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Comprehensive Analysis and Test Program for GSI-191 Closure (PA-SEE-1090)

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LIST OF ACRONYMS AND ABBREVIATIONS

ACC	Accumulator(s)
ACRS	Advisory Committee on Reactor Safeguards
AFP	Alternate Flow Path
B&W	Babcock and Wilcox
BAMT	Boric Acid Mixing Tank
BAP	Boric Acid Precipitation
BAPC	Boric Acid Precipitation Control
BAST	Boric Acid Storage Tank(s)
BB	Barrel/Baffle
BN	Bottom Nozzle
BWST	Borated Water Storage Tank(s)
Cal-Sil	Calcium Silicate
CCI	Centrifugal Charging Injection
CE	Combustion Engineering
CFR	Code of Federal Regulations
CFT	Core Flood Tank(s)
CL	Cold Leg(s)
CLB	Cold Leg Break(s)
CS	Containment Spray
CSS	Containment Spray System
CVCS	Chemical and Volume Control System
DB	Design Basis
DEG	Double-Ended Guillotine
DH	Decay Heat
DHC	Decay Heat Cooler(s)
DHR	Decay Heat Removal
ECCS	Emergency Core Cooling System
EOP	Emergency Operating Procedure(s)
EPRI	Electric Power Research Institute
FA	Fuel Assembly(s)
GL	Generic Letter
GR	Guidance Report
GSI	Generic Safety Issue
HHSI	High Head Safety Injection
HL	Hot Leg(s)
HLB	Hot Leg Break(s)
HLSO	Hot Leg Switchover

LIST OF ACRONYMS AND ABBREVIATIONS

HPI	High Pressure Injection
HPSI	High Pressure Safety Injection
IHSI	Intermediate Head Safety Injection
LBLOCA	Large Break LOCA
LCP	Lower Core Plate
LEF	Lower End Fitting
LHSI	Low Head Safety Injection
LOCA	Loss-of-Coolant Accident
LOCADM	Loss-of-Coolant Accident Deposition Model
LP	Lower Plenum
LPI	Low Pressure Injection
LPSI	Low Pressure Safety Injection
LSP	Lower Support Plate
LTCC	Long-Term Core Cooling
MOV	Motor Operated Valve
NEI	Nuclear Energy Institute
NPSH	Net Positive Suction Head
NRC	Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
p:f	Particulate-to-Fiber Ratio
PA	Project Authorization
PCT	Peak Cladding Temperature
PIRT	Phenomena Identification and Ranking Table(s)
PWR	Pressurized Water Reactor(s)
PWROG	Pressurized Water Reactor Owners Group
RAS	Recirculation Actuation Signal
RBS	Reactor Building Spray
RCS	Reactor Coolant System
RHR	Residual Heat Removal
RV	Reactor Vessel
RVVV	Reactor Vessel Vent Valve(s)
RWST	Refueling Water Storage Tank
RWT	Refueling Water Tank
SCS	Shutdown Cooling System
SCHX	Shutdown Cooling System Heat Exchanger(s)
SE	Safety Evaluation(s)
SEE	Systems & Equipment Engineering

LIST OF ACRONYMS AND ABBREVIATIONS

SG	Steam Generator(s)
SIT	Safety Injection Tank(s)
SIS	Safety Injection System
SoK	State of Knowledge
SSO	Sump Switchover
STP	South Texas Project
TH	Thermal-Hydraulic(s)
TN	Top Nozzle
U.S.	United States
UCP	Upper Core Plate
UHSN	Upper Head Spray Nozzle(s)
UP	Upper Plenum
UPI	Upper Plenum Injection
WCAP	Westinghouse Technical Report Number Preface (formerly Westinghouse Commercial Atomic Power)
ZOI	Zone of Influence

1 EXECUTIVE SUMMARY

The Pressurized Water Reactor Owners Group (PWROG) has undertaken a comprehensive test and analysis program as part of the resolution to generic safety issue (GSI) 191 to increase the fibrous debris limits per fuel assembly (FA). This report documents the methodology that member utilities can use to assess the time-dependent collection of fibrous debris in the reactor vessel (RV), which can then be used for final closure of Nuclear Regulatory Commission (NRC) Generic Letter (GL) 2004-02 and GSI-191. This work provides an alternative approach to the method detailed in WCAP-16793-NP-A, Rev. 2 for defining an in-vessel fibrous debris limit and provides a means for increasing the currently established in-vessel fibrous debris limit of 15 g/FA.

Title 10 Code of Federal Regulations (CFR) 50.46 requires that long-term core cooling (LTCC) be demonstrated for all break sizes and locations in the reactor coolant system (RCS). The technical development of this program is predicated on two fundamental criteria: (1) that decay heat removal (DHR) is assured such that the core temperature is maintained at an acceptably low level, and (2) that boric acid precipitation control (BAPC) is assured by maintaining the boron concentrations in the RV remain below the solubility limit.

This volume consolidates the results of five separate, but interrelated elements of the PWROG program. The individual program elements are described in detail in separate volumes, the collection of which, including the present volume (Volume 1), constitute WCAP-17788. The methodology for calculating the in-vessel debris limits are plant-specific and depend on inputs for each plant (or group of identical plants). This program is applicable to all Westinghouse, Combustion Engineering (CE), and Babcock and Wilcox (B&W) pressurized water reactor (PWR) Nuclear Steam Supply System (NSSS) plants.

Large, double-ended breaks are the focus of GSI-191 resolution since the effects of debris from these breaks bound all other break sizes. The break locations are divided into hot leg breaks (HLBs) and cold leg breaks (CLBs). Both break scenarios must be considered independently given the difference in system response, timing of debris introduction to the fuel, and the benefits of alternate flow paths (AFPs) for hot leg breaks.

This report further divides the plants into those that initially begin sump recirculation with ECCS recirculation flow to the cold legs and those that initially begin with ECCS recirculation flow to the upper plenum (UPI plants). Section 5 identifies the major assumptions used in the methodology for both types of plants. For plants that initially start with cold side recirculation, Section 4.2 outlines the methodology for HLB and Section 4.3 outlines the methodology for CLB. Sections 6 and 7 provide the details of the methods for calculating the amount of fiber delivered to the RCS for HLB and CLB, respectively. For UPI plants, Section 8 provides the methodology for both break locations. For the spectrum of large breaks, this methodology can be used to ascertain that the amount of debris generated in containment does not ultimately result in an excessive amount of debris (fiber and particulate) delivered to the RV such that LTCC is compromised.

The increased fiber limits may be applied for moderate to high fiber plants to justify the current debris source terms for deterministic closure of NRC GL 2004-02. High fiber plants may also apply this methodology to establish a basis for risk informed evaluation and closure of GL 2004-02. The remaining plants, and all plants, can exercise the methodology to ensure margin in response to possible plant design changes and/or operability assessments.

2 INTRODUCTION & BACKGROUND

2.1 PROGRAM INTRODUCTION AND PURPOSE

This report presents the final results of a program coordinated and funded by the PWROG to develop a deterministic approach and methodology for assessing the time-dependent collection of fibrous debris in the RV for member utilities. This assessment can then be used for final closure of NRC GL 2004-02 (Reference 2-1) and GSI-191. This work provides an alternative approach to the method detailed in WCAP-16793-NP-A, Rev. 2 (Reference 2-2) for defining an in-vessel fibrous debris limit and provides a means for increasing the currently established in-vessel fibrous debris limit of 15 g/FA.

The technical development of this program is predicated on two fundamental criteria which, if satisfied, ensure LTCC as defined in 10 CFR 50.46 (Reference 2-3) in the presence of entrained debris. These criteria are:

1. Decay Heat Removal - DHR requires that sufficient coolant be supplied to the core such that the core temperature is maintained at an acceptably low level. For previous GSI-191 evaluations, the maximum allowable post-quench peak cladding temperature (PCT) is 800°F (Reference 2-2). This conservative limit will be retained.

2. Boric Acid Precipitation Control - BAPC requires that boron concentrations in the RV remain below the solubility limit.

This volume consolidates the results of five separate, but interrelated elements of the PWROG program. The individual program elements are described in detail in separate volumes, the collection of which, including the present volume (Volume 1), constitute WCAP-17788. These respective program elements are:

- Volume 2 – Comprehensive Analysis and Test Program for GSI-191 Closure (PA-SEE-1090) – Phenomena Identification and Ranking Tables (PIRT) for GSI-191 Long-Term Cooling

- Volume 3 – Comprehensive Analysis and Test Program for GSI-191 Closure (PA-SEE-1090) – Cold Leg Break Evaluation Method for GSI-191 Long-Term Cooling

- Volume 4 – Comprehensive Analysis and Test Program for GSI-191 Closure (PA-SEE-1090) – Thermal-Hydraulic Analysis of Large Hot Leg Break with Simulation of Core Inlet Blockage

- Volume 5 – Comprehensive Analysis and Test Program for GSI-191 Closure (PA-SEE-1090) – Autoclave Chemical Effects Testing for GSI-191 Long-Term Cooling

- Volume 6 – Comprehensive Analysis and Test Program for GSI-191 Closure (PA-SEE-1090) – Subscale Head Loss Test Program Report

This program is applicable to Westinghouse, CE, and B&W PWR NSSS plants. The methodology for calculating the in-vessel debris limits described in this report is plant-specific and depends on inputs for each plant (or group of identical plants). The general approach for all plants is to separately assess the

debris limits for the CLB and HLB scenarios. Both break scenarios must be considered independently given the difference in system response, timing of debris introduction to the fuel, and the benefits of alternate flow paths (AFPs) for hot leg breaks.

The development of the PWROG program considers the results of a phenomena identification and ranking table (PIRT) (Volume 2). Information assembled by the PIRT determined, in part, the necessary testing and analysis. The development of the program was further informed by various oversight efforts including an independent third party review contracted to assess the results of previous in-vessel testing program efforts, and a challenge review board tasked with review of the proposed program described in this WCAP.

For the CLB scenario, a core inlet fiber limit is established such that a uniform debris bed does not form at the core inlet and exchange flow between the core and lower plenum (LP) is maintained. This exchange flow transports boron solute from the core region to the LP which slows the buildup rate of boron concentrations in the core region. Further, a methodology was developed (Volume 3) for plants to calculate a plant-specific in-vessel debris load to ensure that it remains below the established limit.

For the HLB scenario, the thermal-hydraulic (TH) analyses (Volume 4) establish the time-dependent blockage conditions and availability of the AFPs to ensure that cooling flow is available such that the cladding temperature limit is not exceeded. The correlation between the losses modeled in the TH analyses and the losses attributed to an actual debris bed is developed by physical (subscale) head loss testing (Volume 6). Critical inputs for the head loss testing (debris types and characterization) have been developed based on the range of prototypical conditions for plants. The chemical effects evaluation (Volume 5) establishes the minimum time for the formation of post loss-of-coolant accident (LOCA) sump fluid chemical effects (precipitates) for each plant or plant groups. The general approach is to confirm that the onset of precipitates for all plant groups is beyond the critical time defined by the TH analyses.

The collection of these analytic and testing programs establishes a methodology that may be applied on a plant-specific basis to establish allowable debris quantities (grams of fiber per FA) for those accident scenarios that generate debris and for which the Emergency Core Cooling System (ECCS) and Containment Spray System (CSS) is aligned to the containment sump for accident mitigation (i.e., LOCA). The results are predicated on deterministic methods (analysis and testing) and are applicable to those utilities attempting GL 2004-02 closure using a deterministic approach. The methods developed herein represent an alternative to the generic limit previously developed in WCAP-16793-NP-A, Rev. 2 (Reference 2-2). The plant-specific debris limits that result from the methods developed by this program may also be applied as the basis for a risk informed analysis as appropriate.

It should be noted that the discussions presented in this report apply to the effects of debris downstream of the sump strainer in the RV only. Any mention of "debris bed" is in reference to debris collecting at the core inlet.

2.2 HISTORICAL BACKGROUND

On September 13, 2004, the NRC issued GL 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized-Water Reactors" (Reference 2-1)

as the primary vehicle for addressing and resolving concerns associated with GSI-191. The GL required 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 ECCS and 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 strainer(s) for a variety of breaks and break locations. Resolution of the generic issue also requires that the effects of debris that pass through (penetrate or bypass) the sump strainer are addressed. In particular, the PWROG completed an evaluation of the impact of debris accumulation at the core inlet and the consequential effect on core cooling. The results of this comprehensive analysis and testing program are documented in WCAP-16793-NP-A, Rev. 2 (Reference 2-2). The NRC issued a Safety Evaluation (SE) documenting approval of the method as modified by conditions and limitations identified in the SE.

The methodology presented in WCAP-16793-NP-A, Rev. 2 provides a single conservative value of 15 g/FA for all plants. The NRC SE for WCAP-16793-NP-A, Rev. 2 accepts 15 g/FA as a limit for the HLB scenario. A fraction of this value is also considered acceptable for the CLB scenario given that fiber and particulate will not provide a bed sufficiently dense to effectively filter the chemical precipitates. As a result, mixing between the core and LP is not precluded during the CLB scenario with the limited quantity of debris.

The WCAP-16793-NP-A, Rev. 2 methodology is based on non-prototypical assumptions regarding debris, timing, and the immediate onset of chemical effects that significantly increase the head loss across a fiber bed that forms at the core inlet. The associated limit is restrictive and does not support closure for a large fraction of the PWROG member plants.

To support utilities that could not otherwise close the in-vessel debris issues for final closure of GL 2004-02 (without substantial modifications to existing insulation systems), the PWROG Executive Committee directed the PWROG to develop and fund a revised in-vessel program to improve upon the WCAP-16793-NP-A, Rev. 2 results. In response, the PWROG sponsored a technical proposal to develop a testing and analysis program.

The NRC also identified that additional programs to increase the fiber limit beyond that approved by WCAP-16793-NP-A, Rev. 2 and the associated SE, would have to address the impact of debris on mixing with the concern that disruption of the communication between the core and LP by accumulated debris would increase the potential for boric acid precipitation (BAP) and would challenge core cooling.

The program that has been completed and documented herein provides a deterministic approach to establishing in-vessel debris limits. This approach is based on plant-specific (or plant group-specific) inputs and design characteristics. This alternate approach is consistent with guidance provided in NRC SECY-12-0093 "Closure Options for Generic Safety Issue – 191, Assessment of Debris

Accumulation on Pressurized-Water Reactor Sump Performance," (Reference 2-4). The program provides for a refined evaluation methodology for determining in-vessel fiber limits and produces final limits that ultimately satisfy the evaluation of LTCC as defined in 10 CFR 50.46. The results may also be applied as the basis for a risk-informed approach to evaluating the in-vessel effects (ECCS performance will otherwise be evaluated from a risk informed perspective).

2.3 REFERENCES

2-1 GL 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized-Water Reactors," ADAMS Accession Number ML042360586, September 2004.

2-2 WCAP-16793-NP-A, Rev. 2, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculation Fluid," July 2013.

2-3 10 CFR Part 50 §50.46, "Acceptance Criteria for Emergency Core Cooling Systems for Light Water Nuclear Reactors," 72 Federal Register 49494, August 28, 2007.

2-4 SECY-12-0093, "Closure Options for Generic Safety Issue – 191, Assessment of Debris Accumulation on Pressurized-Water Reactor Sump Performance," July 2012.

3 TECHNICAL BACKGROUND

3.1 PLANT TERMINOLOGY

In the United States (U.S.) PWR fleet, there are three original equipment manufacturers and designers of the RCS. They are Westinghouse, CE, and B&W. While the different designs contain systems that perform similar functions, they typically have different names. To that end, it is useful to identify the equivalent systems and components involved in LTCC. This comparison is presented in Table 3-1. To avoid confusion, Westinghouse terminology will be used throughout this report when generic discussions are presented.

3.2 DESCRIPTION OF REACTOR VESSEL AND FUEL COMPONENTS

The information in this section is general in nature and is presented for background purposes only. The system descriptions are intended to provide useful information about plant design and configuration but should not be used as input to licensing basis analyses.

The prototypical structure of the RV internals is shown in Figure 3-1 and Figure 3-2. Within the RV, the core barrel is suspended from a large flange above the cold leg connection, forming an annular region called the RV downcomer. The core barrel is equipped with a thermal shield (or neutron pad) which helps protect the RV from neutron fluence. At the bottom of the RV, the core barrel closes with the core support forging, which includes large flow passage holes. The core barrel also supports a diffuser plate and the lower support plate (LSP). The weight of the fuel rests on the lower core plate (LCP) which is supported by small vertical columns that connect the LCP to the LSP and diffuser plate, passing the load to the core support forging. A clearance exists between the core support forging and lower columns in the lower head of the RV. These supports only come into play when there is large down-ward displacement of the core barrel, to which the core support forging is welded. In-core instrumentation penetrates the RV from below.

The square FAs do not fit evenly into the round core barrel. To capture the outer perimeter of the FAs, baffle plates are mounted to the core barrel via horizontally running former plates. These former plates are equipped with holes or gaps to allow flow. Flow into the barrel/baffle (BB) region (the region between the core barrel and baffle plates) is NSSS dependent and described in more detail below. The baffle plates terminate at the top of the active core, just below the upper core plate (UCP). Flow holes or gaps provide for flow out of the BB region. The FAs are located between the LCP and UCP.

Holes in the UCP align the control rod guide tube assemblies. The control rod guide tube assemblies include slotted openings. The primary function of the guide tubes is to ensure that control rod deflection is minimized during insertion and that control rods remained aligned. The control rods themselves are supported at their top by a spider and at the bottom by the control rod guide thimbles in the FA. When the control rods are fully inserted, only the drive shaft occupies an appreciable fraction of the control rod guide tube cross section.

The FAs (Figure 3-3) consist of a bottom nozzle (BN), top nozzle (TN), spacer grids, fuel rods, and control rod thimble tubes (into which the control rods slide for shutdown). The fuel rods and thimble tubes are held in a square array by the spacer grids (Figure 3-4). The BN consists of small openings designed to capture foreign debris during normal operation. The thimble tubes are threaded at their end,

and bolts are used to connect the BN to the thimble tubes. The BN also has angled feet which contain alignment dimples that match corresponding bosses on the LCP. The TN is equipped with a hold-down spring that allows the FA to be held in place without resulting in appreciable stresses due to flow and thermal expansion. The TN has larger, oblong openings allowing the flow to move upward.

All U.S. PWRs have flow paths in the RV that may allow fluid to bypass the heated core during normal operations. Examples include flow through the BB region (for upflow BB plants) and/or flow through the upper head spray nozzles. The B&W, CE, and a portion of the Westinghouse fleet have upflow BB designs that provide a direct flow path between the lower support region and the upper plenum (UP) (Figure 3-5 through Figure 3-7). Westinghouse design upflow plants and B&W plants have pressure relief holes (LOCA holes) that allow direct communication between the BB and core periphery as well. Conversely, Westinghouse downflow plants have limited flow paths between the lower support region and the UP (Figure 3-8). Westinghouse plants also have upper head spray nozzles (UHSNs) that are a credited AFP. The spray nozzles provide a flow path between the top of the downcomer and upper head as shown in Figure 3-9. The size of the spray nozzles are indicated by the upper head temperature during normal operation. There are two categories: T-cold and T-hot plant types. The T-cold design has a fairly large available flow area and low flow resistance between the downcomer and upper head such that increased bypass flow can be expected, and the upper head temperature is consistent with the cold side (i.e., cold leg) temperature. The T-hot design has smaller nozzle openings and will not provide as much bypass flow as the T-cold design such that the upper head temperature is consistent with the hot side (i.e., hot leg) temperature.

Both the BB region (in upflow plants) and the UHSNs may provide a path for coolant to reach the core in the event that the core inlet becomes blocked with debris. In this context, these paths are termed AFPs as they provide an alternate path for coolant to reach the core other than the core inlet.

Table 3-1 Comparison of System and Component Terminology by NSSS Vendor

	B&W	CE	Westinghouse
System Names	Emergency Core Cooling System (ECCS)	Emergency Core Cooling System (ECCS)	Emergency Core Cooling System (ECCS)
	Reactor Building Spray (RBS) System	Containment Spray System (CSS)	Containment Spray System (CSS)
	Decay Heat Removal (DHR) System	Shutdown Cooling System (SCS)	Residual Heat Removal (RHR) System
	Low Pressure Injection (LPI)	Low Pressure Safety Injection (LPSI)	Low–Head Safety Injection (LHSI)
	High Pressure Injection (HPI)	Higher Pressure Safety Injection (HPSI)	High–Head Safety Injection (HHSI)
	Core Flood Tanks (CFTs)	Safety Injection Tanks (SITs)	Accumulators (ACCs)
	High head normal makeup and purification (HPI pumps for all but DB)	Centrifugal Charging Injection (CCI) Pumps	Centrifugal Charging Injection (CCI), Chemical and Volume Control System (CVCS)
Components by Function			
Tank that stores borated water for safety injection/refueling	Borated Water Storage Tank (BWST)	Refueling Water Tank (RWT)	Refueling Water Storage Tank (RWST)
Supplemental tanks with concentrated boric acid solution	Boric Acid Storage Tank (BAST)	Boric Acid Mixing Tank (BAMT)	Boric Acid Storage Tank (BAST)
Pump(s) used to supply low–head safety injection/recirculation flow	Decay Heat (DH) Pump	Low Pressure Safety Injection (LPSI) Pump	LHSI Pump, Residual Heat Removal (RHR) Pump
Pump(s) used to supply high–pressure safety injection/recirculation flow	High Pressure Injection (HPI) Pump	High Pressure Safety Injection (HPSI) Pump	HHSI Pump, CCI Pump, or Intermediate–Head Safety Injection (IHSI) Pump
Heat exchangers that provide decay heat and residual heat removal	Decay Heat Coolers (DHCs)	Shutdown Cooling Heat Exchangers (SCHXs)	RHR Heat Exchangers
Pumps that supply containment spray flow	Reactor Building Spray (RBS) Pumps	Containment Spray (CS) Pumps	CS Pumps
Heat exchangers that cool containment spray	None	SCHXs	CS Heat Exchangers
Nozzles that deliver spray to containment building	Building Spray Nozzles	CS Nozzles	CS Nozzles

