

**PRESSURIZED WATER REACTOR  
SUMP PERFORMANCE EVALUATION  
METHODOLOGY**

May 28, 2004



## ACKNOWLEDGMENTS

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## EXECUTIVE SUMMARY

In response to Generic Safety Issue 191 (GSI-191), “Potential of PWR Sump Blockage Post-LOCA,” Nuclear Energy Institute and the industry formed the PWR Sump Performance Task Force. The primary purpose of the Task Force was to interface with the U.S. Nuclear Regulatory Commission as the issue developed and to champion creation of a methodology document that could be used as a guideline for PWR operators to address the issue. Much of the previous testing and evaluations supporting the Utility Resolution Guide (URG) for BWRs was used as appropriate. However, it was determined early that a standard “cookbook” could not be created for PWRs for several reasons. PWRs vary greatly in containment size, floor layout, sump configuration, required ECCS flows, insulation types and location, and post-LOCA operational requirements. Since it was evident that one guideline could not encompass all PWRs, the NEI methodology document provides basic guidance on approach and various methods available, but recognizes that the best strategy for each plant could involve a combination of methods. Each PWR operator, having unique knowledge of specific plant design and operation, is best qualified to determine the optimum solution strategy. As such, this document does not prescribe a specific combination of methods to the user.

This methodology document provides guidance to each utility in all primary issues that are required to be addressed in resolving this issue. It is to be considered a draft document for purposes of this review. The document picks up after NEI 02-01, which provides guidance on the performance of plant condition assessments and appropriate supporting walkdowns for collecting information to support the methods discussed in this document. This document addresses the major technical components, including debris generation/distribution, debris transport, screen head loss, and pump NPSH. The current document has several open areas that require either more study or testing to address. They include the treatment of long-term chemical effects and calcium silicate head loss correlations. A downstream effects evaluation, a key component of issue closure, is under development. This document also does not address the implementation and/or licensing of any design or operational changes resulting from the use of the evaluation methodology.

Section 1 contains an introduction to the PWR strainer debris issue, including a historical review describing the steps that led to the current understanding. Section 2 is a high-level summary of the overall process considerations that need to be addressed during the evaluation process, while Section 3 describes a Baseline Evaluation Method that may be applied to all PWR’s and provides sample calculation using the Baseline Evaluation Method. In Section 5, refinements in administrative control and design are discussed. Section 6 provides a guidance on a risk-informed evaluation. Section 7 provides guidance for additional design considerations.

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# 1 INTRODUCTION

## 2 1.1 ISSUE DESCRIPTION

3 The postulated rupture of a pipe located inside containment and carrying high-energy fluid is one  
4 of the key factors used in development of the licensing, design, and operational requirements for  
5 nuclear reactors. Although the probability of a high-energy line break (HELB) in a large pipe is  
6 extremely low, it is an event that reactors are designed to withstand, without jeopardizing the  
7 health and safety of the public. This design basis accident (DBA) is referred to as a loss-of-  
8 coolant-accident (LOCA). For some pressurized water reactors (PWRs), a main steam line break  
9 may need to be included if the emergency core cooling system (ECCS) is required.

10 Should such an event ever occur, the high-energy fluid has the potential to damage adjacent  
11 equipment and material. This LOCA-generated debris, including particulates, fibers, and  
12 reflective metal insulation (RMI) foils, may be transported and result in debris blockage of the  
13 ECCS and containment spray system (CSS) pump suction strainers. This scenario raises  
14 concerns that the head loss across the suction screens may exceed the available net positive  
15 suction head (NPSH) margin. As a result, the Nuclear Regulatory Commission (NRC) has  
16 determined that the potential for PWR core damage presents a risk significant enough to warrant  
17 evaluation at every plant, to ensure sufficient NPSH margin exists in the event of this type of  
18 accident.

19 It should be noted that the determination of pipe break locations, zones of influence (ZOI), and  
20 other calculational bases described herein are solely for ECCS strainer design purposes and are  
21 not intended to replace the plant licensing or design bases for other purposes.

## 22 1.2 HISTORICAL OVERVIEW

23 The NRC initially addressed post-accident sump performance under Unresolved Safety Issue  
24 USI A-43. Research on BWR ECCS suction strainer blockage identified new phenomena and  
25 failure modes that were not considered in the resolution of A-43. In addition, operating  
26 experience identified new contributors to debris and possible blockage of PWR sumps, such as  
27 degraded or failed containment paint (coatings). Thus, the NRC Generic Safety Issue GSI-191,  
28 "Assessment of Debris Accumulation on PWR Sumps Performance," was identified in 1998 by  
29 Footnotes 1691 and 1692 of NUREG-0933. The NRC also initiated an expanded research effort  
30 to address these new safety concerns for PWRs.

31 On September 28, 2001, the NRC issued report LA-UR-01-4083, "GSI-191 Technical  
32 Assessment: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump  
33 Performance," (Reference 58). In issuing this report, NRC Research had determined that  
34 post-accident sump blockage is a generic concern for PWRs. Based on this determination, the  
35 PWR industry undertook an effort to develop guidelines that are universally applicable to all  
36 PWRs and may be used by all licensees to evaluate the post-accident performance of a plant's  
37 containment sump. These guidelines and associated methodology are presented in this document.

### 1 1.3 ASSUMPTIONS

2 This section contains the assumptions for the development of an evaluation methodology to  
3 address the potential for containment sump screen blockage following a design basis event. This  
4 evaluation methodology (EM) will be used in support of plant-specific evaluations that address  
5 concerns identified in GSI-191.

6 The major assumptions are:

#### 7 1. Application of Single Failure

8 Consideration of the initiating event will be based on current design analysis  
9 principles. Component and system failure will be limited to credible single failure  
10 scenarios. Only one limiting failure will be applied to the entire analysis, and the  
11 effects of that failure will be consistently applied to all phases of the plant response.  
12 Expected non-faulted system initial conditions, timing, and operating  
13 characteristics will be assumed.

#### 14 2. Evaluation Methodology Scope to Address Materials Typically Used in Industry 15 Applications

16 The evaluation methodology will address materials typically used in the industry as  
17 insulation and coating materials. The guidance will not necessarily explicitly  
18 consider or assess the generation, transport, or accumulation characteristics of  
19 non-traditional materials (i.e., materials used in a single plant or rare applications).

#### 20 3. Application of Risk-Informed Considerations

21 Program methodology is developed primarily using deterministic methods.  
22 Risk-informed considerations, where practical and defensible, may also be used. It  
23 is anticipated that such considerations may be employed in establishing initial  
24 conditions, timing and operating characteristics of plant systems and components.

#### 25 4. Validity of Supporting Data

26 Data employed in the development of the evaluation methodology or applied  
27 directly through the evaluation methodology may not have been produced under a  
28 10 CFR 50, Appendix B program. Such data will be carefully evaluated through a  
29 validation and verification process that may include analytical methods such as  
30 comparison to theoretical predictions or to other similar but independent empirical  
31 results.

32 The following definitions are used throughout this document to describe some of the more  
33 common terms used to describe the various activities related to this issue.

- 1 **Break-Generated Debris** – The remains of broken or dislodged materials (for example,  
2 insulation, coatings, tape, and dust) generated by the action of high-energy fluid released from a  
3 postulated break in a high-energy line inside containment.
- 4 **Emergency Core Cooling (ECC) Sumps** – Active sumps in the reactor containment building  
5 used to recirculate coolant for long term decay heat removal from the reactor core and/or the  
6 containment environment.
- 7 **Encapsulated Insulation** – Encapsulated insulation is insulation covered on all surfaces by sheet  
8 metals or fiberglass cloth. Examples of encapsulated insulation include RMI and calcium silicate  
9 cassettes.
- 10 **Jacketed Insulation** – Jacketed insulation is insulation that is covered on the outside surface of  
11 the pipe by a wide variety of materials. Examples of jacketed material include metal sheets, solid  
12 fiberglass and calcium silicate wrapped with aluminum foil.
- 13 **Latent Debris** – Latent debris is defined as unintended dirt, dust, paint chips, fibers, pieces of  
14 paper (shredded or intact), plastic, tape, or adhesive labels, and fines or shards of thermal  
15 insulation, fireproof barrier, or other materials that are already present in the containment prior to  
16 a postulated break in a high-energy line inside containment. Dust and dirt include miscellaneous  
17 particulates that are already present in the containment prior to a postulated break. Potential  
18 origins for this material include activities performed during outages and foreign particulates  
19 brought into containment during outages.
- 20 **Wrapped Insulation** – Insulation that is covered on the outside by non-metallic wrapping.  
21 Typically, the wrapping is an epoxy impregnated fiberglass mesh that is either fastened to the  
22 insulation by tie wraps or glued to the insulation.
- 23 **Zone of Influence (ZOI)** – The zone of influence represents the zone where a given high-energy  
24 line break (HELB) will generate debris that may be transported to the sump. The size of the ZOI  
25 will be defined in terms of pipe diameters and will be determined based on the pressure  
26 contained by the piping and the destruction pressure of the insulation surrounding the break site.  
27 Three recommended methods for determining the ZOI are:
- 28 • The size of the spherical ZOI can be calculated based on the insulation with the  
29 lowest destruction pressure, and all insulation contained within the ZOI is assumed  
30 to be damaged such that it becomes debris, regardless of insulation type.
  - 31 • For each insulation type, a separate spherical ZOI may be calculated.
  - 32 • The ZOI is defined by a freely expanding jet.
- 33 The destruction pressure for each type of insulation is addressed as follows. The pipe break  
34 radial offset may be accommodated in the calculation of the spherical ZOI size. Similarly, pipe  
35 restraints may be accommodated in the calculation of the spherical ZOI size.

## 1 1.4 ACRONYMS

2	AJIT	Air Jet Impact Test
3	ARL	Alden Research Laboratory
4	ASJ	all-service jacketing
5	BWROG	Boiling Water Reactor Owners' Group
6	CAD	computer-assisted design
7	CEESI	Colorado Experimental Engineering Station, Inc.
8	CFD	computational fluid dynamics
9	COA	Candidate Operator Action
10	CSHL	clean strainer head loss
11	CS	containment spray
12	CSS	containment spray system
13	DBA	design basis accident
14	DBHL	debris bed head loss
15	DEGB	double-ended guillotine break
16	ECC	emergency core cooling
17	ECCS	emergency core cooling system
18	EM	evaluation methodology
19	EOP	Emergency Operating Procedure
20	ERG	Emergency Response Guideline
21	FME	foreign materials exclusion
22	GSI	Generic Safety Issue
23	HELB	high-energy line break
24	HPSI	high-pressure safety injection
25	IOZ	inorganic zinc
26	LANL	Los Alamos National Laboratory
27	LDFG	low-density fiberglass
28	LDSE	Low Density Silicone Elastomer
29	LOCA	loss-of-coolant accident
30	NEI	Nuclear Energy Institute
31	NPSH	net positive suction head
32	NRC	Nuclear Regulatory Commission
33	OEM	original equipment manufacturer
34	OPG	Ontario Power Generation
35	PSE	Plant Support Engineering
36	PWR	pressurized water reactor
37	QA	quality assurance
38	RAI	Request for Additional Information
39	RCDT	reactor coolant drain tank
40	RMI	reflective metal insulation
41	RWST	refueling water storage tank
42	SEM	scanning electron microscope
43	SER	Safety Evaluation Report
44	SI	safety injection
45	SS	Stainless steel

- 1 TBE thin-bed effect
- 2 TKE turbulent kinetic energy
- 3 TSHL total strainer head loss
- 4 UNM University of New Mexico
- 5 URG Utility Resolution Guide
- 6 ZOI zone of influence
  
- 7 1.

## 2 EVALUATION METHODOLOGY OVERVIEW

The methodology described in this document provides guidance for use in evaluating the susceptibility of PWR containment sumps to blockage resulting from the effects of a postulated LOCA. This methodology is based on published studies encompassing the body of knowledge related to debris generation, debris transport and debris head loss following high energy line breaks in nuclear power plants.

The processes and phenomena associated with debris generation, debris transport and headloss are complex. The existing body of knowledge, while extensive, has known limitations that introduce uncertainties in the translation and application of the knowledge base to plant-scale conditions and the wide variability of designs present in PWR containments introduce a need to conservatively apply available data. There is the added difficulty and expense of modeling the large-scale non-linear flow processes affecting debris transport in PWR containments, leading to a need, where possible, to simplify the computational effort.

The evaluation methodology addresses these analytical complications using a process that helps guide the user in developing a technically sound resolution that meets the needs of individual PWR plants. An overview of the evaluation process is shown in Figure 2-1. In general, the containment sump size appropriate for a plant is proportional to the level of conservatism used in the supporting analysis. Resources can either be directed toward refining the analysis methodology (i.e., removing excess conservatism) in order to support a smaller screen size or toward implementation of design modifications (e.g., a larger screen size, replacement of insulation). The appropriate direction will depend on factors that will vary from plant to plant. The evaluation methodology attempts to support this decision process in a step-wise fashion that begin with a conservative baseline set of methods (Section 3) that help identify the dominant design factors for a given plant, followed by separate guidance on possible refinements to the baseline analytical methods (Section 4) and potential design/operational refinements (Section 5).

It is important to note that the Baseline evaluation can be performed utilizing either the current plant configuration or by directly incorporating planned design/operational changes. Performance of the Baseline with planned changes allows a means to assess known areas of susceptibility to screen blockage and enables planned changes to be directly incorporated into the final resolution process.

The evaluation methodology allows for incorporation of either a deterministic evaluation process (Option A) or a risk-informed evaluation process (Option B). The risk-informed evaluation process utilizes industry and NRC efforts to risk-inform Title 10, *Code of Federal Regulations* Section 50.46, "Acceptance criteria for emergency core cooling system for light-water nuclear power reactors," as a suitable technical basis for defining a spectrum of break sizes for debris generation and containment sump strainer performance.

The risk-informed evaluation process (Section 6) allows for use of an alternate maximum break size in analyses that provide additional assurance of fulfilling the long-term cooling requirement of 10 CFR 50.46 and involves two separate analysis steps: 1) a design basis analysis using an



1 alternate maximum break size, and 2) an analysis that demonstrates beyond-design-basis  
2 mitigation capability.

3 In implementing the Option B approach and use of an alternate break size, it is necessary to  
4 demonstrate that an adequate degree of mitigation capability is retained for break sizes between  
5 the new maximum break size and the double-ended guillotine break of the largest pipe in the  
6 reactor coolant system. This “beyond-design-basis” analysis is performed using more realistic  
7 analysis methods and assumptions and allows credit to be taken for non-safety SSCs and  
8 operator actions. In addition, more realistically conservative criteria are applied than those used  
9 in design basis analyses. Section 6.3 provides guidance on an appropriate set of modifications to  
10 the analysis methods and assumptions described in Sections 3, 4 and 5 for use in the Option B  
11 analysis to demonstrate mitigation capability.

12  
13 Guidance is also provided in Section 7, addressing additional design considerations.

Figure 2-1  
PWR Containment Recirculation Sump Performance  
Evaluation Process Overview



1

## 1   **3    BASELINE EVALUATION**

### 2   **3.1   INTRODUCTION**

#### 3   **3.1.1   Purpose**

4   The purpose of this baseline evaluation methodology is to provide licensees with a common and  
5   consistent approach for doing an initial scoping evaluation to evaluate the post-accident  
6   performance of the containment sump screen for a pressurized water reactor (PWR). This  
7   common and consistent method is termed the “*Baseline Evaluation Method.*”

8   The Baseline Evaluation Method, and the guidance to perform the Baseline Evaluation Method,  
9   provides a conservative approach for evaluating the generation and transport of debris to the  
10   sump screen, and the resulting head loss across the sump screen. If a plant uses this method and  
11   guidance to determine that sufficient head loss margin exists for proper long-term Emergency  
12   Core Cooling (ECC) and Containment Spray (CS) function, no additional evaluation for head  
13   loss is required.

14   The same sumps may be used for both long-term ECC for heat removal from the core and  
15   long-term CS for heat removal from the containment environment. Revision 3 of Regulatory  
16   Guide 1.82 (Reference 1) refers to sumps performing this combined or dual function as  
17   Emergency Core Cooling (ECC) sumps. This convention of referring to dual-function sumps as  
18   ECC sumps will be used here.

#### 19   **3.1.2   Background**

20   The probability of a high-energy line break (HELB) of PWR piping inside the Reactor  
21   Containment Building (containment) is extremely low. However, if the event were to occur, it  
22   could result in production of debris that, if transported to and deposited on the containment sump  
23   screens, could challenge the function of the ECC sumps. Specifically, debris that accumulated on  
24   the sump screens would result in an increase in the head loss across the resulting debris bed and  
25   sump screen. This head loss may be sufficiently large to exceed the available net positive suction  
26   head (NPSH) margin of the ECC sumps.

