainties associated with the delivery of fibrous debris transported to the core independent of flow itself.
- The 1.2 multiplier is not related to uncertainties in the decay heat model.

To summarize, the 1.2 multiplier does not add additional flow to the core, only additional debris. Also, the 1.2 multiplier on debris delivered to the core is applied throughout the 30 day time period of interest, thereby providing for a conservatively large amount of fibrous debris to be captured by the core above that needed to match boil-off.

Therefore, the application of the discussion of NSAL-95-001 and NSAL-92-010 is not applicable to the 1.2 multiplier used in this method of evaluating debris fibrous debris collection in the core.

## RAI-3.26

Section 3.4, "Overview of the Method Logic," in describing the calculation logic for the CLB method, clarifies the need to "account for sensible heat and heat of vaporization" when determining the core boil-off requirement based on DH and sump fluid temperature. In addition to the sump fluid temperature, the Reactor Coolant System pressure should be considered as a contributing factor as it defines the boil-off saturation temperature, which determines the degree of subcooling of the coolant. In addition, the system pressure has an effect on the latent heat of evaporation, which is also used to calculate the boil-off rate.

In the list of required inputs to calculate the debris deposition at the core entrance provided in Section 3.6.1, Parameter 11 is identified as "sump fluid temperature curve starting at recirculation initiation," and Parameter 12 is identified as "containment pressure curve starting at recirculation initiation."

What factors and conditions were considered when determining the inputs for Parameters 11 and 12? The response should support the concept that "a method has been developed to conservatively predict and assess the time-dependent delivery of fibrous debris to the RV and core for a CLB." Confirm that the response also applies when determining the "average core boil-off flow" used in the simplified alternate method described in Section 5.

***Response***

The basis for using the "containment pressure curve starting at recirculation initiation" is as follows:

1) The pressure in the reactor vessel is slightly higher than the containment pressure.
2) Therefore, using the containment pressure to evaluate steaming provides for the following:

a. A conservatively smaller total enthalpy change in the coolant to boil than if the reactor vessel pressure were used which, in turn, provides for:
b. A conservatively larger boiling rate than would be predicted using the reactor vessel pressure.

3) The larger boiling provides for a conservatively larger mass of debris-laden coolant to be provided to the core.

To summarize, the use of the containment pressure curve provides for a conservatively large boiling of debris-laden coolant which, in turn, maximizes the debris delivered to the core.

The basis for using the "sump fluid temperature curve starting at recirculation initiation" is as follows:

1) The sump inventory temperature is taken from containment integrity calculations.
2) These temperature histories tend to maximize sump temperatures.
3) The sump temperature history does not credit cooling of the fluid from heat exchangers as it passes from the sump to the core.

To summarize, the use of maximum sump fluid temperatures and neglecting cooling of the pumped fluid to the core also maximizes the boiling of debris-laden coolant in the core which, in turn, maximizes the debris delivered to the core.

No attempt was made to determine the magnitude of the conservatism associated with the use of the containment pressure and the sump fluid temperature. Rather, it was recognized that the use of these values provided additional conservatism to the overall method.

Similarly, the Simplified Alternate Method uses the parameter, $CB_{AVG}$, which is defined as, "Average core boil-off flow, determined by summing the core boil-off flow at transfer to cold-leg recirculation and the core boil-off flow at transfer to hot-leg recirculation, and dividing by 2." Considering that the decay heat is an exponential function, it is readily observed that the use of the average of the core boil-off at transfer to cold-leg recirculation and the core boil-off flow at transfer to hot-leg recirculation provides for a conservatively large amount of debris-laden coolant to be transported to the core.

For example, Figure RAI-3.26-1 contains a core boil-off curve for a typical Westinghouse 4-loop pressurized water reactor. The solid black line represents the calculated core boil-off rate as a function of time after the accident. Assuming that recirculation from the containment sump is initiated at 30 minutes following the initiation of the accident, the solid red line connects the core boil-off rate at the start of recirculation to the core boil-off rate at the start of hot-leg switch-over, which estimated to be at 2 hours after the start of recirculation from the sump. The total amount of debris-laden coolant provided to the core is calculated as the integral under the curve. Clearly, the area under the core boil-off curve is less than the area under the red curve. Furthermore, the greater the time span between start of recirculation from the sump to the start of hot-leg recirculation, the greater the conservatism in coolant mass evaluated using the Simplified Alternate Method (see the blue dashed line). Thus, the Simplified Alternate Method provides for a conservatively large delivery of debris-laden coolant to the core compared to a computed core boil-off curve.