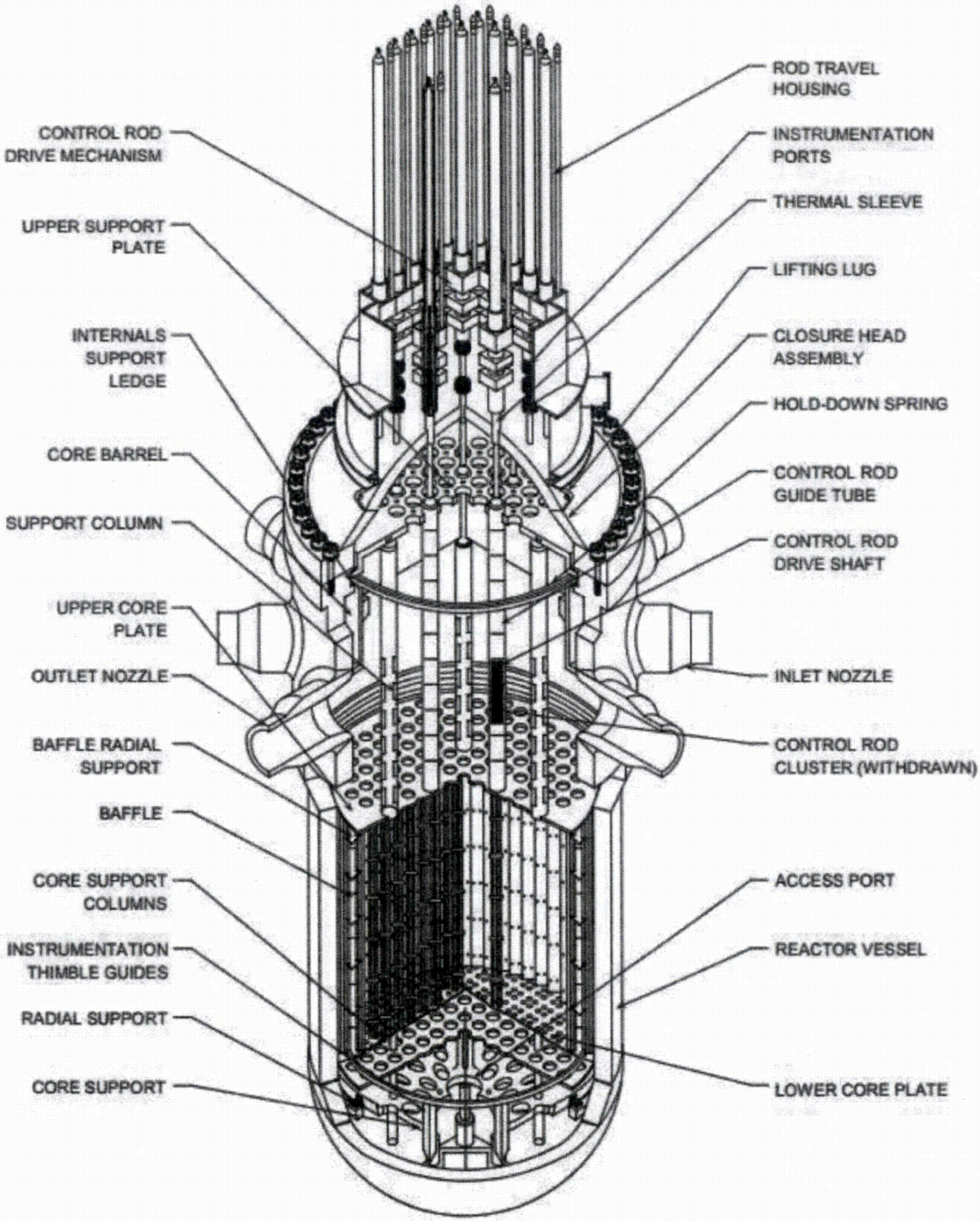

Figure 3-1 Typical Reactor Vessel Internals

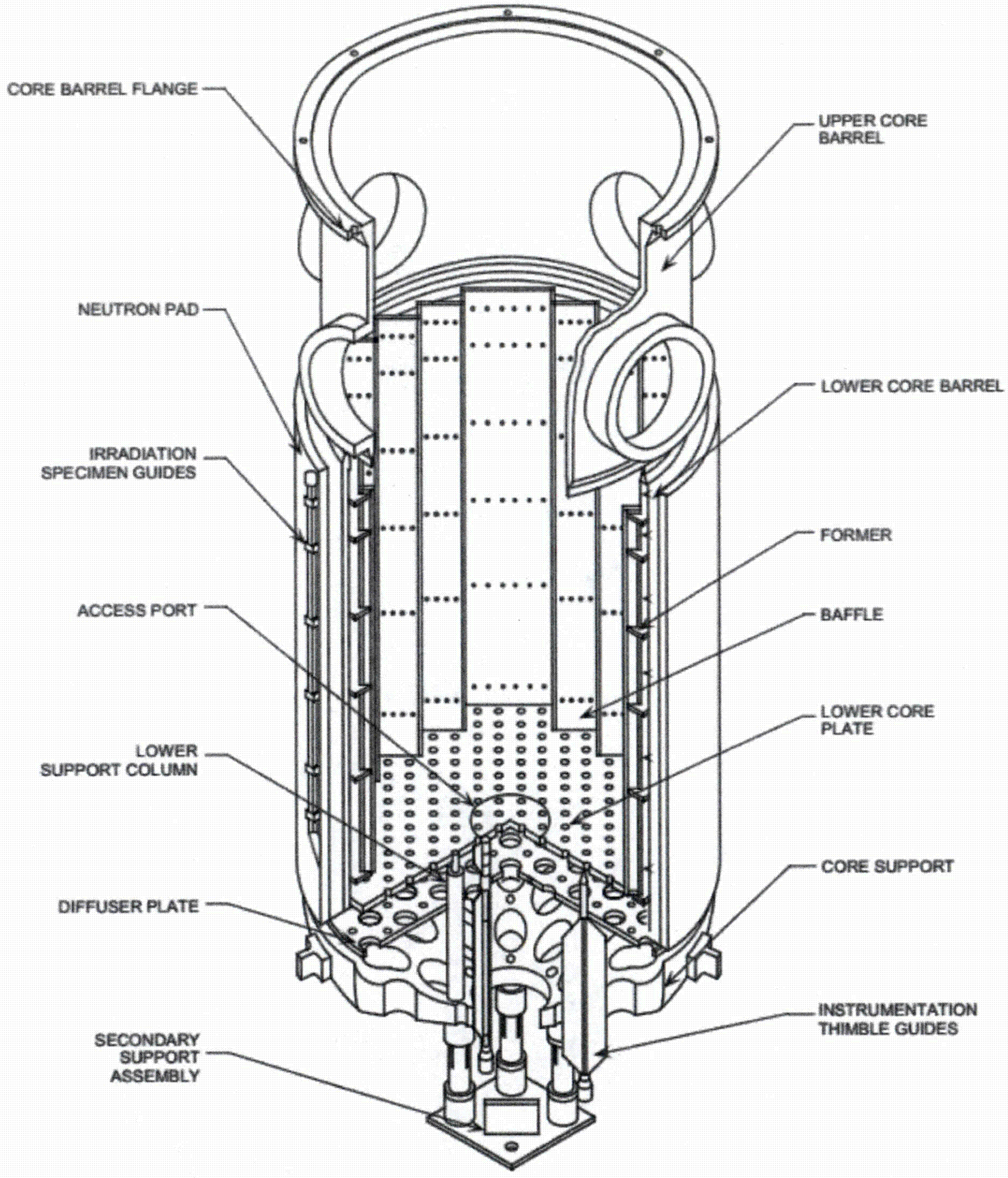

Figure 3-2 Typical Core Barrel Hardware

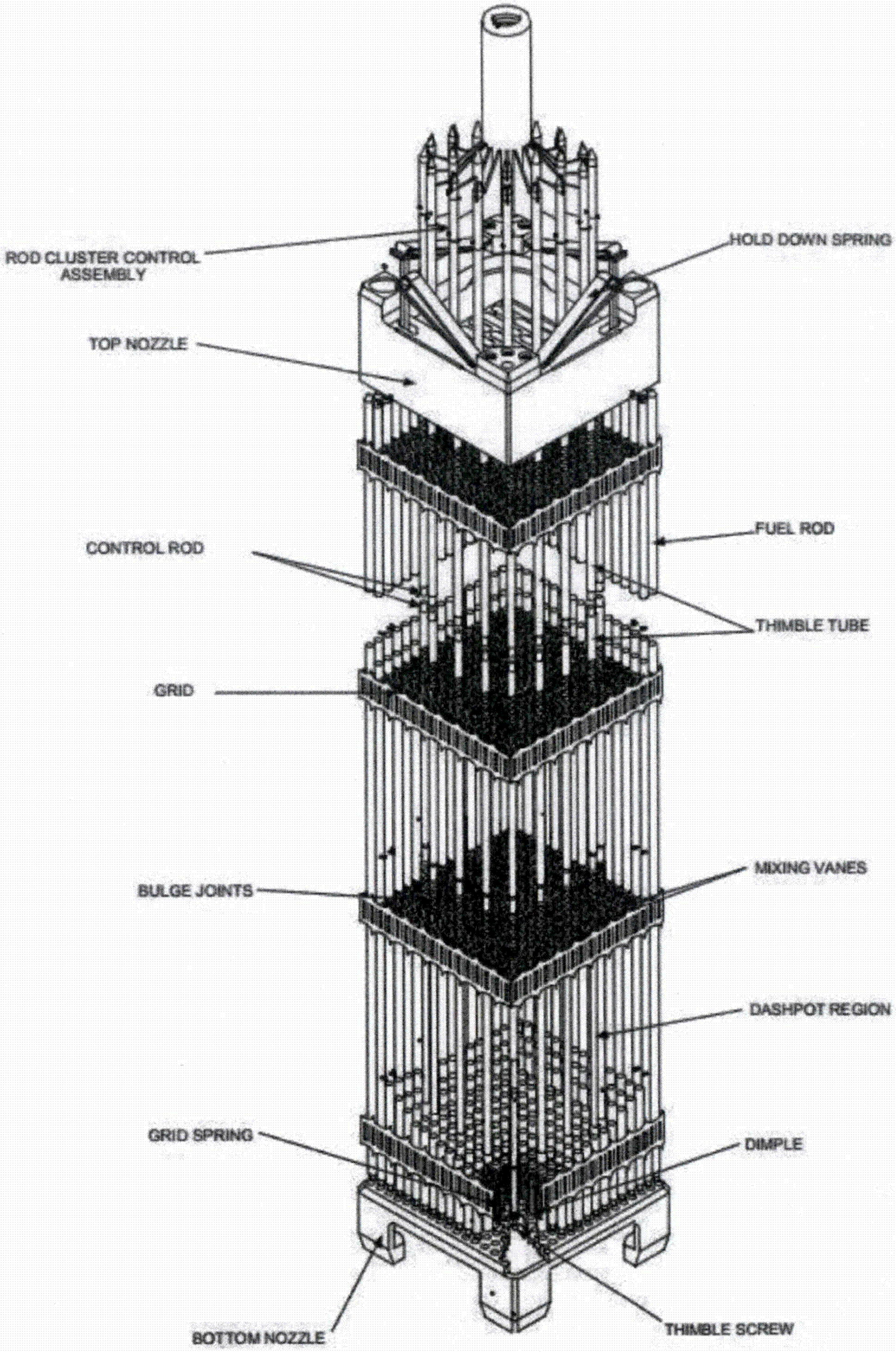

Figure 3-3 Typical Fuel Assembly Components

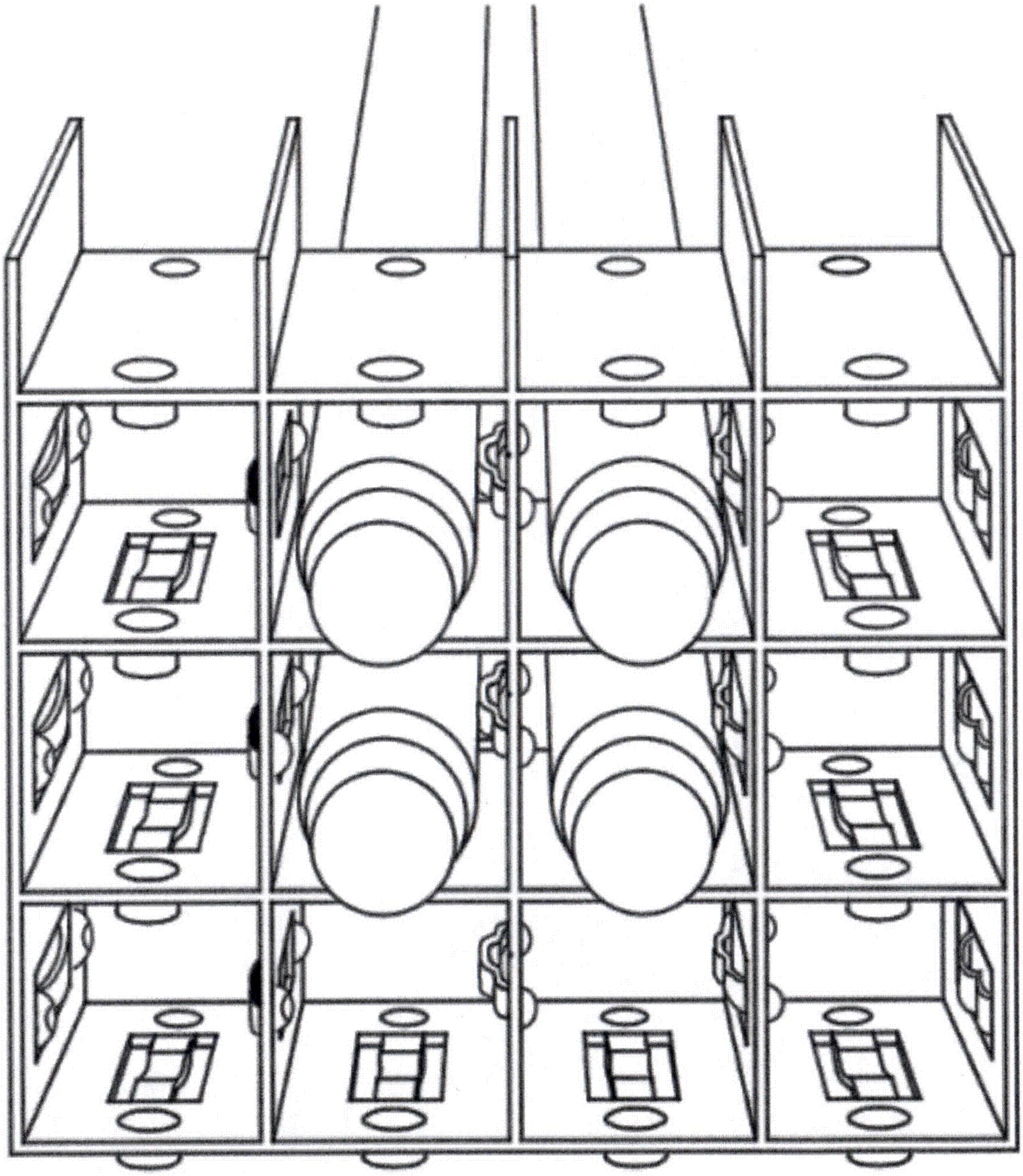

Figure 3-4 Typical Fuel Rod and Spacer Grid Orientation

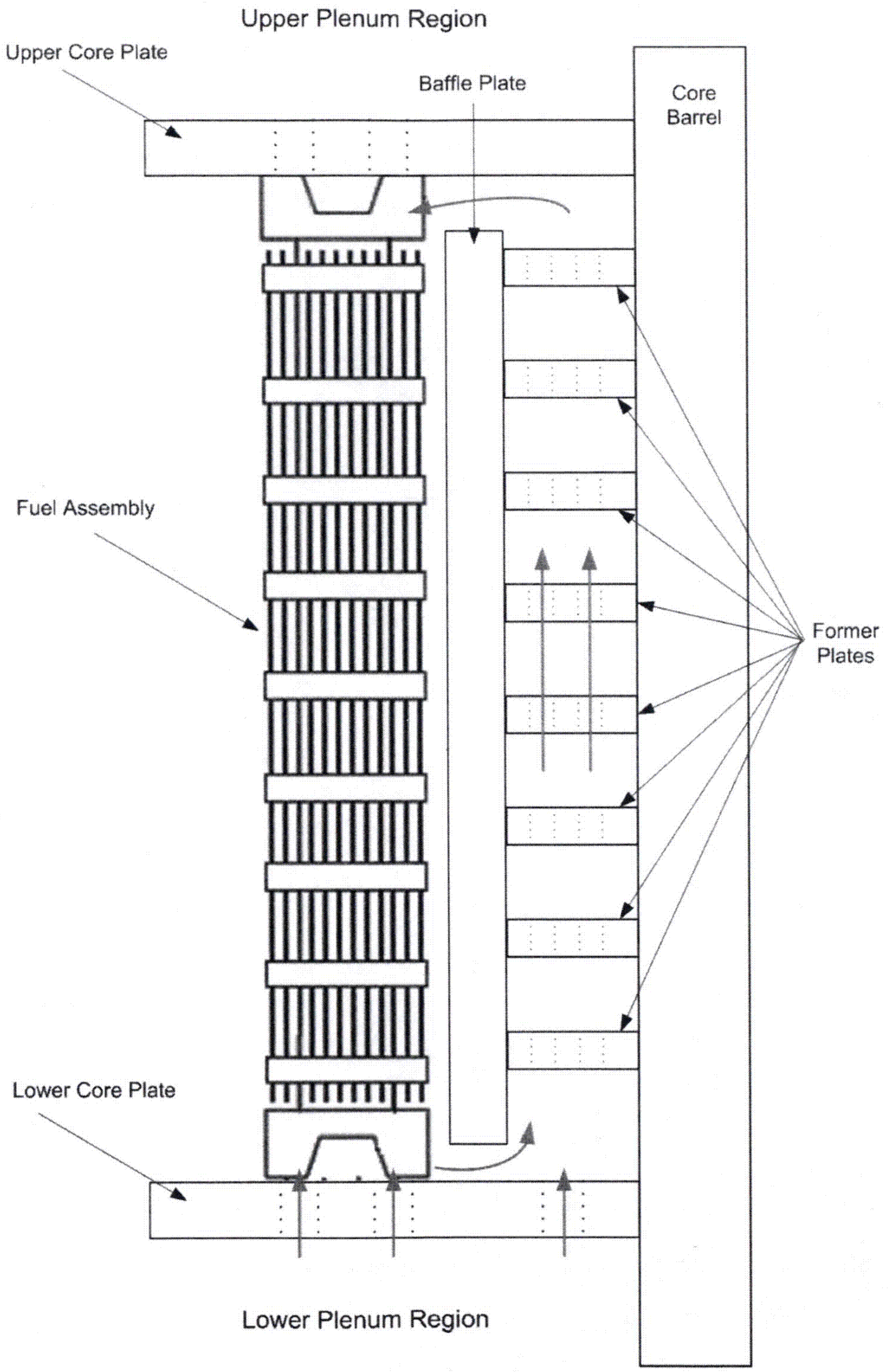

Figure 3-5 Westinghouse Upflow Barrel/Baffle Design (No Pressure Relief Holes)

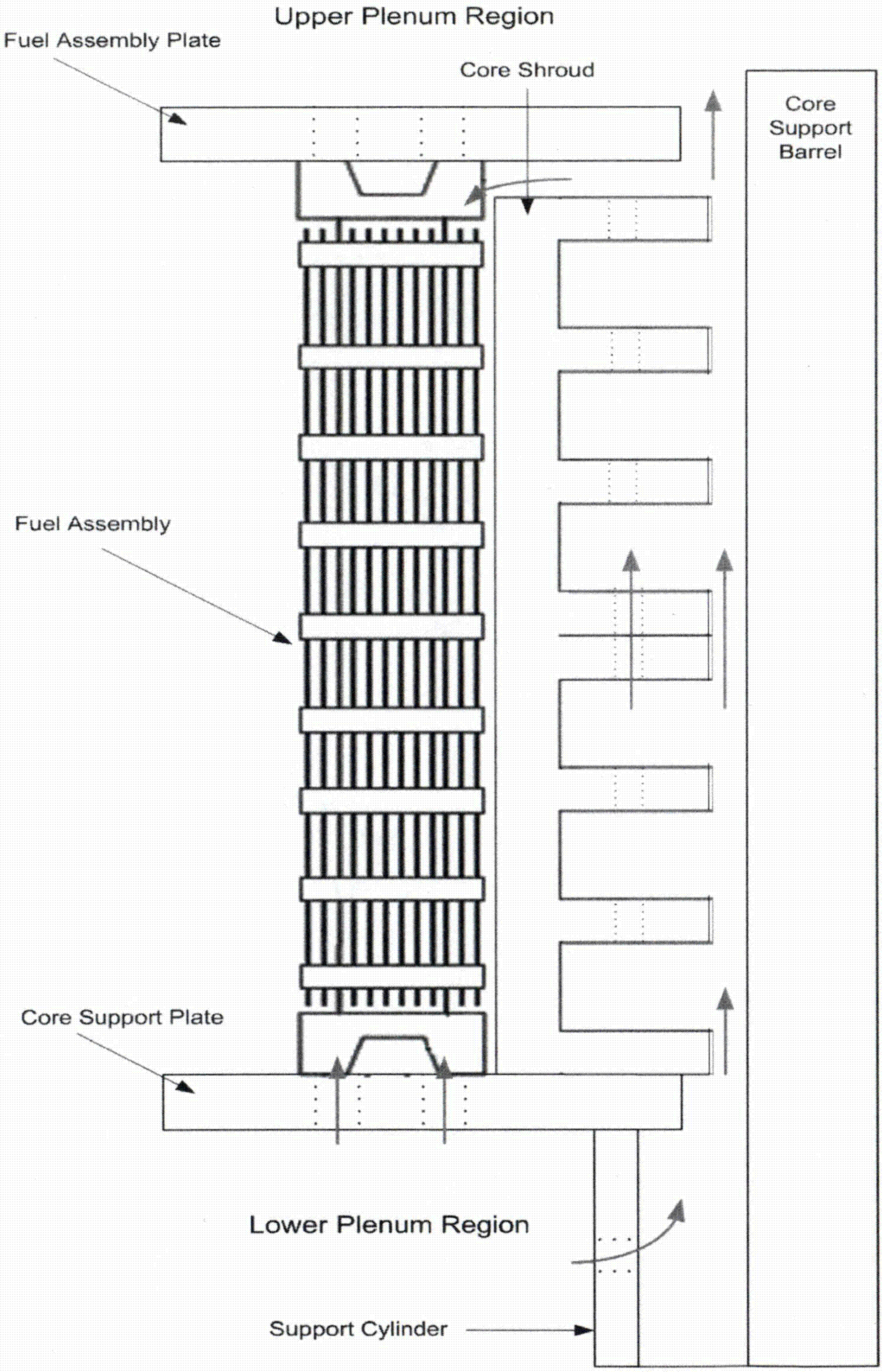

Figure 3-6 CE Barrel/Baffle Design

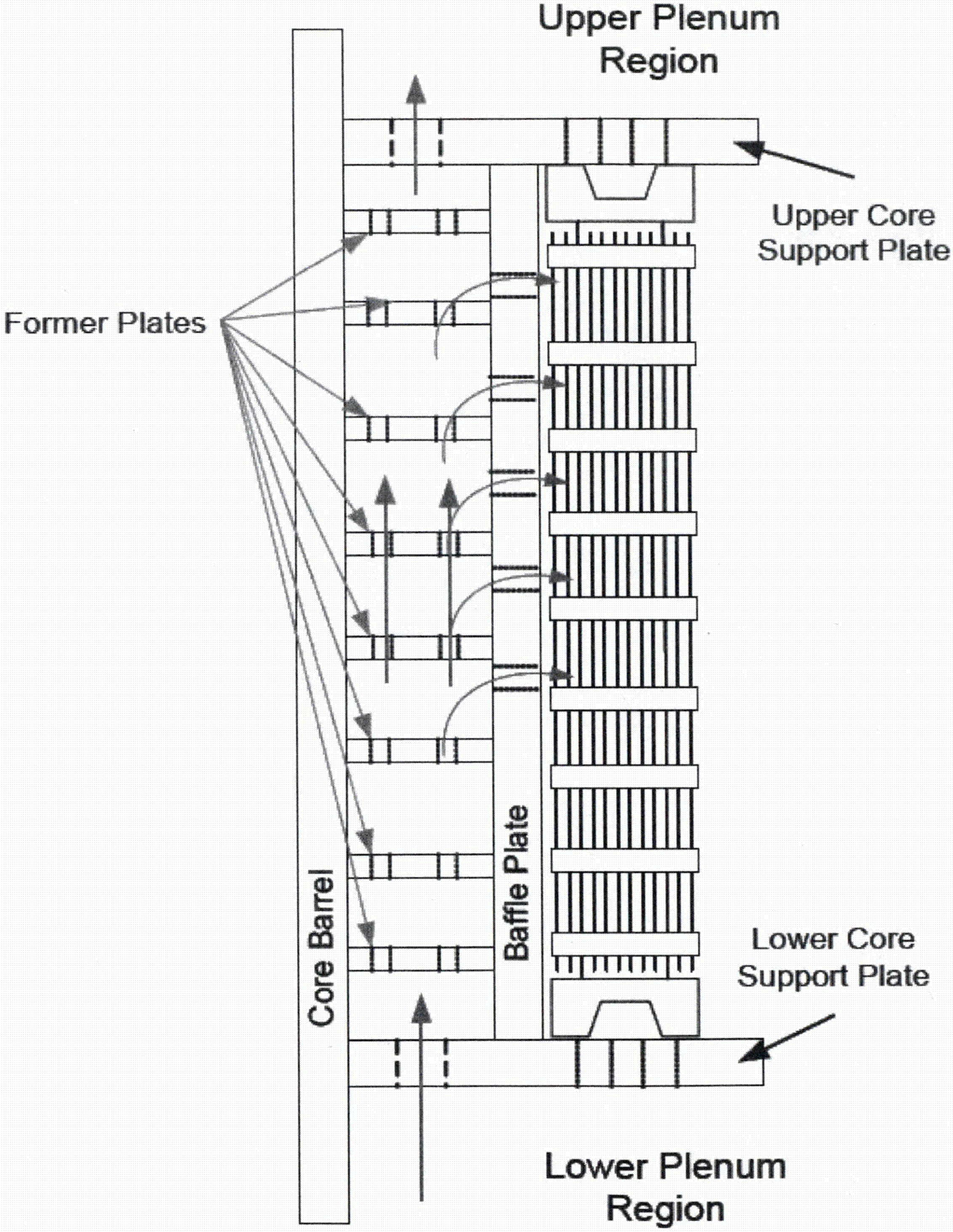

Figure 3-7 B&W Barrel/Baffle Design

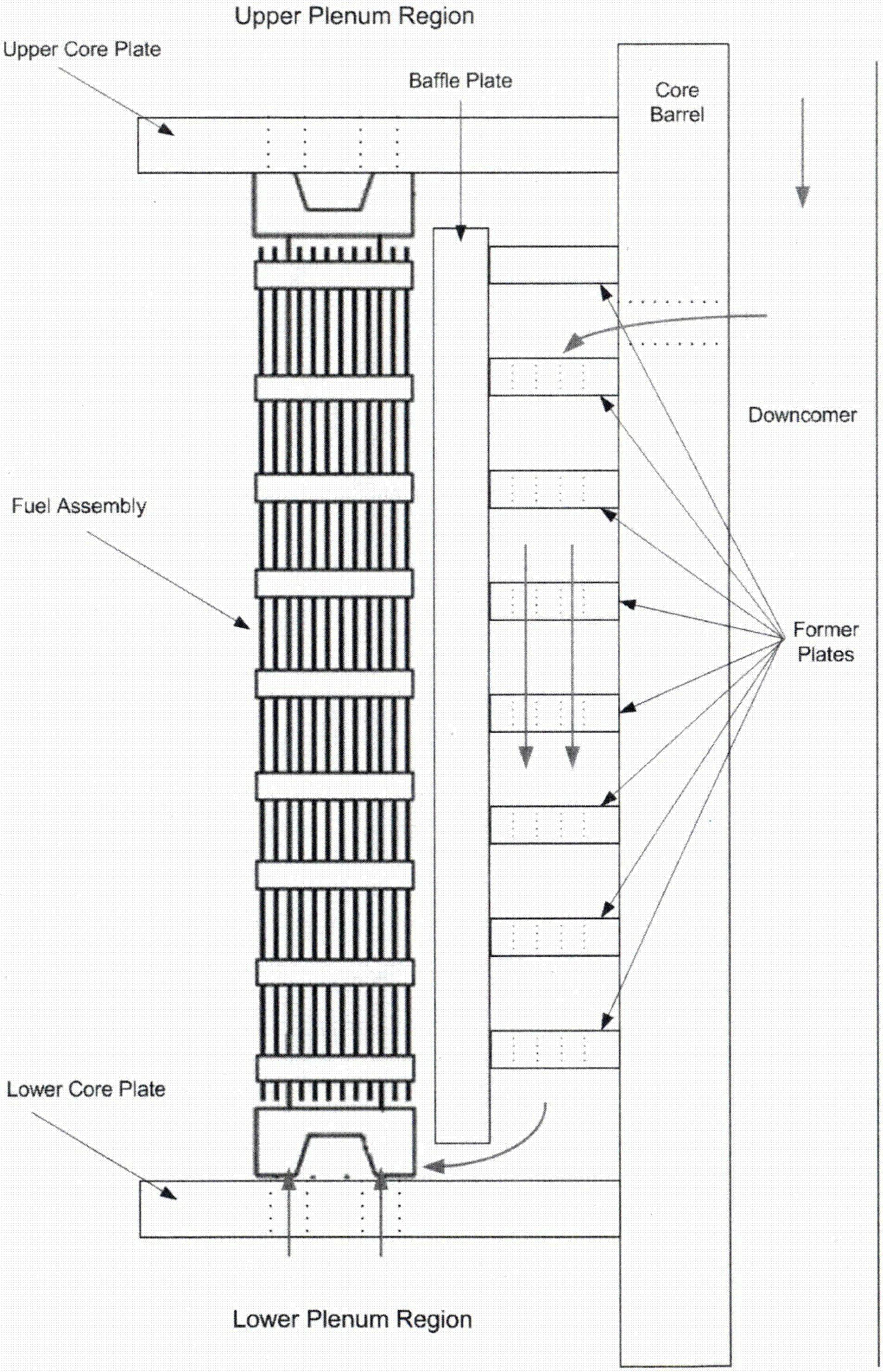

Figure 3-8 Westinghouse Downflow Barrel/Baffle Design

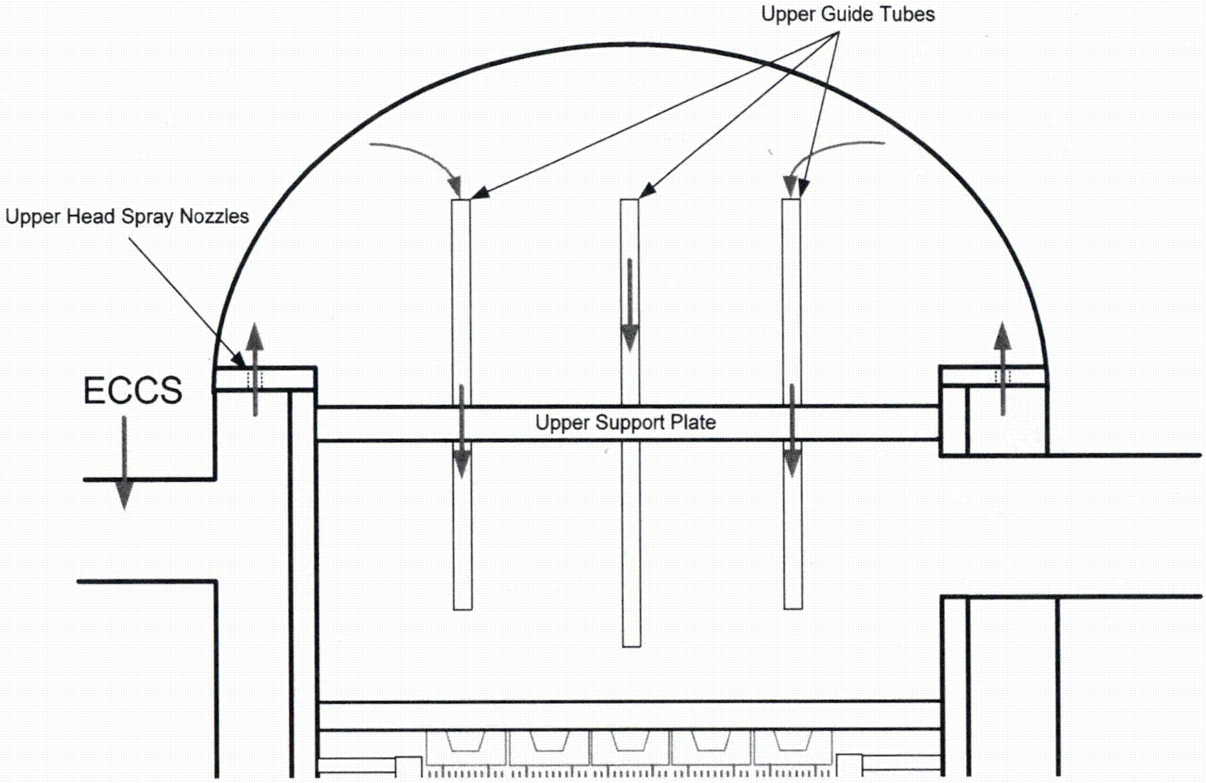

Figure 3-9 Westinghouse Upper Head Spray Nozzle Design

3.3 DESCRIPTION OF PWR LOCA AND SAFEGUARDS OPERATIONS

The material in this section is general in nature and is presented for background purposes only. The system descriptions are intended to provide useful information about plant design and configuration but should not be used as input to licensing basis analyses.

Shortly after a LOCA, a number of safety systems automatically actuate to mitigate the event. In the longer term, operators take action to continue the mitigation and to ensure that the core remains cool. The specific systems that actuate are dependent on the plant design and the plant operating procedures. However, there are general similarities among the U.S. PWR fleet. This section provides an overview of the event in that context.

Note that the descriptions in the following sections relate to plants with cold side ECCS (i.e., plants that initially inject into the cold legs immediately following the LOCA) and are relevant to most of the operating PWR fleet in the U.S. However, there are a small number of plants that initially inject into both the RV UP and into the cold legs. These plants are referred to as upper plenum injection (UPI) plants and are Westinghouse 2-loop designs. While the sequence of events is similar, the flow path to the break during sump recirculation is typically opposite cold leg recirculation plants. Additional discussion of the UPI plant is provided in Section 8.

3.3.1 General Sequence of Events Following a Large Break LOCA

The following is a generic description of a large break LOCA progression in a PWR. Plant-specific designs and operations may result in plant-specific variations from the progression described below.

The large break LOCA (LBLOCA) is characterized by rapid depressurization of the RCS to a pressure in near equilibrium with the containment pressure and low enough to allow the operation of the low head safety injection (LHSI) pumps. Containment is isolated due to high containment pressure. In the short-term, all available ECCS inventory, including the accumulators, is necessary to refill the vessel and recover the core with allowance for a single active failure. The CSS could also be actuated. Supply for both the ECCS and CSS are initially drawn from the refueling water storage tank (RWST). The borated water from this tank helps to reflood the core with fluid containing an effective neutron absorber. Due to RWST injection, the core can be expected to be reflooded and quenched within a few minutes. Fuel cladding temperatures after reflood have decreased to within a few degrees of the liquid saturation temperature.

The RWST contains enough coolant for injection to last approximately 20 minutes at maximum ECCS and CSS flow (i.e., no single failures). Initial safety injection flow is into the cold legs (with the exception of UPI plants, where flow is injected into both the RV UP and cold legs). After the RWST has drained, an alternate source of coolant is required. At this point, the supply water source to the ECCS and CSS is switched from the RWST to the containment sump. Continued availability of this coolant assures LTCC.

At some point after sump switchover (SSO), the Emergency Operating Procedures (EOPs) require that the operators take some action to mitigate potential boric acid buildup in the core. This is primarily a consideration following a CLB where there is limited liquid throughput in the core; as the core continues to boil, boric acid may concentrate. For HLBs, this is generally not a concern, because there is

continuous liquid flow through the core to the break, which continually dilutes the boric acid. However, since the operators do not diagnose the break location, this action is taken for all LOCAs. Westinghouse and CE designed PWRs require switching some or all safety injection to either hot leg recirculation (Westinghouse 3- & 4-loop and CE plants) or simultaneous hot and cold leg recirculation (Westinghouse 2-, 3-, 4-loop and CE plants). Some plants that do not maintain cold leg recirculation after the switch to hot leg recirculation require switching back and forth between hot leg and cold leg recirculation. Some B&W plants may open the decay heat drop line to address boron precipitation, while others may not take this action. The timeline for operator action is plant-specific, but will generally occur between 2 and 12 hours following the LOCA.

3.3.2 ECCS Configuration and Performance during Sump Recirculation

3.3.2.1 Westinghouse Plants

For the Westinghouse design, the ECCS components used during recirculation include the low head safety injection (LHSI) (also known as residual heat removal (RHR)) pumps and high head safety injection (HHSI) pumps, and various motor operated vales (MOVs), throttle valves, and check valves in the flow paths from the sump and the flow paths to the cold legs and to the hot legs.

To meet the single failure criteria, it is necessary that each active component be duplicated. All valves that need to be opened for proper safety injection system (SIS) function are duplicated in parallel; all valves that must be closed are duplicated in series. All pumps are duplicated in parallel and are designed so that only one pump in each group needs to operate to provide sufficient volume of water to cool the core or the containment atmosphere, as the case may be.

The recirculation phase following an accident is automatically or manually initiated either when the RWST low level alarm is actuated or when the operator is prepared to take positive action for a specific accident. Long–term recirculation will be required for any LOCA.

For large breaks, the RCS will be depressurized by the initial blowdown. The RHR pumps are aligned to inject directly to the RCS while also providing the suction source to the HHSI pumps. Component cooling water is supplied to the RHR heat exchangers for cooling the sump water. The recirculation phase can continue with one RHR pump operating for a considerable period of time. If one RHR pump should stop functioning or require maintenance, the second RHR pump can be brought into service.

The spray pump(s) will continue to inject RWST water into the containment through the spray headers until the RWST reaches a low-low level setpoint. In this case, it may be necessary to continue the spray to the containment using recirculation water. This duty can be performed by both the RHR pumps and the containment spray pumps.

The CSS functions to reduce the reactor containment building pressure and quantity of fission products in the containment atmosphere subsequent to a LOCA. Pressure reduction is accomplished by spraying water into the containment atmosphere. The system consists of two independent and identical subsystems. During recirculation, the failure of a single active or single passive component will not prevent the system from performing its safeguard function.

The CSS consists of two pumps, spray ring headers, a number of MOVs, and all necessary piping, instruments, and accessories to make the system operable. For the recirculation mode, manual operation of the system is performed remotely from the control room. When the RWST reaches the low–low level, spray pump suction is switched from the RWST to the containment sump. A separate containment sump suction line is provided to each spray pump. These lines each contain two MOVs in series, in order to provide containment isolation. Two identical spray pumps are installed in the system. Either pump provides sufficient capacity to perform the necessary containment spray function. Spray flow is delivered from the containment sump to the spray headers.

3.3.2.2 Combustion Engineering Plants

For CE design plants, borated water for high pressure and low pressure core injection and containment spray is provided by the Refueling Water Tank (RWT). Upon depletion of the RWT volume, a Recirculation Actuation Signal (RAS) realigns the ECCS and CSS suction to the containment sump. The RAS opens the containment sump recirculation line isolation valves and operators close the RWT discharge isolation valves. Transfer to the recirculation mode can also be established manually.

In the recirculation mode, low pressure safety injection (LPSI) pumps are automatically secured and core flow is provided only by the high pressure safety injection (HPSI) pumps. However, operators may elect to restart LPSI flow during recirculation to provide additional core flow. Only one HPSI pump is required following recirculation since each train of HPSI is designed to provide sufficient flow to make up that inventory lost to boil off at the time of RAS.

Recirculation is required only for a LOCA; no other design bases accidents result in depletion of the RWT volume.

The decay heat and the latent system heat are removed post-accident to the ultimate heat sink by the shutdown cooling system heat exchangers (SCHXs) (through the CSS). In instances where there is sufficient net positive suction head (NPSH), the shutdown cooling system (SCS) can be aligned for LTCC.

3.3.2.3 Babcock and Wilcox Plants

For B&W design plants, post–accident recirculation flow is provided by the low pressure injection (LPI) pumps. The recirculation alignment occurs when the borated water storage tank (BWST) has been drained and SIS inventory for recirculation comes from the containment sump, where the injected inventory collects. Recirculation will be required only for a LOCA.

Only the LPI pumps are aligned to take suction from the sump during the recirculation mode. There are two separate pipes from the sump to the suction side of the LPI pumps and there is an MOV in each line. Depending on the plant, there are either two or three LPI pumps available. On the discharge side of the LPI pumps, there are check valves, MOVs, and the decay heat coolers.

There are two separate injection paths which inject only to the reactor core flood tank nozzles. Each low pressure pump is aligned to one nozzle or two, depending on the plant design. The containment sump is aligned to the containment spray pumps through two separate flow paths during recirculation.

The following component list is provided as a generic guideline for the type of equipment used for post-accident recirculation:

- Pumps: LPI, CS
- Heat exchangers: Decay heat coolers (DHR system)
- Valves: MOVs, checks, throttle
- Other: CS nozzles

B&W units have similar systems and capabilities that are described in more detail for the CE and Westinghouse plants. These systems include those for containment spray, containment atmosphere control and containment isolation. These systems are not described here as they are similar to and function in a like manner as those systems described for the CE and Westinghouse plants.

LTCC after a LBLOCA is well within the capability of a single decay heat removal pump operating at a containment pressure near atmospheric. Heat removal from the containment via containment spray and/or fan coolers will ensure that the containment pressure is near atmospheric pressure in the long–term post–LOCA environment. Therefore, indefinite operation of the high pressure injection (HPI) pumps is not required except under certain single failures for some plants during LTCC after a large break LOCA.

3.3.3 Boric Acid Precipitation Control

All three U.S. PWR designs (Westinghouse, CE, and B&W) use boron as a core reactivity control method and are subject to potential BAP in the core for scenarios that preclude ECCS flow through the core for extended periods following a LOCA. All three plant designs have ECCS features that include an active core dilution mechanism to prevent the core region boric acid concentration from reaching the precipitation point. These dilution mechanisms may or may not require operator action.

The common approach for demonstrating adequate boric acid dilution in a post-LOCA scenario includes the use of simplified methods with conservative boundary conditions and assumptions. These simplified methods are used with limiting scenarios in calculations that determine the time at which appropriate operator action must be taken to initiate an active boric acid dilution flow path or alternately, to show that BAP will not occur. The three U.S. PWR designs have different ECCS configurations, different methodologies, and procedures for BAPC. Nevertheless, there are common approaches, assumptions and simplifications that have been used in virtually all PWR calculations that address the potential for BAP.

For typical plant designs (Westinghouse 2-loop UPI plants excluded), the limiting scenario for BAP is a large cold leg (pump discharge) break where the downcomer is eventually filled, and the excess ECCS flow exits out of the break. The ECCS flow into the core region is largely limited to that quantity boiled-off in the core to remove the decay heat. The steam generated in the core travels around the intact hot leg(s) (or through the internals reactor vessel vent valves (RVVVs) in the B&W designed plants) to exit the break. Boric acid left behind accumulates in the core region and the boric acid concentration in the core region increases.

The calculated rate of increase in boric acid concentration in the core region after a LOCA is directly affected by the assumed liquid volume. During this time, the core and UP are filled with a two-phase mixture for which the liquid content is dependent on the degree of voiding in the core and UP region. The degree of voiding is a function of the core decay heat and RCS pressure, and the pressure drop around the loop (or through the RVVVs) as it affects the hydrostatic balance between the downcomer head and the collapsed liquid level in the core. At low RCS pressures and high decay heat levels, the boiling in the core is vigorous, and the volume of liquid in the core region is smaller. As the decay heat drops off, the boiling becomes less vigorous and more liquid is retained in the core region.

Westinghouse 2-loop UPI plants differ from typical PWR designs in that they utilize low pressure UPI. For these plants, the limiting large break LOCA BAP scenario is a HLB where the cold leg high pressure safety injection may be terminated at or prior to sump recirculation. This scenario is relevant only with the very conservative assumption that all UPI flow in excess of core boil-off bypasses the core region and flows directly out the break (i.e., no mixing in the core and UP).

For Westinghouse design and CE design plants, BAP calculations are used to determine the appropriate time to switch some or all the ECCS sump recirculation flow to the hot leg or to otherwise show that BAP will not occur. For B&W-designed plants, BAP calculations are used to justify plant-specific active boric acid dilution methods or limitations on the dilution methods (e.g., plant-specific auxiliary pressurizer spray flows, protection of the sump strainer(s), prevention of potential water-hammer scenarios in the decay heat piping, challenges to NPSH limits for LPI pumps, hot and cold fluid mixing limits, prevention of BAP inside the decay heat cooler, etc.).

The influence of debris on BAPC and the evaluation completed by this program is discussed in Section 9.1.2 and Section 9.2.2 for the HLB and CLB scenarios, respectively.

3.4 DESCRIPTION OF IN-VESSEL DEBRIS CONCERNS

Once the RWST has drained and the operators switch the ECCS suction source to the containment sump, debris laden coolant may begin to enter the RCS via the ECCS. The concentration of debris entering the RCS is a function of time and is dependent upon the sump condition, strainer filtering efficiency, and the ECCS configuration. For any break location, some portion of debris penetrating the sump strainer, traversing the ECCS, and reaching the RCS will enter the RV and some portion will go elsewhere.

For the fraction of debris that enters the RV, the path it takes is dependent upon the debris properties, specific vessel geometry, flow condition, break location, etc. During cold leg recirculation, flow transports debris through the downcomer, into the lower head where it encounters some form of lower internal configuration consisting of various plates and vertical columns. Some fraction of debris may collect or settle on these components, or it may remain suspended in the flow. Debris that continues with the flow, travels through the core support region and enters the core where it could accumulate, remain suspended in the flow, or exit the RCS through the break. Most likely, in-vessel debris transport results from some combination of the above and is distributed throughout the RV. For hot leg breaks, some fraction of debris may flow out of the break since it is at the RV exit. For cold leg breaks, a significantly smaller portion of the debris that enters the RV will make it to the core due to the break location.

For ECCS recirculation to the hot legs or upper head, flow transports debris into the RV UP where it encounters some form of upper internal configuration consisting of various plates and vertical columns (e.g., control rod guide tube housings, instrument tube housings). Some fraction of debris may collect on these structures, or it may remain suspended in the flow. Debris that continues with the flow, travels through the upper core plate and enters the core where it could accumulate, remain suspended in the flow, or exit the RCS through the break. Most likely, the debris does some combination of the above and is distributed throughout the RV. For hot leg breaks, some fraction of debris may flow out of the break before it reaches the core since it is at the RV exit. For cold leg breaks, debris that is not captured in the core may settle in the RV LP or flow up the downcomer and out of the break.

Concerns have been raised about the potential for debris ingested into the ECCS to affect LTCC when recirculating coolant from the containment sump. The FA bottom nozzles are designed with flow passages that provide coolant flow from the RV LP into the region of the fuel rods. During operation of the ECCS to recirculate coolant from the containment sump, debris in the recirculating fluid that passes through the sump strainer(s) may collect on the bottom surface of the FA bottom nozzle, causing resistance to flow through this path. The collection of sufficient debris on the FA bottom nozzle is postulated to impede flow into the FA and core. Other concerns have been raised with respect to the collection of debris and post-accident chemical products within the core itself. Specifically, the debris has been postulated to either form blockages or adhere to the cladding, thereby reducing the ability of the coolant to remove decay heat from the core. Similarly, chemical precipitates have been postulated to plate out on fuel cladding, again resulting in a reduction of the ability of the coolant to remove decay heat from the core. Finally, debris may concentrate within the heated core region such that the fluid properties in the core change, and subsequently, the heat removal ability of the water/debris mixture is affected.

The potential for localized blockages within the core region, adherence of debris to the heated fuel rods, and plate-out of debris and chemical precipitates are evaluated in WCAP-16793-NP-A, Rev. 2 (Reference 3-1). These evaluations have been found acceptable to the NRC via the SE on Reference 3-1; therefore, no further work on these topics is presented in this report. This report instead focuses on the effects of the following concerns: (1) the effect of blockage by debris at the core inlet and (2) the accumulation and concentration of debris in the core region.

3.5 DEBRIS CONSTITUENTS

The Nuclear Energy Institute (NEI) Guidance Report (GR), NEI 04-07 (Reference 3-2), provides the guidelines for determining the type, size, and quantity of debris that is generated following a LOCA. The GR (Reference 3-2) adopts a two-size distribution for material inside the ZOI of a postulated break: small fines and large pieces. Small fines are defined as any material that could transport through gratings, trash racks, or radiological protection fences by blowdown, containment sprays, or post-accident pool flows. Furthermore, the small fines are assumed to be the basic constituent of the material for fibrous blankets (i.e., individual fibers) and pigments for coatings. The GR (Reference 3-2) assumes the largest openings of the gratings, trash racks, or radiological protection fences to be less than a nominal 4 inches by 4 inches (less than 20 square inches total open area). The remaining material that cannot pass through gratings, trash racks, and radiological protection fences is classified as large pieces.