##### 27   **3.1.2.1   General Accident Scenarios of Concern**

28   Postulated accident scenarios of concern are those that require the plant to initiate recirculation  
29   flow from the containment sump to mitigate the event. Therefore, the primary design basis  
30   accident (DBA) that could present a challenge to the ECC sumps is the loss-of-coolant-accident  
31   (LOCA). However, for some plants, a main steam line break or feedwater break could challenge  
32   ECC sump function as well.

### 1 3.1.2.2 Accident Phenomena

2 Three broad phenomena have been identified as governing post-accident sump performance:

- 3 1. Debris generation – The destruction of insulation and coatings, and erosion of  
4 concrete due to the action of the jet resulting from the postulated pipe break.
- 5 2. Debris transport – The movement of debris generated from the jet due to fluid  
6 movement and associated containment pooling and washdown of containment  
7 sprays, and from the erosion of submerged material, to the sump when the ECC and  
8 CS systems are realigned to draw suction from the containment sump.
- 9 3. Head loss – The development of resistance to flow across the ECC sump screen due  
10 to the transport and collection of debris on the sump screen.

11 The Baseline Evaluation Method provides guidance for licensees to address each of these  
12 phenomena and to address post-accident sump screen performance.

### 13 3.1.2.3 Limits of Evaluation Method

14 The guidance presented in the Baseline Evaluation Method only addresses the phenomena and issues  
15 up to and including head loss across the sump screen. The application of the Baseline Evaluation  
16 Method will provide information that can be used to assess resultant effects on NPSH or pump suction  
17 inventory. Insufficient information presently exists to evaluate the effects of chemical reaction  
18 products on head loss across a sump screen and associated debris bed. Guidelines will be  
19 provided when the data become available. Also, the Baseline Methodology does not include  
20 evaluation of holdup of flow by debris upstream of the sump screen, structural integrity of the  
21 sump screen, or the effects resulting from debris ingestion into the ECC or CS systems through  
22 the sump screen. See Section 7, “Additional Design Considerations,” for guidance on these  
23 topics.

### 24 3.1.2.4 Supplemental Guidance for Refinements to Baseline Evaluation

25 The Baseline Evaluation Method presented in this section provides one suggested approach for  
26 all utilities to perform an evaluation of the susceptibility of their ECC sumps to failure from  
27 debris-induced screen blockage. In addition to the Baseline Evaluation Method and supporting  
28 discussion, an example calculation applying the Baseline Method is provided. The guidance in  
29 this section provides a conservative approach for evaluating the generation and transport of  
30 debris, and the resulting head loss across the sump screen.

- 31 • If a plant uses this Baseline Evaluation Method and determines that head loss  
32 margin exists for proper ECC and CS function, no additional evaluation for head  
33 loss is required.
- 34 • If a plant determines that the results of the baseline approach are not acceptable, or  
35 additional design margin is desirable, the refinement guidance provided in

1 subsequent sections may be used to further evaluate the post-accident performance  
2 of the ECC sump.

### 3 **3.1.3 Data Collection to Support Baseline Evaluation**

4 To perform the sump performance evaluation according to the guidance in this document, it is  
5 necessary to first gather the appropriate plant information. The information needed to support the  
6 baseline sump performance evaluation is similar to that needed to perform a containment  
7 condition assessment walkdown as described in NEI 02-01, "Condition Assessment Guidelines:  
8 Debris Sources Inside PWR Containments" (Reference 2). Therefore, the information primarily  
9 documents the configuration of containment and the potential debris sources contained therein.

10 The information required to perform the assessment can be categorized as follows:

#### 11 1. General containment design information

- 12 • Topographical containment layout drawings
- 13 • Piping isometric drawings
- 14 • Process diagrams
- 15 • Accident analysis of record and associated licensing basis for post-LOCA  
16 recirculation including ECC and CS recirculation flows for various break  
17 sizes, spray sequence and flows, time duration, sump water temperature  
18 profile, etc.

#### 19 2. Insulation details

- 20 • Type(s) of insulation used inside containment (insulation specifications)
- 21 • Volume of insulation material installed
- 22 • Where it was used on equipment, in penetrations, on piping, etc. (drawings)
- 23 • How it was installed; encapsulated, banded, etc. (drawings)
- 24 • Inspection records, if appropriate or available
- 25 • Design changes that may have changed insulation used (specifications and  
26 drawings)

#### 27 3. Penetration details

- 28 • Penetration plan (elevation and azimuth)
- 29 • Drawings of insulation material used in penetrations

#### 30 4. Fire barrier details

- 31 • Type(s) of material used inside containment (material specifications)
- 32 • Where it was used inside containment (drawings)
- 33 • How it was installed (drawings)
- 34 • Inspection records, if appropriate or available

- 1           • Design changes that may have changed fire barrier material or location inside
- 2           containment (specifications and drawings)
  
- 3           5. Protective coatings details
  
- 4           • What coatings were applied
- 5           • Where they were applied
- 6           • QA program requirements
- 7           • Coatings application specification(s)
- 8           • Coatings inspection records
- 9           • Coatings that were applied to purchased equipment and the coatings program
- 10          used to apply them
- 11          • A copy of the “Exempt” or “Unqualified” coatings log, if used at the site
  
- 12          6. Other potential debris sources
  
- 13          • Foreign materials exclusion program documentation
- 14          • Latent debris observed to be inside containment
- 15          • Tagging and labeling procedures or technical instructions
- 16          • References for use of cable ties inside containment

17 The above listing of information is intended to be as complete as possible to support a  
18 plant-specific baseline evaluation. However, plant-specific features may suggest that additional  
19 information should be collected and supporting documents reviewed to support performance of  
20 the baseline evaluation.

### 21 **3.2 METHOD OVERVIEW**

22 The Baseline Methodology utilizes a conservative analytical approach to evaluating the five  
23 main topics associated with post-accident sump performance:

- 24           1. Break selection
- 25           2. Debris generation
- 26           3. Latent debris
- 27           4. Debris transport
- 28           5. Head loss

29 The approach taken in each of these topical areas for the Baseline Methodology is described in  
30 the following sections.

### 1   **3.3   BREAK SELECTION**

2   Discussed in this section are the considerations and guidance for selecting an appropriate  
3   postulated break size and evaluating the location of the postulated break that presents the greatest  
4   challenge to post-accident sump performance.

#### 5   **3.3.1   Introduction**

6   The break selection is the first step in assessing post-accident sump screen performance. Break  
7   selection consists of two considerations:

- 8       1.    The size of the break
- 9       2.    The location of the break

10   The objective of the break selection process is to identify the break size and location that result  
11   in debris generation that is determined to produce the maximum head loss across the sump  
12   screen. Since this location is not known prior to performing the evaluation, the term break  
13   selection refers to a process of evaluating a number of break locations for a given size break to  
14   identify the location that presents the greatest challenge to post-accident sump performance.

#### 15   **3.3.2   Discussion**

16   The objective of the break selection process is to evaluate and identify the break locations that  
17   provide for the following two results:

- 18       1.    The maximum amount of debris that is transported to the sump screen
- 19       2.    The worst combination of debris mixes that are transported to the sump screen

20   The locations that provide for these conditions are identified as “limiting break locations” in  
21   evaluating post-accident sump screen performance.

22   The criterion used to define the limiting break location is the head loss across the sump screen  
23   resulting from deposition of debris on the sump screen; the limiting break location results in the  
24   maximum head loss. As noted above, the limiting break location is not known prior to  
25   performing the evaluation, but is determined by evaluating a number of postulated break  
26   locations. To perform this evaluation, it is necessary to perform the debris generation, debris  
27   transport, and head loss calculations for each postulated break location. Therefore, the selection  
28   of the limiting break site is an iterative process that requires rigor.

29   The guidance below documents the process for determining the limiting break location.

#### 30   **3.3.3   Postulated Break Size**

31   A double-ended guillotine break (DEGB) of piping, including the primary system piping, may be  
32   used as the postulated break size. This approach provides for the prediction of large volumes of  
33   debris from insulation and other materials that may be within the region affected by the fluid

1 escaping through the postulated break. NRC has accepted this as an acceptable approach in the  
2 resolution of ECCS strainer blockage concerns for boiling water reactor (BWR) plants. This  
3 method is applicable to all PWR designs.

4 Some plant designs require recirculation of containment spray for long-term containment cooling  
5 after a main feedwater line break or a main steam line break. Either the same considerations as  
6 for LOCA or the plant's current licensing basis for those breaks may be used for break selection  
7 and size characterization.

### 8 **3.3.4 Identifying Break Locations**

9 Postulation of the break location is somewhat more complex than postulation of the break size.  
10 All reactor coolant system (RCS) piping, and connected piping, must be considered in the  
11 evaluation. Since many break locations are to be considered, a wide range of results should be  
12 expected. Some plant designs require plants to eventually recirculate coolant from the sump for  
13 pipe ruptures other than a LOCA. If this is a part of the plant licensing basis, then these lines  
14 must also be considered when identifying break locations.

#### 15 **3.3.4.1 General Guidance**

16 It is recommended that pipe break locations considered be postulated based on the following  
17 criteria:

- 18 1. For postulated LOCAs, break exclusion zones are disregarded for this evaluation.  
19 In other words, pipe breaks must be postulated in pre-existing break exclusion  
20 zones. For main steam and feedwater line breaks, licensees should evaluate the  
21 licensing basis and include potential break locations in the evaluation, if necessary.
- 22 2. NRC Branch Technical Position MEB 3-1 shall not be used as a basis for  
23 determining potential LOCA break locations. The purpose of the analysis is to  
24 determine the worst possible break with respect to ECCS sump concerns.  
25 Therefore, the location of the pipe break is not chosen based on the stress  
26 distribution or fatigue characteristics of the piping system.
- 27 3. For plants for which main steam line breaks and/or feedwater line breaks must be  
28 considered, the break locations should be consistent with the plant's current  
29 licensing basis.
- 30 4. Pipe breaks shall be postulated at such locations that each location results in a  
31 unique debris source term (i.e., multiple identical locations need not be examined).
- 32 5. Pipe breaks shall be postulated in locations containing high concentrations of  
33 problematic insulation (microporous insulation, calcium-silicate, fire barrier  
34 material, etc.)



- 1           6. Pipe breaks shall be postulated with the goal of creating the largest quantity of  
2 debris and/or the worst-case combination of debris types.
- 3           7. Piping attached to the RCS that is small (< 2 inches in diameter) need not be  
4 considered. Breaks of this size are sufficiently small (and bounded by the larger  
5 breaks) that quantities of debris large enough to challenge the post-accident  
6 operability of the containment sump are not generated.

### 7 **3.3.4.2 Piping Runs to Consider**

8 As a minimum, LOCA breaks in the following lines should be considered:

- 9           1. Hot leg, cold leg, intermediate (crossover) leg and surge line.
- 10           2. Piping attached to the RCS. Examples include, but are not limited to charging lines  
11 and RHR lines.

12 Some plant designs require plants to eventually recirculate containment coolant from the sump  
13 for pipe ruptures other than a LOCA. Two such events are main feedwater breaks and steam line  
14 breaks. If this is a part of the licensing design basis for the plant under consideration, then these  
15 lines must also be considered for this evaluation.

### 16 **3.3.4.3 Other Considerations for Selecting Break Locations**

17 Subsection 3.3.2, "Discussion," identified the objective of break selection as of identifying a  
18 limiting break for post-accident sump performance consideration. Listed below are additional  
19 guidelines to use in selecting break locations that support that objective.

- 20           1. Locations are determined by considering the location of materials (insulation,  
21 coatings, etc.) inside containment relative to the break location and zone of  
22 influence (ZOI). Specifically, look for locations where problematic insulation (for  
23 example, microporous insulation) may be combined with particulate debris. Note  
24 that the location of materials inside containment should have been identified during  
25 the application of NEI-02-01 (Reference 2).
- 26           2. Identify locations for which postulated breaks generate an amount of fibrous debris  
27 that, after transport to the sump screen, creates a uniform fibrous bed of equal to or  
28 greater than 1/8-inch layer to filter particulate debris.
- 29           3. If the insulation does not result in the generation of significant particulate debris  
30 (for example, the insulation in the ZOI is RMI, there is no microporous insulation  
31 inside containment, and fibrous insulation is not affected by the postulated break),  
32 particular attention should be given to the characterization of latent debris sources  
33 as this source may present the limiting debris loading condition with respect to  
34 either fiber, particulates, or both.

#### 1   **3.3.4.4   Selecting the Initial Break Location**

2   To start the break selection evaluation, select an initial break location using the guidance given in  
3   subsections 3.3.4.1 to 3.3.4.3. Multiple breaks will be examined to demonstrate that the limiting  
4   break location was considered. However, using the guidance identified in these sections, it is  
5   possible to identify locations that may be considered to be likely candidates for the limiting  
6   location. Thus, it is suggested that an initial postulated break location be chosen with the  
7   following characteristics:

- 8           1.   Pick the initial break location to be near a large quantity of potential debris and/or  
9           near a combination of potential debris types that are known to challenge post-  
10          accident sump operation. It is suggested that results from a containment condition  
11          assessment, similar to that described in NEI 02-01 (Reference 2) would be useful in  
12          assessing such locations.
- 13          2.   The location is a convenient place to start a sequence of breaks (e.g., at the physical  
14          end of a length of pipe when multiple locations on that length of pipe are being  
15          evaluated).

16   Given the above, it is suggested that a candidate location for the initial break location is the  
17   junction of the primary piping and the steam generator. Two general industry observations  
18   support this suggestion:

- 19          1.   As a consequence of their size, steam generators have a larger volume of insulation  
20          applied to them than does primary system piping.
- 21          2.   It has been observed that steam generators often have several different types of  
22          insulation applied to them.

23   Therefore, the selection of a break location at the junction of primary piping and the steam  
24   generator is a reasonable starting point to address the criteria of evaluating both the maximum  
25   amount of debris that is transported to the sump screen, and the worst combination of debris  
26   mixes that are transported to the sump screen.

#### 27   **3.3.5   Evaluation of Break Consequences**

28   The evaluation of break consequences is the determination of the head loss across the sump  
29   screen as a result of the generation, transport, and accumulation of debris on the sump screen that  
30   is calculated to occur as a result of the postulated break, and the consequential head loss across  
31   the sump screen as emergency core cooling and containment spray recirculation water passes  
32   through the debris bed.

##### 33   **3.3.5.1   Purpose of Break Consequence Evaluation**

34   The purpose of evaluating the consequences of a postulated break is to determine the head loss  
35   associated with that break and its effect on available NPSH for the recirculation pumps. To

1 accomplish this, the following additional evaluations must be performed for each break location  
2 considered:

3 1. Evaluation of the zone of influence (ZOI), the region inside containment that is  
4 affected by the fluid escaping from the postulated break location, resulting in the  
5 generation of debris. As the ZOI is moved about to different break locations, robust  
6 structures (walls) may affect the geometry of the ZOI.

7 2. Evaluation of the debris source term.

8 3. Evaluation of debris transport to the sump screen.

9 4. Evaluation of head loss across the sump screen resulting from debris that has been  
10 transported to and deposited on the containment sump screen.

11 Evaluating break consequences in this way provides for the evaluation of sump screen head loss  
12 as a function of postulated break size and break location.

### 13 3.3.5.2 Selection of Intervals for Additional Break Locations

14 After evaluating the initial break location, additional locations are evaluated and the results  
15 compared, to determine the limiting location for the break size used.

16 For primary piping, it is suggested that the break location be moved at 3-foot increments along  
17 the pipe being considered. This break frequency provides for an acceptable determination of the  
18 limiting break location with respect to:

19 1. The maximum volume of debris that may be generated and transported to the sump  
20 screen.

21 2. The worst combination of debris that may be generated and transported to the sump  
22 screen.

23 It is expected that, as the plant-specific analysis develops, it will be determined and documented  
24 by inspection that the number of cases requiring detailed analysis can be limited based on debris  
25 inventory, similarity of transport paths, and piping physical characteristics.

26 The same strategies need not be applied when considering main steam line or feedwater line  
27 breaks. A sufficient number of breaks, consistent with the plant-specific design and licensing  
28 basis, should be considered to reasonably bound variations in debris generation by the size,  
29 quantity, and type of debris.

30 For attached piping, only the length of pipe run up to the flow isolation point need be considered.  
31 This approach will account for debris generation from postulated pipe breaks, including  
32 single-sided breaks, from attached piping. There is no need to consider pipe breaks in attached

1 piping beyond the isolation points since such breaks, should they occur, will not result in the  
2 plant evolving to recirculation from the containment sump to mitigate the event.