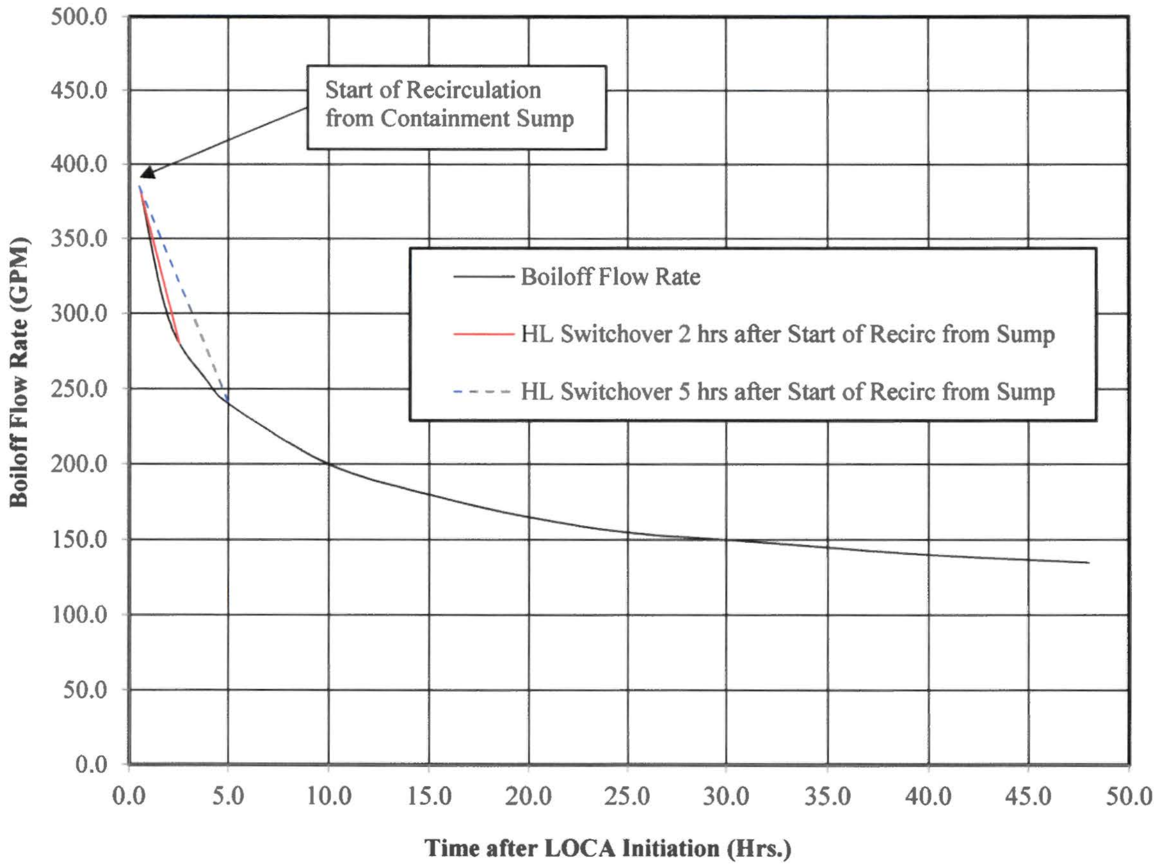


**Figure RAI-3.26-1 Boil-off Curve for a Westinghouse 4-loop PWR**

No attempt was made to determine the magnitude of the conservatism associated with the use of the average of the core boil-off rate at the start of recirculation and the core boil-off rate at the start of hot-leg switch-over. Rather, it was recognized that the use of this value provided additional conservatism to the overall method.

**RAI-3.32, Vol. 1 and Vol. 3**

Section 3.5 "Equations," explains that the equations for calculating the amount of fiber delivered to the core inlet are solved explicitly as a difference from time step to time step and that they can be easily solved by hand. In addition, Section 3.5.8, "Suggested Time Step Interval," states in part that "for this evaluation, a time step of one minute is suggested."