For in-vessel effects, the debris of interest is small fines, which can be further characterized as either particulates or fibers. The debris characteristics for small fines are described in

Section 3.4.3.6, Reference 3-2. The characteristic sizes listed are the most conservative values that can be associated with debris transport and head loss since they are the size that will have the highest transport factor and causes the highest head loss in a debris bed.

In addition to particulate and fibrous material, corrosion products may form due to chemical interactions among the material in containment and the sump fluid, which contains buffering agents and boric acid. Among the materials that are found inside containment and are susceptible to chemical reactions with the post-LOCA solution are aluminum, zinc, and non-metallic materials such as some coatings, thermal insulation (e.g., Cal-Sil, fiberglass), and concrete. The resulting chemical precipitates may include aluminum oxyhydroxide, sodium aluminum silicate, and calcium phosphate. These materials can combine with a debris bed resulting in an increased head loss across the bed. For in-vessel considerations, this can result in a reduced capability to maintain the necessary cooling flow through the core.

3.6 LIMITING SCENARIO

10 CFR 50.46 (Reference 3-3) requires that LTCC be demonstrated for all break sizes and locations in the RCS. To date, evaluations of in-vessel effects for GSI-191 have assumed that the double ended guillotine (DEG) break is limiting with respect to establishing debris. This assumption is based in part on the following points: (1) the largest break generates the largest amount of debris and will therefore deliver the most debris to the RCS; and (2) the largest break has the highest ECCS flow rates, which will minimize the potential for settling of particulate and fibrous debris in the containment and therefore maximize the transport of these types of debris to the RCS and deliver the debris to the RCS sooner than lower flow rates, which challenges core DHR since decay heat decreases with time.

This section outlines the basis for why a DEG break is limiting and can be considered as the only break for setting in-vessel debris limits. Assuming that the largest breaks will produce a limiting amount of debris, it is proposed that this condition will deliver the most debris to the RCS at the earliest time. Support for this conclusion is developed in the following steps:

1. Debris generation – A description and partial quantification of the debris in containment will be developed based on break size. It will be shown that larger breaks have the potential to generate more debris.

2. Timing of debris arrival to RCS – The effect of debris arrival time as it relates to the core debris limit will be discussed. It will be shown that for breaks that generate sufficient debris, the ECCS flow rates and timing of SSO are similar.

3. Debris delivered to RCS – An evaluation of the debris that can reach the RCS will be developed based on sump strainer coverage and filtration efficiency. It will be shown that the debris delivered to the RCS is proportional to the amount of debris that reaches the sump strainer.

3.6.1 Debris Generation

Debris in containment is either latent (i.e., dirt and dust that already exists in containment regardless of break size or location) or is generated by the effects of the break. All plants have latent debris that is

independent of break size. Debris generated by the effects of the break fall into two categories: (1) insulation materials and qualified coatings within the ZOI of the break that fail due to jet impingement and (2) unqualified coatings that are assumed to fail as a result of the post-LOCA environment. All unqualified coatings are assumed to fail regardless of break size and ZOI and are further assumed to fail as particulates independent of break size (unless specific testing shows otherwise) and require no further discussion. Debris generated within the ZOI, however, is a function of break size and will vary accordingly.

The ZOI is defined as the volume about the break in which the fluid escaping from the break has sufficient energy to dislodge insulation, coatings, and other materials within the zone. For a DEG break, the boundary of the ZOI is assumed to be spherical, with the center of the sphere located at the break site. The use of a spherical ZOI is intended to encompass the effects of jet expansion resulting from impingement on and reflection from structures and components.

For single-sided breaks, cracks, or split/slot breaks, the ZOI is represented as a hemisphere. Since the radius of a ZOI for a DEG break is expressed as the ratio of distance from the break to the target (L) to the break diameter (D_{break}), or L/D_{break}, the radius of hemispherical ZOI for a break having an equivalent diameter as a DEG break is the same as the radius of the sphere for a DEG break. The volume of the ZOI for a single sided, split / fish-mouth break, however, is one-half (1/2) that for the DEG break.

To determine the limiting amount of debris generated in containment, a survey of the RCS and attached piping is performed and the ZOI is moved along the pipe as appropriate. The amount of debris generated for a given ZOI in a given location is compared against all other ZOIs in all other locations. Typically, the maximum debris generation is for a DEG break in one of the large RCS pipe runs. Smaller breaks and single-sided breaks will not generate as much debris.

A volume ratio approach may be used to scale the amount of debris generated by full-area DEG break to a smaller break. This approach assumes that possible debris sources are uniformly distributed within the ZOI volume and that reducing the ZOI will not move the debris source outside of the ZOI. The break is evaluated based on the reduction in volume of the spherical ZOI. Since the volume, V, of a sphere is proportional to the radius to the third power, as the break becomes smaller, the volume of the ZOI decreases quickly. It should also be noted that for breaks on smaller pipes, the quantity of debris generated may be slightly larger than that assumed using the volume ratio approach due to the proximity of other insulated piping. This difference is negligible when comparing the quantity of debris generated for a large DEG to that of a small DEG or partial pipe break.

Table 3-2 shows an approximate reduction in debris with break size using this approach relative to a 36" DEG break for both the DEG break and single-sided breaks. It is clear that the amount of debris generated decreases quickly with a reduction in break size. Even for DEG breaks in attached piping (typically starting around 0.5 ft^2, or 4.8 inches in diameter for a DEG break), the amount of debris generated relative to a DEG break on the primary RCS piping will be small. As break size decreases, the amount of fiber approaching the sump strainer quickly approaches the latent fiber load only.

Table 3-2 Example Debris Ratio Calculations

Break Diameter		Debris Ratio	
(in)	(ft)	DEG Break to 36 inch DEG Break	Single-Sided Break to 36 inch DEG Break
36	3	1	0.5
33	2.75	0.77	0.39
30	2.5	0.58	0.29
27	2.25	0.42	0.21
24	2	0.30	0.15
21	1.75	0.20	0.10
18	1.5	0.13	0.06
15	1.25	0.07	0.04
12	1	0.04	0.02
6	0.5	0.005	0.002

3.6.2 Timing of Debris Arrival and ECCS Flow Rate

Larger break sizes depressurize the RCS more quickly than smaller breaks. Since ECCS flow rate is a function of RCS pressure, two possible effects occur as a result: (1) smaller breaks may draw down the RWST slower and delay the time of SSO, which may affect the amount of debris that can be tolerated in the RCS; or (2) smaller breaks may result in lower ECCS flow rates that can affect the approach velocity to and capture efficiency of sump strainer(s) and the delivery rate of debris to the RCS.

LOCA analyses have shown that a 0.5-ft^2 break will depressurize the RCS in much the same fashion as a full-area DEG break. The depressurization rate is slightly slower, but the minimum pressure reached is well below the point at which the ECCS injection flow rate becomes constant (low head safety injection pumps have constant flow rates below approximately 50-80 psid). The difference in timing of reaching the low head injection set point will be delayed by a few minutes at most. Consequently, the variation in time of SSO will not be significantly different among break sizes between approximately 0.5 ft^2 and a DEG break of the RCS piping. Further, the minimum RCS pressure will be similar between the two break sizes such that the total low head ECCS flow rate will be the same. However, the debris generated by the 0.5 ft^2 break (break diameter of 9.6 inches for a single sided break or 4.8 inches for a DEG break) will be less than two percent of that generated for the full area DEG break (Table 3-2), a value far less than necessary to meet or exceed the in-core fiber limit.

3.6.3 Debris Delivered to Reactor Coolant System

The debris that is generated within the ZOI, along with any latent debris and unqualified coatings, is transported to the containment sump. While the ECCS and CSS are drawing from the clean RWST, the break effluent is accumulating in the sump where the velocities in the sump are low and the debris is

essentially suspended in the liquid. Once the transition of the ECCS and CSS pump suction from the RWST to the sump is complete, this debris will be drawn towards the sump strainers. As fiber arrives at the sump strainer, it will begin to collect in localized areas on the sump strainer. These areas will increase the local pressure drop such that flow and fiber will be diverted to adjacent locations. In this manner, the debris bed will spread across the sump strainer and develop a bed over the entire strainer surface as it spreads.

In their proposed GSI-191 Resolution Criteria for "Low Fiber" Plants[1] (Reference 3-4 and Reference 3-5), NEI suggested that a "Low/No Fiber plant" has a sump strainer capture efficiency of 55 percent (i.e., 45 percent of the debris passes through the strainer). A "Low/No Fiber plant" is defined as a plant with essentially only latent fiber (i.e., no fibrous insulation within a ZOI). Therefore, a capture efficiency of 55 percent or more can be assumed for latent fiber loads (i.e., fiber masses).

As additional fiber is considered in the system and continues to build, the capture efficiency of the sump strainer will increase up to the point that the sump strainer is completely covered. Once the entire strainer is covered, then the filtration efficiency will plateau at approximately 100 percent. This behavior was noted during testing performed for South Texas Project (STP) (Reference 3-7). The following is noted from Reference 3-7:

1. Under clean strainer conditions, the minimum observed capture efficiency was evaluated to be about 65 percent.

2. Over several tests, the filtration efficiency was observed to increase in an approximately linear manner from the clean strainer value to about 100 percent.

3. Once 100 percent filtration efficiency was observed, it remained constant.

4. Limited shedding of fibrous debris from the bed formed on the strainer was observed.

The filtration efficiency for the STP tests suggests that the sump strainer capture efficiency increases as the fiber load (i.e., fiber mass) on the strainer increases. After complete coverage, the shedding observed in the STP sump strainer tests demonstrates that a limited amount of fibrous debris will continue to penetrate the sump strainer.

This result has also been demonstrated for other plant designs and is illustrated in Figure 3-10. While the fraction of fiber penetrating the sump strainer and reaching the RCS continually decreases as the fiber load on the strainer increases, the total amount of fiber passing through the strainer continues to increase with the fiber load reaching the sump strainer (as evidenced by the integral of the curve).

[1] Reference 3-6 documents the NRC's review of the criteria proposed by NEI. In their review of the proposed NEI GSI-191 Resolution Criteria, the NRC noted that that the guidance was, ". . . high level guidance and there are a number of details that individual licensees will need to document to clearly establish the new licensing basis for their plant." The enclosure to the NRC's letter offered additional considerations for plants to use when developing the plant-specific licensing basis.

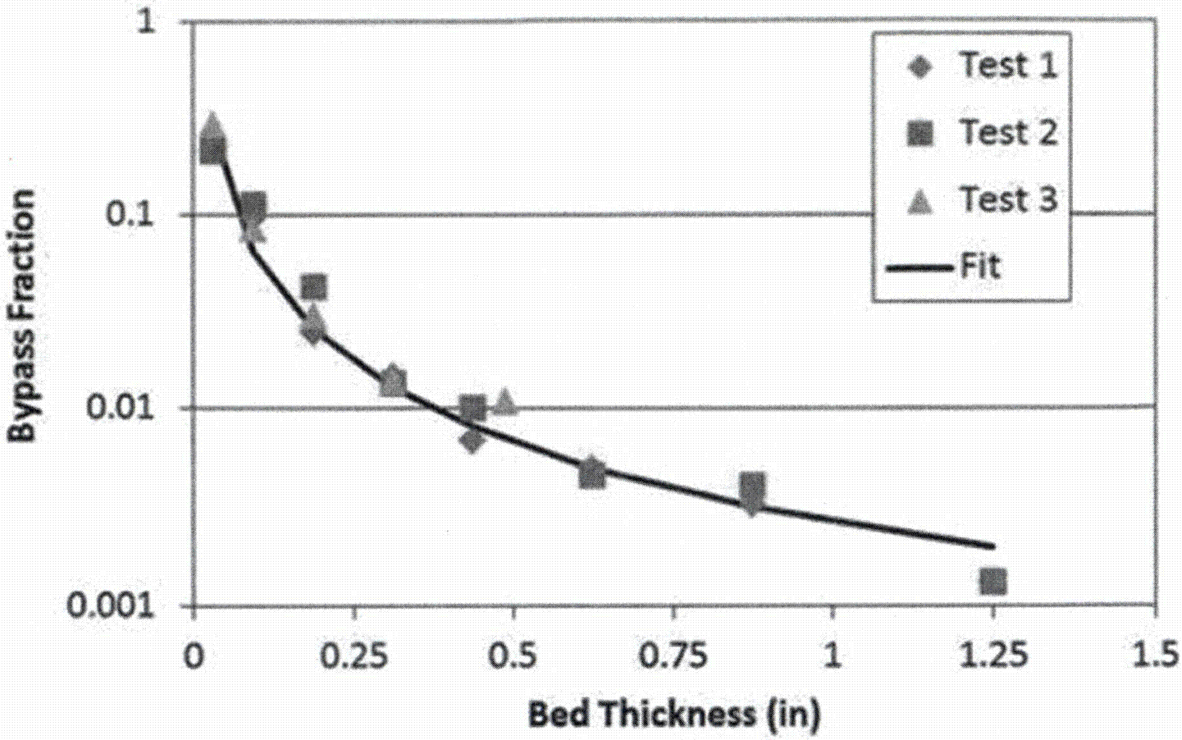

Figure 3-10 Strainer Bypass Fraction as a Function of Theoretical Debris Bed Thickness

3.6.4 Conclusions

As described above, a description and partial quantification of the debris in containment demonstrates that larger breaks generate significantly more debris than smaller breaks. In fact, debris generated within the ZOI quickly decreases with break size such that negligible debris relative to a DEG break in the RCS piping is noted for breaks below 0.5 ft^2.

The effect of debris arrival time and ECCS flow rate as it relates to the core debris limit was also discussed. Breaks above approximately 0.5 ft^2 will not significantly change the time of SSO or the ECCS flow rate.

Finally, an evaluation of the debris that can reach the RCS was developed based on sump strainer coverage, which is related to the amount of debris that reaches the sump strainer. For the smallest amounts of fiber (i.e., latent fiber only), sump capture efficiency was shown to be approximately 55 to 65 percent. As fiber amounts increase, the strainer capture efficiency will increase as well until the strainer is completely covered, at which point the capture efficiency approaches a maximum. After the sump strainer is completely covered, some debris will continue to penetrate the sump strainer due to shedding. Therefore, the amount of fiber penetrating the sump strainer and reaching the RCS is proportional to the amount of debris reaching the sump strainer. Since larger breaks will generate sufficient debris to completely cover the sump strainer, larger breaks will deliver more debris to the RCS.

It is concluded that the largest breaks will produce the largest amount of debris, which will deliver the most debris to the RCS at the earliest time. Therefore, DEG breaks are evaluated for establishing in-vessel debris limits.

3.7 LONG-TERM CORE COOLING REQUIREMENTS AND ACCEPTANCE CRITERIA

The acceptance criteria are established to adequately maintain LTCC after a postulated LOCA event. The two aspects of LTCC that pertain to the 10 CFR 50.46 (Reference 3-3) are:

1. Decay Heat Removal - DHR requires that sufficient coolant be supplied to the core such that the core temperature is maintained at an acceptably low level.

2. Boric Acid Precipitation Control - BAPC requires that boron concentrations in the RV remain below the solubility limit.

For previous GSI-191 evaluations, DHR was assured if the maximum core PCT remains below 800°F (Reference 3-1). This conservative value is retained for this evaluation. Further, in the event that debris deposits on the fuel rods, the thickness of the buildup can be no more than 0.050 inch[(2)].

For the DEG HLB scenario with core inlet blockage, BAPC requires demonstrating adequate break quality to flush boron from the RV and demonstrating adequate core mixing such that the entire core volume can be assumed to be a near homogeneous boron concentration.

For the DEG CLB scenario, BAPC requires demonstrating that the core inlet debris load does not create a uniform blockage such that communication between the core and LP remains and that BAPC measures remain effective at flushing boron from the RV.

3.8 CURRENT DEBRIS LIMITS

The PWROG sponsored a previous program to provide analyses and information on the effects of debris and chemical products on core cooling for PWRs when the ECCS is realigned to circulate coolant from the containment sump. The intent was to demonstrate adequate heat removal capability for all plant scenarios. This program is documented in WCAP-16793-NP, Rev. 0.

After working through responses to NRC RAIs on the topical report (which included further testing to address NRC staff questions), WCAP-16793-NP-A, Rev. 2 (Reference 3-1) was submitted to the NRC for formal review. This report included the results of a significant experimental test program that investigated blockages formed on approximately one-third height test assemblies. The debris composition tested included particulate and fiber debris, as well as post-accident chemical products. The

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[2] Debris deposition on the fuel rods is addressed using the LOCADM methodology described and approved in WCAP-16793-NP-A, Rev. 2 (Reference 3-1). This process is still a part of the methodology to address the in-vessel effects of GSI-191. However, no changes to this methodology are presented herein and the use of the LOCADM as described in Reference 3-1 continues to be applicable.

program was performed such that the results of this program apply to the fleet of PWRs, regardless of the design (Westinghouse, CE, or B&W).

The evaluation considered the design of the PWR, the design of the open-lattice fuel, the design and tested performance of replacement containment sump strainer(s), the tested performance of materials inside containment, and the tested performance of fuel assemblies in the presence of debris. Specific areas addressed in this evaluation included:

- Blockage at the Core Inlet
- Collection of Debris on Fuel Grids
- Collection of Fibrous Material on Fuel Cladding
- Protective Coating Debris Deposited on Fuel Clad Surfaces
- Production and Deposition of Chemical Precipitates
- Coolant Delivered from the Top of the Core

The following acceptance bases were established for the evaluation of the topical areas identified above:

1. The maximum clad temperature shall not exceed 800°F.
2. The thickness of the cladding oxide and the fuel deposits shall not exceed 0.050 inch in any fuel region.
3. The maximum fibrous debris that reaches the core after a LOCA is less than or equal to 15 g/FA.

These acceptance bases were applied after the initial quench of the core and are consistent with the LTCC requirements stated in 10 CFR 50.46 (Reference 3-3). They do not represent, nor are they intended to be, new or additional LTCC requirements. These acceptance bases demonstrate that local temperatures in the core are stable or continuously decreasing and that debris entrained in the cooling water supply will not affect decay heat removal. The 800°F cladding temperature was selected based on autoclave data that demonstrated oxidation and hydrogen pick-up was minimal at and below the 800°F temperature. Therefore, there would be minimal reduction in post-LOCA load carrying capability. A discussion of the technical basis for the 800°F temperature is given in Appendix A, Reference 3-1. The 0.050 inch limit for oxide plus deposits was selected so as to preclude the formation of deposits that would bridge the space between adjacent rods and block flow between fuel channels. Finally, FA testing has demonstrated that the most severe combinations of fibrous, particulate, and chemical precipitant debris loads with less than or equal to 15 g/FA of fiber will not impede core cooling.

In order to demonstrate reasonable assurance of LTCC, all plants must evaluate the areas identified above and demonstrate they are bounded by the debris load acceptance criteria, maximum fuel cladding temperature and maximum deposit thickness requirements. Specifically:

- Adequate flow to remove decay heat will continue to reach the core even with debris from the sump reaching the RCS and core. Plants that operate at (or below) 15 grams of fiber per FA can state that debris that bypasses the sump strainer will not build an impenetrable blockage at the core inlet.

- Decay heat will continue to be removed even with debris collection at the FA spacer grids. Plants that operate at (or below) 15 grams of fiber per FA can state that debris that bypasses the sump strainer will not build an impenetrable blockage at the fuel spacer grids. This assertion is bolstered by numerical and first principle analyses.

- Fibrous debris, should it enter the core region, will not tightly adhere to the surface of fuel cladding. Thus, fibrous debris will not form a "blanket" on clad surfaces to restrict heat transfer and cause an increase in clad temperature. Therefore, adherence of fibrous debris to the cladding is not plausible and will not adversely affect core cooling.

- Protective coating debris, should it enter the core region, will not restrict heat transfer and cause an increase in clad temperature. Therefore, adherence of protective coating debris to the cladding is not plausible and will not adversely affect core cooling.

- The chemical effects method developed in WCAP-16530-NP-A (Reference 3-8) was extended to develop a method to predict chemical deposition on fuel cladding. The calculational tool, LOCADM, can be used by each utility to perform a plant-specific evaluation. It is expected that each plant will be able to use this tool to show that decay heat would be removed and acceptable fuel clad temperatures would be maintained.

- PWRs use boron as a core reactivity control method and are subject to concerns regarding potential post-LOCA BAP in the core. In light of NRC staff and Advisory Committee on Reactor Safeguards (ACRS) challenges to the simplified methods commonly used, it has recently become clear that additional insights and new methodologies are needed to answer fundamental questions about boric acid mixing and transport in the RCS and potential precipitation mechanisms that may occur both during the ECCS injection phase and the sump recirculation phase after a LOCA.

- The PWROG FA test results demonstrated that sufficient flow will reach the core to remove core decay heat. The debris load acceptance criteria developed is bounding and applicable to all PWR plants, including UPI plants.

In conclusion, WCAP-16793-NP-A, Rev. 2 (Reference 3-1) stated that a very conservative, bounding, and generic limit of 15 grams of fiber per FA could be established. This limit is independent of particulate and chemical precipitate quantity. The report also concluded that higher limits could be possible depending on plant-specific conditions.

The NRC concurred with the acceptance criteria and stated conclusions when issuing the SE on Reference 3-1. However, there are 15 conditions and limitations associated with the limits approved in WCAP-16793-NP-A, Rev. 2 (Reference 3-1). While many of these conditions provided guidance to utilities on what information is needed in a GL 2004-02 submittal and how to properly use the information in the report, some of them also provided guidance on what should be considered for increasing the debris limits if that path was chosen. Of relevance are the following limitations (*italics* added to identify actions):

1. Licensees should confirm that their plants are covered by the PWROG sponsored fuel assembly tests by confirming that the plant available hot-leg break driving head is equal to or greater than that determined as limiting in the proprietary fuel assembly tests and that flow rate is bounded by the testing. Licensees should validate that the fuel types and inlet filters in use at the plant are covered by the test program (with the exception of LTAs). Licensees should limit the amount of fibrous debris reaching the fuel inlet to that stated in Section 10 of the WCAP (15 grams per fuel assembly for a hot-leg break scenario).

   Alternately, licensees may perform plant-specific testing and/or evaluations to increase the debris limits on a site-specific basis. The available driving head should be calculated based on the core exit void fraction and loop flow resistance values contained in their plant design basis calculations, considering clean loop flow resistance and a range of break locations. Calculations of available driving head should account for the potential for voiding in the steam generator tubes. These tests shall evaluate the effects of increased fiber on flow to the core, and precipitation of boron during a postulated cold leg break, and the effect of p/f ratios below 1:1. The NRC staff will review plant-specific evaluations, including hot- and cold-leg break scenarios, to ensure that acceptable justification for higher debris limits is provided.

3. Section 3.1.4.3 of the WCAP states that alternate flow paths in the RV were not credited. The section also states that plants may be able to credit alternate flow paths for demonstrating adequate LTCC.

   If a licensee chooses to take credit for alternate flow paths, such as core baffle plate holes, to justify greater than 15 grams of bypassed fiber per fuel assembly, the licensee should demonstrate, by testing or analysis, that the flow paths would be effective, that the flow holes will not become blocked with debris during a LOCA, that boron precipitation is considered, and that debris will not deposit in other locations after passing through the alternate flow path such that LTCC would be jeopardized.

5. In RAI Response number 18 in Reference 13, the PWROG states that numerical analyses demonstrated that, even if a large blockage occurs, decay heat removal will continue. The NRC staff's position is that a plant must maintain its debris load within the limits defined by the testing (e.g., 15 grams per assembly).

   Any debris amounts greater than those justified by generic testing in this WCAP must be justified on a plant-specific basis.

12. Section 3.1 of the WCAP discusses a prototypical test program designed to establish limits on the amount of debris that could bypass the ECCS sump strainer, enter the core, and still allow adequate flow to enter the core to ensure adequate LTCC. The WCAP states that a test protocol and test procedures were developed to include investigation of possible thin bed effects and that the debris used in testing represented debris that could be present in the RCS following a LOCA.

Plants that can qualify a higher fiber load based on the absence of chemical deposits should ensure that tests for their conditions determine limiting head losses using particulate and fiber loads that maximize the head loss with no chemical precipitates included in the tests. Note that in this case, licensees must also evaluate the other considerations discussed in Item 1 above.

This work provides an alternative approach to the method detailed in WCAP-16793-NP-A, Rev. 2 (Reference 3-1) for defining an in-vessel fibrous debris limit and provides a means for increasing the currently established in-vessel fibrous debris limit of 15 g/FA by addressing the above concerns.

3.9 REFERENCES

3-1 WCAP-16793-NP-A, Rev. 2, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculation Fluid," July 2013.

3-2 NEI 04-07, Rev. 0, "Pressurized Water Reactor Sump Performance Evaluation Methodology," December 2004.

3-3 10 CFR Part 50 §50.46, "Acceptance Criteria for Emergency Core Cooling Systems for Light Water Nuclear Reactors," 72 Federal Register 49494, August 2007.

3-4 Letter from John C. Butler (NEI) to Stewart N. Bailey (U.S. NRC), "Transmittal of GSI-191 Resolution Criteria for "Low Fiber" Plants," ADAMS Accession Number ML113570219, December 2011.

3-5 Attachment to ML113570219, "GSI-191 Resolution Criteria Low/No Fiber Plants," ADAMS Accession Number ML113570226, 2 pages, December 2011.

3-6 Letter from William H. Ruland (U.S. NRC) to John C. Butler (NEI) "NRC Review of Nuclear Energy Institute Clean Plant Acceptance Criteria for Emergency Core Cooling Systems," ADAMS Accession Number ML120730181, May 2012.

3-7 STP-RIGSI191-V03.06, Rev. 5, "South Texas Project Risk-Informed GSI-191 Evaluation, Filtration as a Function of Debris Mass on the Strainer: Fitting a Parametric Physics-Based Model," June 2013.

3-8 WCAP-16530-NP-A, Rev. 0, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," March 2008.

4 METHOD FOR CALCULATING FIBER LIMIT

The method for calculating the in-vessel debris limits described in this report is plant-specific and depends on inputs for each plant (or group of identical plants). The remainder of this report details a method that utilities can use to assess plant-specific debris limits for closure of NRC GL 2004-02.

As discussed in Section 3.6, large breaks are the focus of GSI-191 resolution. Further, the break locations are divided into HLBs and CLBs. Both break scenarios must be considered independently given the difference in system response, timing of debris introduction to the fuel, and the benefits of alternate flow paths (AFPs) for hot leg breaks. Section 5 identifies the major assumptions used in the methodology. For plants that initially start with cold side recirculation, Section 4.2 outlines the methodology for HLB, and Section 4.3 outlines the methodology for CLB. Sections 6 and 7 provide the details of the methods for calculating the amount of fiber delivered to the RCS for HLB and CLB, respectively. For UPI plants, Section 8 provides the methodology for both break locations. For the spectrum of large breaks, this methodology can be used to ascertain that the amount of debris generated in containment does not ultimately result in an excessive amount of debris (fiber and particulate) delivered to the RV such that LTCC is compromised. The evaluation process is illustrated in Figure 4-1.

The methodology is predicated, in part, on plant-specific ECCS strainer design and the efficiency of that strainer to collect debris. Containment recirculation sump strainers are designed to act as filters to collect post-accident debris, thus preventing a wide range of debris from entering the ECCS and CSS. However, a portion of the debris may be sufficiently small or deformable to actually "pass through" the recirculation sump strainer(s) and enter the ECCS and CSS. This "pass through" (also sometimes called "bypass" or "penetration") debris in the ECCS may then enter the RCS. For either a HLB or a CLB, the CSS flow is returned to the containment where it eventually returns to the sump and is again filtered by the recirculation sump strainer(s) before the coolant enters either the ECCS or the CSS.

Where available, quantification of that fraction of debris that penetrates the sump strainer(s) should be used. Otherwise, conservative assumptions must be applied to ultimately determine allowable fiber quantities in containment. Plants that have performed strainer testing have quantified the total penetration considering several time-dependent mechanisms. These may include initial penetration of debris as it builds on the sump strainer, continued penetration of debris if the sump strainer is not fully covered, and debris shedding if the strainer is fully covered. Flow (and the corresponding debris) to the CSS suction can also be considered if it is in operation.

Formation of chemical precipitates must also be considered. As described previously, the in-vessel fiber evaluations documented in WCAP 16793-NP-A Rev. 2 (Reference 4-1) demonstrated significant head loss in the presence of the chemical precipitate surrogate used during testing, thereby limiting the fiber quantities. In the present effort, the method assumes that all chemical precipitates are sufficiently delayed and do not form until after a critical point where sufficient cooling occurs as a result of flow directed through the AFPs. Total core blockage due to debris and or chemical effects after this point (approximately 4 to 6 hours) is assumed. In all cases, this method assumes that chemical precipitates form at 24 hours if they don't form earlier.

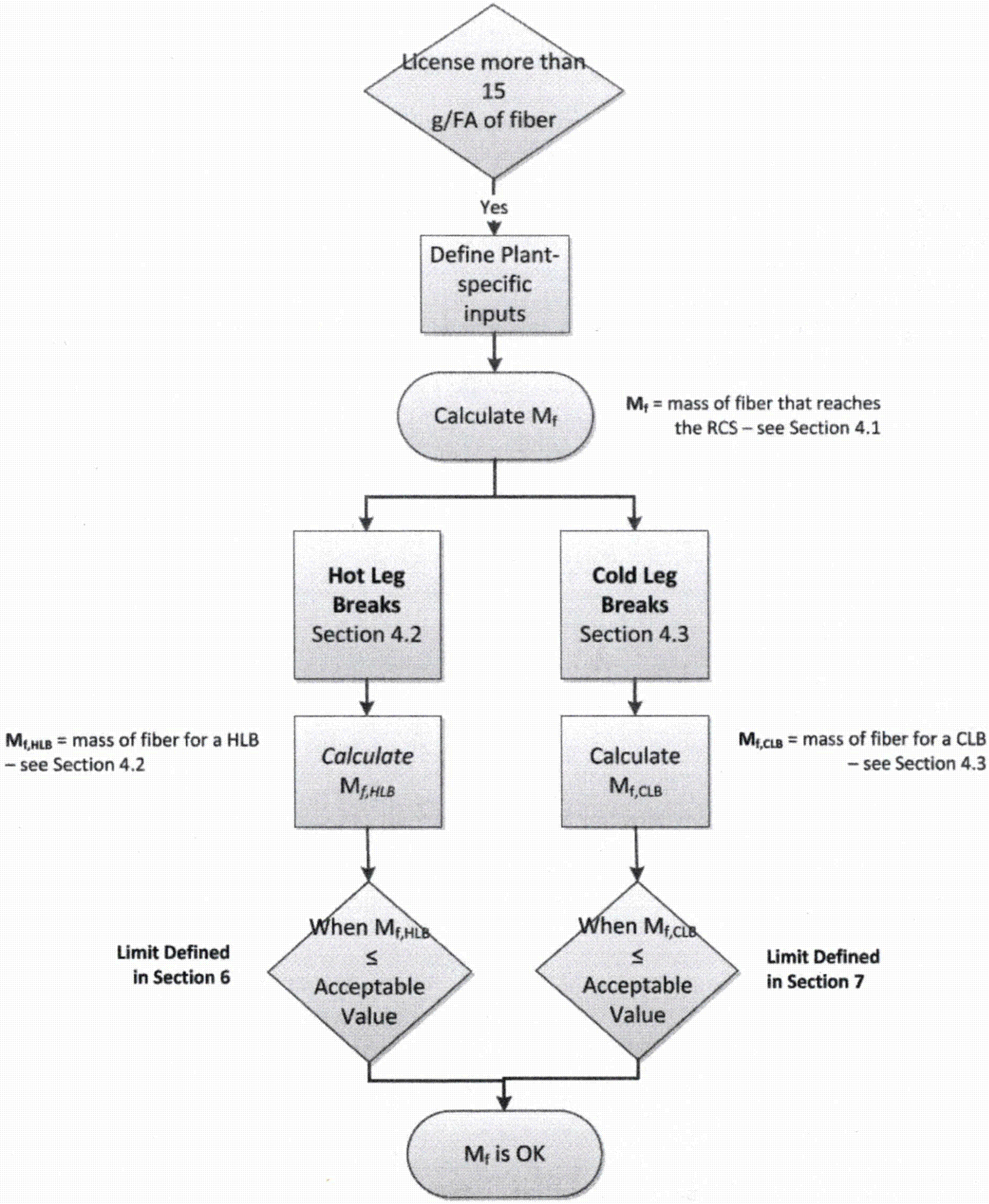

Figure 4-1 Process Diagram for Determination of Plant-Specific In-Vessel Debris Limit

The debris limits defined using this method applies to all fuel designs that are in production by Westinghouse and AREVA as of January 2015 with one notable exception. AREVA fuel with the **TRAPPER™** fine mesh filter showed markedly different results from the **FUELGUARD™** filter design in the WCAP-16793-NP-A, Rev. 2 (Reference 4-1) testing. However, the **TRAPPER** fine mesh filter design is no longer in production, and was therefore not tested in this program. If it is used, it would only be used in a limited quantity in the core periphery or center core location. The use of the **TRAPPER** fine mesh filter fuel design in limited quantities would not alter the limits defined by this methodology. The method presented here may be used for fuel designs developed after January 2015 provided the applicability of this method to those designs is evaluated.

The discussion in this section pertains directly to the Westinghouse, CE, and B&W plants that initiate cold side injection immediately following the break. Discussions pertaining to UPI plants are provided in Section 8.

4.1 DEFINITION OF IN-VESSEL DEBRIS

For the purposes of defining in-vessel debris, it is useful to explicitly define what is meant by "in-vessel." The initial concern of GSI-191 is that, following a LOCA, debris generated within containment from the break could collect on the sump strainer(s) and create sufficient resistance to the recirculating flow such that LTCC might be challenged. The effect of the debris that may pass through the sump strainer(s) and enter the ECCS where it may accumulate at the core inlet and on components or the fuel must be also considered.

The sump strainer "bypass fraction" is the portion of debris transported to the sump strainer that is not collected on the sump strainer, and instead passes through the sump strainer and is transported into either the CSS or RV. Fluid that goes to the CSS is returned to containment without reaching the fuel. Only debris that reaches the RV and enters the core region has the potential to block the cooling water flow to the fuel within the RV. Therefore, the methods for calculating in-vessel debris described in this document define the amount of debris that can reach the RV itself and enter the core region and is not necessarily the amount of debris that bypasses the sump strainer.

Once in the RV, debris can travel to and possibly accumulate in multiple locations. For CLBs with cold side recirculation or HLBs with hot side recirculation, some debris may exit the break and return to containment while the rest of the debris will continue into the RV. For HLBs with cold side recirculation or CLBs with hot side recirculation, essentially all of the debris will enter the RV. In the RV, debris that is held up on large components (e.g., neutron pads or LP internals) will not compromise core cooling, because the flow areas around these obstructions are large and cannot be completely blocked by debris. Settling in the RV LP will occur where the fluid velocities are low, facilitating "dead zones" for accumulation of significant quantities of debris. This precludes blockage of the flow paths in lower region of the LP. Debris collecting in these locations is, however, conservatively neglected.

TRAPPER and FUELGUARD are trademarks or registered trademarks of their respective owners. Other names may be trademarks of their respective owners.