### 3 **3.4 DEBRIS GENERATION**

#### 4 **3.4.1 Introduction**

5 Following identification of postulated break locations, the next step taken in evaluating post-  
6 accident sump performance is to determine an appropriate zone of influence (ZOI) within which  
7 the resultant break jet would have sufficient energy to generate debris. It is noted that not all  
8 debris that is evaluated to be generated is in a form that may be transported to the sump. Thus,  
9 evaluation of debris generation from a postulated break is a two-step process:

- 10 1. Evaluate an appropriate ZOI in which debris is generated.
- 11 2. Evaluate the characteristics of the debris generated.

12 Included in this second step is the identification of transport characteristics of the debris  
13 generated by the postulated break. Thus, the evaluation of debris generation for a given break  
14 location is an exercise of establishing the appropriate size and shape of the ZOI, mapping that  
15 ZOI volume over the spatial layout of insulated piping, and calculating the volume of insulation  
16 within that ZOI. The final step to evaluating debris generation is the application of a size  
17 distribution to the debris generated within the ZOI volume that will be used to evaluate debris  
18 transport.

19 The identification of the ZOI and resulting debris generation for postulated pipe breaks (LOCA,  
20 main steam line or feedwater) is both plant- and break-specific. Presented in this section is  
21 guidance in establishing the appropriate ZOI and resulting debris characteristics for LOCA. This  
22 guidance is also applicable to postulated main steam line and feedwater line breaks

#### 23 **3.4.2 Zone of Influence**

24 The zone of influence is defined as the volume about the break in which the fluid escaping from  
25 the break has sufficient energy to generate debris from insulation, coatings, and other materials  
26 within the zone. For the baseline calculation, it is recommended that the boundary of the ZOI be  
27 assumed to be spherical, with the center of the sphere located at the break site. The use of a  
28 spherical ZOI is intended to encompass the effects of jet expansion resulting from impingement  
29 on structures and components. Use the guidance in subsections 3.4.2.1 and 3.4.2.2 to determine  
30 the ZOI for a postulated pipe break.

31 Guidance on the identification of other, more realistic ZOIs is given in Section 4.

##### 32 **3.4.2.1 Recommended Size of Zone of Influence**

33 To determine the radius of the spherical ZOI needed to represent the effects of the jet originating  
34 from a postulated pipe break, the ANSI/ANS 58.2-1988 standard (Reference 3, Section 3.2.7)  
35 was used. Appendices B, C, and D of Reference 3 provide the guidance necessary to determine

1 the geometry of a freely expanding jet. Guidance is provided for jets originating from a variety  
2 of reservoir conditions, including subcooled conditions.

3 The guidance in Reference 3 was used to determine the geometry of a jet originating from a  
4 postulated break in a PWR piping system. A subcooled reservoir and flashing break flow were  
5 assumed for the calculations as detailed below. The following steps were followed in performing  
6 the calculations:

- 7 1. The mass flux from the postulated break was determined using the Henry-Fauske  
8 model, as recommended in Appendix B, for subcooled water blowdown through  
9 nozzles, based on a homogeneous non-equilibrium flow process. No irreversible  
10 losses were considered.
- 11 2. The initial and steady-state thrust forces were calculated based on the guidance in  
12 Appendix B of Reference 3, and the postulated reservoir conditions detailed below.
- 13 3. The jet outer boundary and regions were mapped using the guidance in  
14 Appendix C, Section 1.1 of Reference 3 for a circumferential break with full  
15 separation. The input to the equations from Appendix C for the thermodynamic  
16 conditions at the asymptotic plane was calculated using principles of  
17 thermodynamics and the postulated conditions in the reservoir.
- 18 4. A spectrum of isobars was mapped using the guidance in Appendix D of  
19 Reference 3. Several isobars were considered of interest, including the 10 psi  
20 isobar. The 10 psi isobar was of interest as NEDO-32686 (Reference 4) identifies  
21 10 psi as the destruction pressure of jacketed Nukon insulation with standard bands  
22 or unjacketed Nukon.
- 23 5. The volume encompassed by the various isobars was calculated using a trapezoidal  
24 approximation to the integral. A study was performed to ensure that the results of  
25 the volume calculations are not sensitive to the resolution of the trapezoidal  
26 approximation. Since the volume result only represents the volume encompassed  
27 by the isobars in a free jet, the volume encompassed by results was doubled to  
28 represent the double-ended guillotine break (DEGB).
- 29 6. The radius of an equivalent sphere was calculated to encompass the same volume  
30 as twice the volume of a freely expanding jet calculated from step 5, above.

31 The radius calculated in step 6, above, is taken to be the radius of the ZOI that will be used to  
32 calculate the volume of debris generated from a postulated break.

33 The jet expansion calculations were based on the following conditions:

- 34 1. A circular break geometry was used for the calculations. This break geometry is  
35 representative of both a postulated DEGB of primary piping as well as the DEGB  
36 of piping attached to the RCS. The complete breaking of a pipe, either primary

1 piping or piping attached to the RCS, provides for a maximum debris generation  
2 volume as there are two ends of the break to release fluid.

- 3 2. Fluid reservoir conditions of 2250 psia and 540°F were used for the calculations.  
4 The corresponding stagnation enthalpy and subcooling used in the calculations are  
5 547.2° Btu/lbm and 102.7°F, respectively. These conditions are intended to  
6 represent a PWR cold leg at full power and provide for a conservatively large ZOI  
7 compared to hot-leg conditions at power operations.
- 8 3. Ambient pressure of 14.7 psia was used. This is conservative since no credit is  
9 taken for containment backpressure (the increase in containment pressure that  
10 would result from the release of mass and energy into the containment as a result of  
11 the postulated break).

12 The ZOI is expressed as the ratio of the radius of the equivalent ZOI sphere to break size  
13 diameter. This allows the ZOI to be expressed independently of the break size.

14 The use of a spherical ZOI is conservative compared to jet impingement evaluations previously  
15 reviewed and approved by the NRC. It is noted that, for a number of plants, a 10D value is  
16 assumed for the limit of jet damage. This is based on NUREG/CR-2913, dated January 1983. As  
17 an example, the acceptability of this approach is documented in the Supplement 6 of the Watts  
18 Bar Safety Evaluation Report (SER):

19 *The applicant has given the staff information requiring the analysis of jet*  
20 *impingement loads for postulated breaks. In FSAR section 3.6A.1.1.2, test data and*  
21 *analysis developed in NUREG/CR-2913, "Two Phase Jet Loads," dated*  
22 *January 1983, are used to establish the criterion that unprotected components*  
23 *located more than 10 diameters from a pipe break are without further analysis*  
24 *assumed undamaged by a jet of steam or subcooled liquid that flashes at the break.*  
25 *The staff has previously reviewed the methodology used in NUREG/CR-2913 for*  
26 *determining the effects of such a jet on components at a distance greater than*  
27 *10 diameters and has found it acceptable.*

## 28 **Protective Coatings**

29 The criteria for DBA-qualification, or designation as "Acceptable," of protective coatings  
30 (paints) applied to systems, structures, and components in PWR containments do not provide  
31 data concerning coatings exposed to direct impingement of fluids. As such, the ZOI for  
32 DBA-qualified coatings or coatings determined to be "Acceptable," applied to PWR containment  
33 surfaces, which results from fluid impingement from the break jet, has not been clearly defined.

34 However, an extensive body of data exists related to removal of industrial protective coatings by  
35 high-pressure and ultra-high-pressure waterjetting. Examination of the data and associated  
36 industry standards, compiled since the mid-1980s, reveals that industrial protective coating  
37 systems, identical to the DBA-qualified and "Acceptable" coatings applied to systems,  
38 structures, and components in PWR containments, require a water jetting pressure of at least

1 7,000 psig to initiate destruction of sound coatings. This ability of coatings to withstand high and  
2 ultra-high pressure has been reviewed and documented in a paper prepared by a recognized  
3 industry coatings expert (Reference 5), included as Appendix A.

4 Based on evaluation presented, a destruction pressure of 1000 psi is chosen for coatings that  
5 meet DBA-qualified or "Acceptable" criteria. This is conservative for the following reasons:

- 6 1. The value of 1000 psi is seven to eight times lower than the pressures that have  
7 been observed in industrial practice to remove coatings using waterjet technology.
- 8 2. The initial RCS pressure of 2250 psi is about one-quarter of the pressures that have  
9 been observed in industrial practice to remove coatings using waterjet technology.
- 10 3. Industrial experience with waterjet technology to remove coatings requires  
11 application of the high-pressure jet at close proximity of the surface to which the  
12 coating is applied (< 12 inches from the jet nozzle discharge) for extended periods  
13 of time (> 60 seconds).
- 14 4. The blowdown of a PWR RCS due to a large LOCA is on the order of 30 seconds.
- 15 5. The break discharge pressure decreases over the duration of the blowdown period.

16 Thus, it is concluded that the use of a value of 1000 psi as the destruction pressure for  
17 DBA-qualified and "Acceptable" protective coatings is both appropriate and conservative. The  
18 recommended ZOI to be used to evaluate protective coatings debris for the baseline containment  
19 sump evaluation is listed in Table 3-1.

20 This same industrial experience suggests that the mechanism of coating removal by waterjets is  
21 erosion. The observed coating debris sizes are in the range of 10 microns to 50 microns, not  
22 flakes or chips. Thus, it is recommended that the coating debris generated within the ZOI  
23 representing 1000 psi be treated as fine particulate debris. It is further recommended that this  
24 coating debris be considered highly transportable.

#### 25 **3.4.2.2 Selecting a Zone of Influence**

26 For the baseline calculation, the ZOI for a break is selected based on the potentially affected  
27 insulation inside containment with the minimum destruction pressure. This ZOI is then applied to  
28 all insulation types. As discussed in the previous section, this approach provides for the  
29 calculation of a conservatively large value for debris generation.

**Table 3-1. ZOI Radii for Common PWR Insulation and Coatings Materials**

Insulation Types	Destruction Pressure (psi)	ZOI Radius/Break Diameter	
		Calculated Value	Recommended Value
Protective Coatings (epoxy and epoxy-phenolic paints)	1000 <sup>(Ref. 5)</sup>	0.24	1.0
Protective Coatings (untopcoated inorganic zinc)	333 <sup>(Ref. 5)</sup>	0.55	1.0
Transco RMI Darchem DARMET	190 <sup>(Ref. 6)</sup>	1.11	1.3
Jacketed Nukon with Sure-hold <sup>®</sup> bands Mirror <sup>®</sup> with Sure-Hold <sup>®</sup> bands	150 <sup>(Ref. 6)</sup>	1.51	1.6
K-wool	40 <sup>(Ref. 6)</sup>	3.73	3.8
Cal-Sil (Al. cladding, SS bands)	24 <sup>(Ref. 7)</sup>	5.45	5.5
Temp-Mat with stainless steel wire retainer	17 <sup>(Ref. 6)</sup>	7.72	7.8
Unjacketed Nukon, Jacketed Nukon with standard bands Knaupf	10 <sup>(Ref. 6)</sup>	12.07	12.1
Koolphen-K	6 <sup>(Ref. 6)</sup>	16.97	17.0
Min-K Mirror <sup>®</sup> with standard bands	4 <sup>(Ref. 6)</sup>	21.53	21.6

- 1
- 2 **3.4.2.3 The ZOI and Robust Barriers**
- 3 For a given break location, the boundary of the spherical ZOI is drawn about the break. It is
- 4 possible that this boundary will extend beyond robust barriers such as walls and components.
- 5 Such barriers will terminate further expansion of the ZOI.
- 6 1. In the case of a wall, the sphere will be truncated at the intersection of the sphere
- 7 and wall.
- 8 2. For a component or structural components such as supports, a pressurizer, steam
- 9 generator, reactor coolant pump or jet shields, the area in the shadow of the
- 10 component or structure will be free from damage.



1 There is sufficient conservatism in drawing the sphere that it is not reasonable that a jet reflected  
2 off of a wall or structure would extend further than the unrestrained sphere. Furthermore, there  
3 are precedents for this conclusion in the BWROG URG. When evaluating targets for jet  
4 impingement, jets were terminated when a robust barrier was encountered. Reflected jets were  
5 not considered as they were bounded by the conservatism in the approach taken.

#### 6 **3.4.2.4 Simplifying the Determination of the ZOI**

7 Given the complexity of the analysis as a whole, it may be desired to make conservative  
8 assumptions with the goal of simplifying the analysis. For example, for some breaks it may be  
9 only slightly more conservative and much simpler to assume that an entire subcompartment (but  
10 not outside the subcompartment) becomes the ZOI.

11 Once the boundary of the ZOI has been defined, proceed with determining the amount of debris  
12 that is generated within the ZOI.

#### 13 **3.4.2.5 Evaluating Debris Generation within the ZOI**

14 Once the ZOI has been determined, calculate the amount of debris generated within the ZOI.  
15 Information about the type, location, and amount of debris sources within the containment is  
16 obtained from plant drawings and the results of a condition assessment walkdown such as  
17 described in NEI 02-01 (Reference 2). The characterization of the debris (transport  
18 characteristics) is evaluated using the guidance of the following section.

#### 19 **3.4.2.6 Sample Calculation**

20 The following is a sample calculation of a ZOI and the debris that would be generated within that ZOI.

- 21 1. For the sample calculation, a single break size and break location will be assumed  
22 and evaluated.
- 23 2. The break will be assumed to be at the base of the steam generator<sup>1</sup>. The reason for  
24 this choice is that often, more than one type of insulation is applied to steam  
25 generators. Figure 3-1 shows a sample schematic of a reactor coolant system.
- 26 3. It will also be assumed that walkdown data for the plant are available and  
27 documented in sufficient detail to support this evaluation. For the purposes of this  
28 evaluation, it will be assumed that the walkdown was performed by dividing the  
29 containment into zones and recording the amount of insulation in each zone. The  
30 debris generation zones defined from the walkdown are also shown in Figure 3-1  
31 and are labeled as Zone A1, Zone A2, etc. Note that the plant layout and  
32 engineering judgment are used to define the zones used to record the location of  
33 insulation inside containment.

---

1 A 10-inch break is an idealization for the steam generator. It is used here to illustrate the calculation method.

- 1           4. The postulated break will be assumed to occur in Zone A4. For this sample  
2 calculation, it is assumed that the walkdown records show the amount of insulation  
3 in Zone A4 to be:

- 4           • 300 ft<sup>3</sup> of Nukon insulation  
5           • 15,000 ft<sup>2</sup> of RMI

- 6           5. A 10-inch break of piping attached to the RCS is assumed. The corresponding ZOI  
7 is evaluated as follows:

8           The diameter of the break is taken as:

$$9 \qquad D_{\text{BREAK}} = 10 \text{ inches}$$

10           Using the criteria identified above, the minimum destruction pressure for insulation is  
11 used to determine the ZOI. From Table 3-1, the recommended ratio of ZOI radius to  
12 break diameter is:

$$13 \qquad \frac{r_{\text{ZOI}}}{D_{\text{BREAK}}} = 12$$

14           The radius of the spherical ZOI is calculated as:

$$15 \qquad r_{\text{ZOI}} = D_{\text{BREAK}} \times \frac{r_{\text{ZOI}}}{D_{\text{BREAK}}} = 10 \text{ inches} \times 12 = 120 \text{ inches} = 10 \text{ ft}$$

16           Thus, the radius of the ZOI is determined to be 10 feet. This ZOI is conservatively  
17 applied to all insulation types in the region within the ZOI for the baseline  
18 evaluation.

- 19           6. A ZOI having a 10 foot radius is superimposed at the base of the steam generator in  
20 Zone A4 of Figure 3-1. From the figure, it is observed that the ZOI includes a  
21 substantial portion of the steam generator and associated reactor coolant system  
22 piping within Zone A4. Insulation is applied to these components. Therefore, for  
23 this sample calculation, a ZOI with a radius of 10 feet is conservatively evaluated  
24 to result in the destruction of all the insulation within Zone A4. This results in the  
25 following volumes of insulation debris:

- 26           • 300 ft<sup>3</sup> of Nukon insulation  
27           • 15,000 ft<sup>2</sup> of RMI.

- 1           7. Using the recommended ratio of ZOI radius to break diameter for coatings of 1.0  
2 that is given in Table 3-1, the radius of the coatings ZOI is evaluated as:

$$3 \quad r_{\text{ZOI}} = D_{\text{BREAK}} \times \frac{r_{\text{ZOI}}}{D_{\text{BREAK}}} = 10 \text{ inches} \times 1.0 = 10 \text{ inches} = 0.833 \text{ ft}$$

4           From Figure 3-1, it is clearly observed that the coating ZOI will not be in contact  
5 with either walls or floors. Furthermore, with a small ZOI for coatings, coated  
6 structures or components may not be within the ZOI. However, a conservative  
7 estimate of the square footage of coatings debris is estimated by using the surface  
8 area of the sphere of the coatings ZOI:

$$9 \quad A_{\text{COATINGS DEBRIS}} = 4\pi r^2 = 4\pi (0.833)^2 = 8.72 \text{ sq. ft}$$

10           Thus, the amount of coating debris generated by the postulated 10-inch break is  
11 conservatively estimated to be 8.72 ft<sup>2</sup>.