Section 6.5 of Volume 1, Subsection 6.5.2.1, "Time Step," also discusses time steps for the hot leg break (HLB) methodology. The HLB method states that an iterative solution with respect to time is necessary and recommends that time step sensitivity be performed. The method suggests that the time step should be small enough to ensure that the important processes behave linearly over each time step. A starting time step value of 100 seconds is recommended.

a. Provide results for an example case analyzed with the CLB method to illustrate the effect of the time step size. Provide the results from two calculations performed with time step sizes of 1 second and 10 seconds and compare the results from the calculation using the recommended time step size of 60 seconds.
b. Provide results for an example case analyzed with the HLB method to illustrate the effect of the time step size. Provide the results from two calculations performed with time step sizes of 1 second and 10 seconds and compare the results from the calculation using the recommended time step size of 100 seconds.
c. Provide quantitative criteria for assuring that the results from a calculation performed with both the CLB and HLB methods produce "stable results" along with justification as to how these criteria will be assured. State how the proposed process assures that an appropriate time step size will be applied to the proposed methods.

***Response***

a. The method described in Section 3 of Volume 3 of WCAP-17788 calculates the mass of fibrous debris collected on the sump screen and in the reactor vessel for a large cold leg break scenario. The method uses an explicit solution technique for the calculation scheme, which implies that the error in calculated solution from the previous time step is sufficiently small that it has negligible effect on the calculations performed for the next time step, and so on. An explicit calculation scheme works well when changes in the governing parameters of interest are small from time-step to time-step.

   The method description in Section 3 of Volume 3 of WCAP-17788 suggests the use of a one minute (60 second) time step to calculate the change in accumulated fibrous debris on the sump screen and in the vessel, as well as a change in fibrous debris concentration remaining in the coolant inventory of the reactor containment building sump. This approach approximates the integral of the rate of fibrous debris captured on the sump screen and in the vessel, as well as the rate of depletion of the fibrous concentration in the sump fluid inventory. There are several factors that favor the use of a one minute time interval, one of which is that minutes are a common unit of time measure for many of the input parameters (e.g., time of sump recirculation (minutes), initiation and termination of ECCS and the CSS

(minutes), Hot Leg switchover (hours or minutes), and ECCS and CSS flow (gallons per minute)).

Using a constant time step for explicit calculations may be likened to the application of trapezoidal rule for integrating the area under a curve. As is the case with the trapezoidal rule, the use of successively smaller time steps in the method of Section 3 of Volume 3 of WCAP-17788 may be expected to provide for an increasingly accurate approximation of the area under a curve (i.e., the integral of the amount of fibrous debris capture on the sump screen and in the vessel, as well as the depletion of the concentration of fibrous debris in the sump inventory).

It is noted that the initial debris concentration in the sump inventory is relatively small when compared to the mass of the coolant inventory. During the long-term cooling period associated with recirculation of sump fluid by the ECCS and CSS of a plant, all plant parameters affecting the ECCS and CSS flows, and hence fibrous buildup at screens and depletion in the sump inventory, are either constant or slowly changing relative to the size of the suggested one minute (60 second) time step.

1) ECCS and CSS flows are constant.
2) At this time during the transient, the decay heat is decreasing in a slow and gradual manner.

Also, as the decay heat slowly decreases, the mass of coolant needed to match boil-off also decreases, thereby minimizing the delivery of debris-laden coolant to the core while increasing the mass of water returned to the sump inventory through the break and re-filtered by the sump screen, further decreasing the fibrous debris concentration supplied to the vessel in the next time step.

To demonstrate the acceptability of a one minute or 60 second time step, sensitivity calculations were performed for three different time step sizes; the recommended one minute (60 second) time step, a ½ minute (30 second) time step, and a 1 second time step. For these sensitivity calculations, calculation inputs were representative of a large 4-loop PWR. Specific inputs to the calculations were:

1) The time of switch-over from injection from the RWST to recirculation from the inventory of the sump was assumed to be at 25 minutes after initiation of the LOCA.
2) The ECCS and CSS flow rates were taken to be 3800 gpm and 3000 gpm, respectively.
3) The active volume of coolant in the reactor containment building sump was taken to be 47,343.93 ft3. At the ECCS and CSS flow rated used in the calculations, the coolant inventory in the sump was turned over once every 52.08 minutes.
4) The initial amount of fibrous debris in the reactor containment sump fluid is 20.4 ft3, or, assuming a density of 2.4 lbs/ft3, 49.44 lbs. of fibrous debris. As there are 193 fuel assemblies in a Westinghouse 4-loop PWR, this mass equates to a fibrous debris loading of 116.2 grams/fuel assembly upstream of the sump screen.

5) A capture efficiency of 55% was assumed for the sump screen. This provided for a maximum of 52.3 grams of fibrous debris per fuel assembly to be available immediately downstream of the sump screen (assuming a single-pass of the initial sump coolant volume through the vessel).