Debris transported to the core inlet may accumulate at the inlet (below the heated core) and/or some portion of that debris may transport upward within the heated core. Accumulation of debris in these locations is addressed in the remainder of this report.

The amount of debris that ultimately reaches the RCS is comprised of the above components. That is:

$$M_f = M_{f,CI} + M_{f,in-core} + M_{f,break} \quad \text{Equation 4-1}$$

where,

M_f = the total fiber mass that reaches the RCS for either break location

$M_{f,CI}$ = the mass of fiber at the core inlet

$M_{f,in-core}$ = the mass of fiber in the heated core

$M_{f,break}$ = the mass of fiber returned to containment via the break (for CLBs with cold side recirculation, this may be a significant fraction of the debris and is credited. For CLBs with hot side recirculation and HLBs this is conservatively assumed to be zero)

As a point of clarification, the discussions that follow focus on fiber only, referring to the final solution as a fiber limit rather than that of combined fibrous and particulate debris. This is done primarily as a means of simplification. Rather than solving the problem for various particulate to fiber ratios, experimental testing described in Volume 6 has determined the most limiting ratio, and that ratio is embedded in the correlations developed in other sections of this volume. The impact of particulate is therefore implicit in the equations used throughout this calculation.

4.2 LARGE HOT LEG BREAKS

Immediately prior to SSO, no debris has entered the system. The clean ECCS liquid flows from the injection location, through the core to the break. Upon transfer of the suction flow to the sump, debris in the sump will be transported to the sump strainer and a portion will pass (bypass) through the sump strainers and eventually enter the RV.

The amount of debris that reaches the RCS for this hot leg break scenario is a function of the accumulation of debris in two locations: (1) at the core inlet and (2) within the core itself. While debris may reach the break (i.e., not be captured in the core during cold side recirculation or go directly to the break during hot side recirculation), it is conservatively assumed not to. How and when the debris arrives at the core inlet or in the heated core is dependent on plant inputs and the occurrence of key events.

The amount of debris that can accumulate at the core inlet and not impede LTCC is defined by a number of supporting analyses. The TH analyses described in Volume 4 determine the earliest time at which complete core inlet blockage can occur and still maintain the cladding temperature below 800°F. This time is defined as t_{block}. These analyses show that before t_{block}, flow through the AFPs alone is not sufficient to keep the cladding temperature below 800°F. After t_{block}, however, the analyses demonstrate that the AFPs are effective for ensuring LTCC.

The autoclave testing described in Volume 5 determined the time at which chemical precipitates from. This time is defined as t_{chem}. Once chemical precipitates form (i.e., t_{chem} is exceeded) the resistance through the debris bed at the core inlet will be greatly increased, and as the fiber load is increased above 15 g/FA, flow through this path may be stopped completely (Reference 4-1). While it is true that flow through the bed will exist for fiber loads less than 15 g/FA, the effect of chemical precipitates on the head loss through these lesser debris beds has not been rigorously studied. It is therefore conservative to assume that no matter the existing fiber load at the core inlet, complete blockage will occur coincident with t_{chem}. That said, if $t_{chem} < t_{block}$, then the method described in this document cannot be used to address GSI-191 concerns related to in-vessel effects until a method is devised or plant changes are made to make $t_{chem} > t_{block}$.

The TH analyses were also used to determine the maximum resistance at the core inlet that would maintain the cladding temperature below 800°F prior to reaching complete core inlet blockage. This parameter is defined as K_{max}. The FA testing with debris described in Volume 6 correlates the head loss at the core inlet due to debris to the actual quantity of debris. In this manner, debris accumulation at the core inlet can be compared to K_{max}. The TH analyses demonstrate that as long as the resistance due to debris is less than K_{max} prior to reaching t_{block}, the cladding temperature remains below 800°F.

At some point in the transient, sufficient debris may accumulate at the core inlet such that flow and debris are diverted to the AFPs. The TH analyses described in Volume 4 provide the conditions at which this occurs and the flow splits between the core inlet and AFPs as well. These parameters are defined as K_{split} and m_{split}, respectively. Debris that travels through these paths may reach the heated core. Further, after hot leg switchover (HLSO) occurs, debris may reach the heated core from the hot legs. The amount of debris that can accumulate in the heated core without affecting LTCC is defined in Section 6.4.

Since the timing of the event is plant dependent, the final debris limits must be established by plant-specific analyses, which are described in Section 6.5. An overview of the process for calculating the amount of debris that reaches the RCS following a HLB is provided in Figure 4-2. The plant-specific inputs are used to calculate $M_{f,\,HLB}$ which is the mass of fiber entering the RV for the HLB scenario. The parameter $M_{f,\,HLB}$ is then compared to the acceptance criteria as described in Section 6.5 to determine if the RV fiber load is acceptable.

To help in understanding the process for defining where debris accumulates for a HLB, it is useful to identify various, key events. Specifically, the following events are significant: time of sump recirculation, activation of AFP, formation of chemical precipitates, and implementation of measures to prevent BAP. These events are expanded upon in the following subsections. As part of the program, a substantial investigation was performed to further understand these various events and the phenomena associated with them. The following subsections also provide an overview of how these times are defined as part of the overall solution for improving the debris limits. Finally, some example timelines are presented to illustrate how the timing affects the location of debris deposited within the RV.

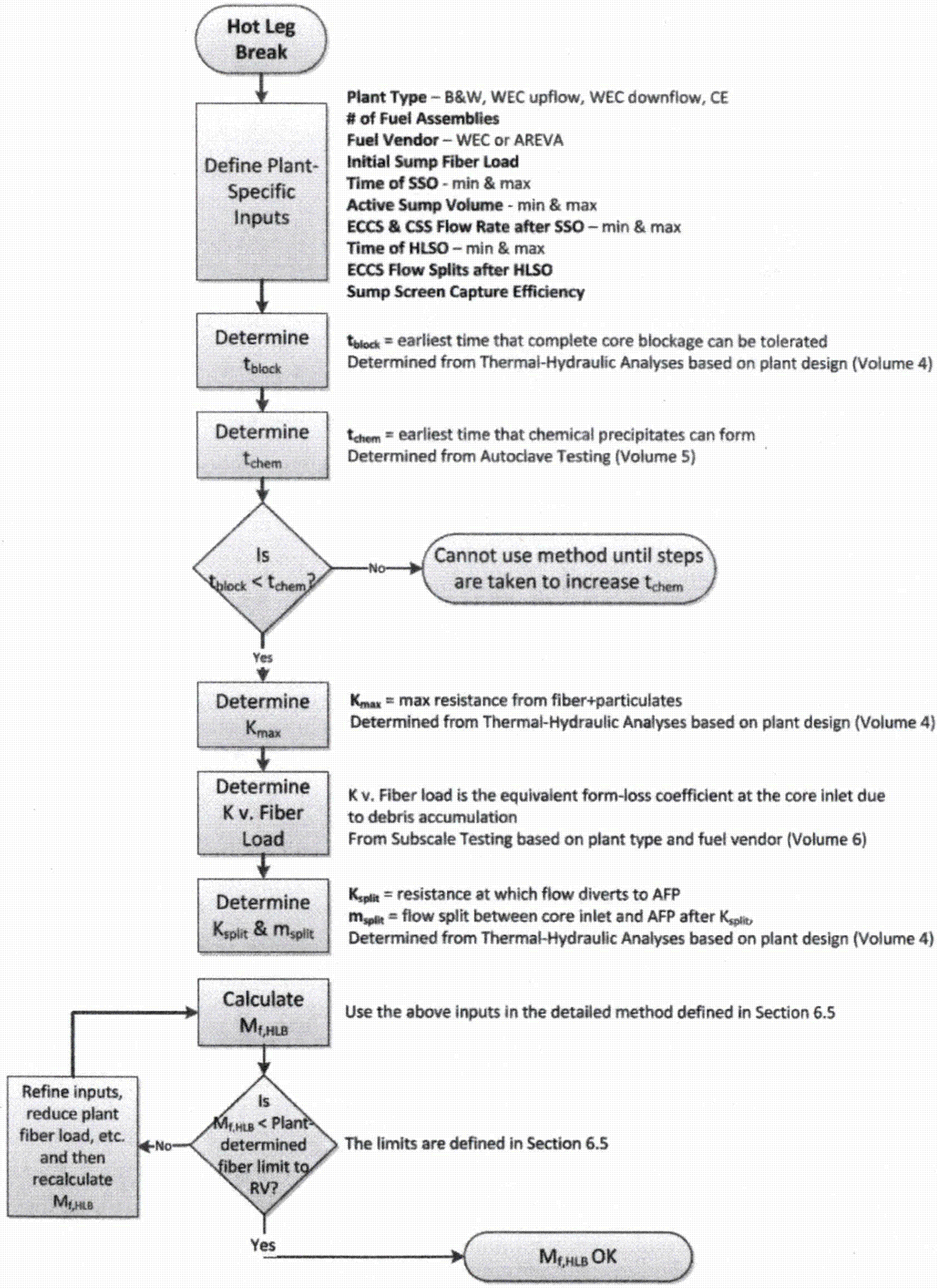

Figure 4-2 Overview of Hot Leg Break Methodology

4.2.1 Time of Sump Recirculation

The time of sump recirculation (or SSO) defines the earliest point at which debris can reach the RCS and is plant dependent. The timing depends on the volume of water sources supplying the ECCS and CSS, ECCS flow rate, and CSS flow rate among other parameters. This time is usually available in plant documentation. Guidance on important considerations for calculating this parameter is provided in Section 6.5.2.6.

4.2.2 Activation of Alternate Flow Path

The AFPs are described in detail in Section 3.2. During post-LOCA scenarios in which debris accumulates at the core inlet, these AFPs may provide flow to the core to remove decay heat at some point after the LOCA. Consequently, these paths can assist in providing adequate flow to maintain LTCC.

Shortly after sump recirculation, any debris that reaches the core LP is conservatively assumed to accumulate at the core inlet and/or lowermost spacer grid. At this point, the in-vessel AFPs do not provide a path for debris to reach the core. As debris accumulates at or near the core inlet, resistance to flow increases and leads to conditions that "activate" the AFP such that flow is diverted through the AFPs and entrained debris is transported to other regions of the core. For a period of time, debris will continue to accumulate at the core inlet but will also pass into the AFP.

A number of items need to be defined for this scenario. First, the resistance that debris imposes to flow as it accumulates at the core inlet needs to be defined. Correlation of the head loss as a function of accumulated debris is determined by the FA testing described in Volume 6. The end result is a core inlet resistance as a function of debris load, which is provided in Section 6.3.

Second, the conditions at which the AFP becomes active need to be defined. These are essentially the conditions under which the flow from the LP begins to split between the core inlet and the AFP. Once the AFP becomes active (i.e., flows up from the LP in the BB or begins to pass fluid through the UHSN), the flow split between the core inlet and AFP needs to be defined so that debris can be appropriately tracked. These details are provided by TH analyses as described in Section 6.1.

Finally, it must be shown that the debris that enters the AFP will not accumulate locally, resulting in subsequent blockage of the limiting flow paths within the AFPs. Verification that the flow paths are not blocked due to accumulation of debris is provided in Volume 6.

4.2.3 Chemical Precipitate Formation

Chemical reactions begin to occur as soon as coolant released from the break comes into contact with debris and other materials inside the containment. Then, as the sump begins cool, continued chemical reactions and the products of those chemical reactions can result in the formation of precipitates. If sufficient debris is present at the core inlet, formation of chemical precipitates can block flow through this path (Reference 4-1). Therefore, the time at which these precipitates form can have a significant effect on the in-vessel debris limit.

The time that chemical precipitates form is plant dependent. However, to better understand the conditions that lead to precipitate formation, significant testing has been completed as part of this program. These efforts are summarized in Section 6.2 and described in detail in Volume 5. The results documented in Volume 5 establish the time to onset of chemical precipitates for all plants, t_{chem}.

Before t_{chem}, the debris in the RV will be comprised of fiber and particulate only. The FA testing described in Volume 6 defines the pressure drop for debris beds made of particulate and fiber only. At the time of t_{chem}, it will be assumed that the core inlet is completely blocked in accordance with the conclusions and SE from WCAP-16793-NP-A, Rev. 2 (Reference 4-1). After this time, the AFPs may be able to provide adequate core cooling. This evaluation is provided by TH analyses as described in Section 6.1.

4.2.4 Implementation of Measures to Prevent Boric Acid Precipitation

As described in Section 3.3.3, each plant will take actions to mitigate the buildup of boric acid in the RV and core. Depending on the plant design, some or all of the ECCS flow may be diverted to the hot legs. By this point in the transient, the amount of debris passing through the sump strainer has substantially decreased. However, some debris can be introduced to the core exit. The evaluation of debris reaching the core from the top is provided in Section 6.4.

4.2.5 Example Timelines

The sequence of events for any given scenario is plant dependent. After SSO, the timing of mitigation actions depend on the available equipment, sump volume, sump chemistry, etc. Further, the timing of activation of the AFP or formation of chemical precipitates depends on the amount of debris in the system, ECCS flow rates, and/or materials in containment. The actual timing of these various events will change where and how debris builds in the RV. For illustration purposes, two cases will be examined. These examples should be used for information purposes only.

In the first case, the sequence of events is: SSO, followed by AFP activation, followed by formation of chemical precipitates, and finally followed by operator action to initiate HLSO. The location of debris accumulation is illustrated by Figure 4-3. In this case, SSO occurs and cold side recirculation continues. Debris begins to build at the core inlet until enough debris has built up such that the AFP becomes active, in which case debris continues to accumulate at the core inlet but is also diverted to the core via the AFP. Once chemical precipitates form, the core inlet is assumed to block completely such that no further fiber or particulate is added to this location; instead all debris then travels through the AFP to the core. Sometime after that, the operators take action to initiate HLSO by switching most of the ECCS flow to the hot legs. Thereafter, debris may be introduced to the core via the AFP (by the small, remaining cold leg recirculation) and the hot leg recirculation.

In the second case, the sequence of events is: SSO, followed by AFP activation, followed by HLSO, and finally followed by formation of chemical precipitates. The location of debris accumulation is illustrated by Figure 4-4. In this case, SSO occurs and cold side recirculation continues. Debris begins to build at the core inlet until enough debris has built up such that the AFP becomes active, in which case debris continues to accumulate at the core inlet but is also diverted to the core via the AFP. Once the operators take action to initiate HLSO by switching most of the ECCS flow to the hot legs, debris may be

introduced to the core via the AFP or core inlet (by the small, remaining cold leg recirculation) and the hot leg recirculation. Once chemical precipitates form, the core inlet is assumed to block completely such that no further fiber or particulate is added to this location; instead all debris from the cold leg recirculation travels through the AFP to the core.

The above examples are only a couple of instances of a sequence of timing that may occur. For example, HLSO may occur before the AFP becomes active and before chemical precipitates form. In this case, debris will continue to accumulate at the core inlet only until HLSO occurs. The process detailed in Section 6.5 includes plant-specific inputs that define how this timeline will evolve for a specific set of conditions.

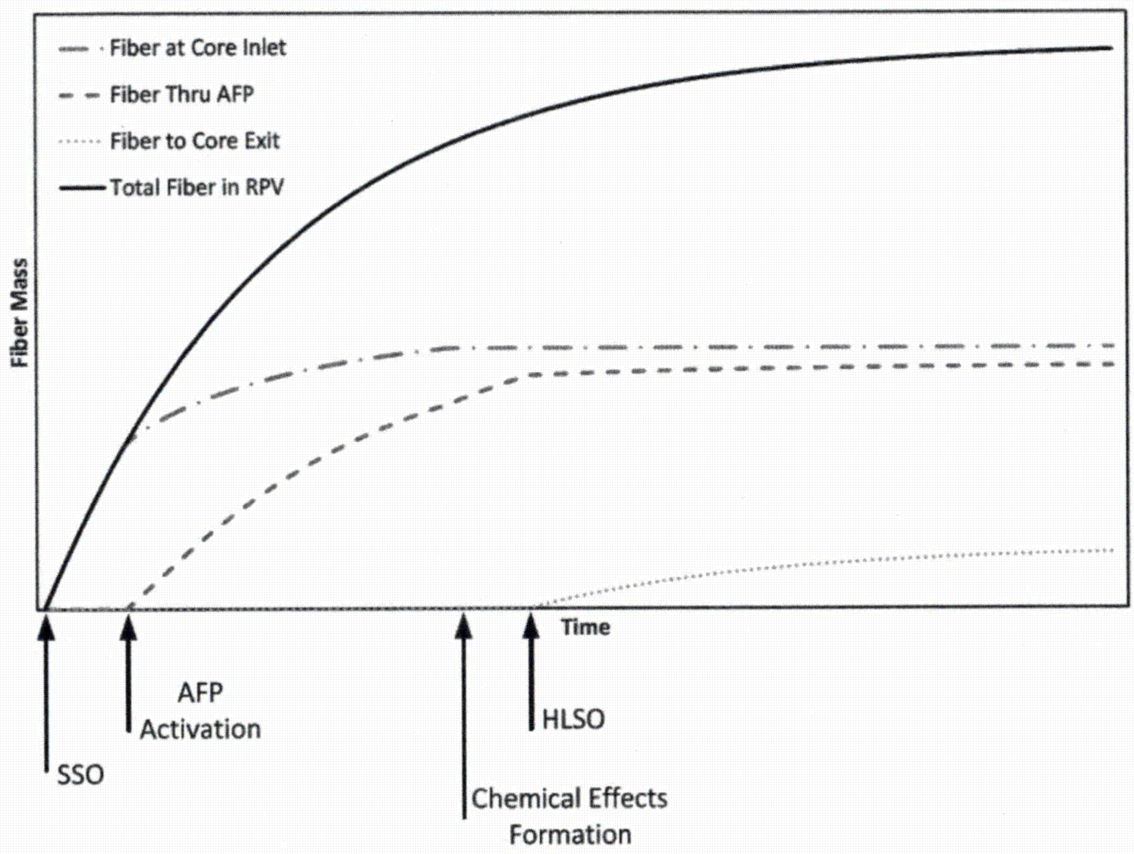

Figure 4-3 Example Timing #1

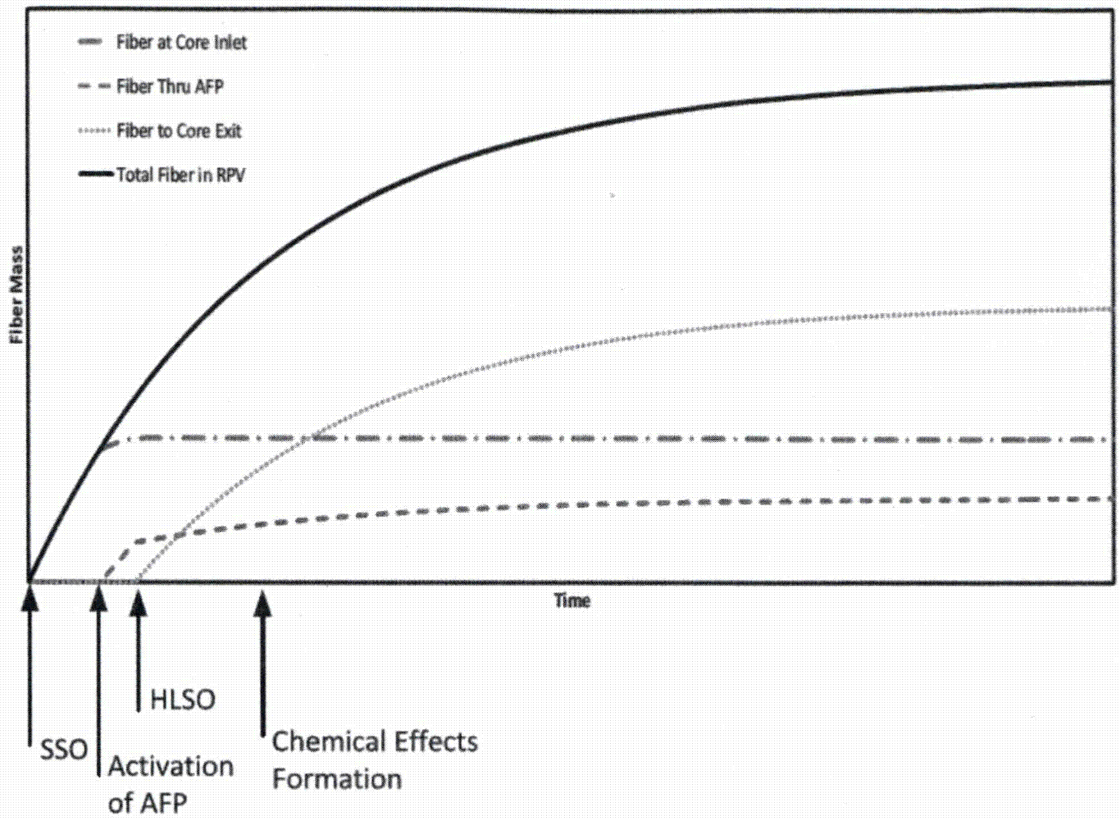

Figure 4-4 Example Timing #2

4.3 LARGE COLD LEG BREAKS

Immediately prior to SSO, similar to the HLB scenario, no debris has entered the system. The clean ECCS liquid flows from the injection location and makes up for the core boil-off. The excess ECCS liquid exits that break and returns to the sump. Upon transfer of the suction flow to the sump, debris in the sump will be transported to the sump strainer and a portion will pass (bypass) through the sump strainer(s) and eventually enter the RV.

After SSO, debris begins to enter the RCS where it may exit the break or continue to the downcomer as described above. Once in the RV LP, it will first approach the core and accumulate near the core inlet (below the heated region of the core).

The spilled coolant from the break and coolant from containment sprays is collected in the sump pool. Chemical reactions begin to occur as soon as coolant released from the break comes into contact with debris and other materials inside the containment. Then, as the sump begins cool, continued chemical reactions and the products of those chemical reactions can result in the formation of precipitates. If sufficient debris is present at the core inlet, formation of chemical precipitates can be collected by the debris at the core entrance, blocking flow through this path (Reference 4-1). Consequently, the time at

which these precipitates form may have a significant effect on the in-vessel debris limit. For the CLB scenario, a maximum fiber limit of [ ]^{a,c} at the core inlet is defined in Section 7.1. This limit is predicated on the fact that: (1) fiber loads at or below the limit will not form a contiguous bed at the core inlet, (2) the pressure drop through the regions of the core inlet with a fiber and particulate bed is negligible, and (3) the addition of chemical precipitates will not further impede flow into the core. Therefore, chemical effects formation need not be considered in the CLB methodology.

As described in Section 3.3.3, each plant will take actions to mitigate the buildup of boric acid in the RV and core. One of these actions is commonly called HLSO. After this point, many plants divert some or all ECCS flow to the hot legs, which can introduce debris at the core exit. Typically following a CLB, the majority of debris that will reach the core has already done so by the time of HLSO. Consequently, any debris that is transported to the RV through the hot leg flow path will be well below the in-vessel debris limit defined in Section 6.4. To that end, the CLB calculation described in Section 7.2 may be stopped at the time of HLSO to define the CLB debris limit. For plants that don't initiate HLSO, debris will continue to build up at the core inlet. The CLB calculation described in Section 7.2 should continue until all debris has been collected on the containment building sump strainer(s) and at the core inlet.

The amount of debris that can collect at the core inlet and not impede LTCC is defined in Section 7.1 to be [ ]^{a,c} The amount of debris that actually reaches the RCS (i.e., the CLB in-vessel debris limit, termed $M_{f,\,CLB}$) and core inlet is determined using the method described in Section 7.2.

4.4 REFERENCES

4-1 WCAP-16793-NP-A, Rev. 2, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculation Fluid," July 2013.

5 MAJOR ASSUMPTIONS

In all scenarios, the following assumptions are made:

1. The fiber and particulate are well mixed in the sump fluid such that a homogeneous mixture is present at the time of sump recirculation. Therefore, the debris transport is proportional to the ECCS flow rate.

2. No debris is held up in any location other than the sump strainer(s), core inlet or within the core. Further, no settling of debris is credited in any location of the RCS. Therefore, the maximum amount of debris reaches the core.

3. Chemical precipitates are assumed to form at 24 hours if the chemical analysis of plant-specific sump chemistry does not indicate that they will form earlier.

4. The fiber is in its constituent form, i.e., individual fibers. This is consistent with maximum transport assumptions.

5.1 HOT LEG BREAKS

The following assumptions are made specifically for evaluating HLBs for plants with initial ECCS to the cold legs only:

5. After transfer to sump recirculation, all debris that enters the RV is assumed to collect at the core inlet until the AFP is activated. No debris enters the in-core region (i.e., no debris penetration through the core inlet). This maximizes the calculated debris load at the core inlet.

6. When chemical precipitates form, the core inlet is assumed to be completely blocked. This initiates flow to the AFP at an earlier time, which reduces the amount of fiber buildup at the core inlet and minimizes the overall fiber limit.

7. It is assumed that debris that travels through the AFP continues to the heated core and does not accumulate in the BB or upper head. Testing of the AFP in Volume 6 indicated that some debris may be held up in this region (although it will not block any of the flow passages). Neglecting this holdup maximizes the debris that is transported to the core.

8. It is assumed that no debris exits the break (i.e., once it is in the RCS, it stays in the RCS). Therefore, the maximum amount of debris reaches the core.

9. The code simulations assume that sump debris will build-up across the core inlet in a uniform manner, and blockage is only considered at the core inlet. This is a simplifying, conservative assumption. In reality, it is expected that the build-up of debris at the core inlet will follow the flow distribution at the core inlet. Some regions of the core with higher power will have a higher flow at the core inlet, while other regions of the core with lower power will have lower flow, or even downflow, at the core inlet. From a DHR standpoint, applying a uniform build-up at the core

inlet is more challenging as was demonstrated in the TH analysis contained in WCAP-16793-NP-A, Rev. 2 (Reference 5-1).

10. The code simulations assume fluid properties of pure water. During the LTCC phase of the post-LOCA transient, the build-up of solute concentrations in the inner regions of the RV can be a concern. If the concentrations reach high enough levels, the effect on fluid properties may need to be considered. Since these analyses will simulate a large HLB scenario, it is expected that the liquid carryover out of the break will be sufficient to limit the concentration build-up of solutes in the RV and thus limit the influence on fluid properties. This assumption is justified by the simulation results discussed in Volume 4, Section 7.

11. In the code simulations, some cases consider an "instantaneous" ramp of core inlet resistance. The instantaneous ramp will occur over a one minute period to aid in code stability. The modeling of debris build-up over one minute is a non-realistic condition since debris transport from the sump to the core inlet occurs over a longer period of time. In other cases, a longer ramp period will be considered. For these cases it will be assumed that the resistance due to the build-up of debris occurs over a more realistic, yet still conservative time period.

12. In the code simulations, a top-skewed power shape is assumed to be most limiting for core uncovery. The uncovery process is governed by boil-off and subsequent dry out that begins at the top of the core and propagates downward. Using a top-skewed power shape will maximize cladding heatup in the event of core uncovery and provides the most challenge for meeting the 800°F acceptance criterion.

13. In the code simulations, it is assumed that the flow path through the thimble tubes is blocked and no bypass flow through the tubes will be credited. This assumption removes an additional path for fluid to reach the core, limiting the paths to either the core inlet or the AFPs discussed above.

14. The code simulations assume that the secondary side is isolated and not depressurized consistent with the short-term LOCA analysis approach. This results in a high secondary side temperature that helps to inhibit flooding of the steam generator (SG) on the primary side such that SG spillover, if predicted, is delayed.

5.2 COLD LEG BREAKS

The following assumptions are made specifically for evaluating CLBs for plants with initial ECCS to the cold legs only.

15. Any debris that reaches the core LP is conservatively assumed to accumulate at the core inlet and/or lowermost spacer grid.

16. 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. A 20 percent increase in the flow required to satisfy boil-off requirements increases the amount of fiber laden fluid reaching the core.

5.3 UPPER PLENUM INJECTION PLANTS

The following assumptions are made specifically for evaluating UPI plants:

17. It is assumed that all debris that enters the RV through UPI enters the core region for the CLB scenario. Given the complex structures within the UP, it is expected that some fraction of debris will be held-up within the UP.

18. For CLBs with cold leg recirculation, it is assumed that all debris enters the RV and is transported to the core inlet.

5.4 REFERENCES

5-1 WCAP-16793-NP-A, Rev. 2, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculation Fluid," July 2013.

6 HOT LEG BREAKS

Debris that enters the RV following a HLB will initially approach the core inlet. The program has performed substantial investigation to understand where this debris might accumulate and the effect that it might have on LTCC. The following subsections provide the details of this work.

The discussion in this section pertains directly to plants that initiate cold side injection immediately following the break. Discussions pertaining to UPI plants are provided in Section 8.

6.1 THERMAL-HYDRAULIC EVALUATION OF REACTOR COOLANT SYSTEM

During operation of the ECCS to recirculate coolant from the containment sump, debris in the recirculating fluid that passes through the sump strainer(s) may collect on the bottom surface of the FA bottom nozzle or FA spacer grids, causing resistance to flow through this path. The collection of sufficient debris on the fuel is postulated to impede flow into the fuel assemblies and core.

As described in Section 3.1, all U.S. PWRs have flow paths in the RV that may allow fluid to bypass the heated core during normal operations. Examples include flow through the BB region (for upflow BB plants) and/or flow through the UHSNs. During post-LOCA scenarios in which the core inlet becomes blocked by debris, these AFPs may provide sufficient flow to the core to remove decay heat at some point after the postulated LOCA. Consequently, it is postulated that these paths can assist in providing adequate flow to maintain LTCC. Additional PWROG work was initiated to examine the effectiveness of AFPs to provide cooling flow to the core that may support an increase in the fibrous debris limit compared to Reference 6-1. These TH analyses are described in detail in Volume 4. The relevant results are summarized here.

For this evaluation, four sets of analyses were performed to evaluate the AFPs for the U.S. PWR fleet:

1. Westinghouse design with upflow BB

2. Westinghouse design with downflow BB

3. CE design

4. B&W design

The plant models and inputs were selected to bound the plants in each class.

The overall goal of this analysis was to evaluate the adequacy of RV AFPs for maintaining LTCC following switchover to recirculation and the postulated formation of a highly resistive debris bed at the core inlet for a large hot leg break LOCA scenario for U.S. PWR plant designs. The objectives for this analysis were met. Specifically, each analysis simulated the evolution of debris bed formation over a range of conditions and determined the following four parameters:

1. The minimum time that complete core inlet blockage can occur and meet the acceptance criteria defined in Section 3.7. This time is defined as t_{block} and represents the earliest possible time for

which chemical precipitates can be tolerated on a completely formed fiber and particulate debris bed at the core inlet, which is assumed to lead to complete core inlet blockage. This value is compared to results from chemical effects testing contained in Volume 5.

2. The maximum resistance at the core inlet that can occur prior to reaching t_{block} and meet the acceptance criteria defined in Section 3.7. This parameter is defined as K_{max} and represents the resistance of a fiber and particulate only bed that can be tolerated from the time of SSO to t_{block}, the earliest allowable time of complete core inlet blockage. This value is compared to the results from subscale head loss testing contained in Volume 6 to establish an upper bound on the amount of particulate and fibrous debris that can be tolerated at the core inlet.

3. The resistance at the core inlet that begins to divert flow into the AFP. This parameter is defined as K_{split} and is a function of ECCS flow rate. The subscale head loss testing has defined a correlation between the amount of fiber and an equivalent form-loss coefficient as discussed in Volume 6. K_{split} can then be used to define how much fiber accumulates at the core inlet before flow is diverted to the AFP.

4. The flow split between the core inlet and the AFP after K_{split}. This parameter is defined as m_{split}. Combined with K_{split} and the subscale head loss test results contained in Volume 6, m_{split} will be used to track where the debris accumulates after flow is diverted to the AFP.

The values that were determined for each plant category are discussed separately below. A summary of the results for K_{max} and t_{block} is provided on Table 6-1. These values and curves are used in Section 6.4 to track the fiber accumulation in the RV and to check to ensure acceptable results. Given that these analyses are conservative representations of a number of plants, margin may be available to individual plants by performing plant-specific analyses to calculate the parameters above using the same methods described in Volume 4.

6.1.1 Westinghouse Upflow Plant Category

1. The minimum time that complete core inlet blockage can be tolerated (t_{block}) was found to be 143 minutes (2.38 hours).

2. The maximum resistance at the core inlet that can be tolerated prior to reaching complete core inlet blockage (K_{max}) was found to be $5x10^5$.

3. The resistance at the core inlet that begins to divert flow into the AFP (K_{split}) was found for a range of ECCS flow rates. These results are shown in Figure 6-1.

4. The flow split between the core inlet and the AFP after K_{split} (m_{split}) was found for a range of ECCS flow rates. A curve that bounds the results was also developed. These results are shown in Figure 6-2.

6.1.2 Westinghouse Downflow Plant Category

1. The minimum time that complete core inlet blockage can be tolerated (t_{block}) was found to be 260 minutes (4.33 hours).

2. The maximum resistance at the core inlet that can be tolerated prior to reaching complete core inlet blockage (K_{max}) was found to be 6x10^5.

3. The resistance at the core inlet that begins to divert flow into the AFP (K_{split}) was found for a range of ECCS flow rates. These results are shown in Figure 6-3.

4. The flow split between the core inlet and the AFP after K_{split} (m_{split}) was found for a range of ECCS flow rates. A curve that bounds the results was also developed. These results are shown in Figure 6-4.

6.1.3 Combustion Engineering Plant Category

1. The minimum time that complete core inlet blockage can be tolerated (t_{block}) was found to be 250 minutes (4.17 hours).

2. The maximum resistance at the core inlet that can be tolerated prior to reaching complete core inlet blockage (K_{max}) was found to be 6.5x10^6.

3. The resistance at the core inlet that begins to divert flow into the AFP (K_{split}) was found for a range of ECCS flow rates. These results are shown in Figure 6-5.

4. The flow split between the core inlet and the AFP after K_{split} (m_{split}) was found for a range of ECCS flow rates. A curve that bounds the results was also developed. These results are shown in Figure 6-6.

6.1.4 Babcock and Wilcox Plant Category

1. The minimum time that complete core inlet blockage can be tolerated (t_{block}) was found to be 20 minutes (0.33 hours).

2. The maximum resistance at the core inlet that can be tolerated prior to reaching complete core inlet blockage (K_{max}) was found to be 1x10^8.

3. The resistance at the core inlet that begins to divert flow into the AFP (K_{split}) was found for a range of ECCS flow rates. These results are shown in Figure 6-7.

4. The flow split between the core inlet and the AFP after K_{split} (m_{split}) was found for a range of ECCS flow rates. A curve that bounds the results was also developed. These results are shown in Figure 6-8.

