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



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

**T.S. Andreychek\***  
**K.F. McNamee**  
**Systems & Equipment Engineering I**

**December 2014**

Verified by: **Y.J. Song\***  
**Systems & Equipment Engineering I**

Approved: **T.D. Croyle\***, Manager  
**Systems & Equipment Engineering I**

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

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

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**LIST OF ACRONYMS AND ABBREVIATIONS**

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.

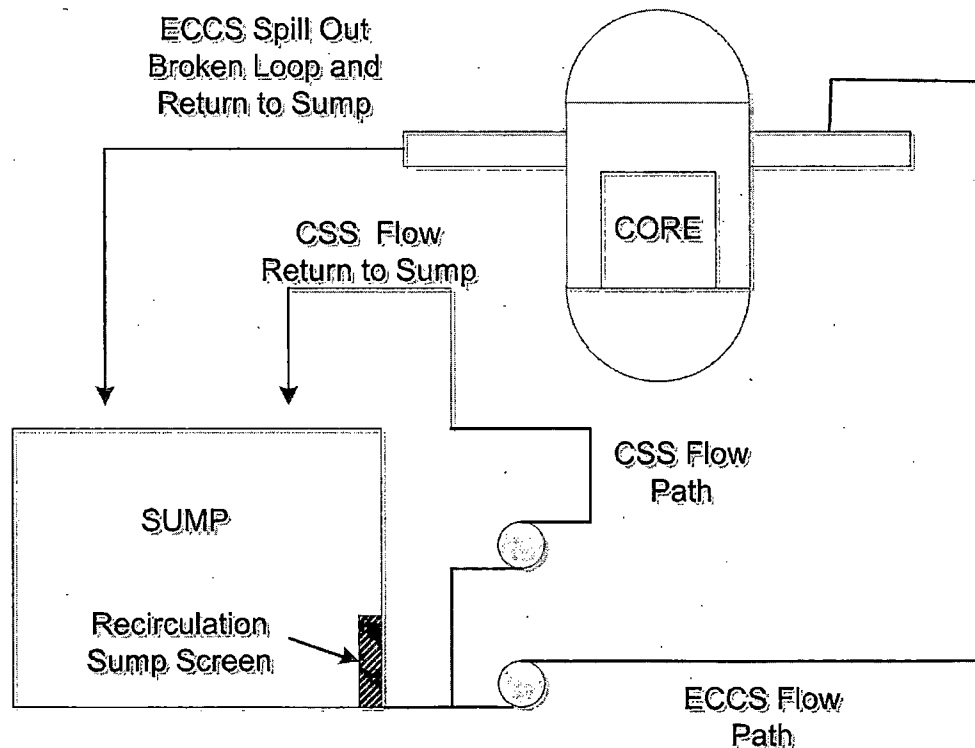


Figure 1 - ECCS and CSS Flow Paths for a CLB



### 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, 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. The 1.2 multiplier on boil-off flow is consistent with the guidance of NSAL-95-001 (Reference 9) 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. A 20% increase in the flow required to satisfy boil-off requirements increases the amount of fiber laden fluid reaching the core.
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 Conservatism

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.