12           The transport characteristics of the debris volumes calculated above are evaluated using the guidance  
13 of the following section. The transport of the debris evaluated using the guidance of Section 3.6, and  
14 the resulting head loss evaluated using the guidance of Section 3.7. The debris generation evaluation  
15 is repeated using the guidance of Section 3.3 until the limiting head loss is evaluated.

### 16   3.4.3 Quantification of Debris Characteristics

#### 17   3.4.3.1 Definition

18           Debris characteristics are:

- 19           • The post-accident (LOCA and/or secondary pipe breaks where applicable) size  
20 distribution of a material.
- 21           • The debris material size and shape as well as the micro-density (i.e., material  
22 density) and macro-density (i.e., as-fabricated density).

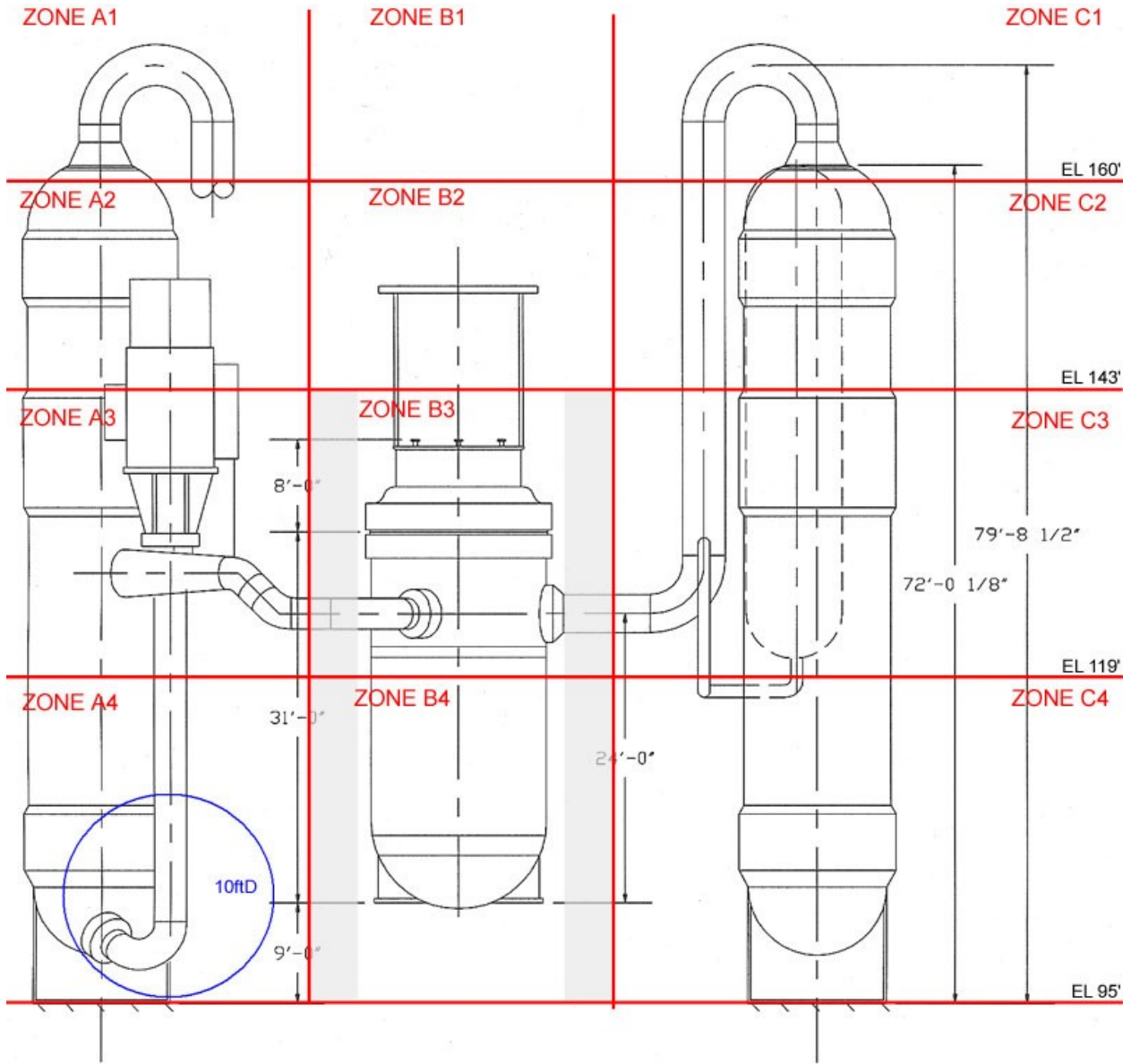
23           Debris characteristics are used in transport and head loss calculations. The debris generation  
24 section provides the following items as inputs to this section:

- 25           • The volume of insulation material in a ZOI.
- 26           • The surface area of the ZOI for coatings.
- 27           • The total quantity of indeterminate<sup>2</sup> and unqualified coatings inside containment.
- 28           • The total quantities of indeterminate and unqualified coatings that have been  
29 applied to piping that are covered by undamaged insulation.

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2           For definitions of DBA-qualified/acceptable, DBA-unqualified/unacceptable, and indeterminate coatings, see  
ASTM D-5144-00, "Standard Guide for Use of Protective Coating Standards in Nuclear Power Plants."

1



2

3 **Figure 3-1. Schematic Showing Reactor Coolant System and Walkdown Zones**

### 1 3.4.3.2 Discussion

2 The first-order debris characteristic is the size distribution of the material inside ZOI of a  
3 postulated pipe break. Following a postulated pipe break, all material inside containment may  
4 also be subjected to containment spray or immersed in the post-accident pool, and additional  
5 debris would be generated; therefore, the characteristics of the debris generated post-blowdown  
6 also need to be identified.

7 There have been numerous schemes developed for classifying debris size distribution of material  
8 inside a ZOI. Most of the classification schemes developed were for low-density fiberglass  
9 blankets manufactured by Performance Contracting Inc. (PCI) and Transco. NUREG/CR-6369  
10 (Reference 16) employs five fibrous debris size classification schemes, with three to six size  
11 designations (e.g., large, medium, and small). NUREG/CR-6224 (Reference 17) adopts a  
12 classification scheme of seven size categories for fiber. As noted in NUREG/CR-6369, the  
13 BWROG URG adopted a fiber classification scheme of two sizes: fines and large.

14 The Air Jet Impact Tests (AJITs) conducted by the BWROG indicated a dependence of the size  
15 distribution of the debris on distance from the nozzle, i.e., the higher the pressure, the larger the  
16 quantity of small debris. As discussed in NUREG/CR-6808 (Reference 6), Section 3.3, an  
17 analytical model could be applied that correlates the size distribution to the spherical ZOI. This  
18 type of modeling requires the understanding of the damage distribution based on applicable  
19 experimental data. Unfortunately, there is a paucity of applicable debris generation test data  
20 applicable for PWR conditions. In the absence of directly applicable experimental data, i.e., tests  
21 conducted with prototypical PWR conditions, for a wide variety of material, the NEI Guideline  
22 adopts a two-size distribution for material inside the ZOI of a postulated break: small fines and  
23 large pieces. Small fines will be defined as any material that could transport through gratings,  
24 trash racks, or radiological protection fences by blowdown, containment sprays, or post-accident  
25 pool flows. Furthermore, the small fines are assumed to be the basic constituent of the material  
26 for fibrous blankets (i.e., individual fibers) and pigments for coatings. This guideline assumes the  
27 largest openings of the gratings, trash racks, or radiological protection fences to be less than a  
28 nominal 4 inches by 4 inches (less than 20 square inches total open area). The remaining material  
29 that cannot pass through gratings, trash racks, and radiological protection fences is classified as  
30 large pieces.

31 Some material in the post-DBA environment will be eroded by the water flows. Additionally,  
32 some debris material may be disintegrated by the water flow. The classification for fibrous  
33 material in the ZOI adopted by this guidance assumes that all fibrous materials classified as  
34 small fines are essentially reduced to the individual fibers. As such, the debris classification  
35 implicitly considers the erosion and disintegration of the debris by conservatively assuming that  
36 they are already of a characteristic size that cannot be further decreased by erosion or  
37 disintegration. For fibrous insulation material, the large pieces are assumed to be jacketed or  
38 canvassed. According to NUREG/CR-6369, jacketed pieces are not subjected to further erosion.  
39 The same conservatism was applied for coatings in the ZOI where this guideline assumes that all  
40 coatings in the coating ZOI are considered to be small fines of the size of the original pigment,  
41 hence not capable of being subjected to erosion or disintegration. For material outside the ZOI,  
42 all insulation material that is jacketed is assumed not to undergo erosion or disintegration by

1 containment spray or break flow. This assumption is based also on NUREG/CR-6369 tests that  
2 showed no erosion of damaged jacketed material, hence the same applies to undamaged jacketed  
3 material. Additionally, PCI has conducted tests on undamaged Nukon blankets to demonstrate  
4 that they are not subject to erosion in a post-DBA environment. The NRC issued a Safety  
5 Evaluation Report (SER) on the tests accepting the PCI test results.

6 The main source of data on debris size distribution of material subjected to simulated pipe break  
7 conditions is that reported in the BWROG URG AJIT tests and the NRC debris transport set of  
8 experiments described in NUREG/CR-6339. This NEI Guideline selected the test of the  
9 insulation that had the most data points (Nukon) that produced the smallest fines and adopted  
10 this point as the bounding value of fines production for unjacketed fibrous blankets. The data of  
11 size distribution following exposure to simulation of a pipe break close to PWR prototypical  
12 conditions are depicted in Table 3-7 of NUREG/CR-6808 for a low-density fiberglass tested at  
13 Ontario Power Generation. That test indicates that 52 percent were of the category defined as  
14 small fines adopted by this guideline. This test suggests that the size distribution for Nukon  
15 blankets in this guideline is conservative for PWR applications. For fibrous insulation materials  
16 that underwent testing at AJIT, this guideline adopted the Nukon blanket size distribution for  
17 fibrous blankets whose destruction pressure was the same or higher than for Nukon blankets. If a  
18 material has a higher destruction pressure, it signifies that the material has a higher resistance to  
19 damage. As such, the size distribution would tend to be larger than a more fragile material  
20 indicated by a lower destruction pressure. Therefore it is conservative to adopt the Nukon blanket  
21 size distribution for material with a higher destruction pressure. For material with an equivalent  
22 destruction pressure as Nukon blankets, engineering judgment suggests that the fraction of fines  
23 should be no worse than for Nukon blankets.

24 The calculation of the quantities for each size category for each of the materials entails  
25 multiplying the volume of each material calculated to be in the ZOI by the percentage of the  
26 two-size distribution recommended below.

### 27 **3.4.3.3 Size Distribution**

#### 28 **3.4.3.3.1 Fibrous Material in a ZOI**

29 The fibrous classification of “small fines” adopted in this guideline can be correlated to the  
30 combination of “small” and “medium” classification of Table 3-7 of NUREG/CR-6369, Vol. 2;  
31 the combination of “small” and “large” classification of Table 2-5 of NUREG/CR-6369, Vol. 1;  
32 Classes 1-6 of NUREG/CR-6224; and the combination of “Fines” and “Large” classification of  
33 the BWROG URG AJIT. The classification of “large pieces” adopted in this guideline can be  
34 correlated to the large category of Table 3-7 of NUREG/CR-6369, Vol. 2; the “large canvassed”  
35 of Table 2-5 of NUREG/CR-6369, Vol. 1; Class 7 and “non-transportable” of NUREG/CR-6224;  
36 and the combination of “canvas” of the BWROG URG AJIT.

37 The following are the material-specific size distribution values adopted by this guideline:

- 38 1. Nukon fiber blankets. This guideline adopts the value of 60 percent for small fines  
39 and 40 percent for large pieces as the size distribution of Nukon (jacketed or

- 1 unjacketed) inside a pipe break ZOI. As noted previously, these values were  
2 selected from the BWROG URG AJIT of Nukon that generated the largest quantity  
3 of small fines and is considered to be applicable to PWR conditions based on the  
4 Ontario Power Generation test reported in NUREG/CR-6808.
- 5 2. Transco fiber blankets. This guideline adopts the value of 60 percent for small fines  
6 and 40 percent for large pieces as the size distribution of Nukon inside a pipe break  
7 ZOI. Transco blankets were not tested by the BWROG at the CEESI AJIT facility.  
8 Transco blankets were used, however, by the NRC at the CEESI AJIT facility as  
9 documented in NUREG/CR-6369. The study shows that the Transco blankets tested  
10 behaved similarly to the Nukon. Given these experimental data, engineering  
11 judgment suggests that Transco low-density fiberglass blankets would behave  
12 similarly to the Nukon fiberglass blankets when subjected to prototypical PWR  
13 DEGB DBA conditions, hence the size distribution adopted for Transco fiberglass  
14 blankets in this guideline is conservative since the size distribution adopted for  
15 Nukon fiberglass blankets was the most conservative size distribution of any of the  
16 AJIT tests of Nukon fiberglass blankets.
- 17 3. Knaupf. Knaupf was tested by the BWROG at the CEESI AJIT facility and shown  
18 to have the same destruction pressure as Nukon. Therefore, engineering judgment  
19 suggests that the size distribution should be no worse than Nukon. Hence, this  
20 guideline adopts the same size distribution for Knaupf as Nukon: 60 percent for  
21 small fines and 40 percent for large pieces.
- 22 4. Temp-Mat. Temp-Mat was tested by the BWROG at the CEESI AJIT facility and  
23 shown to have a higher destruction pressure than Nukon. Therefore, engineering  
24 judgment suggests that the size distribution should be no worse than Nukon. Hence,  
25 this guideline adopts the same size distribution for Knaupf as Nukon: 60 percent  
26 for small fines and 40 percent for large pieces.
- 27 5. K-Wool. K-Wool was tested by the BWROG at the CEESI AJIT facility and shown  
28 to have a higher destruction pressure than Nukon. Therefore, engineering judgment  
29 suggests that the size distribution should be no worse than Nukon. Hence, this  
30 guideline adopts the same size distribution for K-Wool as Nukon: 60 percent for  
31 small fines and 40 percent for large pieces.
- 32 6. Min-K. Absent applicable experimental data, a value of 100 percent small fines is  
33 adopted by this guideline for Min-K in a ZOI.
- 34 7. Generic low-density fiberglass. Absent applicable experimental data, a value of  
35 100 percent small fines is adopted by this guideline for generic fiberglass in a ZOI.
- 36 8. Generic high-density fiberglass. Absent applicable experimental data, a value of  
37 100 percent small fines is adopted by this guideline for generic high-density  
38 fiberglass in a ZOI.

- 1           9.    Generic mineral wool. Absent applicable experimental data, a value of 100 percent  
2           small fines is adopted by this guideline for any type of mineral wool in a ZOI.

### 3   **3.4.3.3.2 Reflective Metallic Insulation (RMI) in a ZOI**

4   The NEI guideline adopts one size distribution classification scheme for all types of RMI  
5   insulation after exposure to the conditions within a PWR ZOI, since their ensuing transport and  
6   head loss guidelines do not differentiate between different types of RMI (i.e., stainless steel or  
7   aluminum).

8           RMI. The NEI guideline adopts the value of 75 percent for small fines and 25 percent for  
9           large pieces as the size distribution of any type of RMI inside a pipe break ZOI. These  
10          values are based on the size distribution of less than 4 inches as listed in Figure 3-7 of  
11          NUREG/CR-6808 based on the two-phase testing of a Diamond Power RMI cassette.  
12          The size of 4 inches was selected as a conservative upper bound of an RMI debris size  
13          that would go through gratings, trash racks, or radiological protection fences by  
14          blowdown, containment sprays, or post-accident pool flows. BWROG URG AJITs of  
15          other types of RMI suggests a significantly larger destruction pressure and a consequently  
16          smaller quantity of small size debris. Engineering judgment suggests that the 75 percent  
17          adopted for the RMI small-size category in this guideline is conservative in that it is  
18          based on the test that resulted in the largest quantity of small RMI debris for a type of  
19          RMI that has the lowest AJIT destruction pressure.