Table 6-1 Summary of Thermal-Hydraulic Output Parameters

Plant Type	K_{max} (-)	t_{block} (min)
Westinghouse Upflow	5.0x10^5	143
Westinghouse Downflow	6.0x10^5	260
CE	6.5x10^6	250
B&W	1.0x10^8	20

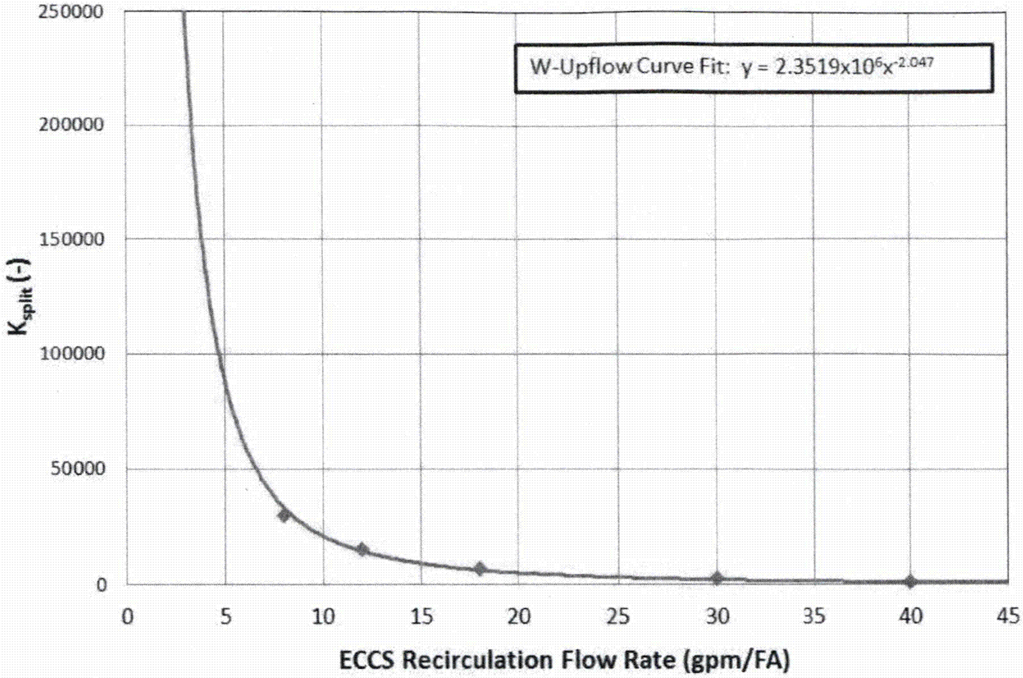

Figure 6-1 K_{split} as a Function of ECCS Recirculation Flow Rate from Westinghouse Upflow Analysis

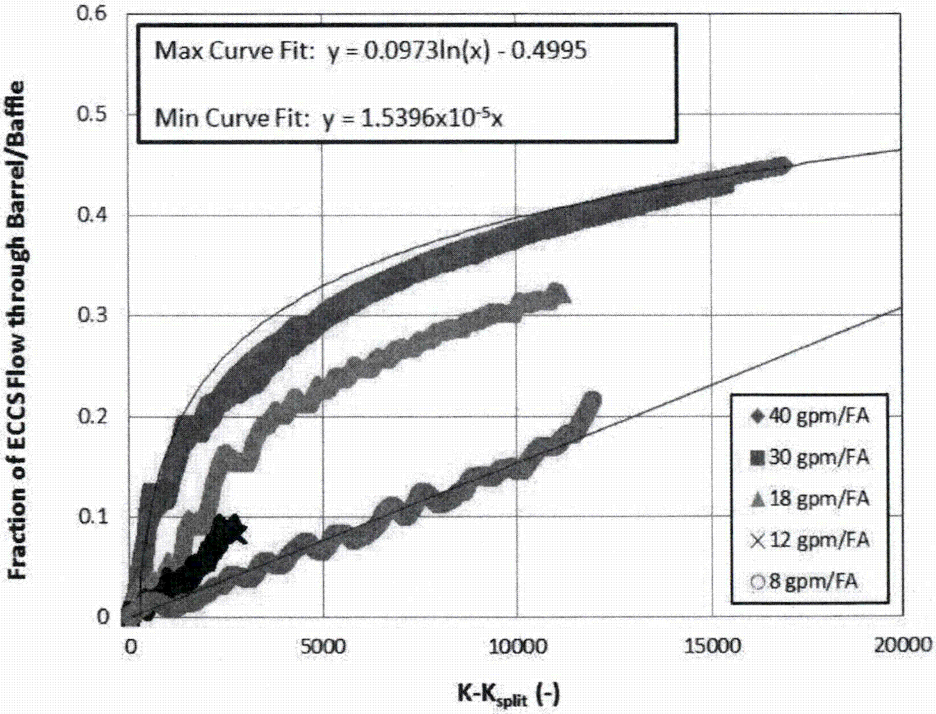

Figure 6-2 Fraction of ECCS Recirculation Flow through the BB following K_{split} from Westinghouse Upflow Analysis

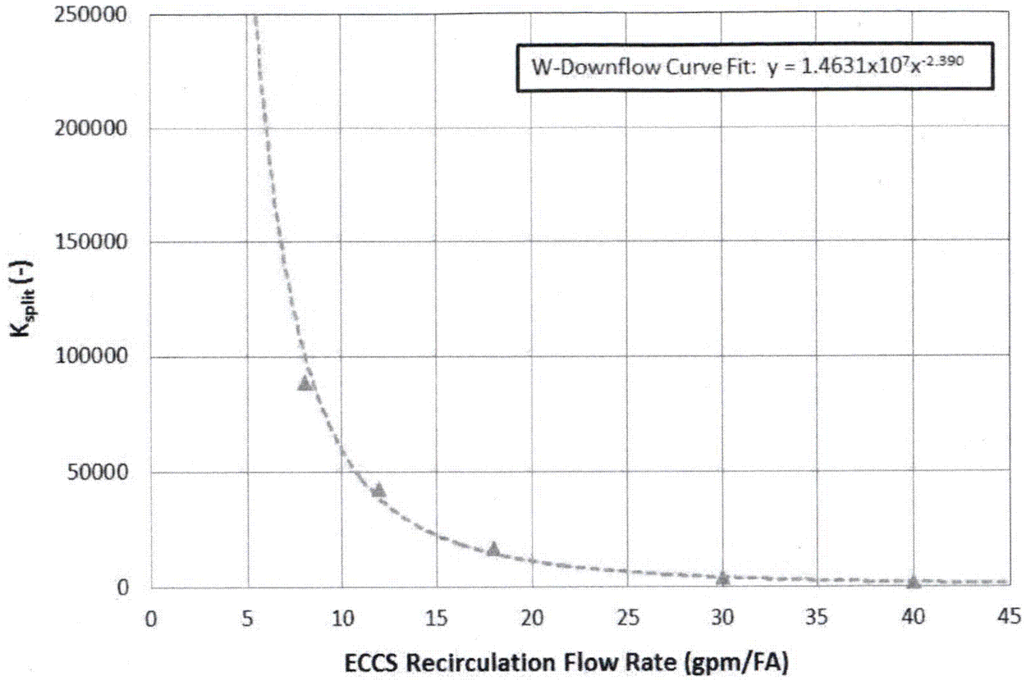

Figure 6-3 K_{split} as a Function of ECCS Recirculation Flow Rate from Westinghouse Downflow Analysis

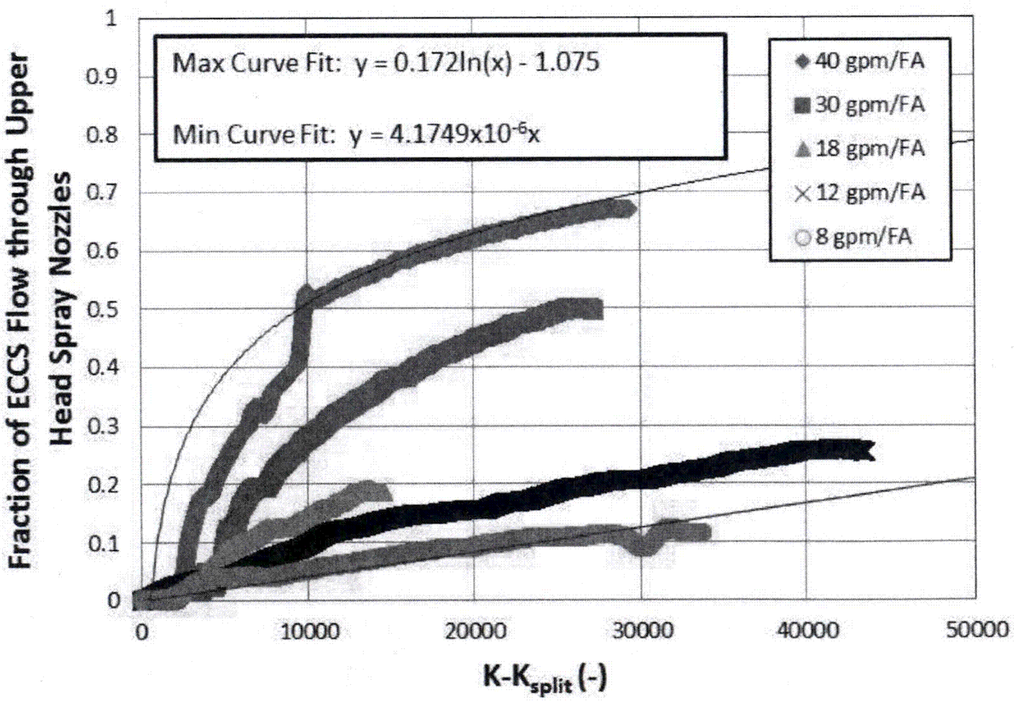

Figure 6-4 Fraction of ECCS Recirculation Flow through the BB following K_{split} from Westinghouse Downflow Analysis

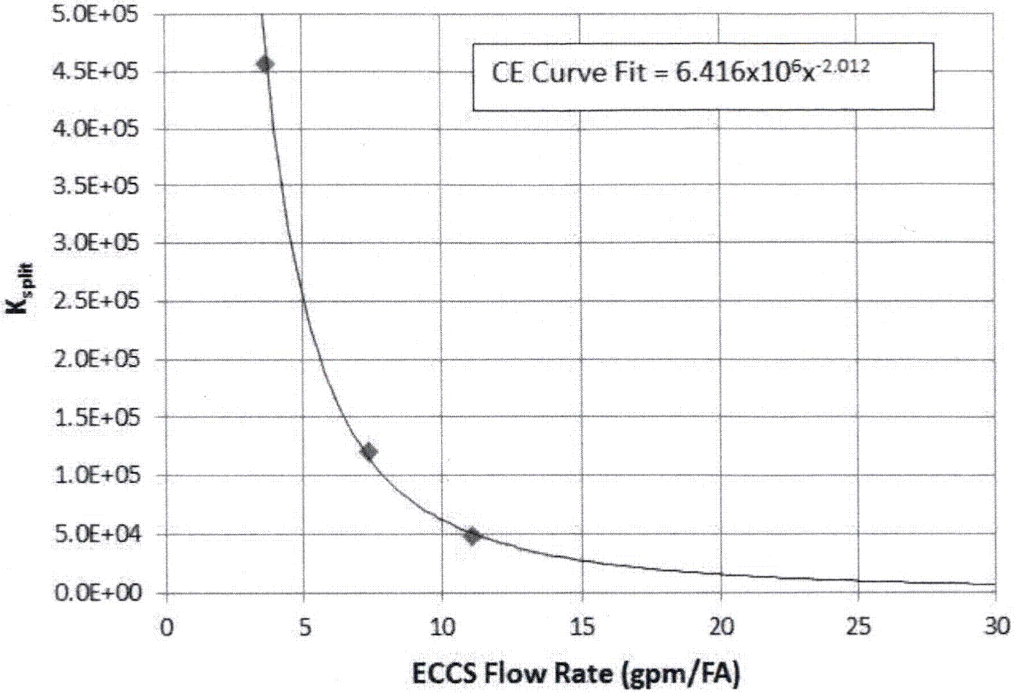

Figure 6-5 K_{split} as a Function of ECCS Recirculation Flow Rate from CE Analysis

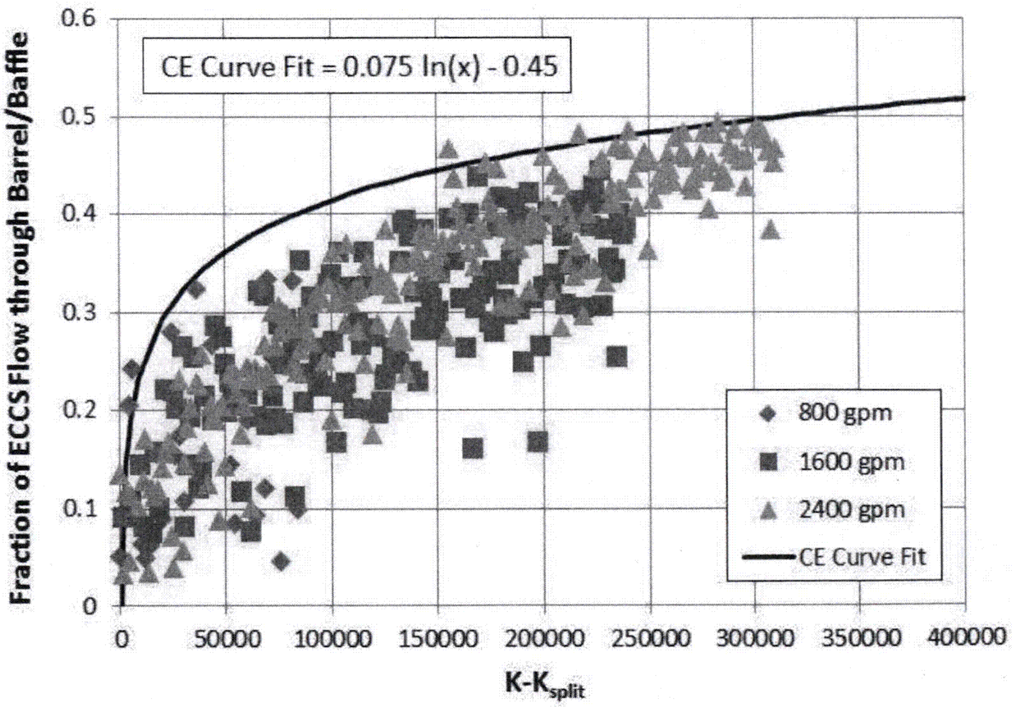

Figure 6-6 Fraction of ECCS Recirculation Flow through the BB following K_{split} from CE Analysis

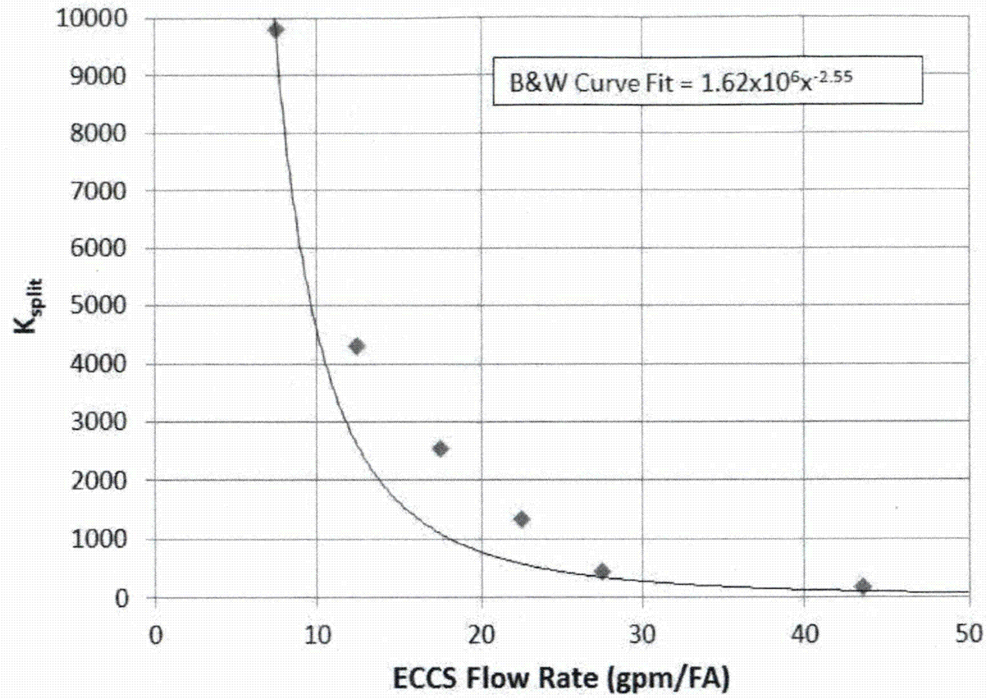

Figure 6-7 K_{split} as a Function of ECCS Recirculation Flow Rate from B&W Analysis

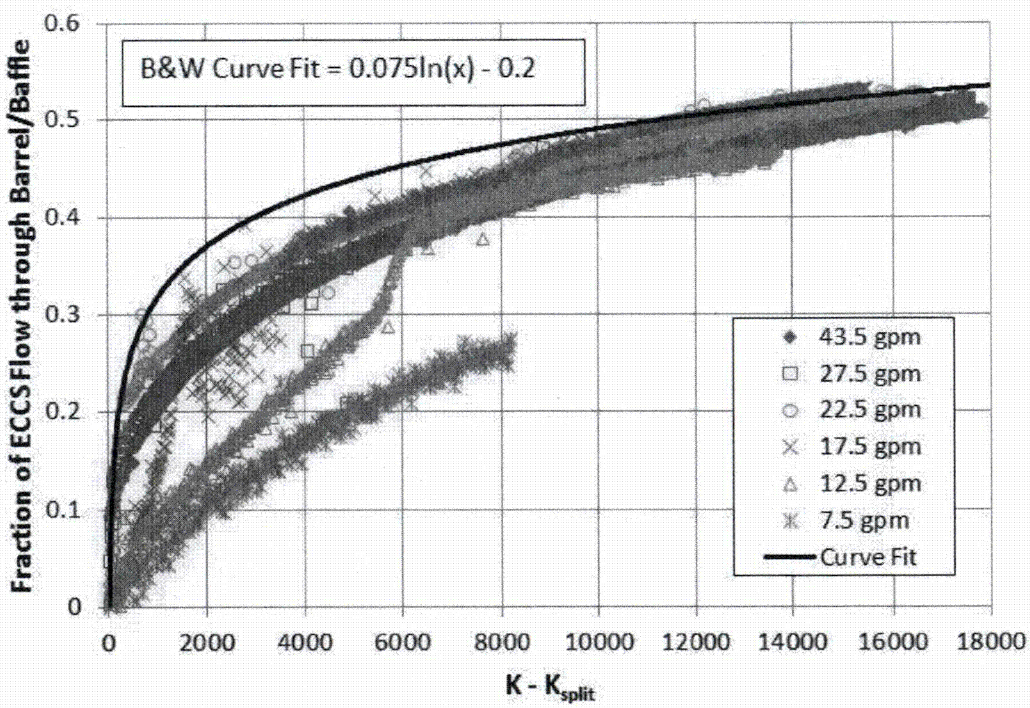

Figure 6-8 Fraction of ECCS Recirculation Flow through the Barrel/Baffle Inlet following K_{split} from B&W Analysis

6.2 CHEMICAL PRECIPITATE FORMATION

As part of this comprehensive program, the experimental study of the chemical products that may form as certain containment materials are exposed to the recirculating coolant in the containment sump under accident conditions was undertaken. The details of this study are provided in Volume 5. The relevant results are summarized here.

The ability of chemical products to clog a fibrous debris bed was demonstrated in WCAP-16793-NP-A Rev. 2 (Reference 6-1). To improve on the fibrous debris limits set in WCAP-16793-NP-A, Rev. 2, the creation of chemical products that would reach the core becomes a critical phenomenon. Determination of the timing of chemical production in the post-LOCA environment is complicated by the large number of possible debris mixtures that could be generated, in combination with variations in coolant chemistries and coolant temperature profiles. For this reason, a large number of autoclave tests were designed to span the range of possible conditions in the industry (based on responses from two industry surveys). There were 45 test groups that represented conditions either at a single plant or a group of 2 to 4 plants. Additional tests were performed to explore how variations in different test parameters affected the generation of chemical products. Variations in pH, debris dispersion, and material quantities were explored.

The purpose of the testing was to investigate post-accident corrosion, dissolution, and precipitation reactions by running autoclave experiments that simulated post-LOCA plant conditions. The timing of any precipitation reactions (t_{chem}) was of primary importance, since the early generation of chemical products in conjunction with a core inlet debris bed could block the core flow when high flow must be maintained ($t_{chem} < t_{block}$ – see Section 6.1 for definition of t_{block}), whereas later precipitation and core blockage could be tolerated because adequate coolant flow could be achieved through AFPs ($t_{chem} > t_{block}$).

Tested materials were exposed to representative containment sump conditions as determined by the industry survey responses mentioned above. Both the containment sump chemistries and temperatures were representative of the post-LOCA scenario being simulated. Water samples were taken for chemical analysis, turbidity measurements, and timed filtration tests. The results were used to screen plants for the onset of chemical product generation.

The chemical effects tests demonstrated that for most plants the generation of chemical products was delayed beyond 6 hours (360 minutes). This conservatively exceeds all values of t_{block} (Table 6-1), the time when sufficient core cooling will be provided by flow through AFPs available within the RV to cool the core, per Section 6.1.

A method was also provided for plants to demonstrate that chemical effects are delayed beyond the time when AFPs can provide sufficient core cooling (i.e., $t_{chem} > t_{block}$). Plants have two options to demonstrate delayed chemical effects:

1. Showing that bounding plant conditions match test conditions producing an acceptable delay of chemical effects.

2. Establishing that aluminum release and plant pH and temperature conditions preclude aluminum precipitation until after the time when the core can be cooled by AFPs. This can be accomplished by reference to a precipitation map provided in Volume 5.

Option 2 is possible because the testing demonstrated that under a wide range of representative plant conditions, the precipitation of aluminum was the only chemical process that produced significant chemical effects. Option 2 may be useful if a plant makes a modification in their projected post-LOCA conditions such that the plant no longer matches any of the conditions tested in this research.

6.3 CORE INLET DEBRIS LIMIT

Core inlet debris limits are determined using experimental data from the subscale test facility. The details of the test facility and experiments are provided in Volume 6. The relevant results are summarized here.

The subscale facility is a well-scaled test apparatus that represents approximately one-quarter of a full-area FA. The facility is designed to conduct systematic separate effects tests under well-controlled laboratory conditions in order to generate fundamental debris bed resistance data. The facility is capable of operating over a wide range of conditions representative of those expected in a PWR during the post-LOCA phase of a postulated accident.

When defining the core inlet debris limits for a large HLB, it is assumed that debris laden coolant entering the RV through the ECCS during sump recirculation will be transported to the core inlet region where it has the potential to collect on fuel components. The core inlet region is defined as the region extending downstream of the lower core plate to the first spacer grid. This region includes the FA lower end fitting and any additional filtering grids that the specific fuel design may have (e.g., Westinghouse P-grid) before reaching the first spacer grid. This region is assumed to be part of the non-boiling region of the core and consists of single phase liquid. A detailed description of the core inlet geometries tested in the subscale facility to define the final debris limits are provided in Sections 3.5.3 and 3.5.4, Volume 6 for Westinghouse and AREVA fuel products, respectively.

The core inlet debris limit, defined by the subscale facility testing, considers only fibrous and particulate debris constituents and it is assumed that the arrival of significant chemical precipitates results in complete core inlet blockage. Although this test program did not confirm this assumption experimentally, previous testing (Reference 6-1) has demonstrated that the collection of chemical precipitates on a fibrous debris bed > 15 g/FA results in high resistances such that flow through the core inlet is significantly reduced. Since the overall methodology described in this report assumes complete core inlet blockage with the arrival of chemical precipitates, there was no need to perform tests that included chemical precipitates in the subscale facility.

6.3.1 Analysis of Subscale Final Limits Data

The scaling analysis presented in Volume 6 demonstrates that the subscale facility is comparable to a full-area FA in terms of distortions related to pressure drop across a debris bed. It has been shown that the geometric scale of the subscale facility has negligible distortion when compared to a full-area FA. It has also been shown that the dominant physical phenomena expected to drive debris bed head loss are reasonably preserved. Using the flow area ratio between the subscale and a full-area FA it is possible to

relate the subscale debris loading to that of a full-area FA. It is also possible to relate the subscale flow condition to that of the full-area FA using the same flow area ratio.

Subscale testing determined that a low-flow condition was limiting because fiber penetration through the lower end fittings tested was minimized. Minimizing the quantity of fiber penetration resulted in a single debris bed on the upstream edge of the lower end fitting. Experimental results confirmed that, for the debris loadings tested, a single debris bed formed at the lower end fitting resulted in a higher overall pressure drop compared to tests performed at higher flow rates that created multiple beds within the test section. For this reason, the low flow tests are used to conservatively define the final core inlet debris limits.

Subscale testing also determined that capture geometry has a strong influence on the pressure drop across a debris bed. As a result, the subscale data sets used to define the final core inlet debris limits are different for each fuel vendor since their respective core inlet geometries are significantly different. Figure 6-9 shows the debris bed pressure drop as a function of fiber load (i.e., fiber mass), scaled to a full-area FA from the final limits data sets for Westinghouse and AREVA fuel. This is Figure 6-1 in Volume 6.

a,c

Figure 6-9 Limiting Conditions from Subscale Head Loss Testing Scaled to a Full-Area Fuel Assembly

Using the pressure drop data shown in Figure 6-9, a dimensionless form-loss coefficient can be calculated for the limiting subscale datasets. This parameter is defined as K_{test} and is different for the two core inlet geometries tested.

Recall that the TH analyses described in Section 6.1 calculated a value for K_{max} for each plant category. This parameter is the maximum resistance that can be tolerated at the core inlet due to fiber and particulate debris alone. Since the flow area at which the debris bed was built in the subscale facility is different than the flow area that the debris bed was modeled in the TH analysis, K_{test} cannot be compared directly to K_{max}.

First, an equivalent form-loss coefficient needs to be derived from the subscale form-loss coefficient (K_{test}) for each of the four plant categories from the TH analysis. The equivalent form-loss coefficients are defined as K_{eq} and can be compared directly to K_{max} from the TH analyses. They are also used in conjunction with K_{split} and m_{split} to determine when the AFP is active and what the fraction of debris through the AFP is following K_{split}.

Using the core inlet pressure drop data shown in Figure 6-9, a dimensionless form-loss coefficient is calculated using:

$$K_{test} = \frac{2g_c dP}{\rho v^2} \quad \text{Equation 6-1}$$

where:

dP = measured debris bed pressure drop

ρ = liquid density

v = average superficial velocity through the debris bed

Subscale testing was completed at low pressures using liquid at 130°F. At atmospheric pressure, the liquid density at the tested temperature is 61.55 lbm/ft^3.

The average superficial velocity through the debris bed is calculated using:

$$v = \frac{\left(\frac{Q}{A_{column}} + \frac{Q}{A_{BN}}\right)}{2} \quad \text{Equation 6-2}$$

where:

Q = volumetric flow rate prescribed during the test

A_{column} = subscale column flow area

A_{BN} = bottom nozzle flow area used in the subscale facility

Next, since the flow area of the subscale column is different from the flow area at which the resistance due to debris accumulation was simulated in the T/H analyses, an equivalent form-loss coefficient needs to be calculated by taking the ratio of the flow areas squared:

$$K_{eq} = K_{test} \frac{{A_{TH}}^2}{{A_{column}}^2} \qquad \text{Equation 6-3}$$

where:

A_{TH} = flow area used in the TH analysis to simulate resistance due to a debris bed

The equivalent form-loss coefficient calculated using Equation 6-3 can be compared directly to the TH results.

6.3.2 Westinghouse Fuel

Using Equations 6-1, 6-2, and 6-3, an equivalent form-loss coefficient can be calculated for each plant category considered in the TH analyses for Westinghouse fuel.

First, Equation 6-2 is used to calculate the average superficial velocity through the debris bed. The Westinghouse final dataset used the Final-Low flow reduction curve shown in Figure 3-8, Volume 6. From Section 3.4, Volume 6, the subscale column flow area is 16 in^2. From Table 3-7, Volume 6, the Westinghouse tested bottom nozzle flow area is [ ]^{a,c}

With the average superficial velocity calculated, the pressure drop data from Figure 6-9, along with the liquid density, is used to calculate the dimensionless form loss coefficient, K_{test}. Figure 6-10 shows K_{test} plotted as a function of cumulative fiber load for Westinghouse fuel.

Next, an equivalent form-loss coefficient is calculated for each plant category using Equation 6-3. Since the TH analyses for Westinghouse upflow and downflow BB plants used the same flow area, only three equivalent form-loss calculations are required; Westinghouse NSSS, CE NSSS, and B&W NSSS. From Section 6, Volume 4, the flow areas used in the TH analyses for the three NSSS designs are; [ ]^{a,c} respectively.

Figure 6-11 shows the equivalent dimensionless form-loss coefficients, K_{eq}, for each NSSS design that is applicable to plants with Westinghouse fuel. Also shown in the figure are linear curve fits derived to fit the equivalent form loss-coefficient data. These curve fits are described in detail below and are used in the method for verifying the hot leg break in-vessel fiber limits, as described in Section 6.5, to calculate resistance at the core inlet. This is necessary to determine when the AFP activates and to determine the fraction of debris that travels through the AFP once it activates.

[ ]a,c

Figure 6-10 Subscale Dimensionless Form-Loss Coefficient for Westinghouse Fuel

[ ]a,c

Figure 6-11 Subscale Equivalent Dimensionless Form-Loss Coefficients for Various NSSS Designs with Westinghouse Fuel

The equivalent form-loss coefficient curve fits are broken into three discrete regions that are related to the physical particulate capture mechanisms present in a fibrous debris bed as observed in the subscale testing. For the Westinghouse core inlet fuel geometry, at fiber loads less than [ ][a,c] the fiber bed formed at the core inlet is not an efficient particulate filter. Since only a small fraction of the total injected particulate load captures in the fiber bed, the pressure drop, and thus, the dimensionless resistance remain relatively low. As the fiber load increases beyond [ ][a,c] the filtration efficiency improves, because of the additional fiber and particulate, and the resistance rate increases. As the fiber load continues to increase beyond [ ][a,c] the debris bed is capturing particulates at nearly 100 percent efficiency and the rate of resistance increase is at its highest.

A simple linear relation between debris bed resistance and fiber load is used for each of the three regimes:

$$K_{eq} = mM_f + b \quad \text{Equation 6-4}$$

where:

m = slope of linear relation

M_f = cumulative fiber load (g/FA)

b = y-intercept of linear relation

Table 6-2 provides the slope and y-intercept for the three regimes applicable to Westinghouse fuel for each of the three NSSS designs.

Table 6-2 Equivalent Dimensionless Form-Loss Coefficient Linear Relations for Various NSSS designs with Westinghouse Fuel

NSSS Design	slope (m)	y-intercept (b)
	[	][a,c]
Westinghouse		
CE		
B&W		

With the equivalent form-loss from the subscale data defined, it can now be compared directly to the T/H analysis results to determine the limiting fiber load for debris bed formation at the core inlet. This is done by using the linear relation for regime 3, rearranging to solve for the mass of fiber and setting K_{eq} equal to K_{max}. Table 6-3 provides the results of this calculation for the four plant categories considered in the TH analysis. The Westinghouse upflow and downflow BB categories use the same relation for equivalent form-loss. Since K_{max} from the CE and B&W plant categories results in an equivalent resistance that is greater than the maximum debris load tested, the maximum debris load is chosen as the acceptable fiber load for these plant categories. It is noted that these are the acceptable core inlet fiber loads prior to reaching t_{block}. For times after t_{block}, the core inlet fiber load can exceed the values shown in Table 6-3 since complete core inlet blockage can be tolerated at times after t_{block}. This is described further in Section 6.5.

Table 6-3 Acceptable Core Inlet Fiber Loads Prior to Reaching t_{block} for Various NSSS designs with Westinghouse Fuel		
Plant Category	**K_{max}**	**Acceptable Core Inlet Fiber Load (g/FA)**
Westinghouse Upflow Barrel/Baffle	$5x10^5$	[
Westinghouse Downflow Barrel/Baffle	$6x10^5$	
CE	$6.5x10^6$	
B&W	$1x10^8$	]a,c
Note: [1] [ ]a,c is the maximum debris load tested. K_{max} is greater than the resistance due to this debris load.		

6.3.3 AREVA Fuel

The same approach is taken for determining equivalent form-loss coefficients for AREVA fuel.

The AREVA final dataset also used the Final-Low flow reduction curve shown in Figure 3-8, Volume 6. From Section 3.4, Volume 6, the subscale column flow area is 16 in^2. From [ ]a,c the AREVA tested bottom nozzle flow area is [ ]a,c

With the average superficial velocity calculated, the pressure drop data from Figure 6-9, along with the liquid density, is used to calculate the dimensionless form loss coefficient, K_{test}. Figure 6-12 shows K_{test} plotted as a function of cumulative fiber load for AREVA fuel.

[ ]a,c

Figure 6-12 Subscale Dimensionless Form-Loss Coefficient for AREVA Fuel

Next, an equivalent form-loss coefficient is calculated for each plant category using Equation 6-3. Since the TH analyses for Westinghouse upflow and downflow BBs used the same flow area, only three equivalent form-loss calculations are required; Westinghouse NSSS, CE NSSS, and B&W NSSS. From Section 6, Volume 4, the flow areas used in the TH analyses for the three NSSS designs are; [ ]^{a,c} respectively.

Figure 6-13 shows the equivalent dimensionless form-loss coefficients, K_{eq}, for each NSSS design that is applicable to plants with AREVA fuel. Also shown in the figure are linear curve fits derived to fit the equivalent form loss-coefficient data. These curve fits are described in detail below and are used in the method for verifying the hot leg break in-vessel fiber limits, as described in Section 6.5, to track the resistance at the core inlet. This is necessary to determine when the AFP activates and to determine the fraction of debris that travels through the AFP once it activates.

[ ]^{a,c}

Figure 6-13 Subscale Equivalent Dimensionless Form-Loss Coefficients for Various NSSS Designs with AREVA Fuel

The equivalent form-loss coefficient curve fits are broken into three discrete regions that are related to the physical particulate capture mechanisms present in a fibrous debris bed observed in the subscale testing. For the AREVA core inlet fuel geometry, at fiber loads less than [ ]^{a,c} the fiber bed formed at the core inlet is not an efficient particulate filter. Since only a small fraction of the total injected particulate load captures in the fiber bed, the pressure drop, and thus, the dimensionless resistance remain relatively low. As the fiber load increases beyond [ ]^{a,c} the filtration efficiency improves because of the additional fiber and particulate, and the resistance rate increases. As the fiber load

continues to increase beyond [ ]a,c the debris bed is capturing particulates at nearly 100 percent efficiency and the rate of resistance increase is at its highest.

Table 6-4 provides the slope and y-intercept used in Equation 6-4 for the three regimes applicable to AREVA fuel for each of the three NSSS designs.

Table 6-4 Equivalent Dimensionless Form-Loss Coefficient Linear Relations for Various NSSS designs with AREVA Fuel

NSSS Design	slope (m)	y-intercept (b)
	[	]a,c
Westinghouse		
CE		
B&W		]

With the equivalent form-loss from the subscale data defined, it can now be compared directly to the TH analysis results to determine the limiting fiber load for debris bed formation at the core inlet. This is done by using the linear relation from regime 2 for the Westinghouse categories and regime 3 for the CE and B&W plant categories, rearranging to solve for the mass of fiber and setting K_{eq} equal to K_{max}. Regime 2 is used to determine the acceptable fiber load for the Westinghouse plant categories in this case because K_{max} for the Westinghouse plant categories falls within regime 2. Table 6-5 provides the results of this calculation for the four plant categories considered in the TH analysis. The Westinghouse upflow and downflow BB categories use the same relation for equivalent form-loss. Since K_{max} from the B&W plant category results in an equivalent resistance that is greater than the maximum debris load tested, the maximum debris load is chosen as the acceptable fiber load for this plant category. It is noted that these are the acceptable core inlet fiber loads prior to reaching t_{block}. For times after t_{block}, the core inlet fiber load can exceed the values shown in Table 6-5 since complete core inlet blockage can be tolerated at times after t_{block}. This is described further in Section 6.5.

Table 6-5 Acceptable Core Inlet Fiber Loads Prior to Reaching t_{block} for Various NSSS designs with AREVA Fuel

Plant Category	K_{max}	Acceptable Core Inlet Fiber Load (g/FA)
Westinghouse Upflow Barrel/Baffle	5×10^5	[ ]a,c
Westinghouse Downflow Barrel/Baffle	6×10^5	
CE	6.5×10^6	
B&W	1×10^8	]

Note: [1] [ ]a,c is the maximum debris load tested. K_{max} is greater than the resistance due to this debris load.