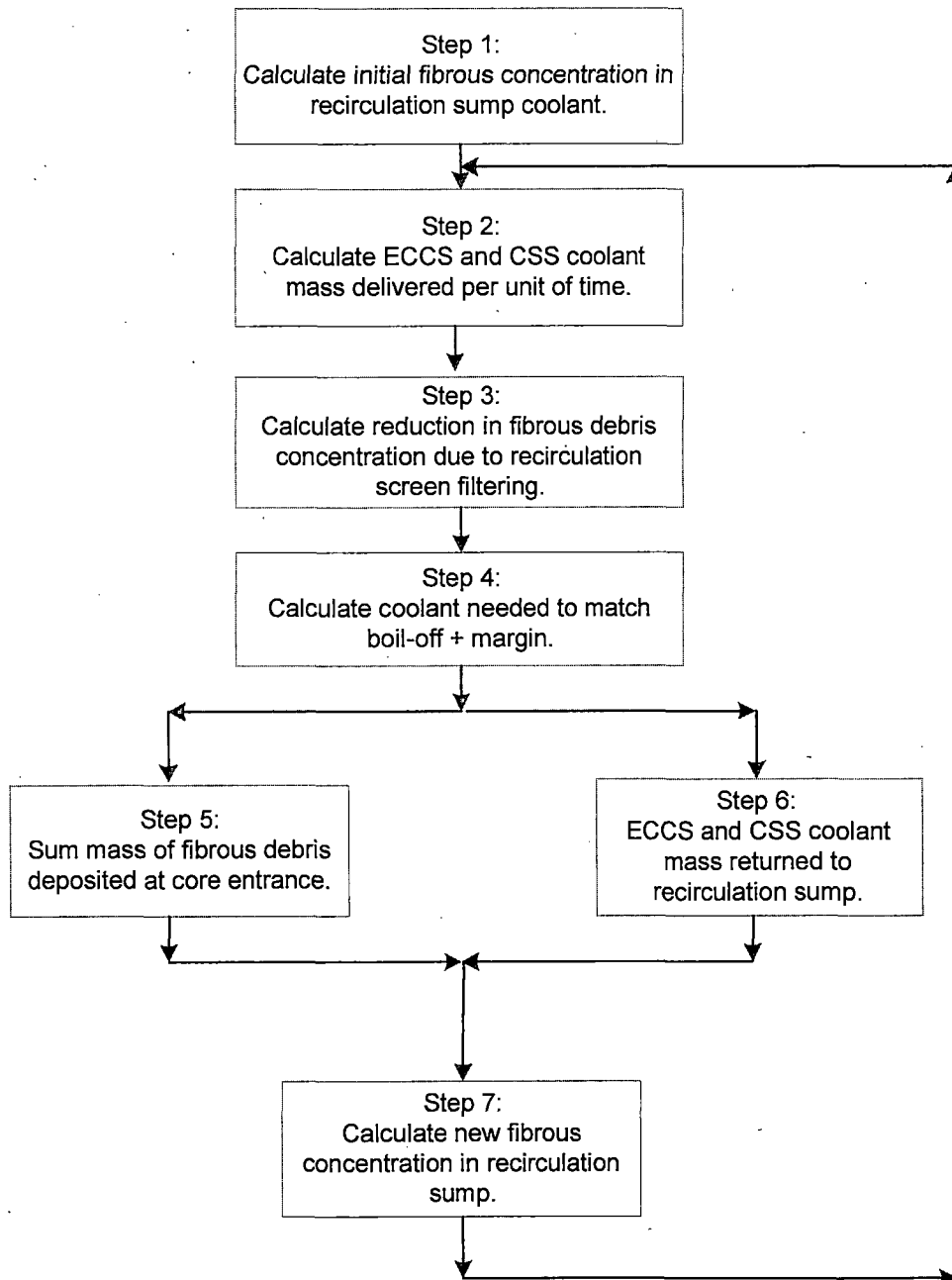


Figure 2 - Flow Chart for CLB Method Calculations

### 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<sub>M</sub>.

And the subscripts are defined as:

*fiber* = Transportable fibrous debris in the form of fiber fines that is available to the coolant inventory; lb<sub>M</sub>.

*Sump Coolant* = Refers to mass of coolant in recirculation sump; lb<sub>M</sub>.

*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 <sub>M</sub> /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 <sub>M</sub> /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:

<i>ECCS</i>	=	Refers to the ECCS.
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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:

<i>CSS</i>	=	Refers to the CSS.
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### 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:

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

Where the parameters are defined as:

$\Delta C^*$	=	Remaining concentration of fibrous debris in coolant passing through the sump screen; ppm.
$\phi_{EFF}$	=	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:

<i>Rated Power</i>	=	Rated power of the reactor: Btu/min
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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 <sub>M</sub> .
$\Delta h_f$	=	Change in enthalpy of the liquid coolant: Btu/lb <sub>M</sub> .

And the subscripts are defined as:

$T$	=	Temperature: °F.
<i>Saturation</i>	=	Refers to saturation temperature at containment pressure.
<i>Sump</i>	=	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<sub>M</sub>.

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. 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.

### 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  $lb_M$  to grams; 0.0022026 g/ $lb_M$ .

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.

Thus, for the reasons noted above and from a practical consideration, a one minute time step for this calculation is suggested.

### 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 <sup>3</sup>
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 <sup>3</sup>
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<sub>M</sub>/ft<sup>3</sup> may be used for low-density fiberglass and latent fibrous debris. An appropriate as-manufactured density value should be used for high-density fiberglass.

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 of 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 +  $2\sigma$  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 in the 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:

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

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 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 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,  $20.60 \text{ ft}^3$
- Define the sump volume,  $47343.93 \text{ ft}^3$
- Define the concentration of fiber in the sump pool,  $4.35\text{E-}04 \text{ ft}^3/\text{ft}^3$
- 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  $1.958\text{E-}04 \text{ ft}^3/\text{ft}^3$
- Determine core boil-off requirement based on sump fluid temperature and core decay heat,  $2.507\text{E+}05 \text{ lb}_M/\text{hr. @ 1500 seconds}$
- 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 1 and the steps above, implementation of the methodology would provide a fiber quantity at the time of HLSO of  $6.04 \text{ g/FA}$  at the fuel based on a fiber load of  $116.197 \text{ g/FA}$  upstream of the sump screen and 45% fiber bypass (55% fiber capture).

**Table 1 – Input Collection**

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

Parameter	Units	Value	Comment
Active sump volume	ft <sup>3</sup>	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 <sup>3</sup>	8.0, NUKON 0.1, E-glass 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 <sub>M</sub> , convert to equivalent NUKON 2.4 lb <sub>M</sub> /ft <sup>3</sup> ).
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 defensible 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 defensible 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 non-zero value when justified or defensible value is available.
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 defensible 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.
Decay heat curve	NA		ANSI/ANS 1971+20% for baseline calculation.



Parameter	Units	Value	Comment
Access to referenceable steam tables	NA		Used to determine latent heat of vaporization and sump water density using sump fluid temperature.
<b>Plant flow rates:</b> 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.

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 methodology.

## 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

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