### 20   **3.4.3.3.3 Other Material in ZOI**

- 21          1.    Calcium silicate. There is a wide variety of calcium silicate type insulation installed  
22          in PWRs. Some include fiberglass fibers as reinforcement, others use organic  
23          fibers, and some of the Cal-Sil used up to the late 1950s used asbestos fibers. The  
24          Cal-Sil solubility also varies by manufacturer, with some Cal-Sil dissolving  
25          promptly in hot water, whereas some dissolves at a significantly lower rate. The  
26          only publicly available size distribution data on the reaction of an unspecified  
27          Cal-Sil to a two-phase jet are found in Table 3-6 of NUREG/CR-6808. Test 5  
28          indicated that the size categories adopted by this guideline would be 50 percent for  
29          small fines and 50 percent for large Cal-Sil pieces. Given the uncertainties in the  
30          subsequent erosion by the post-DBA water, this guideline assumes that 100 percent  
31          of Cal-Sil in a ZOI is destroyed as small fines.

- 32          2.    Microtherm. Absent applicable experimental data or qualification documentation, a  
33          value of 100 percent small fines is adopted by this guideline for Microtherm in a  
34          ZOI.

- 35          3.    Koolphen. Absent applicable experimental data, a value of 100 percent small fines  
36          is adopted by this guideline for Koolphen in a ZOI.

- 37          4.    Fire barrier. Absent applicable experimental data, a value of 100 percent small fines  
38          is adopted by this guideline for all types of fire barrier material in a ZOI.



- 1           5.    Lead wool. Absent applicable experimental data, a value of 100 percent small fines  
2           is adopted by this guideline for all types of lead wool material in a ZOI.
- 3           6.    Coatings. All coatings within the coatings ZOI are considered in this guideline to  
4           fail when subjected to DBA conditions. Guidance concerning the determination of  
5           the Coatings ZOI is contained in Appendix A. Absent applicable experimental data,  
6           a coating debris size value of 100 percent small fines (10  $\mu\text{m}$  IOZ equivalent) is  
7           adopted by this guideline for all types of coating material in the ZOI.

#### 8    **3.4.3.3.4 Material Outside the ZOI**

9    Material outside the ZOI can be subjected to containment spray and/or be immersed in the  
10   post-DBA pool. Under these circumstances, some material could become debris and become  
11   subject to transport to the sump screen. Material and components that meet equipment  
12   qualification requirements (i.e., material and components on the Environmental Qualification  
13   list) have been demonstrated not to degrade in a post-DBA environment so they will not  
14   contribute to the post-DBA debris load.

- 15           1.    Covered (jacketed) undamaged insulation. Nukon blankets are EQ-qualified and as  
16           such will not be damaged by the post-DBA environment outside the ZOI. The scant  
17           publicly available data for reaction of jacketed fibrous insulation material to  
18           post-DBA conditions that exist come from the NRC. The NRC tests were  
19           performed on low-density fiber (Transco blankets) and reported in  
20           NUREG/CR-6369, Volume 1. Both series of tests were conducted with pieces of  
21           blankets that had been subjected to the air jet impact tests at the AJIT facility. No  
22           intact blankets were tested. NUREG/CR-6369 concluded that partially torn  
23           insulation blankets that retained their cover were unlikely to be eroded by water  
24           flow from washdown and spray. Based on these tests and the EQ of Nukon  
25           blankets, this guideline adopts the position that covered (jacketed) undamaged  
26           insulation material outside the ZOI will not generate transportable debris. (Covered  
27           or jacketed insulation is any insulation in which the raw material, e.g., fiberglass  
28           bats, is covered or encapsulated by another material).

#### 29           2.    Other material outside the ZOI.

- 30           •    Fire barrier. Applying the same logic as was concluded in NUREG/CR-6339  
31           for partially torn insulation that retained their wrappings/covers/jackets, all  
32           jacketed covered, or wrapped fire barriers are presumed not to degrade in the  
33           post-accident environment, and hence not generate debris. Fire barrier  
34           materials that are not jacketed, wrapped, or covered are presumed to fail as  
35           small fines.
- 36           •    Lead wool. The lead wool blankets have the same general covers as the  
37           Nukon and Transco blankets. As such, the conclusions of the NRC  
38           experiments are applicable. The NEI Guideline considers that all lead wool  
39           blankets outside the ZOI will not be damaged by the post-DBA environment.

- 1 • Unjacketed insulation. All materials outside the ZOI that are unjacketed, e.g.,  
2 fiberglass bats without any covering, are presumed to fail to small fines.
- 3 • Coatings. DBA-qualified and acceptable coatings<sup>3</sup> located outside the  
4 coatings ZOI are considered in this guideline not to fail when subjected to  
5 containment spray or immersed in the post-DBA pool. All indeterminate and  
6 DBA-unqualified and unacceptable coatings are considered in this guideline  
7 to fail. This baseline guideline considers all indeterminate and  
8 DBA-unqualified and unacceptable coatings as a single category of coating,  
9 producing debris of the same characteristic independent of the type of  
10 coating, when subjected to containment spray or immersed in the post-DBA  
11 pool. All types of coatings on piping or components covered with undamaged  
12 insulation are considered in this guideline not to contribute to the post-DBA  
13 debris source term.

#### 14 3.4.3.4 Calculate Quantities of Each Size Distribution

15 The total quantity of each size distribution for each material is the summation of the size  
16 distribution for the debris size quantity in the ZOI added to the debris size quantity outside the  
17 ZOI. To calculate the quantity of debris size for a material<sup>4</sup>, the process is:

- 18 1. To obtain the quantity of small fines, multiply the volume of a material in the ZOI  
19 computed in the debris generation section by the recommended value of the small  
20 size percentage.
- 21 2. To obtain the quantity of large pieces, multiply the volume of a material in the ZOI  
22 computed in the debris generation section by the recommended value of the large  
23 size percentage.
- 24 3. Recent surveys of U.S. PWR containments per NEI 02-01 have determined that the  
25 majority of the coatings on structures, systems, and components within  
26 containment can be classified into three major categories:
  - 27 a. Inorganic zinc primers
  - 28 b. Epoxy primers and topcoats
  - 29 c. Epoxy phenolic primers and topcoats

30 Plant-specific information should be used to estimate the thickness of the coatings.  
31 For those plants that do not have detailed plant-specific information, the following  
32 guidance is provided. For coatings within the ZOI, multiply the area of the coating  
33 ZOI as determined in the debris generation section by the thickness of the coating

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3 For definitions of DBA-qualified/acceptable, DBA-unqualified/unacceptable, and indeterminate coatings, see ASTM D5144-00, "Standard Guide for Use of Protective Coating Standards in Nuclear Power Plants."

4 Plant-specific information size distribution based on qualification testing should be used in lieu of the general recommendation of the NEI Guideline.

1 system: 3 mils inorganic zinc primer plus 6 mils epoxy/epoxy phenolic topcoat<sup>5</sup> to  
 2 obtain the quantity (volume) of coating debris small fines from a ZOI. Coatings  
 3 within the ZOI will be reduced, worst case, post-DBA to small ( $10\ \mu\text{m}^6$ ), pigment-  
 4 sized particles (see Table 3-3).

5 To obtain the quantity (volume) of coating debris outside the ZOI, multiply the total area of  
 6 DBA-unqualified/unacceptable and indeterminate coatings<sup>7</sup> in containment by the worst case of  
 7 3 mils inorganic zinc primer. Note that epoxy and epoxy phenolic coating failure outside the ZOI  
 8 will result, in all likelihood, in debris that are relatively larger, highly cohesive, and no smaller in  
 9 the worst case than  $25\ \mu\text{m}$ . Unfortunately, there are no applicable experimental data as to the size  
 10 distribution of failed DBA-unqualified/unacceptable and indeterminate coatings when subjected  
 11 to a post-DBA environment. As such, the assumption that an equivalent volume of inorganic zinc  
 12 particulate debris (particle size  $10\ \mu\text{m}$ ) is conservative.

### 13 3.4.3.5 Sample Calculation

14 Material in the ZOI:

- 15 • Total volume of Nukon blankets in ZOI:  $300\ \text{ft}^3$
- 16 • Quantity of small fines of Nukon in the ZOI:  $300\ \text{ft}^3 * 60\% = 180\ \text{ft}^3$
- 17 • Quantity of large pieces of Nukon in the ZOI:  $300\ \text{ft}^3 * 40\% = 120\ \text{ft}^3$
- 18 • Total area of RMI material in ZOI:  $15,000\ \text{ft}^2$
- 19 • Quantity of small fines of RMI in the ZOI:  $15,000\ \text{ft}^2 * 75\% = 11,250\ \text{ft}^2$
- 20 • Quantity of large pieces of RMI in the ZOI:  $15,000\ \text{sq ft} * 25\% = 3,750\ \text{ft}^2$

21 Coatings:

22 The baseline sample plant has not conducted a detailed containment coating walkdown. From the  
 23 debris generation, the coating ZOI has a radius of 10 inches. The surface area of a 10-inch sphere  
 24 is  $8.7\ \text{ft}^2$ . The total quantity of failed coatings from the ZOI can be calculated as:  $8.7\ \text{ft}^2 * 7.5\ \text{E-4}\ \text{ft}^8 = 0.007\ \text{ft}^3$  of IOZ equivalent debris.

26 From the plant Appendix R, the total quantity of coatings in containment is  $190,000\ \text{ft}^2$ . From the  
 27 plant construction records a total of  $160,000\ \text{ft}^2$  can be shown to be DBA qualified. Hence the  
 28 total quantity of DBA-unqualified/unacceptable and indeterminate coatings is estimated to be

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5 Typical dry-film thickness values for inorganic zinc primers and epoxy/epoxy phenolic primers and topcoats are taken from coating manufacturer's product data sheets (for instance, Carboline CZ 11, Carboline Phenoline 305 primer and finish, Ameron D-6, Ameron D-9, Ameron Amercoat 66) for coating products currently installed in U.S. PWR containments.

6 The 10-micron size is conservative (i.e., more transportable and causes higher head losses) than the larger sizes suggested in subsection 3.3.3 and Appendix A.

7 For definitions of DBA-unqualified/unacceptable and indeterminate coatings, see ASTM D5144-00, "Standard Guide for Use of Protective Coating Standards in Nuclear Power Plants."

8  $9\ \text{mils} = 7.5\ \text{E-04}\ \text{ft}$

1 30,000 ft<sup>2</sup>. The total quantity of small fines coating from outside ZOI: (30,000 ft<sup>2</sup> of total  
 2 quantity of unqualified and undetermined coating in containment less the 0 ft<sup>2</sup> of unqualified and  
 3 undetermined coating on piping that is covered by undamaged insulation.) \* 2.5E-4 ft<sup>9</sup> = 7.5 ft<sup>3</sup>  
 4 of IOZ equivalent debris.

### 5 **3.4.3.6 Debris Characteristics for Use in Debris Transport and Head Loss**

6 The debris characteristics for the small fines size adopted by this guideline are those in the  
 7 following tables labeled as characteristic size. The next sections describe the characteristics of  
 8 common fibrous coatings and particulate debris.

9 The characteristic sizes listed are the most conservative values that can be associated with debris  
 10 transport and head loss since they are the size that will have the highest transport factor and  
 11 cause the highest head loss. Other small debris characteristic sizes can be adopted in lieu of those  
 12 listed for materials that have applicable transport and head loss experimentally determined  
 13 characteristic sizes. Plant-specific data can supersede these where necessary and appropriate.

### 14 **Mass Insulation**

15 This class of insulation includes low-density fiberglass (~2.4 lbm/ft<sup>3</sup>), medium-density  
 16 fiberglass, and preformed fiberglass, as well as fiber felt materials. It also includes microporous  
 17 insulation such as MinK and Microtherm, as well as calcium silicate insulation.

18 There are three principal types of mass insulation in PWR containments:

- 19 • Fibrous insulation (including asbestos)
- 20 • Granular insulation (calcium silicate and microporous)
- 21 • Cellular insulation

22 The characteristic densities and sizes for thermal insulation materials that have been identified as  
 23 potential debris in nuclear containments are listed in Table 3-2. Some are listed by trade names  
 24 and some by generic names, whereas others are listed as a system and still others as simply an  
 25 insulation material. For materials not listed, the manufacturer should be contacted to obtain the  
 26 type of information listed in Table 3-2.

27 Fibrous insulation materials include fibrous glass wool such as Performance Contracting's  
 28 Nukon, Transco Products' Thermal Wrap<sup>®</sup>, pre-formed fiberglass pipe (made by Owens-Corning,  
 29 Knaupf, and Johns-Manville), and fiberglass pipe and tank wrap (from the same three  
 30 manufacturers).

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9 3 mils = 2.5 E-04 ft

**Table 3-2. Mass Insulation Material Debris Characteristics<sup>(1)</sup>**

Debris Name	Insulation Material Description	As-Fabricated Density (lb/ft <sup>3</sup> )	Material Density (lbm/ft <sup>3</sup> )	Characteristic Size <sup>(2)</sup>	
				µm	inch
PCI's Nukon Blankets	Removable and reusable blankets with woven glass fiber cloth covering fibrous glass insulating board (referred to by the NRC as a "LDFG")	2.4	159	7.0 fiber diameter	28E-05
Fiberglass – preformed pipe	Knauf fibrous glass wool preformed into cylindrical shapes	4.0 +/- 10% or	159	7.5 fiber diameter	30E-05
Fiberglass – preformed pipe	Owens-Corning fibrous glass wool preformed into cylindrical shapes	3.5 to 5.5	159	8.25 fiber diameter	33E-03
Fiberglass – pipe and tank wrap	Fibrous glass wool wrap, using perpendicularly oriented fibers, adhered to an all-service jacketing (ASJ) facing (made by Knauf, Owens-Corning, and others)	3.0 +/- 10%	159	6.75 fiber diameter	27E-05
Transco's Thermal Wrap Blankets	Removable and reusable blankets with woven glass fiber cloth covering fibrous glass insulation )	2.4 <sup>(Ref. 17)</sup>	159	5.5 fiber diameter	22E-05
Knauf	Knauf ET Panel (LDFG similar to Nukon)	2.4	159	5.5 fiber diameter	22E-05
Temp-Mat and Insulbatte	Glass fibers needled into a felt mat; these are trade names of insulation products made by JPS Corp.	11.8 <sup>(Ref. 9)</sup>	162 <sup>(Ref. 9)</sup>	9.0 fiber diameter	36E-05 max. average <sup>(Ref. 13)</sup>
Cellular Glass	Foamglas is the trade name for this cellular glass product made by Pittsburgh Corning Corporation	6.1 to 9.8 (mean value of 7.5)	156	NA	0.05 to 0.08 pore size, grain size unknown
Kaowool	Needled insulation mat made from ceramic fibers; Kaowool is a trade name for a family of ceramic fiber products made by Thermal Ceramics, Inc.	3 to 12 <sup>(Ref. 10)</sup>	160 to 161	2.7 to 3.0 fiber diameter	10.8 to 12.0 E-05
Cerawool	Needled insulation mat made from ceramic fibers; Cerawool is a trade name for a family of ceramic fiber products made by Thermal Ceramics, Inc.	3 to 12 <sup>(Ref. 10)</sup>	156 to 158	3.2 to 3.5 fiber diameter	12.8 to 14.0E-05
Mineral Wool	Generic name for families of products made by Rock Wool Mfg., Roxul, Fibrex, IIG, and others	4, 6, 8, 10 are standard	90	5 to 7 fiber diameter	20 to 28 E-05

1

**Table 3-2. Mass Insulation Material Debris Characteristics<sup>(1)</sup> (Cont'd)**

Debris Name	Insulation Material Description	As-Fabricated Density (lb/ft <sup>3</sup> )	Material Density (lbm/ft <sup>3</sup> )	Characteristic Size <sup>(2)</sup>	
				µm	inch
K <sup>®</sup>	Trade name of microporous insulation products made by Thermal Ceramics, Inc. from fumed silica, glass fibers, and quartz fibers	8 to 16	NA	< 0.1	< 4E-06
Calcium Silicate	Manufactured by IIG in three locations (2 use diatomaceous earth, 1 uses expanded perlite)	14.5	144 <sup>(Ref. 11)</sup>	5 µm mean particle size (2 to 100 µm range) <sup>(Ref. 16)</sup>	20E-05
Microtherm	Microporous Insulation	5 to 12 <sup>(Ref. 13)</sup>	NA	<0.2	<4.0E-06
Asbestos	Structural fiber used in Cal-Sil type ins.	7 to 10 <sup>(Ref. 12)</sup>	153	1 to 8	4 to 32E-05

1. For materials not listed, the manufacturer should be contacted for the information.
2. The sizes listed are to be used in the NUREG/CR-6224 head loss correlation as initial values in the absence of applicable experimental data.