6.4 IN-CORE DEBRIS LIMIT

As has been described previously, debris may enter the RCS as early as the time that the plant is placed in sump recirculation. Because the debris is well mixed within the sump and the Stokes number is significantly less than one, it travels in proportion to the ECCS flow rate.

Once in the RCS, where the debris is transported depends on the break location, plant design, and operator actions. Most plants in the U.S. (Westinghouse UPI plants excluded) initially direct ECCS injection to the cold legs. For these plants, debris will initially approach the core inlet where testing has shown that it may capture below the heated core near the core inlet, either at the bottom nozzle or at the first mechanical spacer grid. If debris does not capture at this location, it will continue to the heated region of the core. As the transient progresses, debris may begin to enter the heated core through two possible mechanisms. First, the resistance to debris at the core inlet may build to the point that the AFP becomes active, directing flow and debris through the AFP to the core region. The TH analyses described in Section 6.1 identify the conditions under which the AFP becomes active. Second, the operator may take action to initiate HLSO in which all or a fraction of the ECCS flow is transferred to the hot leg to mitigate the buildup of boric acid in the core. The exact ECCS configuration after HLSO is plant-specific. However, after HLSO, some or all of the ECCS reaches the core from the top. If there is debris in this coolant, it may be introduced to the heated core. Therefore, the total amount of debris to reach the core must include the contribution from both the AFP and the hot leg.

The discussion in the following subsections provides the basis for a fiber limit of [ ]^{a,c} in the heated core region (i.e., in-core), which is in addition to the fiber limit established at the core inlet. This amount of fiber (and associated particulate) will not compromise core cooling or established BAPC actions.

6.4.1 Activation of Alternate Flow Path

The specific geometry of the AFP and how fluid from that region reaches the core is dependent on the plant design. TH analyses have shown that, in general, the flow patterns in the core are up through the hot fuel assemblies and down in the core peripheral and lower power assemblies regardless of plant design or the amount of blockage at the core inlet (see Section 6.1 for a detailed discussion and basis). For Westinghouse and CE plants with upflow BB designs and no pressure relief holes in the core barrel, debris will flow up through the BB region and join the core downflow on the periphery of the core near the top of the fuel assemblies. B&W plant designs and some Westinghouse upflow BB plant designs have pressure relief holes in the core barrel from near the core mid-plane to the top of the core. These are the locations that debris will pass into the core region, enter the peripheral fuel assemblies and join the core downflow.

For Westinghouse plants with downflow BBs, the BB region does not communicate with the top of the core and the AFP credited is the path through the upper head spray nozzles. As resistance due to the collection of debris at the core inlet builds, the downcomer level increases and eventually reaches the UHSN elevation. At this point, debris laden coolant will flow through the UHSN, drain through the upper guide tubes and reach the core exit where it will tend toward the core periphery and join with the pre-established core flow patterns described above.

Testing in the subscale loop demonstrated that debris entering the AFP will not block the flow paths in that region (Volume 6). The testing demonstrated that some debris will accumulate in the AFP without blocking the flow passages. However, it is conservative to neglect this accumulation to maximize debris transport to the core. Therefore, any debris that reaches the AFP will be assumed to travel on to the core.

6.4.2 Post Hot Leg Switchover

For plants that initiate HLSO, coolant will enter the RCS in one or more hot legs. Depending on the time in the event that HLSO is initiated, it is likely that the sump strainer has filtered out most or all of the debris. However, there may be some debris remaining in the sump that introduces debris later in the event. In any case, the coolant and debris will either exit the break or reach the top of the core.

It is expected that some or all of the hot leg recirculation flow will exit the broken loop, taking debris with it back to containment, where it will be re-filtered before returning to the ECCS. However, it is conservative to neglect this break carryover of debris with respect to debris accumulation in the core. Therefore, any debris that enters the RV through the hot leg will be assumed to reach the core region.

6.4.3 Justification for In-Core Debris Limit

In all scenarios, a number of pieces of information can be used to justify that [ ]^{a,c} of fiber can be tolerated in the heated core (in addition to what can be tolerated at the core inlet). This section provides the details of this information for any plant type that initially starts cold leg ECCS recirculation (including times after HLSO). UPI plants are discussed in Section 8.

6.4.3.1 Debris Accumulation

Shortly after the time of SSO, the core is boiling vigorously, and the average void fraction is greater than 50 percent. Even after 6-12 hours, the decay heat is high enough to generate boiling in the core, and the void fraction is greater than 20 percent. Given that all or most of the debris reaches the core region within the first few hours, debris will be entering a highly voided core region.

The boiling process, in and of itself, precludes significant debris accumulation. While the general flow patterns in the core are well established by the TH analyses (Section 6.1), the local flow patterns are quite complex due to the nature of the boiling process. Boiling at any given location in the core is quite erratic. The instabilities of the boiling process introduce energy to the fluid that varies with time and location. In the event of debris beginning to accumulate at the leading edge of a spacer grid (similar to what is seen at the core inlet – see Figure 6-14), the perturbations of the local conditions due to this small debris buildup will lead to boiling that will dislodge the debris before a large, contiguous bed can be established that significantly interrupts the core flow patterns. Therefore, debris beds like those seen at the core inlet will not establish in the presence of boiling. Rather, local blockages around spacer grid dimples, springs and other areas with small clearances are expected that do not significantly impact decay heat removal or create conditions that could lead to premature BAP (see Figure 6-15).

The discussion above is supported by testing sponsored by the PWROG as described in WCAP-17360 (Reference 6-3). This testing was performed to investigate the heat transfer behavior of buffered and unbuffered boric acid solutions with and without debris under conditions simulating that expected during

the LTCC phase following a post-LOCA transient. The testing considered a 3x3 heated rod bundle with a heated length of 22 inches. The loop was open to the atmosphere at the top and fluid was provided to the bottom of the bundle to replace the fluid lost to boiling. Debris was introduced with the fluid and continually concentrates in the test section since no fluid was drawn from the top. The testing included an equivalent fiber load of [ ]^{a,c} with a p:f ratio of [ ]^{a,c} for a total debris loading of [ ]^{a,c} of fiber and particulate. AlOOH was included as a chemical precipitate surrogate.

The results of the testing program documented in Reference 6-3 indicate, in part, that for the test rig design and debris loadings used, [ ]^{a,c}

These test results represent a cold leg break scenario. [ ]^{a,c} The same response can be expected for a hot leg break scenario when debris begins to reach the core through the AFP or after HLSO. The TH analyses described in Section 6.1 show that the flow through the AFPs are in excess of the boil-off rate of the core. To that end, a significant amount of liquid is reaching and exiting the break. Since the debris is traveling with the liquid, it is expected that a significant portion of the debris will exit the break and return to containment and be re-filtered on the sump strainer before returning to the RCS. The amount of debris that exits the break (or remains in the core) is dependent on plant conditions. While a plant-specific analysis may try to quantify this effect, the general solution proposed by the PWROG is to neglect any debris exiting the break and assume that any debris reaching the core remains in the core. To that end, the 3x3 testing indicates that up to [ ]^{a,c} of fiber per FA can be tolerated in the core region in the presence of boiling.

As the transient progresses, the core decay heat will decrease, which decreases boiling in the core. In particular, lower power regions of the core (i.e., the core periphery) may stop boiling while the higher power assemblies continue to boil. In these liquid only regions of the core, it may be possible that debris may begin to accumulate on the leading edge of the spacer grid. Subscale testing has demonstrated that flow through a debris bed made of fiber and particulate only will continue for fairly high amounts of fiber (on the order of [ ]^{a,c}). The addition of chemical precipitates may preclude flow through established debris beds of more than 15 g/FA. However, any debris bed that forms in the liquid only region of the core will not extend across the entire core, because boiling continues in the higher power assemblies. The open lattice fuel design will allow flow around any of these types of blockages. Should any region near a blockage become starved for flow, the fluid will heat up and eventually boil. The boiling will either dislodge a debris bed (if it formed on the top side of the spacer grid), or the decreased density of the boiling region will draw fluid in to replace the boiled off fluid (if the debris beds have formed on the bottom side of the grids and are not dislodged by boiling). In either case, the open lattice design of the fuel will ensure that the core is cooled and that localized regions with increased boron concentration will not develop even for blockages across small portions of the core.

While boiling precludes buildup at the leading edge of a spacer grid, the energy from the boiling process may force debris into internal grid locations such as the springs or dimples (see Figure 6-15). The limited size of these geometric features limits the expanse of the debris collection such that the effects would be localized. However, the boiling process will continue to force liquid either through the debris collection or very near it such that cooling will continue. In the extreme case that some volume in the spacer grid around a single rod is starved of flow, axial conduction through the cladding to the region just upstream or downstream of the blockage is sufficient to keep the cladding cool as demonstrated in WCAP-16793-NP-A, Rev. 2 (Reference 6-1). The open lattice design of the fuel assemblies ensures that fluid is free to flow just upstream and downstream of these localized blockages.

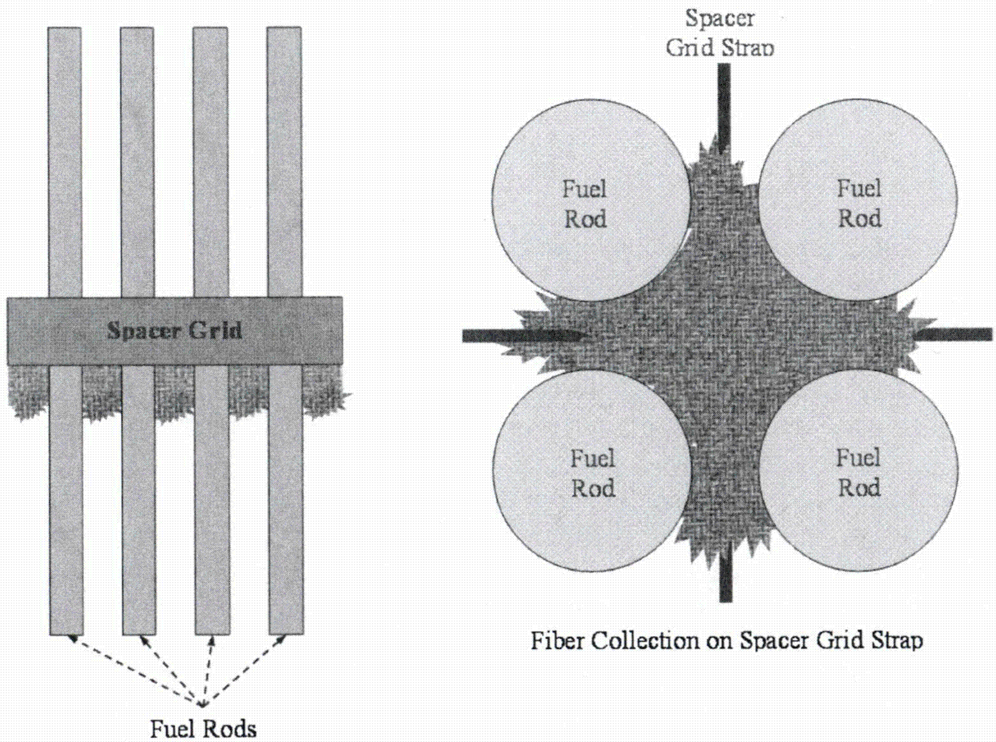

Figure 6-14 Fiber Collection on Leading Edge of Spacer Grid

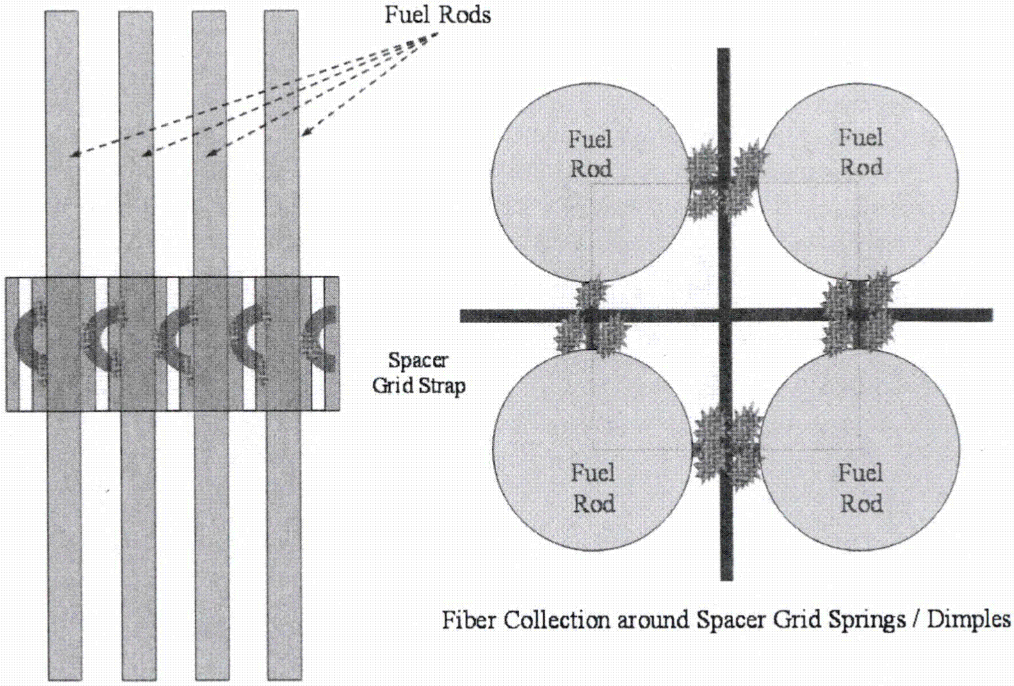

Figure 6-15 Fiber Collection on Internal Springs of Spacer Grid

6.4.3.2 Effect of Debris on Cladding Heat Removal

The addition of debris may have an effect on the fluid properties in the core and the subsequent heat removal ability of the water/debris mixture. There is ample work in the open literature to indicate that the addition of suspended particulates in a fluid will actually improve heat transfer. Sannervik (Reference 6-4) measured the heat transfer coefficient for mixtures with particle concentrations of 0, 10, 20, and 30 percent and found that from 0 to 10 percent concentration, heat transfer coefficient doubled. From 10 to 20 percent, there was an additional 25 percent increase, and a 35 percent increase from 10 to 30 percent. The reason stated is that the "particles interact with the wall boundary layer, causing fluid mixing and enthalpy exchange with the fluid inside the pipe, a mechanism similar to heat transfer by turbulent eddy convection." Similar results were found by the experiments of Kianjah and Dhir (Reference 6-5), in which 30 μm and 100 μm glass particles showed heat transfer enhancements between 25 percent and 170 percent, with the smaller particles being more effective. This is also analogous to subcooled nucleate boiling and dispersed two-phase flow where liquid droplets improve the wall to steam heat transfer coefficient because of the mixing effects. This two-phase enhancement effect is well supported by EPRI NP-3485 (Reference 6-6) and Volume 8 of Multiphase Science and Technology, Dispersed Flow (Reference 6-7). It is clear that the addition of debris that remains in suspension will enhance heat transfer up to approximately 35 percent concentrations. At higher concentrations, this may not be the case as the insulating effects of the debris begin to outweigh the turbulent enhancement effects. The following calculation relates the heated core concentrations of debris with these data.

The concentration of debris is the relative mass of debris to the volume of liquid in the core. A volume ratio of debris to liquid is also useful to calculate. Based on the TH analyses described in Section 6.1, it is reasonable to assume the core is no more than 50 percent voided. The system codes predict some smaller void fraction at the point that liquid will enter the core, but assuming a larger core void fraction will conservatively minimize the core liquid volume. The volume of liquid in the core can then be calculated using the core flow area and the elevation difference between the bottom of the heated core region (the approximate location of the core inlet blockage) and at least the bottom of the hot leg (location of the break). In reality, there has to be some weir height above the bottom of the hot leg in order for liquid to exit the break. For this calculation, that height will be neglected such that the core liquid volume is minimized.

On a per FA basis, the CE plants have the smallest core flow area. From the TH analyses (Section 6.1), one FA has an area of [ ]^{a,c} The flow area of the UP above a single assembly is [ ]^{a,c} The volume of liquid in the core per FA can then be calculated as:

$$V_{Core} = (1 - Core\ Void\ Fraction) * Core\ Height * Core\ Area \qquad \text{Equation 6-5}$$

[ ]^{a,c}

Similarly, the volume of liquid above the core per FA can be calculated using an approximate height of three feet from the top of the core to the bottom of the hot leg:

$$V_{UP} = (1 - Core\ Void\ Fraction) * Height * Area \qquad \text{Equation 6-6}$$

[ ]^{a,c}

The total volume is then:

$$V_{Total} = V_{Core} + V_{UP} \qquad \text{Equation 6-7}$$

[ ]^{a,c}

The volume of debris is calculated based on the proposed limit of fiber in the core region and the material density of fiber and particulate. A fiber density of 156.1 lbm/ft^3 is used to represent individual fibers (Reference 6-8). Particulates that may reach the core are varied in density. A smaller density will maximize the volume of debris. Therefore, a particulate density of 100 lbm/ft^3, which corresponds to dirt and dust, will be used (Reference 6-8). One hundred grams of fiber is 0.22 lbm. As discussed above, above 35 percent concentrations, core heat transfer may be affected. To that end, the mass of particulates that produces this concentration can be determined.

The volume ratio of debris to fluid per FA is calculated by:

$$R_{debris,core} = \frac{V_{debris}}{V_{FA}}$$ Equation 6-8

where

$$V_{debris} = \frac{M_f}{\rho_f} + \frac{M_p}{\rho_p}$$ Equation 6-9

[ ]a,c

$M_f = mass\ of\ fiber$

$M_p = mass\ of\ particulate$

$\rho_f = density\ of\ fiber$

$\rho_p = density\ of\ particulate$

Combing and rearranging to solve for mass of particulates yields:

$$M_p = \left(R_{debris,core} \cdot V_{FA} - \frac{M_f}{\rho_f}\right) \cdot \rho_p$$ Equation 6-10

[ ]a,c

The concentration of debris per FA is then:

[ ]a,c

The corresponding particulate-to-fiber (p:f) ratio is then [ ]a,c

This calculation represents the limiting case, which assumes all debris remains in suspension with no debris exiting the break. Given that the p:f ratios expected in the core are less than that calculated above, the concentrations expected in the core are well within the range of conditions studied in the literature. Therefore, it can be concluded that the addition of debris in the core that remains in suspension will not degrade the ability of the core fluid mixture to remove core decay heat.

The debris will displace water, which if great enough can have an effect on core cooling. If sufficient debris is present to effectively reduce the core mixture level below the top of the core, then core cooling may be compromised. The amount of liquid above the top of the core was conservatively determined to be greater than [ ]a,c The volume of debris at the limiting condition calculated above is

[ ]^{a,c}

Therefore, only if all of the debris is concentrated above the core can the amount of liquid displaced be sufficient to reduce the core mixture level below the top of the core. For the particulate loads expected (i.e., less than half of that calculated above) the core will not uncover.

6.4.4 Summary and Conclusion

The discussion in the preceding subsections provides the basis for a conservative in-core fiber limit of [ ]^{a,c} This limit is in addition to the amount of fiber that can be tolerated at the core inlet. This amount of fiber (and associated particulate) will not compromise core cooling or established BAPC actions. This value is used in Section 6.5 to ensure acceptable results.

6.5 METHOD FOR VERIFYING HOT LEG BREAK IN-VESSEL DEBRIS LIMITS

Using the information from the previous sections, a method for calculating plant-specific fiber limits for large HLBs for cold leg recirculation plants was developed. (While this Section 6 pertains mainly to cold side recirculation plants, the method presented here is flexible enough to also analyze UPI plants. Guidance on how to do this is provided as needed below.) The details of this method are described here in enough detail that plant engineers can determine a plant-specific fiber limit using the calculation method of their choosing. Demonstration cases using the described method are also provided for use by utilities as an additional way of validating their calculations. The sections below are intended to provide the information necessary for a utility engineer to implement the method and replicate the results.

6.5.1 Overview

Following a large HLB, debris can accumulate in the RV in a number of locations depending on the time in the event and plant-specific parameters. For the purposes of tracking the fiber, there are several key times that should be noted:

1. Beginning of Sump Recirculation
2. Activation of AFP
3. Complete Core Inlet Blockage
4. BAPC Action

Fiber injection begins at the time of SSO. Thereafter, the rate of fiber injection to the RV is a function of ECCS flow rate, sump strainer bypass, containment spray flow rate, and total system liquid mass, as described in greater detail below. Knowing the rate of injection and an estimate of the initial fiber load, a mass of fiber injected into the system as a function of time can be calculated.

With the exception of UPI plants, all of the ECCS recirculation flow to the RCS is initially through the cold legs. Consequently, the net ECCS flow rate reaching the RV LP is equal to the total ECCS flow rate,

since the only path to the break at this point in the transient is through the RV. Neglecting hold-up and settling between the ECCS strainer and the RV, it is assumed that all debris that reaches the ECCS system will reach the RV LP.

The TH analyses described in Section 6.1 show that, for some period of time immediately after SSO, the flow into the core is only through the core inlet. That is, the AFP is not active in transporting debris to the core and debris buildup is only at the core inlet. As debris accumulates at the core inlet, the resistance through this flow path increases. Eventually, the BB channel or UHSNs will offer less resistance than the core inlet, and flow will begin to divert through this AFP as a result. Because of the relatively low mass of particulate and fibrous debris, the motion of the debris is tightly coupled to the fluid motion and is therefore assumed to be uniformly distributed throughout the fluid. As a result, flow through the AFP will take with it a fiber mass ratio equal to the mass flow ratio. During this period, debris continues to accumulate at the core inlet while also transporting a fraction to the core region by way of the AFP. If either K_{max} is reached (the maximum resistance due to debris that can be tolerated at the core inlet from fuel testing) or t_{chem} is reached (the time that chemical precipitates are calculated to form), the core inlet is assumed to become completely blocked, after which time debris will be delivered to the core via the AFP only. Finally, the operators will take some action to mitigate boric acid buildup in the core region. For most plants, this means that debris can potentially be introduced directly to the core exit. The timing of this action may occur at any point such that the AFP may or may not be active or the core inlet may or may not be blocked. Clearly, the events that occur during this time period are plant dependent (see Section 4.2). While not strictly rigorous, the above discussion is useful in tracking and discussing debris accumulation.

For every plant, there is a limit to the amount of fiber that can be tolerated within the RV. This limit is a combination of debris in the core itself as described in Section 6.4 and the debris at the core inlet as defined by subscale testing in Section 6.2. When a plant aligns ECCS to sump recirculation, some or all of the fiber that penetrates the sump strainers is transported through the ECCS to the RV. An understanding of the post-LOCA system response can be used to track where the fiber might end up in the RV such that a fiber limit can be calculated. The criteria are that: (1) the fiber accumulation in the heated region of the core does not exceed the in-core limit defined in Section 6.4 or (2) the fiber accumulation at the core inlet does not exceed the core inlet limit defined in Section 6.3. For all HLB and ECCS configurations, no credit is taken for debris that might exit the break. (For UPI plants, this means that after simultaneous recirculation is initiated, credit is not taken for debris lost out the cold leg break.) Therefore, the HLB debris limit is defined as the sum of the fiber that is captured at the core inlet and the heated core region (in-core):

$$M_{f,HLB} = M_{f,CI} + M_{f,in-core} \quad \text{Equation 6-11}$$

where,

$M_{f,HLB}$ = the total fiber mass limit for hot leg breaks

$M_{f,CI}$ = the mass of fiber at the core inlet

$M_{f,in-core}$ = the mass of fiber in the heated core

The mass of fiber that reaches the heated core can travel through two paths, either the AFP or from hot leg recirculation (either UPI or after HLSO):

$$M_{f,in-core} = M_{f,AFP} + M_{f,CE} \qquad \text{Equation 6-12}$$

where,

$M_{f,AFP}$ = the mass of fiber that reaches the heated core through the AFP

$M_{f,CE}$ = the mass of fiber that reaches the heated core through the core exit

6.5.2 Inputs

Several inputs are needed to perform this evaluation. Details of how to define these inputs are provided in the following sub-sections. The following fixed inputs are required:

1. Time Step
2. Plant Type
3. Fuel Vendor
4. Number of FAs
5. Initial Sump Fiber Load

In addition to these fixed inputs, there are inputs that can vary within a range of values. Because it's not known whether the plant will be limited by the core inlet fiber load or the in-core fiber load; two separate cases will need to be analyzed. The first case biases the inputs in order to maximize the core inlet fiber load, and the other case biases the inputs to maximize the in-core fiber load. Recommendations for each of these inputs are discussed in detail in the subsections below, with guidance on how to calculate the inputs (i.e., where to obtain min/max volumes, what conditions to determine min/max flow rates, whether to include containment sprays, etc.). Table 6-6 presents the combination of inputs that should be used to calculate the two limiting cases.

6. Time of SSO
7. Active Sump Volume
8. Time of Chemical Effects, t_{chem}
9. Sump Strainer Bypass Fraction
10. CSS Flow Rate
11. ECCS Flow Rate after SSO

12. Time of HLSO and Resulting Flow Splits

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.

Time step sensitivity should be performed in order to demonstrate stable results calculated by the chosen time step. The time step should be small enough such that the important processes, namely the injection of fiber, behave linearly over each time step. A starting value of 100 seconds is recommended.

6.5.2.2 Plant Type

The values for t_{block} as well as the correlations used to calculate K_{split} and m_{split} are dependent on plant type, as described in Section 6.1. Therefore, the plant design must be identified. The plant types of interest for this analysis are:

1. B&W Design
2. Westinghouse Upflow BB Design
3. Westinghouse Downflow BB Design
4. CE Design

6.5.2.3 Fuel Vendor

The core inlet head loss with debris is dependent on fuel vendor, as described in Section 6.3. Therefore, the fuel vendor must be identified. The fuel vendors of interest for this analysis are:

1. AREVA
2. Westinghouse

6.5.2.4 Number of Fuel Assemblies

The total number of fuel assemblies is used to calculate the value of K_{split}, as described in Step 6 of Section 6.5.3. This value is fixed for each plant and therefore does not need to be parameterized.

6.5.2.5 Initial Sump Fiber Load

The initial sump fiber load is plant dependent and should bound the largest total sump fiber load 30 days after event initiation. This fiber load consists only of the fiber fines in the sump, not the total of all fiber, as described in Section 3.5.

6.5.2.6 Time of Sump Switchover

The time of SSO, t_{SSO}, also known as sump recirculation or recirculation activation, defines the start of the analysis, as it marks the beginning of fiber injection into the RV. An early SSO will result in more fiber being injected through the initial flow path prior to operator action to mitigate boric acid buildup (e.g., HLSO, etc.), which will be more likely to challenge the K_{max} criterion. A late SSO will have the opposite effect, decreasing the fiber accumulated at the core inlet and posing a greater challenge to the in-core fiber limit.

The analyzed range of t_{SSO} should therefore bound all possible times for a large hot leg break. This means that a calculation of minimum t_{SSO} should consider the possibility for maximum ECCS and containment sprays depleting the RWST as well as minimal delays for the necessary actions. Meanwhile the maximum t_{SSO} should consider all conditions that would delay the re-alignment to sump suction, such as the minimum rate of RWST depletion and maximum delays for action during a large HLB.

6.5.2.7 Active Sump Volume

The active sump volume is the volume of liquid in the containment sump that actively participates in the recirculation process. Hold-up volumes and "dead" volumes within the sump should be excluded. This volume acts as the system inventory when calculating the concentration of debris to be injected into the RCS. A maximum value will therefore dilute the debris concentration and decrease the rate of injection, while a minimum value will concentrate the debris and increase the rate of injection. Both minimum and maximum sump volume should be examined.

A higher rate of fiber injection will challenge the core inlet criterion, while a lower rate of injection will challenge the in-core criterion.

6.5.2.8 Time of Chemical Effects

The time at which chemical precipitates affect the debris bed, t_{chem}, is governed by the chemical testing described in Section 6.2 and is plant-dependent. The times reported in that section provide the earliest time of chemical precipitates that will cause an earlier diversion of fiber into the core region. The earlier t_{chem} occurs, the more likely it will occur before t_{block}. The plant-specific value calculated should be used as the minimum value for this input. A maximum time of 24 hours should also be analyzed, allowing for more fiber accumulation at the core inlet.

6.5.2.9 Sump Strainer Bypass Fraction

The sump strainer bypass fraction determines the fraction of total available fiber that bypasses the sump strainer, making itself available for transport through the CSS or into the RV. Utilities may perform sump strainer bypass testing to determine the amount of debris that reaches the RCS, and at the same time, determine the capture efficiency of the sump strainer. The suggested protocol for determining debris bypass is described in Reference 6-9. The testing protocol indicates that debris should be introduced in batches with data collected for debris bypass for each batch. These data are then used to estimate the quantity of fiber transported to the RCS. This testing process is conservative as the batch addition

considers bypass for small amounts of fibers reaching the sump strainer. This effectively provides data for smaller break sizes where smaller amounts of debris would be generated.

If test data is not available, Reference 6-10 provides for the use of a 45 percent bypass fraction, stating that, "a plant may use the 45 percent bypass assumption if it can be shown to be valid for their plant conditions."

6.5.2.10 CSS Flow Rate

The containment spray system helps reduce the total mass of debris delivered to the RV by diverting a fraction of debris that bypasses the sump strainer back into the sump. Higher CSS flow rates result in less fiber delivered to the RCS. Therefore, a minimum CSS flow rate should be used if sprays are credited. Additionally, the CSS pump configuration that results in the lowest CSS flow should also be used (e.g., single pump operation in a plant with two trains of CSS).

6.5.2.11 ECCS Flow Rate after Sump Switchover

The ECCS flow rate after the time of SSO is used to calculate the rate of fiber injection into the RV and therefore should reflect the total ECCS flow rate that reaches the RV. It is also used to calculate the value of K_{split}, which is a function of ECCS flow reaching the core inlet. A minimum ECCS flow after SSO will deposit the least amount of fiber at the core inlet and be less capable of diverting flow through the AFP. A maximum value will deposit the most fiber at the core inlet, but will also be more likely to divert flow through the AFP. Since the ECCS flow rate is only used to deliver fiber to the core in this calculation, it should only specify the flow to the RCS and not include the containment spray flow rate regardless of whether CS is actuated.

Both a minimum and maximum ECCS flow rate should be analyzed.

6.5.2.12 Time of HLSO and Resulting Flow Splits

HLSO actions can vary significantly from plant-to-plant. The timing of HLSO can vary (if it occurs at all), a fraction of flow can be recirculated to the HLs simultaneously with recirculation to the CLs, or a complete HL recirculation can be activated. There can also be time varying transition between hot side and cold side recirculation. All of the post-SSO ECCS configurations relevant to the plant being analyzed must be captured or bounded. This can be done effectively by using a time dependent table of flow fractions to the hot side and cold side. For plants that continually switch between hot and cold side recirculation, only a few switches may need to be simulated based on the termination criteria defined in Section 6.5.5. As with the ECCS flow rate, minimum and maximum values should also be examined.

The BAPC licensing basis requires that the actions be performed within a specified time window, typically a target value plus or minus 30 minutes. Therefore, minimum and maximum times should be examined in the analyses. That is, the minimum value would be the initiation time minus the uncertainty; similarly, the maximum time would be the initiation time plus the uncertainty. For those plants that continually switch between hot side and cold side recirculation, it is reasonable to bias every switch in the same direction.

6.5.3 Fiber Injection Rate

In order to determine whether the RV fiber limits are exceeded given an initial sump fiber load, the rate of fiber injection into the system must be known. This can be done by starting with an initial sump fiber load, calculating the rate at which fiber bypasses the sump strainers, and subtracting the mass of fiber diverted through the containment spray system, thus providing a time varying mass of fiber entering the RV. This approach is similar to that developed for the CLB methodology (Volume 3).

The system consists of four major components: the sump, the sump strainer, the containment spray, and the RV. Figure 6-16 presents a schematic of the variables important to the injection and tracking of fiber.

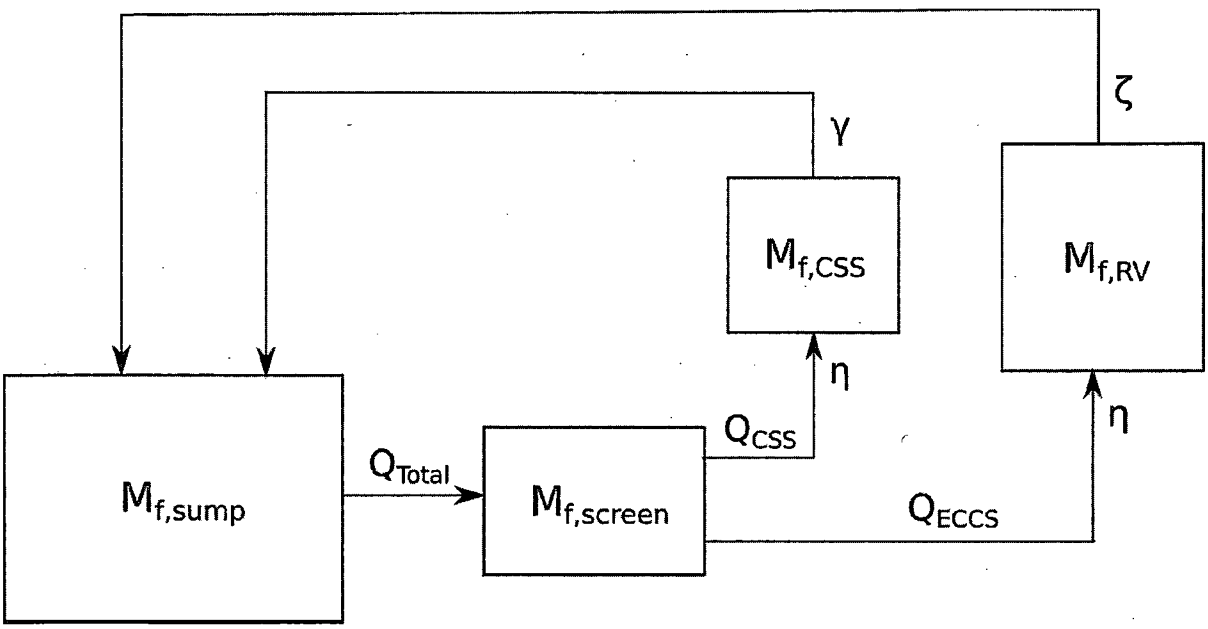

Figure 6-16 System Schematic for Fiber Tracking

The variables in this schematic are defined as follows:

$M_{f,sump}$ = the mass of fiber in the sump

$M_{f,screen}$ = the mass of fiber in the sump strainer

$M_{f,CSS}$ = the mass of fiber in the containment spray system

$M_{f,RV}$ = the mass of fiber in the RV

Q_{total} = the total volumetric flow rate passing through the sump strainer

Q_{CSS} = the volumetric flow rate to the containment spray system

Q_{ECCS} = the total volumetric flow rate entering the RV

η = the bypass fraction of fiber through the sump strainer

γ = the bypass fraction of fiber that transfers from the CSS to the sump

ζ = the bypass fraction through the RV to the break

The rate at which fiber mass changes in each of these components without any simplifications is presented below, beginning with the sump:

$$M'_{f,sump} = \frac{dM_f}{dt}_{in} - \frac{dM_f}{dt}_{out}$$ Equation 6-13

By the time of SSO, there are two sources of fiber injecting into the sump: (1) the fiber being recirculated through the containment sprays, and (2) the fiber being dumped out of the break:

$$\frac{dM_{f,sump}}{dt}_{in} = \gamma\eta Q_{CSS}\frac{M_{f,sump}(t)}{V} + \zeta\eta Q_{ECCS}\frac{M_{f,sump}(t)}{V}$$ Equation 6-14

The outgoing fiber from the sump consists of the fiber delivered to the sump strainer, which is the sump fiber concentration times the total volumetric flow rate through the strainer:

$$\frac{dM_{f,sump}}{dt}_{out} = Q_{total}\frac{M_{f,sump}(t)}{V}$$ Equation 6-15

The rate of change of fiber load in the sump is therefore equal to:

$$M'_{f,sump} = \gamma\eta Q_{CSS}\frac{M_{f,sump}(t)}{V} + \zeta\eta Q_{ECCS}\frac{M_{f,sump}(t)}{V} - Q_{total}\frac{M_{f,sump}(t)}{V}$$ Equation 6-16

The sump strainer fiber load increases due to the total flow rate across it (ECCS plus CSS flow) and is a function of the strainer bypass fraction, η. Note that this also means that the bypass fraction is inversely proportional to sump strainer fiber load. For utilities that have information on the time dependent behavior of the sump strainers, η can be modified accordingly; whereas, for those utilities that only have the average bypass fraction, η should be treated as a constant.

$$M'_{f,screen} = Q_{total}\frac{M_{f,sump}(t)}{V} - \eta Q_{CSS}\frac{M_{f,sump}(t)}{V} - \eta Q_{ECCS}\frac{M_{f,sump}(t)}{V}$$ Equation 6-17

The fiber mass in the containment spray system is equal to the fiber mass concentration through the sump strainer times the volumetric flow rate entering the containment spray, the same concentration times the fraction of fiber that exits the CSS and ultimately returns to the sump, γ.

$$M'_{f,CSS} = \eta Q_{CSS}\frac{M_{f,sump}(t)}{V} - \eta\gamma Q_{CSS}\frac{M_{f,sump}(t)}{V}$$ Equation 6-18

The RV fiber load increases as a function of the ECCS flow rate and fiber load past the sump strainer. It can also decrease due to fiber transported out of the break.

$$M'_{f,RV} = \eta Q_{ECCS}\frac{M_{f,sump}(t)}{V} - \eta\zeta Q_{ECCS}\frac{M_{f,sump}(t)}{V} \qquad \text{Equation 6-19}$$

Equations 6-16 through 6-19 provide a description of the system in the most general sense. However, in deriving the equations used to track fiber for the HLB methodology, two major conservative assumptions are made. First, all fiber that enters the RV remains in the RV, meaning that no credit taken for fiber removal by the break. This is implemented by setting ζ equal to zero. The second major assumption is that any fiber that is diverted to the CSS will return to the sump, meaning that no credit is taken for fiber capture throughout the containment building. This is implemented by setting γ to 1.0. While these assumptions serve as conservative simplifications, they do not preclude a utility with information about these parameters from implementing them accordingly.