6) For the purposes of this sensitivity evaluation, the decay heat was held constant at its 25 minute value. This assumption maximized the flow to the core for the duration of interest for the calculation and therefore maximizes the amount of debris calculated to collect in the vessel which, in turn emphasizes the difference in calculated debris deposition in the vessel as a function of the size of the time step used in the calculation.

The calculations were run for 12 hours of problem time after initiation of recirculation from the reactor containment building sump. The results of the sensitivity calculations are shown in Figure RAI-3.32-1. Time t=0 of the plot is to be taken as the start of recirculation; 25 minutes after initiation of the LOCA. A green line with green triangles as markers represents the results using a 60 second time step, a red line with red squares as markers represents the results of the 30 second time step, and a light blue line with solid diamonds as markers represents the results of the 1 second time step (see the legend on the right-hand side of Figure RAI-3.32-1). The difference between the results of the three time step durations are sufficiently small that they overlay one another on the plot of Figure RAI-3.32-1 and are indiscernible.

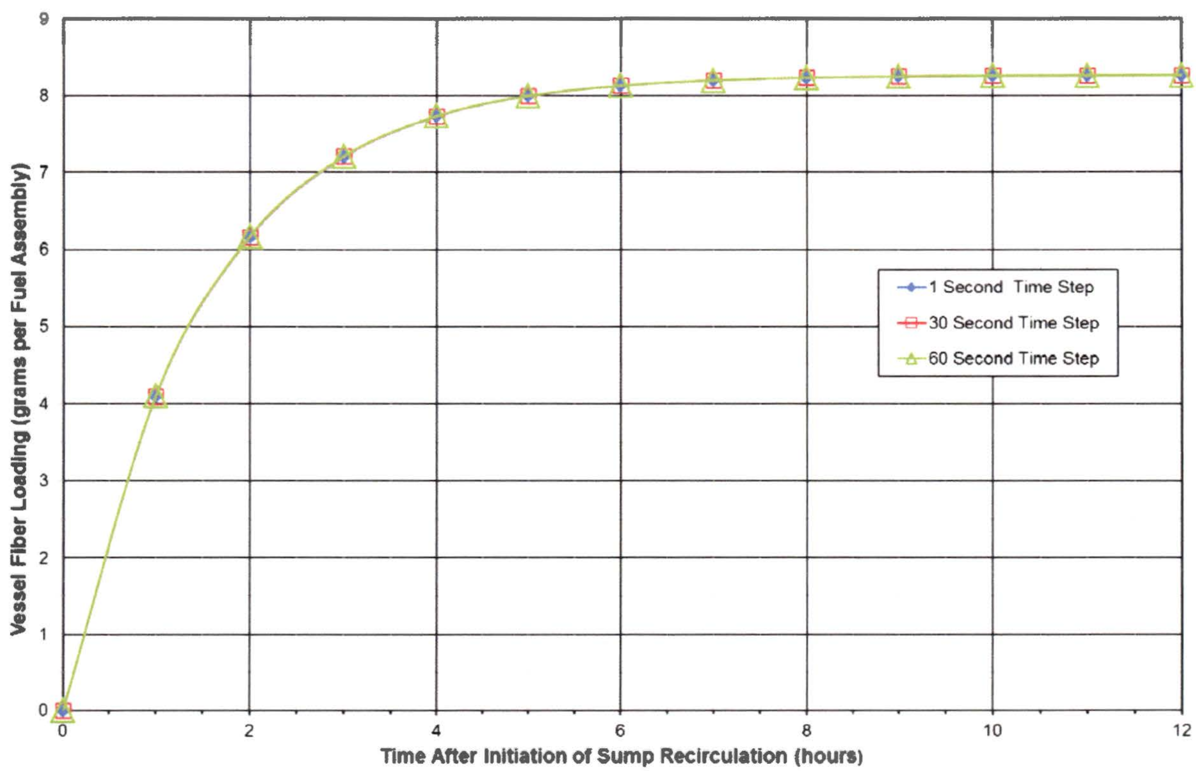


**Figure RAI-3.32-1 Reactor Vessel Fibrous Debris Collection as a Function of Time Step Selection**

From the plot of Figure RAI-3.32-1, it is concluded that following initiation of recirculation from the reactor containment building sump (time = 0), there is negligible difference between the three sets of results using three different time steps.