2

3 The NRC refers to the insulation fillers in Nukon, Thermal Wrap, and Knaupf-ET as “low  
4 density fiberglass” (LDFG). The LDFG materials are soft, loose and contain minimal binders.  
5 There are extensive test data for LDFG. There are also some glass fiber felt mat insulation  
6 materials and these include Temp-Mat<sup>®</sup> and Insulbatte<sup>®</sup> insulations, both made by JPS Corp., as  
7 well as some by other trade names such as AlphaMat<sup>®</sup> by Alpha Inc. Again, these are relatively  
8 soft and loose. Other fibrous materials include ceramic felt mat insulation, two of which are  
9 Kaowool<sup>®</sup> and Cerawool<sup>®</sup>, both by Thermal Ceramics, Inc.

10 Finally, there are mineral wool insulation products with a number of different trade names,  
11 forms, and densities. Major North American manufacturers include Rock Wool Manufacturing,  
12 Roxul, Fibrex, IIG, and Thermafiber. These materials have higher densities and are generally  
13 stiffer, having more binder and particulate. While mineral wool has been widely used in Europe,  
14 it has limited use in North American nuclear containments. Mineral wool was the original  
15 drywell piping insulation at the Barseback Plant that was blown off by a lifted steam relief valve  
16 and which subsequently blocked ECCS strainers. In general, mineral wool is available in  
17 densities that are at least twice those of comparable fibrous glass wool insulations, up to ~10 pcf.

18 Asbestos insulation may be encountered at some plants. It is typically used as a structural fiber in  
19 calcium silicate insulation and sold under the trade name Unibestos.

20 Granular insulation materials include calcium silicate and microporous insulation. All the  
21 calcium silicate insulation in North America has been manufactured without the use of asbestos  
22 since about 1972. Produced by various manufacturers over the years, today all calcium silicate is  
23 manufactured by IIG, a joint venture between Calsilite Corp. and Johns-Manville Corp., at three

1 factories. The only microporous insulation manufactured in North America is MinK,  
2 manufactured by Thermal Ceramics, Inc. today but by Johns-Manville for many years.  
3 Microtherm, manufactured in the UK, is also available in North America.

4 The only cellular insulation in Table 3-2 is cellular glass. Most of what has been installed in U.S.  
5 nuclear plants has been manufactured by Pittsburgh Corning Corporation and is known by its  
6 trade name, Foamglas<sup>®</sup>. This is an inorganic, rigid, and brittle cellular insulation typically used in  
7 containments on chilled water lines. However, for reference, there are numerous other types of  
8 cellular insulation available that are organic compounds. These include melamine, polystyrene,  
9 polyisocyanurate, phenolic, polyimide, polyolefin, flexible elastomeric, and polyurethane foams.  
10 There are numerous trade names by which these are known. The best known is Dow Chemical's  
11 Styrofoam, which is polystyrene foam insulation.

## 12 **Failed Coatings**

13 To properly characterize coating debris for the head loss evaluation, the type, mass, application  
14 thickness, particle sizes, and surface area or volume are necessary inputs, and these should be  
15 specified to the extent practicable in the debris generation and debris transport calculations. The  
16 quantity of a failed coating is adequately specified by the mass of the coating and its density.  
17 Alternatively, the surface area of the failed coating, along with its thickness and the density, can  
18 be used to determine the mass.

19 Unless replaced by plant-specific information of higher value, Table 3-3 lists the bulk density  
20 and the characteristic size and shape for various types of coating debris, and these can be used  
21 for the evaluation. The actual size distributions of these materials in a post-DBA environment are  
22 not known. Thus, the table lists particle sizes that are conservative (i.e., small) for head loss  
23 evaluations. Plant-specific data, if available, can supersede these data.

24 The following types of coatings are commonly found within PWR containments: inorganic zinc  
25 (IOZ), epoxy, epoxy-phenolic and alkyd. The densities for the epoxy, epoxy-phenolic, and alkyd  
26 coatings listed in Table 3-3 are based on specific gravities presented in the "Performance of  
27 Containment Coatings During a Loss of Coolant Accident." (Reference 18). The density for IOZ  
28 is 437 lbm/ft<sup>3</sup> as reported by Carboline for the zinc dust used in the formulation of CarboZinc-11.

29 This guidance assumes complete destruction of coatings within the coating ZOI. In the absence  
30 of specific experimental data about the debris particle size distribution for IOZ, alkyds, epoxy,  
31 and epoxy-phenolic coating debris generated by high-pressure water or steam jets in the ZOI, a  
32 diameter of 10 μm is assumed as the characteristic size of coating debris generated within the  
33 ZOI. The 10-μm characteristic diameter is the nominal diameter of unbound zinc particles and  
34 also the alkyd pigment particles of failed coatings. Coatings outside the ZOI that have not been  
35 demonstrated to be DBA-qualified or "acceptable," or whose qualification is "indeterminate,"  
36 are assumed to fail as chips. A typical lower bound for epoxy and epoxy-phenolic coating chip  
37 thickness is 1 mil (25.4 μm). A 10-micron (10 μm) diameter is assumed as the characteristic size  
38 of debris from IOZ and alkyd coatings outside the ZOI that have not been demonstrated to be  
39 DBA-qualified or "acceptable," or whose qualification is "indeterminate."

1

**Table 3-3. Coating Debris Characteristics**

<b>Generic Coating Material</b>	<b>Material Density (lb/ft<sup>3</sup>)</b>	<b>Characteristic Size (μm)</b>	<b>Characteristic Size (ft)</b>
Inorganic Zinc (IOZ)	457	10 <sup>(1)</sup>	3.28E-05 <sup>(1)</sup>
Epoxy and Epoxy Phenolic Coating Chips (outside ZOI)	94	25 <sup>(2)</sup>	8.20E-05 <sup>(2)</sup>
Epoxy and Epoxy Phenolic Coating Particles (in ZOI)	94	10 <sup>(1)</sup>	3.28E-05 <sup>(1)</sup>
Alkyd Coating	98	10 <sup>(1)</sup>	3.28E-05 <sup>(1)</sup>
Aluminum	90	10 <sup>(2)</sup>	3.28E-05 <sup>(2)</sup>

1. Spherical particle diameter
2. Flat plate thickness

## 2 **3.5 LATENT DEBRIS**

### 3 **3.5.1 Discussion**

4 The potential for latent debris in containment during plant operation that may impact head loss  
5 across the emergency core cooling sump screens should be considered. Therefore, it is necessary  
6 to determine the types, quantities, and locations of latent debris sources.

7 Due to the variations in containment design and size from unit to unit, many miscellaneous  
8 sources should be evaluated on a plant-specific basis. It is not appropriate for the licensees to say  
9 that their foreign materials exclusion (FME) programs can entirely eliminate sources of  
10 miscellaneous debris unless plant-specific walkdowns verify this. Plant-specific walkdown  
11 results can be used to determine a conservative amount of dust and dirt to be included in the  
12 debris source term. The walkdown will not be able to directly measure this type of debris.  
13 However, it is possible to quantify the amount of debris with additional steps.

14 It is recommended that the following activities be performed to quantify the amount of latent  
15 debris inside containment:

- 16 • Calculate the horizontal and vertical surface areas inside containment. This  
17 calculation will determine the total area with the potential for accumulation of  
18 debris.
- 19 • Evaluate the resident debris buildup. It is necessary to determine the amount of  
20 debris present on surfaces inside containment.
- 21 • Define the debris characteristics. This information will be used in subsequent steps  
22 of the sump performance evaluation.



- 1           • Calculate the total quantity and composition of debris. This information will also be  
2           used in subsequent steps of the sump performance evaluation, such as evaluation of  
3           the transport of latent debris to the sump screen and the resulting head loss.

4 Detailed guidance for accomplishing the recommended activities for quantification of the  
5 amount of latent debris is provided below.

### 6 **3.5.2 Baseline Approach**

7 Latent debris is a contributor to head loss across the sump screen and should be evaluated  
8 accordingly. Information is provided in the guidance below to evaluate the quantity of latent  
9 debris with sufficient rigor to eliminate excessive conservatism. Note, however, that in many  
10 cases, the contribution to head loss by latent debris will be small in comparison to that caused by  
11 debris from other sources such as insulation materials. In these cases, latent debris will not  
12 determine the course of action for mitigating ECCS sump strainer issues.

13 The impact on the results of the sump performance evaluation as a whole should be considered  
14 before performing an extremely rigorous analysis of latent debris loading. While it is possible to  
15 evaluate the effects of latent debris to a high degree of detail, use of conservative strategies is  
16 recommended. Furthermore, the use of conservative strategies in the evaluation of latent debris  
17 effects can provide for more head loss analysis margin and can improve operational flexibility if  
18 sump modifications are made.

#### 19 **3.5.2.1 Estimate Horizontal and Vertical Surface Area Inside Containment**

20 Estimates are made of the horizontal and vertical surface areas. Vertical surfaces such as walls  
21 and sides of equipment are considered although a significant amount of debris does not typically  
22 collect on vertical surfaces in the absence of factors that promote adhesion of solids to the  
23 surface.

24 The following is a sample of the surfaces that are included in the surface area estimate:

- 25           • Floor area  
26           • Walls  
27           • Cable trays  
28           • Major ductwork  
29           • Control rod drive mechanism coolers  
30           • Tops of reactor coolant pumps  
31           • Equipment (such as valve operators, air handlers, etc.)

32 Other surfaces should be included as appropriate for plant-specific applications (junction boxes,  
33 etc.).

1 Use the following guidance in the calculations:

2 1. Flat surfaces are considered to be floors, cable trays, AOV diaphragms, and other  
3 flat or nearly flat surfaces. The bases for this are:

4 • Unless the surface is highly convoluted (e.g., a heat exchanger or similar  
5 device), assuming a flat surface will not have a significant effect on the  
6 surface area calculation. Furthermore, the area projected onto the horizontal  
7 plane by the surface would be the key determining factor for the settling and  
8 accumulation of debris. For example, while a series of heat exchanger fins  
9 may have a large surface area, a significant percentage of that area could be  
10 vertical which would preclude accumulation of debris on much of the surface  
11 area.

12 • The surface area calculations are greatly simplified if the intricacies of  
13 surfaces are not explicitly accounted for.

14 2. Half of the surface area of round surfaces such as conduits and ladder rungs is used.  
15 The basis for this assumption is that the lower half of the surface area is either  
16 inverted or tangent to the vertical plane, so accumulation of debris in this area does  
17 not occur. In reality, it is likely that the percentage of surface area susceptible to  
18 debris accumulation is less than half, because it is unlikely that debris would  
19 remain on the regions of the surface that are nearly vertical.

20 3. Ten percent of the vertical surfaces inside containment is used. The basis for this  
21 assumption is that accumulation of debris on vertical surfaces will typically not  
22 occur, but is considered for conservatism. Although walls are considered, the  
23 containment dome itself is not considered. Debris accumulation on this surface is  
24 precluded because it is inverted or tangent to the vertical plane.

25 4. Perform thorough calculations to determine the surface area to be considered for  
26 each area of containment. The information needed to perform the calculations can  
27 be obtained through plant drawings (plans) and photographic evidence obtained  
28 during containment walkdowns.

29 5. If exact dimensions are unavailable, use estimated dimensions. Acceptable sources  
30 of estimated dimensions are plant drawings (plans) that do not include explicit  
31 dimensions for the component in question (i.e., a representation of the component  
32 is shown but not detailed) and photographic evidence. Conservatively large values  
33 shall be used when dimensions are estimated and bases for the values used shall be  
34 provided.

### 1 3.5.2.2 Evaluate Resident Debris Buildup

2 Although recent sampling of surfaces inside containment at a number of plants indicated that it is  
3 likely that the maximum mass of latent debris inside containment is less than 200 pounds, it is  
4 recommended that a survey of the containment be performed, with the objective of determining  
5 the quantity of latent debris.

6 Surveying the containment for latent debris will ensure that higher-than-average debris loads are  
7 accounted for and will allow plants to take advantage of smaller latent debris loading if lower  
8 quantities are present.

9 Note that it will be necessary to perform periodic surveys (as part of outage efforts) to validate  
10 that there has been no significant change in the latent debris load inside containment. This  
11 evaluation of the presence of foreign material is described in NEI-02-01 (Reference 2). The  
12 necessary rigor of these surveys is dependent on the effectiveness of the licensee's FME and  
13 housekeeping programs with respect to containment cleanliness. If the licensee has rigorous  
14 programs in place to control the cleanliness of containment and documents the condition of  
15 containment following an outage, it is adequate to perform inspections and limited sampling of  
16 surfaces. If the cleanliness of containment is not controlled through rigorous programs, or if the  
17 programs in place do not address all areas of containment, it is necessary to perform more  
18 comprehensive surveys.

#### 19 3.5.2.2.1 Evaluate the Resident Debris Buildup on Surfaces

20 To quantify the amount of latent debris on horizontal surfaces in containment, determine the  
21 thickness of the debris layer on a surface and the surface area the layer covers. This information  
22 can be used with the macroscopic debris density (with respect to volume) to determine the mass  
23 of debris present.

24 Use the following steps to evaluate the resident debris buildup on horizontal surfaces:

25 1. Divide containment into areas based on the presence of robust barriers. This will  
26 allow differing (from section to section) latent debris concentrations and  
27 compositions to be adequately represented and will facilitate subsequent debris  
28 transport calculations. Examples of appropriate areas include:

- 29 • Accumulator rooms
- 30 • In-core instrumentation room
- 31 • Loop subcompartments
- 32 • Steam generator or pressurizer subcompartments

33 2. Determine representative surfaces for each section of containment. For each  
34 section, this involves defining survey areas of known dimensions. The number of  
35 sampling areas examined per section of containment must be determined on a  
36 plant-specific basis. Use the following guidance to select representative surfaces:

- 1           • If the worst surface in a given section can be readily identified, it is  
2           acceptable to use that surface to represent the entire section. For example, if  
3           little or no debris is present on the surfaces in a section except for one, that  
4           one surface can be used to represent the debris accumulation in the entire  
5           section.
  
- 6           • If multiple surfaces have debris accumulation with different compositions  
7           and thicknesses, it is necessary to sample each of the surfaces to adequately  
8           represent the latent debris load for that section.
  
- 9           • If the area has a uniform and homogeneous latent debris load, a convenient  
10          surface can be chosen as the representative surface.

11          3. Survey the representative surfaces in each section to measure the debris quantity.  
12          Take care to ensure that all health physics procedures are followed for any samples  
13          collected. Two strategies are recommended.

- 14          • Collect the debris using equipment that will allow measurement of the  
15          quantity of debris at a later time. The volume of debris collected is then  
16          divided by the surface area to determine the thickness of the debris layer.

17                 The collection method should allow estimation of the debris layer thickness  
18                 and not change the macroscopic density of the debris that is collected. An  
19                 acceptable method for collection is the use of swipes to remove the debris  
20                 from the area in question. Since there is the potential to damage samples  
21                 during the collection process, take care to not destroy or otherwise change the  
22                 physical properties of the debris.

- 23          • Measure or estimate the thickness of the debris layer directly. Since it is  
24          unlikely that a measurement device (such as calipers) can determine the layer  
25          thickness directly, it is recommended that the layer thickness be determined  
26          by comparison to an object of known or measurable thickness. Since the  
27          debris layers are expected to be quite thin (mils or fractions of mils),  
28          comparison to objects like sheets of paper or very thin sheets of metal is  
29          recommended.

30                 While it is possible to determine the thickness of the debris layer to an acceptable  
31                 degree of accuracy, it may be difficult to accomplish, even if the debris layer is of  
32                 uniform thickness and homogeneous composition. Therefore, care should be taken  
33                 in the measuring process to achieve the most accurate results possible.

34          4. Calculate the thickness of the debris layer, based on the quantity of debris collected  
35          and the surface area of the sampling area.

### 1 3.5.2.2.2 Evaluate the Quantity of Other Miscellaneous Debris

2 In addition to determining the amount of latent debris accumulation on surfaces, other  
3 miscellaneous debris sources are to be accounted for in the debris source term. The survey of  
4 containment for these materials is to be performed consistent with the guidance in NEI 02-01  
5 (Reference 2). Use the following guidance for each source to be considered:

- 6 • Equipment tags: Determine the number and location of equipment tags of each  
7 material type (paper, plastic, metal) within containment. Evaluate the transport of  
8 tags to the sump screen when performing the debris transport analysis  
9 (Section 3.6). Although paper tags may dissolve in the post-accident containment  
10 environment, it is conservative to assume that they remain intact and available for  
11 transport to the sump screen. This assumption shall be used unless there is  
12 information that indicates the tags will not remain intact.
  