With these assumptions in mind, the general equations used to govern fiber transport are simplified into equations 6-20 through 6-23.

$$M'_{f,sump} = Q_{total}\frac{M_{f,sump}(t)}{V} \qquad \text{Equation 6-20}$$

$$M'_{f,screen} = Q_{total}\frac{M_{f,sump}(t)}{V} - \eta Q_{CSS}\frac{M_{f,sump}(t)}{V} - \eta Q_{ECCS}\frac{M_{f,sump}(t)}{V} \qquad \text{Equation 6-21}$$

$$M'_{f,CSS} = 0 \qquad \text{Equation 6-22}$$

$$M'_{f,RV} = \eta Q_{ECCS}\frac{M_{f,sump}(t)}{V} \qquad \text{Equation 6-23}$$

Solving for this system of differential equations with an initial sump fiber load of $M_{f,sump}(0)$ and zero fiber in all other locations produces the equations used to track the fiber load versus time in the sump, sump strainer, and RV, respectively:

$$M_{f,sump}(t) = M_{f,sump}(0) \times e^{-\frac{t}{V}(\eta Q_{ECCS} - Q_{total}(\eta-1))} \qquad \text{Equation 6-24}$$

$$M_{f,screen}(t) = \frac{(\eta-1)M_{f,sump}(0) \times Q_{total}\left(1 - e^{\frac{t}{V}(\eta Q_{ECCS} - Q_{total}(\eta-1))}\right)}{\eta Q_{ECCS} - Q_{total}(\eta-1)} \qquad \text{Equation 6-25}$$

$$M_{f,CSS}(t) = 0 \qquad \text{Equation 6-26}$$

$$M_{f,RV}(t) = \frac{\eta Q_{ECCS} M_{f,sump}(0)}{\eta Q_{ECCS} - Q_{total}(\eta-1)}\left(1 - e^{-\left(\frac{t}{V}(\eta Q_{ECCS} - \eta Q_{total} + Q_{total})\right)}\right) \qquad \text{Equation 6-27}$$

6.5.4 Potentially Limiting Cases

Given the range of possible values for each of the preceding inputs, two potentially limiting scenarios should be considered. The first is a scenario that most challenges the K_{max} criterion at the core inlet, and the second is one that most challenges the maximum fiber load criterion in the core (i.e., [ ]^{a,c}).

Based on the discussion provided for each of the inputs in Section 6.5.2, Table 6-6 presents the combinations of inputs needed in order to calculate the two potentially limiting cases.

Table 6-6 Input Biasing for Potentially Limiting Cases

Parameter	Core Inlet Limiting Conditions	In-Core Limiting Conditions
Time of SSO	min	max
Active sump volume	min	max
Time of chemical precipitates	max	min
Sump strainer bypass fraction	max	max
CSS flow rate	min	min
ECCS flow rate	max	min
Time of HLSO	max	min

6.5.5 Methodology

Once the inputs are defined, the following steps can be used to determine whether or not the RV fiber load criteria are met for a hot leg break for a given sump fiber load. Two separate cases should be run; one that challenges the core inlet fiber limit, and one that challenges the in-core fiber limit. This is done to ensure that the bounding scenario is captured. The combination of inputs necessary for these two cases is provided in Table 6-6.

The existing fiber load at the start of each time step is used to calculate the flow splits. The fiber is then deposited using these splits, and the resistances at each location are calculated based upon the fiber loads at the end of the time step.

1. Obtain the minimum acceptable time of complete core inlet blockage, t_{block}, and the maximum core inlet resistance prior to complete core inlet blockage, K_{max}. These values are developed in Section 6.1 and are shown on Table 6-1. These values will be used as termination criteria in Step 10.

2. Begin the time iteration by starting at the time of SSO. Further, no debris is injected to the system until SSO, so no calculations are needed prior to this time.

3. Calculate the fiber load in the sump, sump strainer, and RV at the current time using the equations derived in Section 6.5.3

4. Calculate the mass of fiber injected into the RV since the previous time step:

$$M_{f,inj}(t) = M_{f,RV}(t) - M_{f,RV}(t - \Delta t) \qquad \text{Equation 6-28}$$

5. Obtain the volumetric ECCS flow rate, Q_{ECCS}, and split between CL (θ_{CL}) and HL (θ_{HL}) for the current time. The ECCS flow split between the cold side and hot side is governed by the plant-specific EOPs and is a function of time. Any time-varying transition between injection locations should be captured as well. The flow splits will be used to calculate the core inlet resistance, K_{split}, volumetric flow rates, and fiber loads in Steps 8, 9, 6 and 3, respectively.

6. Using the calculated flow split between the AFP and core inlet from Step 9 of the previous time step, as well as the split between cold side and hot side recirculation from Step 5, calculate the liquid volumetric flow rates approaching the core inlet, AFP, and core exit. These flow rates reflect the flows in the presence of the existing debris bed (i.e., prior to the addition of the debris associated with the current time step).

$$Q_{CI} = (1 - m_{split}) \times \theta_{CL} \times Q_{ECCS} \qquad \text{Equation 6-29}$$

$$Q_{AFP} = m_{split} \times \theta_{CL} \times Q_{ECCS} \qquad \text{Equation 6-30}$$

$$Q_{CE} = \theta_{HL} \times Q_{ECCS} \qquad \text{Equation 6-31}$$

where,

Q_{CI} = the volumetric flow rate in gpm approaching the core inlet

Q_{AFP} = the volumetric flow rate in gpm approaching the AFP

Q_{CE} = the volumetric flow rate in gpm approaching the core exit

Q_{ECCS} = the volumetric flow rate in gpm entering the RV after the time of SSO

m_{split} = the fraction of total cold side flow diverted into the AFP

θ_{CL} = the fraction of total flow diverted into the cold leg

θ_{HL} = the fraction of total flow diverted into the hot leg

7. Using the mass of fiber injected into the RV in Step 3 and the flow splits calculated in Step 6, calculate the fiber load at the core inlet, AFP, core exit, and total. Knowing the total mass of fiber injected into the system in a given time interval and the flow rates at each core location, the mass of fiber at each location can be calculated by assuming that the fluid and debris are well mixed.

$$M_{f,CI}(t) = \frac{Q_{CI}}{Q_{ECCS}} \times M_{f,inj}$$ Equation 6-32

$$M_{f,AFP}(t) = \frac{Q_{AFP}}{Q_{ECCS}} \times M_{f,inj}$$ Equation 6-33

$$M_{f,CE}(t) = \frac{Q_{CE}}{Q_{ECCS}} \times M_{f,inj}$$ Equation 6-34

$$M_{f,RV}(t) = M_{f,CI} + M_{f,AFP} + M_{f,CE}$$ Equation 6-35

where,

$M_{f,inj}$ = the mass of fiber injected into the system over the current time step, as calculated in Step 4.

8. Calculate the core inlet K factor using the mass of fiber at the core inlet calculated in Step 7. This calculation is made by first checking to see if complete core inlet blockage has occurred. If not, then the K factor is calculated based on the results of the subscale testing.

   a. Check for an infinite core inlet K factor (i.e., complete blockage of the core inlet). If the core inlet is completely blocked then all fluid and debris is transported to the AFP. There are two potential conditions which can force the core inlet resistance to infinity: chemical effects in the presence of a sufficient debris bed or exceeding the maximum fiber load tested.

   Once chemical precipitates form (i.e., t_{chem} is exceeded) the resistance through the debris bed will be greatly increased, and as the fiber load is increased above 15 g/FA, flow through this path will be stopped completely. While it is true that flow through the bed will exist for fiber loads less than 15 g/FA, the effect of chemical precipitates on the head loss through these lesser debris beds has not been rigorously studied. It is therefore conservative to assume that, so long as there exists a fiber load at the core inlet, complete blockage will occur coincident with t_{chem}. This is accomplished by setting the K factor to a value large enough ($1x10^{20}$) to prevent all flow through the inlet, thus diverting all flow through the AFP. The subscale testing was performed up to a maximum fiber load. Due to a lack of data, once the fiber load at the core inlet exceeds the maximum tested value, it must be conservatively assumed that the core inlet becomes completely blocked.

   b. If the core inlet K factor is not infinite, then it can be calculated as a function of the existing core inlet fiber bed, governed by the fuel-specific correlation developed during subscale testing, which is based on fuel vendor and plant design. Details of these correlations are presented in Section 6.3.

9. Compare the core inlet K calculated in Step 8 to K_{split}. If K is less than or equal to K_{split}, then m_{split} is zero, and flow continues to pass through the core inlet only, with all fiber depositing at

the inlet. If the core inlet K factor is greater than K_{split}, then calculate the flow split between the core inlet and AFP. Flow is diverted through the AFP according the value of m_{split}, with a fraction of fiber captured at the core inlet and the remaining fiber passing through the AFP into the core region. This fiber split is directly proportional to m_{split}, as the fluid and debris are assumed to be well mixed. For core inlet K-factors of 1×10^{20} (i.e., complete core inlet blockage) m_{split} is set to 1.0. The K_{split} and m_{split} correlations are plant-type dependent and described in Section 6.1 and shown in Figure 6-1 through Figure 6-8. If two curve fits are provided, the max fit should be used to minimize the debris buildup at the core inlet. The calculated m_{split} values should be given an upper bound of 1.0.

10. Now that the core inlet fiber load is known, the following stopping criteria can be tested:

    a. If the core inlet K factor is greater than K_{max} before the time of t_{block}, then the calculation does not meet the acceptance criteria defined by the TH analyses (Section 6.1). In this case, steps should be taken to reduce the sump fiber load or minimize the delivery of debris to the RCS (e.g., credit CSS or decrease the strainer bypass fraction).

    b. If the in-core ($M_{f,AFP} + M_{f,CE}$) fiber load is greater than the maximum allowable in-core fiber limit (Section 6.4 for non-UPI plants and Section 8 for UPI plants), then adequate core cooling cannot be guaranteed.

    c. If the total RV fiber load (core inlet plus in-core) exceeds the in-core limit of [ ]^{a,c} then the calculation should be terminated. This is done because fiber capture at the core inlet cannot be guaranteed. This criterion ensures that in the event that debris penetrates the core inlet, the in-core limit is not exceeded due to that penetration.

    d. If using this method to analyze a CLB for a UPI plant, an additional stopping criterion is needed at the core inlet. As discussed in Section 8, after simultaneous recirculation is re-established, the core inlet fiber load, $M_{f,CI}$, cannot exceed [ ]^{a,c}

    If the case fails on any criterion, steps should be taken to reduce the sump fiber load or minimize the delivery of debris to the RCS (e.g., credit CSS or decrease the strainer bypass fraction).

11. Iterate in time until the sump fiber load is depleted. This is determined as the time at which the sump fiber load is less than 1 percent of the initial sump fiber load. At this point, it is reasonable to terminate the calculation:

$$\frac{M_{f,sump}(t)}{M_{f,sump}(0)} \leq 0.01, \text{ terminate calculation} \qquad \text{Equation 6-36}$$

    If the calculation is terminated based upon this criteria, then all of the acceptance criteria have been met and the plant conditions analyzed have been shown not to challenge core cooling for a HLB scenario.

6.5.6 Example Calculations

This section provides example calculations that can be used to verify an implementation of this methodology. Two cases are discussed below; however, additional cases with time dependent results are available to the utilities upon request. Note that the inputs for these cases are not intended to reflect realistic plant conditions; rather, they are intended to test implementation of the methodology. Also note, the time values for inputs are relative to the initiation of the LOCA event, whereas time values in the methodology are relative to the time of sump recirculation.

The first case has a time of chemical precipitation, t_{chem}, coincident with the time of SSO. Because chemical effects will cause complete core inlet blockage at the initiation of the transient, all fiber injected into the RV will accumulate in the core. Given an initial sump fiber load, the final fiber load in the RV can be calculated. The inputs for Case 1 are provided in the Table 6-7.

Table 6-7 Test Case Inputs

Input Parameter	Case 1	Case 2
Plant Type	CE	B&W
Number FA	225	177
Fuel Type	AREVA	Westinghouse
Time Step (sec)	100	100
Sump Volume (gal)	350000	350000
Sump Strainer Bypass Fraction	0.45	0.1
Initial Sump Fiber Load (g/FA)	100	1000
t_{SSO} (hr)	4.3	0.5
t_{chem} (hr)	4.3	6
ECCS Flow after SSO (gpm)	1000	5000
CSS Flow (gpm)	0	1000
HL ECCS Flow Split (time (hr), fraction)	0, 0.0, 1.49, 0.0, 1.5, 0.5, 1E6, 0.5	0, 0.0, 1.49, 0.0, 1.5, 0.5, 1E6, 0.5
CL ECCS Flow Split (time (hr), fraction)	0, 1.0, 1.49, 1.0, 1.5, 0.5, 1E6, 0.5	0, 1.0, 1.49, 1.0, 1.5, 0.5, 1E6, 0.5

Given the inputs for Case 1, the final fiber load in the core can be predicted using Equation 6-27 from Section 6.5.3. Since only the RV fiber load at the end of the event is needed, the equation can be simplified, as the exponential term approaches zero as time approaches infinity:

$$M_{f,RV}(t_{end}) = \frac{\eta Q_{ECCS} M_{f,sump}(0)}{\eta \mathrm{Q}_{\mathrm{ECCS}} - \mathrm{Q}_{total}(\eta - 1)} \quad \text{Equation 6-37}$$

$$M_{f,RV}(t_{end}) = -\frac{0.45 \times 1000 \times 100}{0.45 \times 1000 - 1000(0.45-1)} = 45\ g/FA$$

The methodology should therefore calculate a RV fiber load of 45 g/FA, with all of that fiber located in the core.

If the utility would like to know the margin between their analyzed sump fiber load and their acceptable sump fiber load, this can be accomplished through iteration. The calculation would be performed again with a higher sump fiber load until finding the highest load that does not violate the criteria established in Step 10 of Section 6.5.6. For Case 1, the maximum allowable initial sump fiber load is [ ]^{a,c} since any more fiber would result in an in-core fiber load greater than the maximum allowable value of [ ]^{a,c}

Case 2 exercises more of the method: fiber injection, diversion through the AFP, HL switchover, and chemical effects. The complexity of this case prevents any hand calculation of the result, as was done for Case 1. Instead, a single time iteration through Case 2 is provided using the input in Table 6-7, along with key results of the calculation in order to clarify the methodology.

First obtain the values of t_{block} and K_{max} from Table 6-1, as these will be used throughout the calculation. Since Case 2 is a B&W plant, K_{max} should equal $1x10^8$, and t_{block} should equal 20 minutes. Next set the initial problem time equal to t_{SSO}, as this marks the beginning of fiber injection. Begin the iterative loop over time by incrementing the time by the time step. The first iteration should therefore be calculating values at 100 seconds, the amount of time that has passed since SSO.

Calculate the fiber load at the sump, sump strainer, and RV at 1900 seconds (100 seconds after SSO) using Equations 6-24, 6-25, and 6-27, respectively, from Section 6.5.3:

$$M_{f,sump}(100) = 1000e^{-\left(\frac{100}{350000 \times 60}(0.1 \times 5000 - 0.1 \times 6000 + 6000)\right)} = 972.3\ g/FA$$

$$M_{f,screen}(100) = \frac{6000 \times 1000 \times (0.1-1)}{0.1 \times 5000 - 6000(0.1-1)}\left(e^{-\left(\frac{100}{350000 \times 60}(0.1 \times 5000 - 0.1 \times 6000 + 6000)\right)} - 1\right)$$

$$= 25.37\ g/FA$$

$$M_{f,RV}(100) = \frac{0.1 \times 5000 \times 1000}{0.1 \times 5000 - 6000(0.1-1)}\left(1 - e^{-\left(\frac{100}{350000 \times 60}(0.1 \times 5000 - 0.1 \times 6000 + 6000)\right)}\right) = 2.35\ g/FA$$

A check is made on this calculation by ensuring that the sum of the fiber loads in the sump, strainer, and RV equal the initial sump fiber load at all times:

$$M_{f,sump}(0) = M_{f,sump}(t) + M_{f,screen}(t) + M_{f,RV}(t) \qquad \text{Equation 6-38}$$

At 100 seconds, the calculation passes this check.

$$1000 = 972.3 + 25.37 + 2.35$$

Next calculate the mass of fiber injected into the RV over the previous time step.

$$M_{f,inj}(100) = M_{f,RV}(100) - M_{f,RV}(100 - 100) = 2.35\ g/FA$$

Since there was no fiber in the system previously, the amount injected is equal to the total fiber load in the RV.

Obtain the volumetric ECCS flow split between the cold and hot legs. According to the inputs, 100 percent of the ECCS flow is directed to the cold legs until 1.5 hours after LOCA initiation. Since SSO occurs at 1800 seconds for this case and the first iteration is at 1900 seconds after LOCA, all ECCS flow is still directed to the cold legs.

Calculate the volumetric flow to the core inlet, AFP, and core exit. Use the m_{split} value of the previous time step.

$$Q_{CI} = (1 - 0) \times 1.0 \times 5000 = 5000\ gpm$$

$$Q_{AFP} = 0 \times 1.0 \times 5000 = 0$$

$$Q_{CE} = 0.0 \times 5000 = 0$$

Using the mass of fiber injected into the RV calculated previously and the flow splits from above, calculate the fiber load at the core inlet, AFP, core exit, and total.

$$M_{f,CI}(t) = \frac{5000}{5000} \times 2.35 = 2.35\ g/FA$$

$$M_{f,AFP}(t) = \frac{0}{5000} \times 0$$

$$M_{f,CE}(t) = \frac{0}{5000} \times 0$$

$$M_{f,RV}(t) = 2.35 + 0 + 0 = 2.35\ g/FA$$

The core inlet K factor can now be calculated according to Step 8. First, determine if the inlet resistance should be infinite. Because t_{SSO} is less than t_{chem} , the chemical precipitates have not yet arrived. Similarly, because there is not yet any fiber in the system, the core inlet fiber limit has not yet been exceeded. Therefore, the K factor will not be set to infinity, but will instead be calculated according to Step 8b. For a B&W plant with Westinghouse fuel, Table 6-2 provides the core inlet K factor as a function of fiber load at the core inlet:

[ ]^{a,c}

Calculate the values of K_{split} and m_{split}. Since Case 2 is a B&W plant type, the calculation is as follows:

$$K_{split} = 1.62 \times 10^6 \times \left(\frac{5000}{177}\right)^{-2.55} = 323.2$$

$$\Delta K = K - K_{split} = 4209$$

$$m_{split} = 0.075 \ln(4209) - 0.2 = 0.4259$$

Test the stopping criteria:

1. K(100) is less than K_{max}.
2. The in-core fiber load is 0 grams at 100 seconds; therefore, the in-core limit is not exceeded.
3. The total RV fiber load is less than the in-core limit.
4. Since this is not a UPI plant, this criterion can be ignored.

None of the criteria are violated; therefore, the calculation may continue.

Check whether 99 percent of the sump fiber has been depleted.

$$\frac{972.3}{1000} = 0.972$$

Since 97 percent of the sump fiber load still remains to be injected, the time should be iterated and the loop repeated.

The Table 6-8 presents the primary results of interest for both cases, which can be used as a form of validation.

Table 6-8 Hot Leg Break Example Case Results

Result	Case 1	Case 2
$M_{f,screen}$ $(\frac{g}{FA})$	54.45	906.12
$M_{f,RV}$ $(\frac{g}{FA})$	44.55	83.9

6.6 REFERENCES

6-1 WCAP-16793-NP-A, Rev. 2, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculation Fluid," July 2013.

6-2 [

]a,c

6-3 WCAP-17360-P (Proprietary) and WCAP-17360-NP (Non-Proprietary), "Small Scale Unbuffered and Buffered Boric Acid Nucleate Boiling Heat Transfer Tests with Sump Debris in a Vertical 3x3 Rod Bundle," May 2012.

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6-5 Kainjah and Dhir, "Experimental and Analytical Investigation of Dispersed Flow Heat Transfer," Experimental Thermal and Fluid Science, 1989.

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6-9 NEI Publication, "Revised Draft Generic Guideline, Strainer Filter Bypass Test Protocol," December 7, 2011.

6-10 Letter from John C. Butler (NEI) to Stewart N. Bailey (U.S. NRC), "Transmittal of GSI-191 Resolution Criteria for "Low Fiber" Plants," ADAMS Accession Number ML113570219, December 22, 2011.

7 COLD LEG BREAKS

During the recirculation phase for a CLB LOCA, the ECCS draws suction from the sump. Containment recirculation sump strainers are designed to act as filters to collect post-accident debris, thus preventing a wide range of debris from entering the ECCS and CSS. However, a portion of the debris may be sufficiently small or deformable to actually "pass through" the recirculation sump strainer and enter the ECC and CS systems. This "pass through"' (also sometimes called "bypass") debris in the ECCS may then enter the CSS (if they are operating) or the RV. Once in the RV, the portion of coolant flow into the RV LP 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. Any excess coolant flow exits the break and returns to containment. The excess flow returned to containment via the break or CSS flow is ducted to the sump and again filtered by the recirculation sump strainer before the coolant enters either the ECCS or the CSS.

Unlike hot leg breaks, flow through the AFP is not considered for cold leg breaks. The resistance to flow of the BB region is much higher than the resistance to flow though the core inlet, even with debris accumulation. Further, the upper head spray nozzles are above the liquid level due to the break location. Therefore, all flow and debris will approach the core through the core inlet.

The discussion in this section pertains directly to plants that initiate cold side injection immediately following the break. Discussions pertaining to UPI plants are provided in Section 8.

7.1 COLD LEG BREAK IN-VESSEL DEBRIS LIMIT

Following a CLB, the ECCS liquid from each CL runs to the break, ensuring that the downcomer is full to at least the bottom of the CL nozzles. The core level is established by the manometric balance between the downcomer liquid level, the core level, and RCS pressure drop through the loops or RVVVs. During the time-frame of interest, the net ECCS flow to the core is only what is required to make up for core boiling due to decay heat. Most of the ECCS liquid spills directly out of the break. The flow downstream of the core at recirculation is two-phase with entrained liquid or a bubbly flow, wherein the flow and elevation heads balance the downcomer elevation head to produce a flow rate matching decay heat.

Debris at the core inlet following a CLB can have two effects on the results. First, it may present a resistance that decreases the flow into the core that is needed to remove core decay heat. The available driving head for forcing flow into the core is fixed by the break location. If debris builds too large a resistance and the core inlet flow is reduced sufficiently, the fluid lost to steam production may not be replaced such that the core uncovers and begins to heat up.

Second, a blockage at the core inlet may inhibit the density driven transport of high concentration boric acid from the core to the LP such that the expected timing of BAP in a RV changes significantly. One of the margins credited in BAP evaluations is the availability of the LP volume for boric acid mixing. However, the closure of GSI-191 has brought crediting this margin into question due to concerns related to the influence of a debris bed during a large CLB. The concern is that if a debris bed forms at the core inlet, it will inhibit communication between the core and LP and reduce the transport of high concentration boric acid into the LP.

In order to adequately address these two concerns, a core inlet fiber limit of [ ]a,c following a CLB is established. This limit is supported by the following discussion.

For debris to challenge LTCC following a CLB, it must build up contiguously or continuously across the core inlet. This is not likely to happen for the following reasons.

The velocities in the LP following a CLB are low (on the order of inches/second). At these velocities, some of the debris of the size expected to reach the RV will settle in the LP. Any debris that approaches the core inlet will do so at a slow rate and with little kinetic energy, such that it will not lodge in the fuel lower end fitting but instead be loosely held there by the flow. Any flow variation or instability will easily dislodge the debris.

Debris that does approach the core inlet will encounter an oscillatory and non-uniform flow field driven by the many mechanisms that drive flow oscillations at the core inlet in the state of the system described above. These include, but are not limited to: manometric instabilities, instabilities due to the phase change (boiling) in the heated core, instabilities due to system effects (pressure oscillations due to steam flow through the loops, condensation on ECCS liquid, presence of loop seals, etc.), density differences between the core and LP (initially due to temperature differences and later due to possible boric acid buildup in the core versus LP), and chimney effect due to variations in the core power distribution (higher power assemblies will preferentially draw in fluid from the LP compared to lower power assemblies). Any one of these effects is capable of precluding a contiguous and continuous debris bed from forming at the core inlet. Instead, large open areas will exist at the core inlet such that flow between the core and LP is not impeded.

Testing summarized in Reference 7-1 demonstrated the ability of density differences due to boric acid concentration gradients between the core and LP to dislodge debris, or in some cases, preclude the buildup of debris. The testing consisted of an adiabatic, separate effects test that takes advantage of the same test apparatus constructed to define the core inlet limit for a HLB in Section 6.3. The test was designed to simulate the post-LOCA density gradient that exists between the core and LP by using a high density brine solution injected downstream from the core inlet geometry. The injected brine created the necessary density gradient to transport mass through the core inlet geometry in the presence of a [ ]a,c debris bed. This result clearly demonstrated the fragility of a debris bed of this size.

If debris were to form a contiguous and continuous bed across the core inlet (i.e., all FAs have [ ]a,c fiber load all the time), the pressure drop through this bed would be small. Testing at higher superficial velocities for the HLB scenario demonstrated that a [ ]a,c (Volume 6). At lower velocities, the pressure drop would be even lower.

For plants that perform a HLSO, the realignment of the system will do two things. First it will remove the motive force holding the debris at the core inlet by stopping or reducing the cold side recirculation (at least temporarily). Second, the flow rate from the hot legs will travel down the heated core to the inlet and dislodge the debris bed as it travels to the cold leg.

For all of these reasons, a core inlet fiber limit of [ ]a,c is an acceptable debris limit for CLBs.

7.2 METHOD FOR VERIFYING COLD LEG BREAK IN-VESSEL DEBRIS LIMIT

As part of the current program, 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 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 RV and core is captured near the core inlet. The discussion in this section pertains directly to the Westinghouse, CE, and B&W plants that initiate cold side injection immediately following the break. Discussions pertaining to UPI plants are provided in Section 8.

The method is an extension of the approach described in Section 5.0 of WCAP-16406-P-A (Reference 7-2). 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 strainers and near the core inlet. The method uses plant-specific values in the calculation method to track fibrous debris through the sump strainer and through the ECCS, the CSS, and to the RV 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. This mass of fiber is termed $M_{f,\,CLB}$. A description of the method and the inputs required for the method to operate on a specific plant is detailed in Volume 3. A summary is provided here.

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, cold leg safety injection, and core boil-off requirements. Figure 7-1 provides a general schematic of the flow paths for coolant when the ECCS and the CSS are realigned from drawing suction from the RWST 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 strainer 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 strainer, 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 strainer(s) 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.

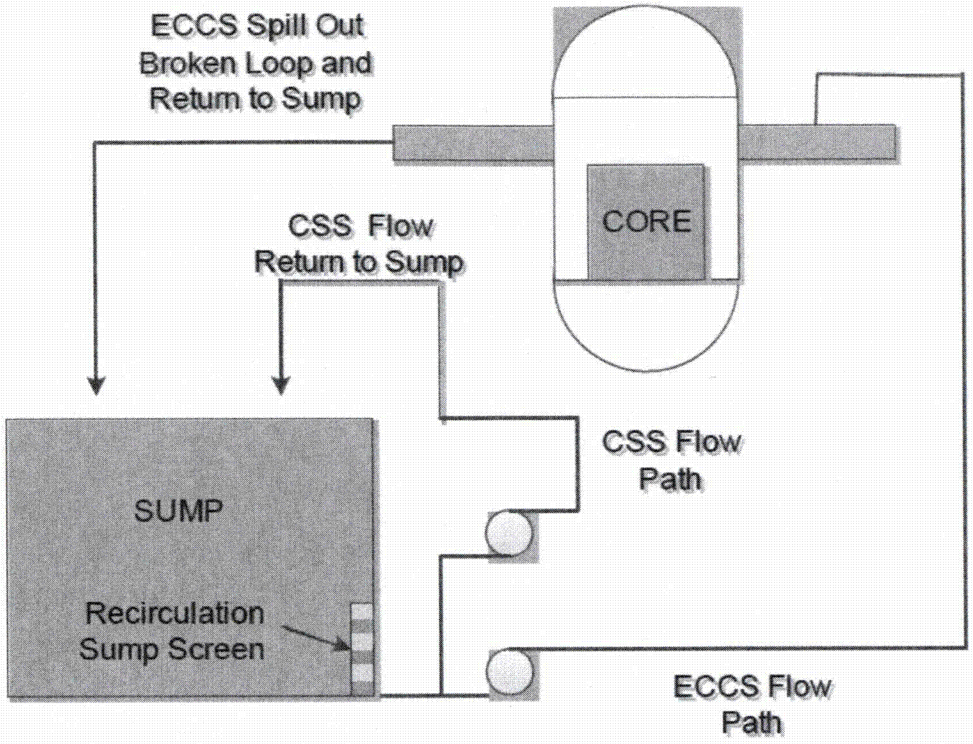

Figure 7-1 ECCS and CSS Flow Paths for a Cold Leg Break

The constituent equations for the method are presented in Volume 3, Section 3 and are consistent with those used in prior debris depletion evaluations (Reference 7-3). Along with the method itself, assumptions and input parameters for the calculations have been identified. An example calculation is presented in Volume 3, Section 4.

As an alternative to the CLB method described in Section 10.2, a simplified method is presented in Volume 3, Section 5.

These methods were developed for use by utilities to evaluate plant-specific PWR CLB performance in the presence of post-LOCA debris.

1. These methods provide 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 core inlet CLB fiber limit (established in Section 7.1). A value lower than this defined fiber limit is interpreted as an acceptable condition to provide for LTCC of the core.
2. Alternatively, a utility can use these methodologies to develop a plant-specific limit on the amount of fiber that can bypass the recirculation sump strainers in a CLB scenario and still stay beneath the core inlet limit defined in Section 7.1. This limit can then be used in conjunction with HLB limits using the method described in Section 6.5 to determine the overall plant-specific limit on fiber bypassing the sump strainer.

7.3 REFERENCES

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7-2 WCAP-16406-P-A, Rev. 1, "Evaluation of Downstream Sump Debris Effects in Support of GSI-191," March 2008.

7-3 WCAP-16530-NP-A, Rev. 0, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," March 2008.

8 UPPER PLENUM INJECTION PLANTS

For Westinghouse 2-loop UPI plants, initial ECCS flow to the RV from the RWST is through the cold legs and injection nozzles located in the UP. At transfer to sump recirculation, ECCS flow to the cold legs is secured, and flow to the UP is maintained. Therefore, during the sump recirculation phase of the transient, the direction of liquid flow through the core is the reverse of plants with typical cold leg ECCS alignments.

For a large hot leg break scenario, the bulk of flow into the RV UP during sump recirculation flows out the break, carrying the bulk of suspended debris with it. The two-phase mixture level is maintained at or above the break elevation. Flow into the core region is by gravitational force and is only that needed to replenish the coolant boiled away. Excess ECCS flow is discharged through the break. Therefore, the LTCC phase for a large hot leg break scenario represents the minimum core flow condition for a UPI plant. It also represents the condition with the minimum debris load reaching the core since a significant fraction of debris entering the UP will be carried out the break with the excess ECCS flow and re-filtered by the containment sump strainers.

For a large cold leg break scenario, ECCS flow delivered to the UP flows through the core and out the break. Since core flow is in excess of that required to replenish the coolant boiled away, boiling in the core will be suppressed. In addition, since all ECCS flow delivered to the UP has the potential to travel through the core, all debris entering the UP also has the potential to enter the core region. Therefore, a large cold leg break represents the limiting scenario for UPI plants since it results in the greatest debris load expected to reach the core region.

Some UPI plants utilize cold leg recirculation to control boric acid concentration within the core. Cold leg recirculation would be established several hours after transfer to sump recirculation to aid in flushing boric acid from the core in the event of a hot leg break. Plants other than the UPI design use hot leg recirculation to flush boric acid from the core in the event of a cold leg break. Since cold leg recirculation is initiated several hours after sump recirculation begins, the quantity of debris in the containment sump available for transport to the cold leg (bottom of the core) will be depleted due to collection on the sump strainer, collection in the RV, and collection in containment due to entrapment or settling in the containment sump liquid.

8.1 COLLECTION OF DEBRIS IN THE REACTOR VESSEL

Considering the above, debris begins to enter the RV in an UPI plant within the UP. Regardless of break location, boiling in the core is vigorous at transfer to sump recirculation and dispersed flow exists at the top of the core and UP. Given the high void fraction within the UP, ECCS flow exiting the UPI nozzles is in the form of a jet. The jets impact structures within the UP which help to disperse the flow and increase turbulence. Liquid that reaches the top of the core from the UP may be in the form of large droplets or liquid films falling from the structures within the UP. Liquid in the two-phase mixture above the hot leg elevation may drain into the hot legs and smaller droplets generated in the UP will be entrained by steam and can exit the RV or be deposited on the UP structures. Since debris is expected to be uniformly distributed within the ECCS flow, debris will follow a similar flow path; a fraction of debris will enter the top of the core, a fraction will exit the RV, and a fraction may collect and remain within the UP structures.