The hour-by-hour differences between the calculations performed using the three time steps are summarized in Table RAI-3.32-1.

**Table RAI-3.32-1 Comparison of Reactor Vessel Fibrous Debris Collection as a Function of Time Step Size**

| | **Fibrous Debris Collected (grams per fuel assembly)** | | | **Comparison** | |
|---|---|---|---|---|---|
| **Time (hours)** | 1 Second Time Step | 30 Second Time Step | 60 Second Time Step | Absolute Difference (60 sec -1 sec) | Percent Difference |
| 0 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 1 | 4.0869 | 4.0948 | 4.1029 | 0.0160 | 0.3920 |
| 2 | 6.1528 | 6.1608 | 6.1690 | 0.0162 | 0.2628 |
| 3 | 7.1972 | 7.2032 | 7.2094 | 0.0122 | 0.1701 |
| 4 | 7.7251 | 7.7291 | 7.7333 | 0.0082 | 0.1065 |
| 5 | 7.9920 | 7.9945 | 7.9972 | 0.0052 | 0.0649 |
| 6 | 8.1269 | 8.1284 | 8.1300 | 0.0031 | 0.0386 |
| 7 | 8.1951 | 8.1960 | 8.1969 | 0.0018 | 0.0226 |
| 8 | 8.2295 | 8.2300 | 8.2306 | 0.0011 | 0.0130 |
| 9 | 8.2470 | 8.2472 | 8.2476 | 0.0006 | 0.0073 |
| 10 | 8.2558 | 8.2559 | 8.2561 | 0.0003 | 0.0041 |
| 11 | 8.2602 | 8.2603 | 8.2607 | 0.0005 | 0.0058 |
| 12 | 8.2625 | 8.2625 | 8.2626 | 0.0001 | 0.0012 |

From the tabular listing given in Table RAI-3.32-1, the following observations are made:

1) Using a smaller time step for the calculations results in a slightly smaller amount of fibrous debris collection in the reactor vessel.
2) Over the range of time steps studied, the maximum difference in calculated debris collection is less than 0.4% at 1 hour after initiation of recirculation from the reactor containment building sump.
3) At the time range of most interest, from 3 to 6 hours after initiation of recirculation from the reactor containment building sump, the difference in calculated fibrous debris collected is:
    a. Less than 0.2% at 3 hours, and,

b. Less than 0.04% at 6 hours.

4) At 12 hours after initiation of recirculation from the reactor containment building sump, there is essentially no difference in the calculation of fibrous debris collection for any of the three time steps considered.

This small variation is expected for the following reasons; the majority of the ECCS coolant, along with all of the CSS flow (approximately 93% of the total of the ECCS and CSS flow), is recirculated back to reactor containment building sump inventory where it is again filtered by the sump strainer before being made available to enter the core, and the governing parameters in the calculation are changing slowly.

Although this exercise is performed to evaluate the impact of time step on the calculated debris collection in the vessel, the assumptions made for this comparison are conservative as they maximize the differences between calculated fibrous debris collection for the following reasons:

1) The decay heat was held at a constant value equal to the decay heat at the time of switchover from RWST (volume of borated water outside of the reactor containment building) injection to sump recirculation for the 12 hour duration of the calculations. As the decay heat remained high, the flow drawn into the core remained high, maximizing the deposition of fiber in the reactor vessel.

2) The coolant inventory of the reactor containment sump will cool down as the event progresses. The time step evaluation presented here conservatively neglects this cooldown, thereby also neglecting the increase in sensible heating of the coolant entering the core that is required before steam is generated. The assumption of maintaining the high temperature of the coolant in the sump at the time of switchover from injection from the RWST to recirculation from the reactor containment building sump maximizes the steaming rate, and consequently the mass of coolant delivered to the core during the time step assessment.

3) Conservative methods are used to estimate the amount of fibrous debris that is generated and transported to the sump during the initial blowdown from a large cold leg break and the washdown of that debris into the sump fluid during the drain down of the RWST (no credit is taken for the deposition of fibrous debris on intervening structures in the flow of spilled coolant as it flows to the sump screen). This provides for a conservatively large initial debris concentration of fibrous debris in the sump fluid.

4) The evaluation of fibrous debris accumulation in the vessel is based on the time to switchover from cold leg injection to hot leg recirculation which ranges from about 2 to 3 hours to about 6 to 8 hours for most plants with a 2 or 3 plants possibly extending to about 12 hours. However, the amount of fibrous debris used to calculate an initial fibrous debris concentration is the 30 day limit used to evaluate sump screen performance, which also accounts for erosion for those plants that generate fiberglass debris. This is an additional conservatism in the CLB calculation method.