- 13 • Tape: Determine the amount and location of each type of tape within containment.  
14 Evaluate the transport of tape to the sump screen when performing the debris  
15 transport analysis (Section 3.6). Although FME and housekeeping programs will  
16 remove most of the tape used during outage and construction activities, there may  
17 still be quantities present in containment. These pieces of tape could be in  
18 inaccessible areas or attached to components in plain view. Pieces of tape that have  
19 partially disintegrated from being in containment during plant operation should be  
20 considered in the latent debris source term. Additionally, tape affixed to surfaces  
21 such as ladder rungs to improve grip shall be assumed to fail and become  
22 transportable debris.
  
- 23 • Stickers or placards affixed by adhesives: Include items such as stickers and signs  
24 that are not mechanically attached to a structure or component in the latent debris  
25 source term. Evaluate the transport of these materials to the sump screen when  
26 performing the debris transport analysis (Section 3.6). It is likely that adhesives  
27 would fail in post-accident conditions. Assume that all stickers and placards affixed  
28 by adhesives fail and become transportable debris.

### 29 3.5.2.3 Define Debris Characteristics

30 Debris characteristics can be defined using two methods:

- 31 • Analyze debris samples to determine composition and physical properties.
- 32 • Assume composition and physical properties of the debris, using conservative  
33 values.

34 Because of the additional rigor and complexity as well as the additional time required to perform  
35 detailed analysis of the samples, it is recommended that conservative characteristics (with  
36 respect to head loss, as documented in Section 3.7) are assumed for the latent debris. The  
37 following debris characteristics should be used:

- 1           •     Use an appropriate fiber/particulate mix for the plant being evaluated.
- 2           •     Fiber density = 62.4 lbm/ft<sup>3</sup>. The basis for this value is that it effectively makes the  
3           fiber neutrally buoyant, which results in maximum transport to the sump screen.
- 4           •     Particle density = 100 lbm/ft<sup>3</sup>. The basis for this value is that most particulate  
5           material can be categorized as “dirt.” A representative material would likely be soil  
6           or sand, brought into containment during outage activities or construction.  
7           According to Reference 19, the densities of “Earth,” dry and packed and “Sand” are  
8           both 95 lbm/ft<sup>3</sup>. Therefore, 100 lbm/ft<sup>3</sup> is recommended.
- 9           •     Particle diameter = 10 μm. Based on typical diameter of dust particles  
10          (Reference 20), a diameter of 10 μm is suggested. This diameter is conservatively  
11          small with respect to transport to the sump screen, since the diameter of “dirt”  
12          particles such as earth or sand is larger than that of dust. Furthermore, the diameter  
13          of 10 μm is consistent with the size of particles of failed coatings (Reference 21).

14 Note that ongoing research efforts by NRC and Los Alamos National Labs may provide  
15 additional information regarding the physical characteristics of latent debris.

16 If it is decided to analyze the debris samples to determine the composition and physical  
17 properties, the work should be performed by a laboratory experienced in material identification,  
18 analysis of the macroscopic and microscopic properties of material samples, and handling of  
19 radioactive materials. Note that there are challenges to effectively determining the debris  
20 characteristics by analysis:

- 21           •     It is likely that thorough analysis of samples would be extremely expensive,  
22           possibly with little benefit.
- 23           •     It is potentially impractical or impossible to separate the debris from the media or  
24           device used to capture it.
- 25           •     It is possible that the macroscopic density of the debris as well as other  
26           characteristics will be changed during the sampling process or transportation to the  
27           analysis facility. These changes in characteristics would result because it is likely  
28           that the debris is not a homogenous solid; therefore it is possible for the debris to be  
29           compacted, damaged, or otherwise manipulated.

#### 30 **3.5.2.4 Determine Fraction of Surface Area Susceptible to Debris Accumulation**

31 Not all areas are susceptible to accumulation of debris. For example, housekeeping activities at  
32 some plants may involve cleaning floors with special wipes, vacuum cleaners, or other methods. In  
33 these cases, the areas that are within the scope of the cleaning program could have essentially no  
34 debris accumulation, whereas inaccessible areas of the same surface could have an accumulation of  
35 debris. A single debris layer thickness would not accurately represent the entire surface.

1 It is appropriate to conservatively assume that the entire surface area is susceptible to debris  
2 accumulation. If it is unreasonable to use this assumption, in addition to determining the total  
3 horizontal surface area inside containment (per subsection 3.5.2.1) it is necessary to determine  
4 the fraction of the surface area of each component and surface that is susceptible to debris  
5 accumulation. To accomplish this, evaluate the fraction of the surface area susceptible to debris  
6 accumulation a component-by-component or surface-by-surface basis using the results from  
7 subsections 3.5.2.1 and 3.5.2.2 as input. Use the following guidance:

- 8 1. Assume that 100 percent of the surface area is susceptible to debris accumulation  
9 for inaccessible areas as well as accessible areas that are not thoroughly cleaned  
10 and documented as clean per plant procedures prior to restart (e.g., cable trays,  
11 junction boxes, and valve operators), and floors with gratings sitting on flat  
12 surfaces.
- 13 2. Evaluate the fractional area susceptible to debris accumulation for smooth floor  
14 areas and other surfaces cleaned per plant procedures prior to restart on a case-by-  
15 case basis. Considerations include the method of cleaning (e.g., pressure washing  
16 versus vacuuming) and accessibility of areas. Because of wide variations in  
17 containment design and effectiveness of housekeeping and FME programs,  
18 evaluations must be performed on a plant-specific basis.

19 For all cases in which the area susceptible to debris accumulation is reduced, a  
20 conservatively large fractional area susceptible to accumulation must be  
21 determined, and bases must be provided for the fractions used. Use the following  
22 guidance:

- 23 • Calculate the total surface area of the surface being considered.
- 24 • Calculate the area of the surface that is clean. Use simplifying assumptions  
25 that will result in a conservatively small clean area.
- 26 • Calculate the ratio of potentially dirty area to the total area.

### 27 **3.5.2.5 Calculate Total Quantity and Composition of Debris**

28 The final step in determining the quantity of latent debris located inside containment is to  
29 compute the total quantity of latent debris using the results from subsections 3.5.2.1 to 3.5.2.3 as  
30 input.

31 Use the following guidance when performing the final calculations:

- 32 1. The calculations should be performed on an area-by-area basis (consistent with  
33 subsections 3.5.2.1 to 3.5.2.3). Performing the calculations in this way will  
34 facilitate adequate representation of the debris densities and characteristics in the  
35 different areas inside containment.

- 1           2.    Compute the total quantity of debris for each area by multiplying the total surface  
2           area susceptible to debris accumulation by the debris layer thickness for the area of  
3           containment being considered.
- 4           3.    Include quantities of other types of latent debris such as tape, equipment tags, and  
5           stickers.
- 6           4.    Categorize and catalog the results for input to the debris transport analysis.

### 7   **3.5.3   Sample Calculation**

8   The sample calculation considers the bottom level of containment. Equipment tags, tape, and stickers  
9   have been excluded from this example since minimal calculations are required for these items and  
10  guidance is included in Reference 2. The following surfaces are included in the calculation:

- 11           •    Floor areas
- 12           •    Cable trays
- 13           •    Sump drain pumps

14  For an actual calculation, more detail and rigor are required to document all the surface area on a  
15  given level of containment. Since this is a sample calculation, only representative examples were  
16  used.

17  Subsection 3.5.3.1 documents the calculation of the horizontal areas for complex rooms and  
18  cable trays. Subsection 3.5.3.2 documents the calculation of the amount of debris present in the  
19  area being considered.

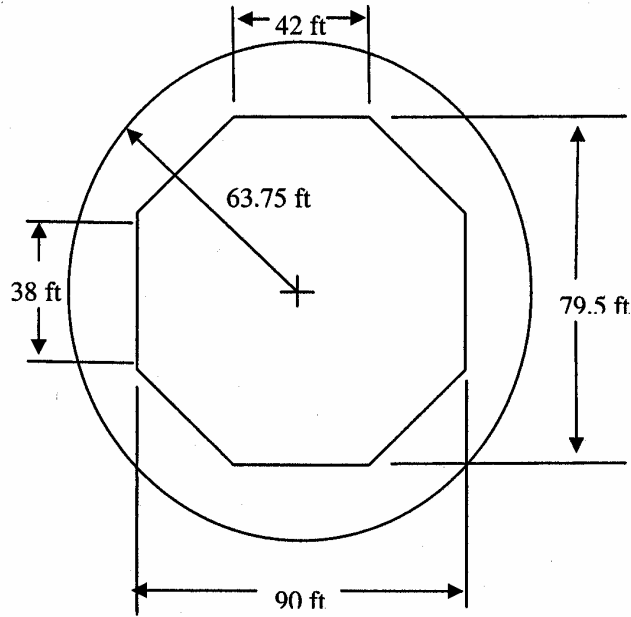
#### 20  **3.5.3.1   Calculate Horizontal Surface Area**

21  The examples below show the calculation of a number of complex floor areas. Rooms of simpler  
22  geometry are calculated with less effort and therefore, examples of those calculations have not  
23  been shown.

- 24           1.    Calculate area between containment shell and steam generator (SG) compartments.

25           The floor area between the containment shell and SG compartments looks roughly  
26           like the region between the octagon and circle in the figure below:





1

2

Therefore, the area of the octagon is calculated as:

3

$$A = (90 \text{ ft}) (75 \text{ ft}) - (4) (0.5) [(0.5) (79.5-38)] * [(0.5) (90-42)]$$

4

$$A = 5754 \text{ ft}^2$$

5

Subtract area of octagonal region from round region:

6

$$A = \pi (63.75 \text{ ft})^2 - 5754 \text{ ft}^2$$

7

$$A = 7014 \text{ ft}^2$$

8

Subtract area of the reactor coolant drain tank (RCDT) room and excess letdown heat exchanger room (these areas protrude from the rough octagonal shape):

9

10

$$A = 7014 \text{ ft}^2 - 56 \text{ ft}^2 - 94.6 \text{ ft}^2$$

11

$$A = 6914 \text{ ft}^2$$

12

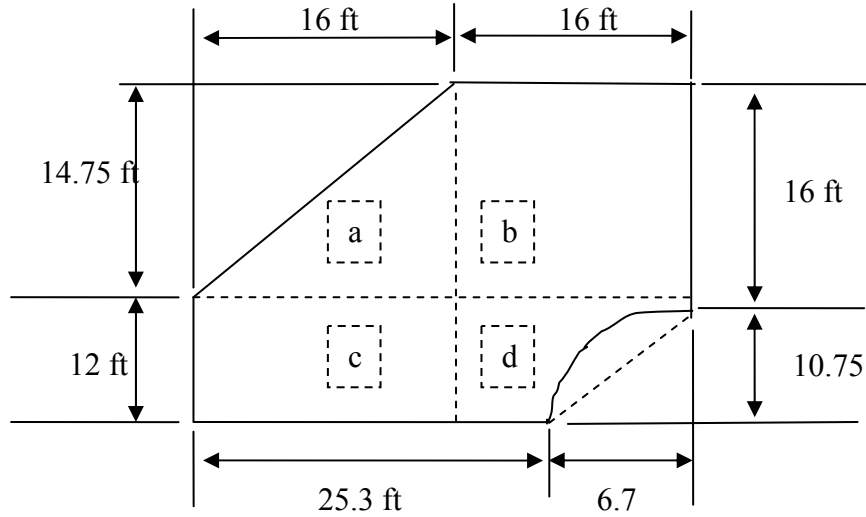
2. Calculate area inside SG compartments.

13

Each SG compartment has a shape and dimensions roughly like the shape with the solid border below. To simplify the calculations, the room was divided into four regions and the round wall was assumed to be straight:

14

15



1

$$A = a + b + c + d$$

2

$$a = 0.5(16 \text{ ft})(14.75 \text{ ft}) = 118 \text{ ft}^2$$

3

$$b = (16 \text{ ft})(14.75 \text{ ft}) = 236 \text{ ft}^2$$

4

$$c = (12 \text{ ft})(16 \text{ ft}) = 192 \text{ ft}^2$$

5

$$d = (16 \text{ ft})(12 \text{ ft}) - (0.5)(10.75 \text{ ft})(6.7 \text{ ft}) = 156 \text{ ft}^2$$

6

$$A = 466 \text{ ft}^2$$

7

8

$$A_{\text{total}} = 4(A) \quad (\text{since there are four steam generators})$$

9

$$= 1864 \text{ ft}^2$$

10

3. Calculate area inside seal table room.

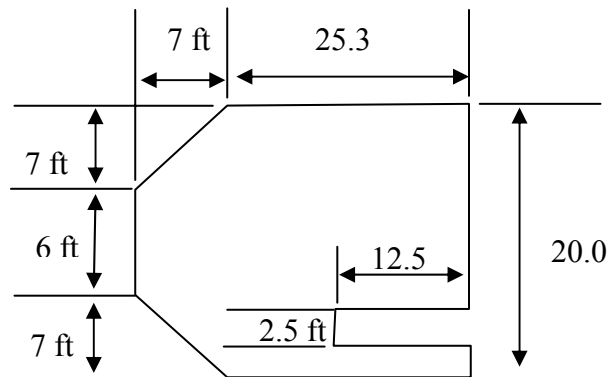
11

The geometry of the seal table room is as shown in the figure below. One simplifying assumption was with regard to the six-foot-long wall. It is actually curved and protrudes into the room, but was assumed to be straight. This assumption results in prediction of a conservatively large floor area.

12

13

14



15

16

$$A = (32.3 \text{ ft})(20 \text{ ft}) - (2)(0.5)(7.0 \text{ ft})(7.0 \text{ ft}) - (2.5 \text{ ft})(12.5 \text{ ft})$$

17

$$A = 563.8 \text{ ft}^2$$

1           4.    Calculate area of cable trays and other components.

2                   For this sample calculation, 300 linear feet of cable trays was assumed. It was also  
3                   assumed that the trays were 1 foot wide, resulting in a total surface area of 300 ft<sup>2</sup>.  
4                   For all cable trays, the length and width should be documented and used to  
5                   calculate the horizontal surface area.

6                   The other example of component surface area in this sample calculation is the  
7                   rectangular cover on the sump drain pumps, as shown in the spreadsheet below. It is  
8                   noteworthy that the covers over the sump were documented as part of the floor  
9                   area, since there is no floor area considered below them.

10                  Other components were not examined in detail for this sample calculation.  
11                  Components that should be examined include, but are not limited to:

- 12                  •    RCS piping and other piping
- 13                  •    Pressurizer relief tank
- 14                  •    Excess letdown heat exchanger (depending on location)
- 15                  •    Air handling units
- 16                  •    RCS draindown tank and associated heat exchanger
- 17                  •    Junction boxes

18   **3.5.3.2 Calculate Quantity of Debris**

19   This section documents sample calculations of the quantity of debris in the area considered. The  
20   calculations are relatively straightforward. To calculate the mass of debris in a given area:

21                  Volume = (Debris layer thickness) \* (Surface area)

22                  Mass = (Volume) \* (Density)

23   Example results are presented in Table 3-4. It is noteworthy that the results are for demonstration  
24   only and are based on hypothetical debris survey results.

25   **3.6 DEBRIS TRANSPORT**

26   **3.6.1 Definition**

27   Debris transport is the estimation of the fraction of debris that is transported from debris sources  
28   (break location) to the sump screen. The four major debris transport modes considered in the NEI  
29   Guidance are:

- 30                  •    Blowdown transport – the transport of debris by the break jet.
- 31                  •    Washdown spray transport – the vertical transport by the containment sprays/break  
32                  flow.

1

**Table 3-4. Sample Calculation of Debris Quantity**

Description	Length ft	Width ft	Surface Area ft <sup>2</sup>	Layer Thickness in	Percent Clean %	Debris Volume ft <sup>3</sup>	Fiber by Volume %	Fiber			Particulates		
								Volume ft <sup>3</sup>	Density lb/ft <sup>3</sup>	Mass lb	Volume ft <sup>3</sup>	Density lb/ft <sup>3</sup>	Mass lb
<b>Floor Areas</b>													
1			6914.0	1.00E-03	25.0	0.43	50.0	0.22	62.40	13.48	0.22	100.00	21.61
2			1864.0	1.00E-03	25.0	0.12	50.0	0.06	62.40	3.63	0.06	100.00	5.83
3	24.00	8.00	192.0	1.00E-03	0.0	0.02	50.0	0.01	62.40	0.50	0.01	100.00	0.80
4	20.00	6.75	135.0	1.00E-03	0.0	0.01	50.0	0.01	62.40	0.35	0.01	100.00	0.56
5	13.30	11.25	149.6	1.00E-03	0.0	0.01	50.0	0.01	62.40	0.39	0.01	100.00	0.62
6	22.25	4.25	94.6	1.00E-03	0.0	0.01	50.0	0.00	62.40	0.25	0.00	100.00	0.39
7			563.8	1.00E-03	0.0	0.05	50.0	0.02	62.40	1.47	0.02	100.00	2.35
<b>Equipment</b>													
1	6.00	4.00	24.0	1.00E-03	0.0	0.00	50.0	0.00	62.40	0.06	0.00	100.00	0.10
2	300.00	1.00	300.0	1.00E-03	0.0	0.03	50.0	0.01	62.40	0.78	0.01	100.00	1.25
<b>Totals</b>						0.67		0.34		20.91	0.34		33.51
Notes: Sump top plate surface area included in Floor Area #1 Calculations for floor areas #1, 2, 7 documented separately Debris layer thicknesses are hypothetical, not based on actual survey data.													