The flow split and, thus, debris split is dependent on the break location and will be discussed separately for the cold leg and hot leg break scenarios, respectively.

8.1.1 Large Cold Leg Break Scenario

For the large cold leg break scenario, the majority of ECCS flow entering the UP through the UPI nozzles will enter the top of the core. Only a small fraction is expected to bypass the core region and make its way to the break. Flow that enters the top of the core carries debris with it, and the turbulent mixing due to the boiling process will tend to keep the debris suspended in the liquid phase. Debris that does deposit on fuel components is expected to be localized to regions where the boiling is less vigorous (i.e., core periphery). The debris deposits are expected within the spacer grids where the grid springs and dimples create "pinch points" for which debris can readily capture. Section 6.4.3 provides the justification for an in-core fibrous debris limit of [ ]^{a,c} which also applies to UPI plants. While the ECCS alignments and limiting break location for UPI plants may differ from other PWR designs, the debris transport and capture mechanisms within the core region remain the same.

8.1.2 Large Hot Leg Break Scenario

For the large hot leg break scenario, only the fraction of ECCS flow required to make-up for boil-off is expected to enter the core region. The same is true for debris since it is reasonably dispersed within the ECCS flow. For this reason, the in-core debris load for the large hot leg break scenario is bounded by the in-core debris limit expected for the large cold leg break scenario described in Section 8.1.1. However, the large hot leg break scenario is the limiting scenario for BAP since it leads to a pool boiling condition in which boron concentrations can build within the core.

For UPI plants that control boron concentrations in the core by switching a fraction of the ECCS flow back to the cold leg(s), it must be ensured that the flushing flow through the core is not impeded by debris induced resistance at the core inlet. Therefore, for the large hot leg break scenario, if the debris source is not depleted by the time cold leg recirculation is established, the quantity of debris entering the cold leg must be tracked and is assumed to collect at the core inlet. The core inlet fibrous debris limit for this scenario is [ ]^{a,c} because it was shown in Reference 8-1 that the arrival of chemical products does not lead to complete core inlet blockage, at this debris load, which ensures that adequate flushing flow through the core will continue.

8.1.3 Method for Verifying In-Vessel Debris Limits

The method for verifying the in-vessel debris limit for UPI plants is similar to that described in Section 6.5. Following switchover to sump recirculation, debris is tracked within the RV and the quantity of debris calculated to enter the core region is compared to the in-core limit. The in-core limit for UPI plants is [ ]^{a,c} which is the same in-core limit for typical cold leg recirculation plants. While the ECCS alignments and limiting break location for UPI plants may differ from other PWR designs, the debris transport mechanisms to the core region can be treated similarly.

For plants that transfer some ECCS flow back to the cold leg(s) to mitigate the potential for BAP, an additional check is required. If the debris source has not depleted at the time cold leg recirculation is established, the quantity of debris entering the cold side of the RCS must be calculated. The calculated

debris quantity is compared to a core inlet fibrous debris limit of [ ][a,c] This debris limit is used because the arrival of chemical products to a fiber bed of this quantity does not lead to complete core inlet blockage such that flushing flow through the core is ensured.

8.2 REFERENCES

8-1 WCAP-16793-NP-A, Rev. 2, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculation Fluid," July 2013.

9 DEBRIS LIMITS AND ACCEPTANCE CRITERIA

The two acceptance criteria for this analysis are identified in Section 3.7. First, DHR requires that sufficient coolant be supplied to the core such that the core temperature is maintained at an acceptably low level. For previous GSI-191 evaluations, the maximum allowable core PCT is 800°F. Second, BAPC requires that boron concentrations in the core region remain below the solubility limit. How these acceptance criteria are met is described in this section.

9.1 HOT LEG BREAK

9.1.1 Decay Heat Removal

Following a HLB, DHR is assured by calculating a fiber load that does not challenge the limits as described in Section 6.5. This method uses the results from a number of interrelated analyses and tests. Implicit in the HLB method are the following three criteria that ensure adequate DHR.

First, t_{block} may not be violated. This means that the core may not become completely blocked for any reason before the time of t_{block}. Two primary mechanisms are assumed to exist that cause complete core inlet blockage, the first of which is the formation of chemical precipitates which occur at t_{chem}. At the time of t_{chem}, it is assumed that the core inlet is completely blocked due to the arrival of chemical precipitates such that no flow can enter the core through the normal flow path. Instead, flow must traverse the AFP. t_{block} was determined by the TH analyses (Volume 4) as the time at which complete core inlet blockage could occur and the AFPs would allow sufficient fluid into the core to keep the peak cladding temperature below 800°F. Therefore, if t_{chem} occurs after t_{block}, DHR is assured.

Similarly, prior to t_{block}, the resistance at the core inlet due to debris must be less than K_{max}. The TH analyses (Volume 4) demonstrated that the cladding temperature remains below 800°F when a resistance equal to K_{max} is applied to the core inlet. Beyond K_{max}, it is assumed that the core inlet is blocked such that the only flow available for DHR is through the AFP. t_{block} was determined by the TH analyses (Volume 4) as the time at which complete core inlet blockage could occur and the AFPs would allow sufficient fluid into the core to keep the peak cladding temperature below 800°F. The subscale testing (Volume 6) defined the resistance at the core inlet as a function of debris load. Therefore, if K_{max} is exceeded after t_{block}, DHR is assured.

The second criterion is that the amount of debris reaching the heated core is less than [ ]^{a,c} This amount of fiber (and associated particulate) will not compromise core cooling, as described in Section 6.4.

Finally, the amount of debris reaching the RV (core inlet plus in-core) is less than [ ]^{a,c} This limit is imposed because fiber capture at the core inlet cannot be guaranteed. This criterion ensures that, in the event that debris penetrates the core inlet, the in-core limit is not exceeded due to that penetration.

Since the method described in Section 6.5 accounts for all of these items, the cladding temperature will remain below 800°F and DHR is assured.

9.1.2 Boric Acid Precipitation Control

Following a large HLB, BAPC is a passive process. The path from the cold side, through the core to the break ensures a continuous flushing flow and boric acid concentrations in the RV remain close to the source concentration.

As debris accumulates at the core inlet, the resistance to flow through the core inlet increases and flow begins to bypass the core inlet through the AFP. Before complete core inlet blockage, flow above the boil-off rate continues to enter the core either through the core inlet alone or through a combination of the core inlet and AFP. The core is well mixed and the break quality is low enough that flushing of boric acid continues. After complete core inlet blockage, flow above the boil-off rate will enter the core through the AFP. The majority of flow that exits the AFP flows into the peripheral core channel and the flow direction is predominately downward. Once in the core periphery, cross flow provides liquid to the central core channels and hot assembly, ensuring that the core is well mixed. Because the amount of liquid entering the core has reduced due to the loss of the core inlet flow path, boiling in the core becomes more vigorous. This leads to more chaotic void motion that tends to increase the overall mixing in the core by enhancing the cross flow radially across the core. Further, the excess flow (above boil-off rate) will carry liquid to the break such that the break exit quality is low enough to ensure that the core is continually flushed even after complete core inlet blockage.

In Reference 9-1, a simple evaluation of BAPC following a large HLB was performed that considered complete core inlet blockage. The purpose of the evaluation was to quantify the amount of liquid carryover out the HLB necessary to preclude BAP before currently established control measures could be implemented.

The major assumptions used in the Reference 9-1 analysis are as follows:

- The transient begins 100 seconds after the LOCA event and assumes that a highly resistive debris bed is present at that time such that the lower plenum volume is not credited as part of the boron mixing volume.
- The initial core boron concentration is equal to the sump mixed mean concentration. The mixed mean concentration is determined by taking all the possible sources of liquid in containment (i.e., RWST, accumulators, RCS, and BIT) and assuming that they are homogenously mixed within the associated control volumes (RV and sump).
- The effective mixing volume used to track the boric acid concentration build-up considers core voiding and a two-phase mixture to the bottom of the hot legs.
- Flow into the core is in excess of boil-off. Flow into the core is assumed to occur through the highly resistive debris bed, or through flow that bypasses the core inlet via AFPs or through some combination of both. Regardless of the flow path, liquid in excess of boil-off is reaching the core.
- Liquid in the effective mixing volume is assumed to be well mixed such that the boric acid concentration is uniform in the mixing volume.

Results from the analysis described above indicate that as little as 5 percent liquid carryover out of the HLB is sufficient to preclude BAP well past any currently established BAPC action times. Assuming 5 percent liquid carryover indicates that flow into the core must be, at minimum, 5 percent in excess of boil-off for this result to hold, because any reduction in core flow would result in a reduction in two-phase mixture level which would reduce the liquid carryover out of the RV and result in a faster build-up of boric acid in the reactor vessel.

With regard to the analysis assumptions, assuming that a debris bed is present at the core inlet 100 seconds after the LOCA event is conservative. Early SSO times occur on the order of 20 min (1200 seconds) and this is the earliest possible time that debris can enter the RV. Further, it will take some finite period of time for a debris bed to form at the core inlet. Prior to the formation of a debris bed at the core inlet, the flushing flow is high such that boron concentrations in the core will be close to the source concentration. Delaying the formation of the debris bed at the core inlet will delay the build-up of boric acid in the core.

The TH analyses also confirm that flow into the core region is in excess of boil-off even after the application of complete core inlet blockage. The analyses also confirm that the core can be considered well mixed due to the boiling process and chaotic void motion.

Finally, due to the large amount of liquid carryover out of the break before and after complete core inlet blockage, BAP is controlled and boron concentrations in the RV will remain well below the solubility limit for the duration of the transient.

Although the Reference 9-1 evaluation was only completed for one PWR plant type, the quantity of liquid carryover predicted in the TH analyses is so high, a rigorous plant- or type- specific analysis is not required to ensure that currently established BAPC measures are appropriate when in-vessel debris is considered.

9.2 COLD LEG BREAK

9.2.1 Decay Heat Removal

Following a CLB, DHR is assured by limiting the fiber build up at the core inlet to [ ]^{a,c} or less as described in Section 7.1. This limit is predicated on the fact that: (1) fiber loads at or below the limit will not form a contiguous bed at the core inlet, (2) the pressure drop through the regions of the core inlet with a fiber and particulate bed is negligible, and (3) the addition of chemical precipitates will not further impede flow into the core. Therefore, the flow into the core will not reduce below that required to make up for the liquid lost to boil-off and the cladding temperature will remain below 800°F.

9.2.2 Boric Acid Precipitation Control

Similarly, following a CLB, BAPC is assured by limiting the fiber build up at the core inlet to less than [ ]^{a,c} as described in Section 7.1. Fiber loads at or below this limit will not form a contiguous bed at the core inlet. Consequently, open areas will remain in the debris bed that will allow communication between the core and LP such that mixing will occur between these regions. Therefore,

the presence of debris will not change the current licensing basis calculations for defining the action time to preclude BAP.

Once the actions are taken to mitigate the buildup of boric acid in the RV and core, debris will not impede the flushing flow needed to dilute the boric acid buildup in the core region. For plants that perform a HLSO, the realignment of the system will do two things. First, it will remove the motive force holding the debris at the core inlet by stopping or reducing the cold side recirculation flow (at least temporarily). Second, the flow rate from the hot legs will travel down the heated core to the inlet and dislodge the debris bed as it travels to the cold leg. For plants that use an alternate means of BAPC (e.g., B&W plants that open the decay heat drop line to increase the flow from the cold side through the core), the lack of a contiguous debris bed at the core inlet means that the additional pressure drop at the core inlet due to debris is negligibly higher than if the debris were not present.

Therefore, the current actions to prescribe BAPC measures for a CLB will continue to keep the boron concentrations in the core region remain below the solubility limit even in the presence of debris.

9.3 REFERENCES

1. OG-13-205, "PWR Owners Group, NRC Technical Concerns Regarding Boric Acid Precipitation in the Presence of In-vessel Fibrous Debris and the Consequential Effects on Long-Term Core Cooling (PWROG PA-SEE-1090 and PA-SEE-1072)," ADAMS Accession Number ML14161A043, May 2013.

10 MARGINS AND CONSERVATISMS

The testing and calculations presented in this report were designed to ensure a conservative fiber load is calculated to address GSI-191 concerns. To that end, the various conservatisms (and where possible, margins) are identified to help define the conservative nature of the calculations. These conservatisms and margins are identified with the intent that individual plants can recover some of these margins on a plant-specific basis.

10.1 DEBRIS TRANSPORT AND ACCUMULATION

Various assumptions in Section 5 relate to debris transport and accumulation throughout the system. Most of these assumptions were made to ensure that debris transports to and accumulates in the most restrictive region of the RCS:

1. Debris is assumed to be in its constituent form (Assumption 4).

2. Debris does not accumulate in any location other than the sump strainer, core inlet, or within the core (Assumptions 2, 7, 17).

3. Debris does not exit the break under the following conditions (Assumptions 7 and 18):

    a. Hot leg recirculation during a CLB

    b. Hot or cold leg recirculation during a HLB

    c. Cold leg recirculation during a CLB in a UPI plant

Further, assumptions are made to ensure that debris generated in containment reaches the sump strainer such that the maximum amount of debris has the opportunity to penetrate the sump strainer. These assumptions are inherent in the testing done by utilities to determine the strainer bypass fraction (i.e., the amount of debris that penetrates the strainer and reaches the RCS). These steps and assumptions represent a significant conservatism in establishing an in-vessel debris limit. In reality, the liquid velocities in much of containment are too low to transport much of the debris to the stump strainer. This is shown by the steps taken in strainer testing to introduce debris immediately upstream of the strainers such that it was able to reach the strainer.

Once debris passes through the sump strainers and reaches the RCS, there are numerous locations where velocities are low and debris may settle out of the flow stream. During cold side recirculation, the velocities in the RV LP are low for the limiting scenarios. Following a CLB, the core inlet flow rate is defined by the core boil-off rate. Following a HLB, the core inlet flow rate may be higher than that of a CLB, yet the limiting scenario was for low flow rates. At these velocities, some of the debris of the size expected to reach the RV will settle in the LP, as was observed during subscale testing (Volume 6). Again, some of the debris of the size expected to reach the RV will settle out of the flow stream before it reaches the core inlet.

For debris that is diverted to the BB region, any accumulation in that region is neglected even though the subscale testing of this region discussed in Volume 6 noted that debris accumulated below the former plates. While the amount was not quantified, the buildup was visible and not insignificant.

For plants that initiate simultaneous hot and cold side recirculation following a HLB, the coolant from the cold legs is used to replace boil-off and cool the core. Consequently, a fraction of the coolant injected into the hot legs is likely to exit the break directly, carrying debris along with it. However, this analysis assumes that if debris enters the RV in a HLB scenario, it remains there.

10.2 HOT LEG BREAKS

10.2.1 Uniform Buildup of Debris

The analyses and method provided in this report assume that debris builds up at the core inlet in a uniform manner (Assumption 9). In reality, the flow patterns approaching the core inlet will not be uniform. Before the ECCS reaches the core inlet, it must travel down the downcomer and turn 180 degrees along the lower hemisphere of the RV to begin the upward progression towards the core inlet. In this region, there are a number of internals structures that impede and direct the flow. Consequently, debris will likely be delivered to the core in a non-uniform manner, leading to a non-uniform distribution of debris at the core inlet. As has been discussed elsewhere in this report, if the debris does not build a uniform bed at the core inlet, then the effects of the resulting debris bed will be less than predicted by the method herein.

10.2.2 Chemical Precipitates and Core Inlet Blockage

The analyses and method provided in this report assume that formation of chemical precipitates and any amount of debris at the core inlet will result in complete blockage (Assumption 6). This assumption is based in part on the results of the testing done for WCAP-16793-NP, Rev. 2 (Reference 10-1) in which the chemical precipitate surrogate Aluminum Oxyhydroxide (AlOOH) was shown to have a significant effect on particulate and fibrous debris beds of more than 15 g/FA. In those tests, conditions were noted that resulted in reduction of flow through the test loop below that required to make up for core boil-off.

This effect has only been shown under controlled test conditions where a uniform bed has developed and the surrogate AlOOH is used. As has been discussed elsewhere in this report, it is not likely that a uniform debris bed will form at the core inlet. Without a uniform bed, any chemical precipitates that form will not have the deleterious effect seen in the controlled test environment. Further, the actual chemical precipitates that form will likely consist of other forms besides AlOOH (Volume 6), and AlOOH has been shown to produce higher pressure drops compared to other precipitates that might form (Reference 10-2).

Therefore, the use of only AlOOH on an assumed uniform and contiguous bed at the core inlet of any debris amount ensures conservative results.

10.2.3 Cladding Temperature

For the HLB evaluation, a cladding temperature of 800°F is used as an acceptance criterion to ensure that decay heat continues to be removed (Section 3.7). The basis for this value is discussed in detail in Reference 10-1, Appendix A. In summary, long-term autoclave testing demonstrated that the increase in

oxide thickness and hydrogen loading was limited when exposed to temperatures of less than 800°F for periods of 30 days. With limited corrosion and hydrogen pickup, the impact on cladding mechanical performance is not significant. Therefore, no significant degradation in cladding properties would occur due to 30-day exposure at 800°F. Further, a top-skewed axial power profile was analyzed (Assumption 12) such that if the core uncovered and heated-up, the cladding temperature response would be maximized.

To meet the acceptance criterion, the cladding temperatures in the TH analyses (Volume 4) were kept below 800°F for all times after SSO in the final cases. Sensitivity studies showed a cladding heatup above 800°F (but well below 2200°F) for approximately 500-800 seconds resulted in a decrease in t_{block} of approximately 20-25 percent and an increase in K_{max} of approximately 20 percent. This relatively mild temperature excursion, lasting no more than 20 minutes in a small section of the core, demonstrates the significant conservatism inherent in the derivation of t_{block} and K_{max}.

10.2.4 Bounding Thermal-Hydraulic Analyses

The TH analyses described in Section 6.1 and Volume 4 used a combination of core power and BB flow resistance that bound all plants in a given category. As a result, the values obtained for K_{max} and t_{block} are conservative for most plants. When calculating K_{max} and t_{block}, a conservatively high value for the BB resistance was used. Reducing the BB resistance will increase K_{max} (i.e., allow more debris to be captured at the core inlet) and decrease t_{block} (i.e., allow complete core inlet blockage earlier). Recovering this margin is most easily done by performing a plant-specific analysis using the approach described in Volume 4.

The TH analyses in Volume 4 also demonstrated that a higher value of K_{max} and an earlier time for t_{block} was calculated at higher ECCS flow rates. In other words, the K_{max} and t_{block} developed at minimum ECCS flow are conservatively applied to all flow rates in the HLB methodology described in Section 6.5. Accounting for the effects of various ECCS flow rates on K_{max} and t_{block} would increase the total amount of fiber that could be tolerated in the RV.

10.2.5 Subscale Test Facility Design

The subscale test facility described in Volume 6 was designed to ensure conservative results. Design features include (1) assuring that a well-developed, uniform flow and uniform distribution of debris was delivered to the test section; (2) no obstructions between the debris injection point and the test section were included (i.e. no lower plenum structures); and (3) the middle section of the lower end filter was used such that the lower core plate did not alter the flow patterns. These design features ensured that debris captured uniformly across the core inlet or spacer grid.

In reality, the flow patterns approaching the core inlet will not be uniform, nor is the region free of obstructions. Before the ECCS reaches the core inlet, it must travel down the downcomer and turn 180 degrees along the lower hemisphere of the RV to begin the upward progression towards the core inlet. In this region, there are a number of internals structures that impede and direct the flow. Further, the holes in the core support plate will redirect flow. Consequently, debris will likely be delivered to the core in a non-uniform manner, leading to a non-uniform distribution of debris at the core inlet. As has been

discussed elsewhere in this report, if the debris does not build a uniform bed at the core inlet, then the effects of the limiting quantities of debris calculated with the method herein will be less than predicted.

Licensees may wish to perform additional testing (either in the subscale facility or in an equivalent) to recover these margins.

10.2.6 Particulates Used in Testing

A number of parameters related to the particulates used in testing were selected to ensure that the most limiting result was obtained. In particular, the particulate-to-fiber (p:f) ratio was varied until a limiting result was obtained, and the particulate size distribution used was conservatively skewed. The conservative effects of these selections are discussed here.

It is not expected that a single size particulate will preferentially pass through the sump strainer. Instead, some distribution of sizes is expected. Any filtering bed at the sump strainer will preferentially capture larger particulates due in part to the bed morphology. Test data show that large particulates are present past the sump strainer, but the testing caps the largest particulate size to [ ]^{a,c} Some subscale testing with particulate size distributions that contained particulates larger than [ ]^{a,c} improved the results.

Not only are the particulate parameters used in testing conservative, but the degree of conservatism is significant and the likelihood of these parameters existing in the most conservative combination is very unlikely. Figures 5-22 and 5-23 of Volume 6 demonstrate why the degree of conservatism is considered significant. [

]^{a,c}

10.2.7 Flow Rates Used in Testing

Testing showed that the most limiting debris beds were developed under minimum ECCS flow rates; therefore, the final head loss correlations were developed under these conditions (see Section 6.3). However, the TH analyses and HLB methodology do not credit the benefits of a higher ECCS flow rate even when such flows are analyzed. At higher flow rates, the subscale testing (Volume 6) demonstrated that multiple debris beds formed, which allows for a higher debris limit. The TH analyses (Volume 4) demonstrated that a higher value of K_{max} and an earlier time for t_{block} was calculated at higher ECCS flow rates. In other words, the correlations developed at minimum ECCS flow are conservatively applied to all flow rates in the HLB methodology described in Section 6.5.

10.2.8 Geometry Used in Testing

The core inlet geometries tested represent the most restrictive geometries currently produced by each vendor. The tested geometries represent fuel for a 17x17 bundle that is intended to be used in Westinghouse 3- and 4-loop plant designs. The openings through the RFA bottom nozzle (for

Westinghouse fuel) and the **FUELGUARD**™ filter (for AREVA fuel) are smaller than similar hardware used in the CE, B&W, and Westinghouse 2-loop plant designs. Larger openings will collect less debris and allow for higher debris limits. In this manner, the results from the 17x17 bundle are conservatively applied to all fuel designs currently in production.

10.2.9 Reactor Vessel Fiber Limits

The maximum fiber limit allowed in the RV is [ ]^{a,c} (Section 6.5.5). This limit corresponds to the maximum allowed debris limit in the heated core and assumes that no debris is captured at the core inlet. Assuming that no debris will capture at the core inlet is very conservative given the geometry of the core inlet structures. Further, the subscale program demonstrated that debris will accumulate to some level at either the lower end fitting (LEF) or the first spacer grid for a wide range of conditions, which imply that some debris will accumulate in these locations. Therefore, it is conservative to assume that none will collect at the core inlet and set a maximum limit to that which can be tolerated in the heated core.

10.3 COLD LEG BREAKS

A number of conservatisms inherent in the CLB approach are outlined in Volume 3, Section 3.3.1. A few of the items related to debris transport and accumulation are discussed in Section 7. The remaining items are reiterated here for completeness.

The CLB methodology is designed to maximize the prediction of debris at the core inlet. A number of assumptions are made to support this effort. First, the minimum sump water volume is assumed. This assumption delivers the highest concentration of fiber to the RCS. More debris delivered earlier results in more debris at the core inlet.

The earliest time of sump recirculation is assumed. Further, the prevailing core power uncertainty is used along with a 20 percent increase in the core decay heat. These inputs and assumptions ensure a conservatively high core decay heat and core boil-off rate. Since the core boiling rate defines the flow rate to the core and the flow rate defines the debris delivery rate, these inputs and assumptions over-predict the amount of debris that reaches the core inlet. On top of this, the amount of fiber entering the core is increased by 20 percent.

A limiting single failure in the ECCS and CSS is assumed. Since the flow to the core is fixed by the core boil-off rate, this assumption minimizes the fraction of ECCS that exits the break and thus minimizes the amount of debris that exits the break and returns to containment to be re-filtered.

The latest HLSO time maximizes fiber capture in the core.

FUELGUARD is a trademark of its respective owner. Other names may be trademarks of their respective owners.

10.4 REFERENCES

10-1 WCAP-16793-NP-A, Rev. 2, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculation Fluid," July 2013.

10-2 B. B. Banh, K. E. Kasza, and W. J. Shack, "Technical Letter Report on Follow-on Studies in Chemical Effects head-Loss Research; Studies on WCAP Surrogates and Sodium Tetraborate Solutions," Argonne National Laboratory, NRC Contract N6100.

11 SUMMARY AND CONCLUSION

The PWROG has undertaken a comprehensive test and analysis program as part of the resolution to GSI-191 to increase the fibrous debris limits per FA. This report documents the methodology that member utilities can use to assess the time-dependent collection of fibrous debris in the RV, which can then be used for final closure of NRC GL 2004-02 and GSI-191. This work provides an alternative approach to the method detailed in WCAP-16793-NP-A, Rev. 2 for defining an in-vessel fibrous debris limit and provides a means for increasing the currently established in-vessel fibrous debris limit of 15 g/FA.

This volume consolidates the results of five separate, but interrelated elements of the PWROG program. The individual program elements are described in detail in separate volumes, the collection of which, including the present volume (Volume 1), constitute WCAP-17788. These respective program elements include a PIRT (Volume 2), a CLB evaluation method (Volume 3), TH analyses for a HLB (Volume 4), autoclave testing for chemical effects (Volume 5), and subscale head loss testing for HLB (Volume 6).

This program is applicable to Westinghouse, CE, and B&W PWR NSSS plants. The methodology for calculating the in-vessel debris limits described in this report are plant-specific and depend on inputs for each plant (or group of identical plants). The general approach for all plants is to separately assess the debris limits for the CLB and HLB scenarios. Both break locations must be considered given the large difference in system response and the relative effects on core cooling and mixing between them.

This report further divides the plants into those that initially begin sump recirculation with ECCS recirculation flow to the cold legs and those that initially begin with ECCS recirculation flow to the upper plenum (UPI plants). Section 5 identifies the major assumptions used in the methodology for both types of plants. For plants that initially start with cold side recirculation, Section 4.2 outlines the methodology for HLB and Section 4.3 outlines the methodology for CLB. Sections 6 and 7 provide the details of the methods for calculating the amount of fiber delivered to the RCS for HLB and CLB, respectively. For UPI plants, Section 8 provides the methodology for both break locations. For the spectrum of large breaks, this methodology can be used to ascertain that the amount of debris generated in containment does not ultimately result in an excessive amount of debris (fiber and particulate) delivered to the RV such that LTCC is compromised.

Results obtained using the methods described herein will result in a conservative calculation of the amount of debris that can be tolerated in the RV and sump. Details of the conservatisms and margins in the method and supporting calculations are detailed in Section 10.

APPENDIX A – PHENOMENA IDENTIFICATION AND RANKING

To support the assessment of chemical reaction products on the acceptable fibrous debris limit per FA, the Phenomena Identification and Ranking Table (PIRT) process was initiated. The objective of the PIRT process is to identify and rank phenomena that are important to chemical effects, TH and transport associated with the post-accident operation of the ECCS in the recirculation mode over the time period of interest. The ranking considers the relative importance of the respective phenomena, and the associated state of knowledge (SoK). Volume 2 documents the efforts of the panel of experts convened to develop a PIRT to support the comprehensive test and analysis program undertaken by the PWROG to increase the currently established fiber limits. This PIRT was developed so that it applies to all U.S. PWR designs, regardless of vendor.

A.1 PIRT SCENARIO IDENTIFICATION, PHASES, AND PERIODS

The scenarios of high importance for chemical effects in the recirculating coolant path post-accident are those accidents that:

1. Introduce debris into the coolant.

2. Require the plant to recirculate coolant from the reactor containment building sump.

To maximize the debris generation, and to provide for the evolution of the ECCS and CSS to evolve from injecting coolant from the RWST to recirculating coolant from the pool of spilled and debris-laden coolant on the containment building floor, an LBLOCA was considered for development of the PIRT.

Two scenarios were used for constructing these PIRT:

1. Large DEG HLB

2. Large DEG CLB

For the purposes of the development of the PWROG GSI-191 PIRT, the accident, regardless of break location, was divided into five phases. The phases and their durations were selected to be consistent with events of significance associated with both the DEG HLBs and CLBs. The phases selected and their durations selected are identified in Table A-1.

A listing and description of significant events that occur in each phase of the hypothetical DEG CLB are listed in Volume 2, Table 6-2. A similar listing and description of significant events that occur in each phase of the hypothetical DEG HLB are listed in Volume 2, Table 6-3.

Table A-1 PIRT Scenario Phases and Phase Duration

Phase	Duration	Description
P1	0 to 30 seconds	Initial depressurization of the RCS (i.e., blowdown)
P2	30 seconds to start of sump recirculation	1. Injection of the RWST/BWST into the RCS 2. Initiation of containment spray
P3(1)	Start of sump recirculation to 12 hrs	1. Beginning of LTCC 2. Realistic time when core flushing is needed
P4	12 hrs to 1 day (24 hrs)	1. Maintain LTCC 2. Cooldown and depressurization of reactor containment building
P5	1 day to 30 days	1. Maintain LTCC 2. Long-term containment building cooldown

Notes:

1. The time when core flushing for B&W plants or hot leg switchover (HLSO) for CE and Westinghouse plants occurs is a plant-specific parameter that can vary from as little as one to two hours after the LOCA occurs to as long as about 14 hours after the LOCA occurs for most plants. A value of 12 hours was chosen to be representative of the time duration that recirculation from the sump may occur without evolving to core flushing or HLSO. However, it is possible that the core flushing flow may be initiated prior to 12 hours or possibly not at all if the core exit subcooling is reestablished for some plants.

A.2 DEVELOPMENT APPROACH FOR THE PWROG GSI-191 PIRT

The time period of interest for the debris entering the RCS within the PWROG GSI-191 PIRT begins with period P3, the time of switchover from injecting from the RWST. During Period P3, the recirculation of debris laden coolant from the sump can enter the RCS and flow to the core with the ECCS flow (for UPI plants, this debris-laden flow is injected directly into the RV UP).

For plants that inject ECCS flow on the cold side of the core, the core coolant flows down the downcomer and into the bottom of the core. Under these flow conditions, there is a potential for debris to collect and form a debris bed at the core inlet and within the core that would challenge LTCC.

The initiation of active boron dilution actions mitigates the build-up of boric acid in the core for postulated CL breaks by either reversing the flow in the core (for CE and Westinghouse plants) or providing another flow path to duct coolant from the core to the sump (HL letdown for B&W plants). Both of these processes provide for the flushing of concentrated boron from the core before boron solubility limits are reached. This flushing will also have the effect of diluting post-accident chemical products that are collected and concentrated in the core during periods P2 and P3 due to the boiling associated with core cooling of a CL break.

At the beginning of period P3 following a DEG CL break, the core power is capable of generating sufficient steam that coolant injected into the HL may not readily reach the core and be effective in matching the core decay heat and initiating a core flushing flow for Westinghouse and CE plant designs. Hence, time periods P1 (i.e., blowdown), P2 (i.e., injection from the RWST) and P3 (i.e., initial recirculation of spilled coolant from the containment recirculation sump until active boron dilution; 12 hours is provided as a representative time before active boron dilution is initiated in this PIRT activity)

are critical for debris generation and transport, which are the focus of this PIRT. However, the PIRT panel unanimously agreed that time periods P4 (12 hours to 1 day – cool down of the core and reactor containment building) and P5 (1 day to 30 days – LTTC) should also be included in this PIRT activity for completeness because these are the periods during which the effects of chemical products become more important. Hence, the PIRT addresses time periods P1 through and including P5, although periods P1 through P3, and particularly P3, are of primary interest for this PIRT.

The PIRT panel recognized that both chemical effects and TH phenomena have the potential to collectively contribute to the overall consequences of post-accident chemical effects on LTCC. Thus, the PIRT panel chose to account for both chemical and TH mixing phenomena in the development of a PIRT for this project.

The chemical effects PIRT is presented in Volume 2, Section 7. The TH PIRT is presented in Volume 2, Section 8. Variations in phenomena related to break location (HLB versus CLB), when they are evaluated to occur, are identified in the PIRT. A discussion of the high ranked phenomenon is provided in Volume 2, Section 9.

A.3 PIRT RECOMMENDATIONS AND DISPOSITION

The PIRT tables provide guidance for the PWROG comprehensive test and analysis effort to close GSI-191. The PIRT panel advanced the following recommendations for consideration by the PWROG upon completion of identifying the phenomena, the ranking of the importance of the phenomena and the assigning of a SoK to the phenomena. Those phenomena and processes that are ranked "H" in importance and "L" for a SoK are candidates for additional study to improve the SoK associated with that phenomena or process. The following details those specific related phenomena and processes identified by the PIRT and the disposition of each within the WCAP-17788 program.

- Radiation-induced debris bed chemical reactions. Concentration of radionuclides leads to locally high radiation fields and changes in dissolution and precipitation processes.
    - Program disposition – Radiation impacts were beyond the scope of the current program. Given the conservatisms and margins built into the entire GSI-191 evaluation process, this is deemed acceptable, as this is unlikely to result in earlier chemical effects than those found without radiation.
- For a CL break, fibrous debris collecting on fuel elements alters flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.
    - Program disposition – Regarding BAP, such effects are considered in Volume 1, Section 9.2.2. Regarding chemical effects, the limits imposed on debris at the core inlet for CL breaks are small enough that filtering debris beds are not formed, and therefore, there is no mechanism to catch sufficient chemical effects to impact cooling flow through the core.
- For a CL break, chemical products in combination with fibrous debris collecting on fuel elements alter flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.

- Program disposition – Regarding BAP, such effects are considered in Section 9.2.2. A uniform bed will not be formed and maintained under CLB conditions at the fiber limits established, so the impact of chemical effects is negligible. Since open regions still exist at the core inlet, communication continues, and mixing pattern alteration is minimal.

- For a HL break, chemical products in combination with fibrous debris collecting on fuel elements alter flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.

  - Program disposition – The TH analysis (Volume 4) assumes complete core inlet blockage with the arrival of chemical effects. Analysis showed that mixing patterns are altered but not to the point that BAP would be expected to occur. Core mixing is dominated by boiling, which in turn keeps core region concentrations uniform. Liquid carryover remains sufficient such that core region remain below the boric acid solubility limit. Regarding chemical effects, the autoclave tests were integrated effects tests. They included fiber both in the autoclave and in the drain time samples. The samples were cooled, giving the opportunity for supersaturation and deposition on fibers.

- Impact of kinetics of precipitation. Non-equilibrium effects are a benefit as they may delay precipitation.

  - Program disposition – The autoclave testing was performed in a prototypic fashion and was not forced to be in equilibrium. Therefore, non-equilibrium effects were captured by the testing.

- Particulate settling in the reactor. Particulate settling may occur due to relatively low, upwards flow (for CL recirculation for CL breaks) within reactor.

  - Program disposition – Particulate settling was not investigated because it is conservatively assumed that all debris that enters the vessel collects at core inlet or transports to the core proper. Both the subscale fuel testing and the autoclave testing took measures to limit or eliminate settling to remain conservative in this regard.

- Deposition. Chemical products formed during all periods may deposit on other surfaces.

  - Program disposition – Some level of chemical product deposition on autoclave walls and materials may have occurred, but if so, this is representative of what happens in the plants' sumps and on their strainers and on other structures and components inside containment. If no chemical remains suspended in the sump fluid to reach the core, the chemical effect on the core is negligible. If it does remain suspended in the sump fluid, then it will be transported to the core and potentially impact debris bed pressure drop; the same happens in the drain time measurements, where the primary available surface for precipitation is the filter (representative of the debris bed on the fuel). Therefore, this has been appropriately represented.