Considering the above, the use of a one minute time step, or smaller, used in the calculation method of Section 3 of Volume 3 of WCAP-17788 to estimate the delivery of fibrous debris to the reactor vessel for a cold leg break will result in essentially the same result. Therefore, a time step of one minute (60 second) or less is reasonable and appropriate for this calculation method.

b. WCAP-17788, Volume 1, Section 6.5 describes the method for calculating a fiber limit following a hot leg break (HLB) for any given plant. This methodology provides an analytical solution to the fiber distribution throughout the system. Because of this, errors are not introduced with each time step as they would be in a numerical solution where the differential equations are approximated. This means that the time step is not as important as it is in many thermal-hydraulic (TH) codes. While the time step does not affect the solutions to the equations, it is necessary for two other reasons: capturing the time dependent boundary conditions such as hot leg switchover and checking the stopping criteria. For both of these needs, the time step should be small enough such that these important events are not missed by a significant amount of time.

WCAP-17788, Volume 1, Section 6.5.6 provides two example calculations for the HLB methodology. As stated therein, these cases can be used to verify an implementation of this methodology. However, the inputs for these cases are not intended to reflect realistic plant conditions; rather, they are intended to test implementation of the methodology. To that end, generic time step sensitivity studies of the nature requested would be of little value.

As described in WCAP-17788, Volume 3, an analytic solution is also used to determine the amount of fiber that reaches the core following a CLB. The solution does not rely on a numerical solution where the differential equations are approximated. The time step sensitivity study performed for the CLB solution confirmed that this calculation method is insensitive to the time step size selected (see Response 3.32a above). Since the HLB method uses a similar mathematical solution as the CLB method, variations in the time step used for the HLB evaluation are not expected to affect the solution to the equations. Therefore, a time step sensitivity study is not required for the HLB methodology described in WCAP-17788, Volume 1, Section 6.5.

c. The acceptability of a one minute (60 second) time step for the cold leg break calculation method has been established in the response to RAI 3.32 (a). In fact, a one minute (60 second) time step provides slightly conservative calculation of fuel assembly debris loading compared to a 1 second time step.

As described in the response to Item (b) of this RAI, generic time step sensitivity studies of the nature requested for the hot leg break method are of little value. For plant-specific applications, it is recommended that each utility perform a time-step sensitivity study as part of their analysis. This process would include selecting a base time step of 100 seconds as described in Section 6.5.2.1 of WCAP-17788, Volume 1. Additional cases should be run in which this time step is varied until it can be demonstrated that the time step used is stable. Stability would be demonstrated by a change of less than one percent in final results.

***Proposed Revision to Volume 1:***

Given the above response, WCAP-17788, Volume 1, Section 6.5.2.1 is revised and expanded to read as follows:

***6.5.2.1 Time Step***

*Because this problem contains time varying boundary conditions, specifically the core inlet resistance and ECCS configuration, an iterative solution with respect to time is necessary. While a time step sensitivity study is not required, the time step selected should be small enough such that the important processes (such as the timing of activation of the AFP, initiation of HLI, or stopping criteria) are captured appropriately. Therefore, a value of 100 seconds or less is recommended.*

***Proposed Revision to Volume 3:***

WCAP-17788, Volume 3, Section 3.5.8 "Suggested Time Step Interval" will be revised as follows:

*For this evaluation, a time step of one minute is suggested for the following reasons:*

- *The mass of fluid inventory in the recirculation sump is large compared to the mass of the ECCS and CSS over a one minute time step. The one minute time step provides for a relatively slow "clean up" of fibrous debris by both the recirculation sump screen and the core. The results of the calculations are therefore insensitive to variations in time step sizes around the one minute value.*
- *The use of a one minute time step provides for small changes in the decay heat curve from time step to time step in the time period of start of recirculation from the sump and beyond. This provides for an accurate calculation of core boil-off mass needed for long-term core cooling.*
- *The use of a one minute time step is convenient for the calculations as the ECCS and CSS flow rates are generally defined in units of gallons per minute.*
- *The use of time steps smaller than one minute have been evaluated and determined to have a negligible impact on the calculated results.*

Thus, for the reasons noted above and from a practical consideration, a one minute time step for this calculation is suggested. This recommendation, however, does not preclude the use of a smaller time step.