2

3

1           •     Pool fill-up transport – the horizontal transport of the debris by break and  
2           containment spray flows to active and inactive areas of basement pool.

3           •     Recirculation transport – the horizontal transport of the debris in the active portions  
4           of the basement pool by the recirculation flow through the ECCS.

### 5     **3.6.2 Discussion**

6     For the NEI Guidance, the methodology used to determine the amount of debris transported is  
7     based on the methodology reported in Section 4.2 of NUREG/CR-6762, Vol. 4 (Reference 25).  
8     Figure 3-2 depicts the generic transport logic tree for use in the NEI Guidance.

9     Transport fractions for each branch are provided for debris from the ZOI as well as debris  
10    outside the ZOI. These transport fractions are provided for three general types of containments:

- 11           •     Highly compartmentalized containments
- 12           •     Mostly un compartmentalized containments
- 13           •     Ice condenser containments

14    Highly compartmentalized containments are those that have distinct robust structures and  
15    compartments totally surrounding the major components of the RCS, e.g., steam generator and  
16    pressurizer. Typical examples of these containments are Westinghouse three-loop plants and  
17    earlier Combustion Engineering (CE) plants with dry ambient atmosphere containments. Mostly  
18    un compartmentalized containments are those that have partial robust structures surrounding the  
19    steam generators. Typical examples are the Babcock and Wilcox (B&W) dry ambient atmosphere  
20    plants. All of the seven ice condenser plants are four-loop Westinghouse plants with no  
21    compartmentalization in the lower containment. For breaks that are not inside a defined  
22    compartment, the transport fractions of the mostly un compartmentalized containments should be  
23    used.

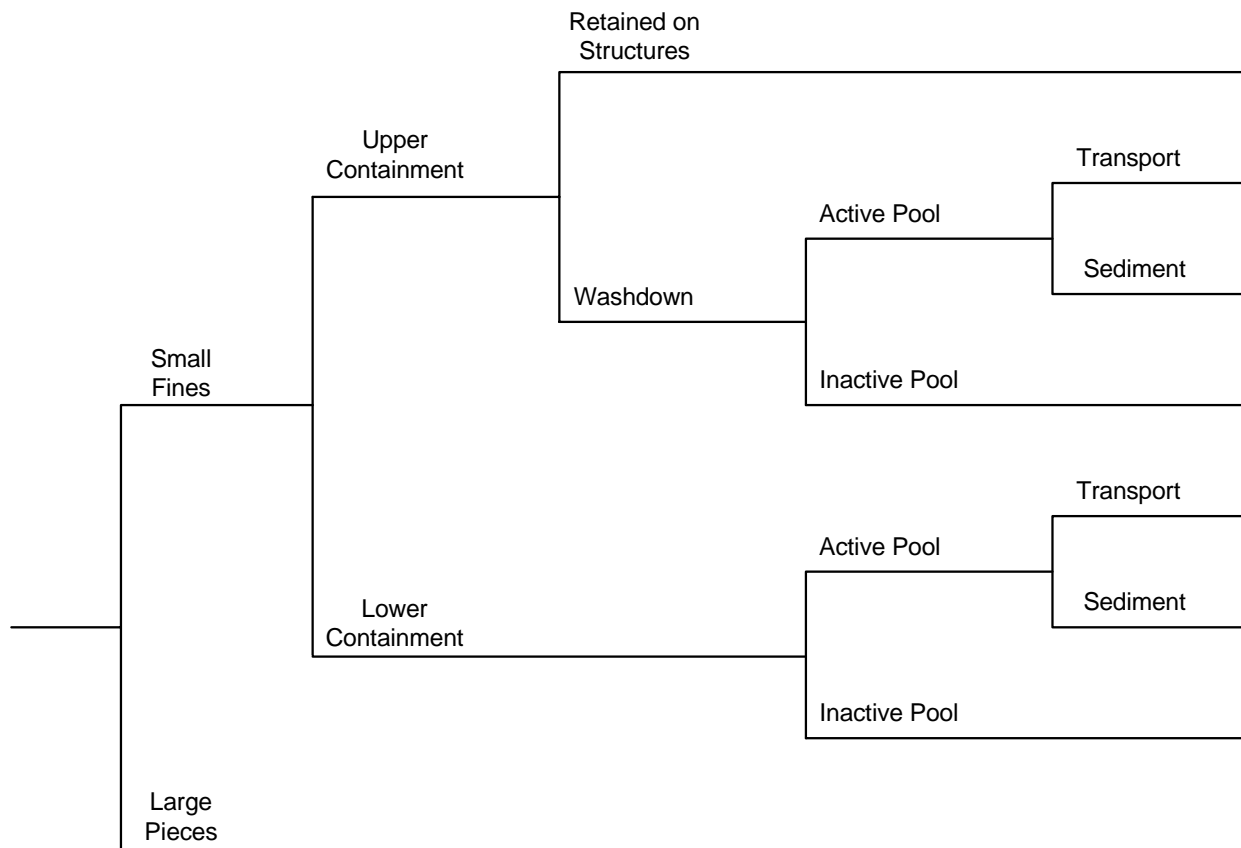
### 24    **3.6.3 Debris Transport**

25    Guidance is provided to calculate the debris transport values for each of the three major types of  
26    containments, for the major categories of debris: fibrous insulation in the break ZOI, RMI  
27    insulation in the break ZOI, other material in the ZOI, and debris outside the ZOI. The type of  
28    material found in each classification is provided in the debris characteristic section and the latent  
29    debris section.

30    The debris characteristic terminologies employed herein are those from the debris characteristics  
31    section. Small fines are defined as any material that could transport through gratings, trash racks,  
32    or radiological protection fences by blowdown, containment sprays, or post-LOCA pool flows.  
33    This guideline assumes the largest openings of the gratings, trash racks, or radiological  
34    protection fences to be less than 4 inches by 4 inches. The remaining material that cannot pass  
35    through gratings, trash racks, and radiological protection fences is classified as large pieces. For  
36    fibrous insulation material, the large pieces are assumed to be jacketed/canvassed, hence not  
37    subjected to further erosion.

1

Debris Size	Blowdown Transport	Washdown Transport	Pool Fill Transport	Recirculation Transport
-------------	--------------------	--------------------	---------------------	-------------------------



2

3

**Figure 3-2. Unquantified NEI Guidance Logic Tree**

1 The Baseline Evaluation guidance considers two transport modes for the containment bottom  
2 floor: pool fill transport and recirculation transport. All plants have a calculation determining the  
3 water level in containment following a DBA. This calculation provides estimates of the volume  
4 of each compartment that are considered to be flooded by the DBA. Using this calculation and a  
5 layout of the containment elevation, an analyst can determine which of the volumes are below  
6 the containment bottom floor. The analyst then needs to review all the lower compartments to  
7 ensure that those volumes do not have drains from the upper part of the containment (e.g.,  
8 refueling pool) that may cause them to participate in the active volumes. This guideline considers  
9 that all volumes at the containment bottom floor elevation will participate in the recirculation  
10 flow path from the containment sprays and break flow to the sump.

11 During the filling of the containment bottom floor pool, as depicted in Figure 1-4 and 1-5 of  
12 NUREG/CR-6808 (Reference 6), the switchover to recirculation has not occurred, hence there is  
13 no preferential direction for water to flow to the sump.

14 In the pool fill transport, this NEI guidance considers that all debris in the containment bottom  
15 floor is uniformly distributed throughout the entire volume of water in containment. This  
16 guidance then considers that the debris transported to the inactive sumps is strictly based on the  
17 ratio of the volume of the inactive sumps to the total water volume in containment at the start of  
18 recirculation. This assumption is clearly conservative, since it ignores the preferential sweeping  
19 of the debris on the containment bottom floor to the inactive sumps by the thin sheets of  
20 high-velocity water. To add to the conservatism, this guidance then considers that all debris  
21 classified as “small fines” or “small RMI pieces” is transported to the sump during recirculation.  
22 Plants can deviate from the Baseline Evaluation guidelines to account for plant-specific features.  
23 Such deviations from the Baseline Evaluation guidance are considered refinements to the  
24 baseline methodology. Additionally, plants may consider implementing refinements identified in  
25 Sections 4 and 5 of this guide.

### 26 **3.6.3.1 Highly Compartmentalized Containment**

27 This guidance assumes that the pipe break in a highly compartmentalized containment occurs at  
28 the bottom of the compartment. For breaks that are not located in the bottom of the compartment  
29 or on upper portion of a compartment, e.g., a main steam line break, the mostly  
30 un-compartmentalized containment values should be used.

### 31 **Fibrous Insulation in the ZOI**

32 The following guidance is provided for all types of fibrous debris in the ZOI.

#### 33 Blowdown Transport

34 Debris transport during blowdown is assumed to cause the small fines debris from the  
35 compartment where the break is postulated to occur to be distributed to all horizontal surfaces  
36 outside the compartments and the dome. Most of the break locations in a compartment are  
37 located in the bottom of the compartment. For conservatism, it is assumed that only 25 percent of  
38 the small fines debris is ejected upward, the rest going to the containment bottom floor. This

1 fraction is derived as a conservative estimate of the free volume in a compartment above the  
2 lower portion of the compartment not occupied by components such as steam generators. The  
3 large debris pieces from the ZOI are assumed to fall to the compartment floor and not be  
4 transported.

#### 5 Washdown Transport

6 Debris transport by the containment spray is assumed to cause all the small fines to be  
7 transported to the containment bottom floor and be evenly distributed on the floor. No transport  
8 of the large pieces is assumed to occur by containment spray.

#### 9 Pool Fill Transport

10 Debris transport in the containment bottom floor pool during fill-up will transport all the small  
11 fines. Some of the small fines will be transported to the inactive volumes of the pool that will not  
12 participate in the recirculation flow, i.e., the cavity under the reactor vessel. The transport factor  
13 to the inactive pools is determined by calculating the ratio of the volumes of the inactive pool to  
14 the total pool volume. No transport of the large pieces is assumed to occur during pool fill-up.

#### 15 Recirculation Transport

16 Debris transport in the containment bottom floor pool during recirculation is assumed to  
17 transport 100 percent of the small fines in the active volumes of the pool to the sump. No  
18 transport of the large pieces is assumed to occur during recirculation.

### 19 **RMI Insulation in the ZOI**

20 The following guidance is provided for all types of RMI debris in the ZOI.

#### 21 Blowdown Transport

22 Debris transport during blowdown is assumed to cause the small RMI debris pieces from the  
23 compartment where the break is postulated to occur to be distributed to all horizontal surfaces  
24 outside the compartment. For conservatism, it is assumed that only 25 percent of the small RMI  
25 debris is ejected upward, the rest going to the containment floor. This fraction is derived as a  
26 conservative estimate of the free volume in a compartment above the lower portion of the  
27 compartment not occupied by components such as steam generators. The large RMI debris  
28 pieces from the ZOI are assumed to fall to the compartment floor and not be transported.

#### 29 Washdown Transport

30 Debris transport by the containment spray is assumed to cause none of the small RMI debris that  
31 are not on the containment bottom floor and are in containment spray pathway to be transported  
32 to the containment bottom floor. The flow velocities and the very shallow pool depths are not  
33 conducive to transport of small RMI debris. No transport of the large pieces is assumed to occur  
34 by containment spray.



## 1 Pool Fill Transport

2 Debris transport in the containment bottom floor pool during fill-up will transport all the small  
3 RMI debris. Some of the small fines will be transported to the inactive volumes of the pool that  
4 will not participate in the recirculation flow, i.e., the cavity under the reactor vessel. The  
5 transport factor to the inactive pools is determined by calculating the ratio of the volumes of the  
6 inactive pool to the total pool volume. No transport of the large RMI pieces is assumed to occur  
7 during pool fill-up.

## 8 Recirculation Transport

9 Debris transport in the containment bottom floor pool during recirculation is assumed to  
10 transport 100 percent of the small RMI debris in the active volumes of the pool to the sump. No  
11 transport of the large RMI pieces is assumed to occur during recirculation.

## 12 **Other Material in the ZOI**

13 All other material in the ZOI, including coatings within the coatings ZOI, will be assumed to  
14 transport similarly to the small fines of fibrous material.

## 15 **Debris from Materials Outside the ZOI**

16 All debris from materials outside the ZOI is considered to be in the active volumes of the pool at  
17 the start of recirculation and 100 percent transported by the active volumes of the pool to the  
18 sump. Latent debris is also considered to be to be in the active volumes of the pool at the start of  
19 recirculation and 100 percent transported by the active volumes of the pool to the sump. This is  
20 conservative since debris from outside the ZOI is not considered to be transported to the inactive  
21 sump.

## 22 **3.6.3.2 Mostly Uncompartmentalized Containment**

23 The following guidance is provided for all types of fibrous debris in the ZOI.

## 24 **Fibrous Insulation in the ZOI**

### 25 Blowdown Transport

26 Debris transport during blowdown is assumed to cause the small fines debris from the  
27 compartment where the break is postulated to occur to be distributed to evenly to all horizontal  
28 surfaces outside the compartments and the dome. The large debris pieces from the ZOI are  
29 assumed to fall to the containment bottom floor and not be transported.

### 1 Washdown Transport

2 Debris transport by the containment spray is assumed to cause all the small fines to be  
3 transported to the containment bottom floor and be evenly distributed on the floor. No transport  
4 of the large pieces is assumed to occur by containment spray.

### 5 Pool Fill Transport

6 Debris transport in the containment bottom floor pool during fill-up will transport all the small  
7 fines. Some of the small fines will be transported to the inactive volumes of the pool that will not  
8 participate in the recirculation flow, i.e., the cavity under the reactor vessel. The transport factor  
9 to the inactive pools is calculated by calculating the ratio of the volumes of the inactive pool to  
10 the total pool volume. No transport of the large pieces is assumed to occur during pool fill-up.

### 11 Recirculation Transport

12 Debris transport in the containment bottom floor pool during recirculation is assumed to  
13 transport 100 percent of the small fines in the active volumes of the pool to the sump. No  
14 transport of the large pieces is assumed to occur during recirculation.

### 15 **RMI Insulation in the ZOI**

16 The following guidance is provided for all types of RMI debris in the ZOI.

### 17 Blowdown Transport

18 Debris transport during blowdown is assumed to cause the small RMI debris pieces from the  
19 compartment where the break is postulated to occur to be distributed to all horizontal surfaces  
20 outside the compartments. For conservatism, it is assumed that all the small RMI debris is  
21 deposited on the containment bottom floor. The large RMI debris pieces from the ZOI are  
22 assumed to fall to the containment bottom floor and not be transported.

### 23 Washdown Transport

24 There is no debris transport by the containment spray of the small RMI pieces since all small  
25 RMI debris is assumed to be transported by the blowdown to the containment bottom floor. Also,  
26 no transport of the large pieces is assumed to occur by containment spray.

### 27 Pool Fill Transport

28 Debris transport in the containment bottom floor pool during fill-up will transport all the small  
29 RMI debris. Some of the small fines will be transported to the inactive volumes of the pool that  
30 will not participate in the recirculation flow, e.g., the cavity under the reactor vessel. The  
31 transport factor to the inactive pools is determined by calculating the ratio of the volumes of the  
32 inactive pool to the total pool volume. No transport of the large RMI pieces is assumed to occur  
33 during pool fill-up.

## 1 Recirculation Transport

2 Debris transport in the containment bottom floor pool during recirculation is assumed to  
3 transport 100 percent of the small RMI debris in the active volumes of the pool to the sump. No  
4 transport of the large RMI pieces is assumed to occur during recirculation.

## 5 **Other Material in the ZOI**

6 All other material in the ZOI, including coatings within the coatings ZOI, will be assumed to  
7 transport similarly to the small fines of fibrous material.

## 8 **Debris from Materials Outside the ZOI**

9 All debris from materials outside the ZOI is considered to be in the active volumes of the pool at  
10 the start of recirculation and be 100 percent transported by the active volumes of the pool to the  
11 sump. Latent debris is also considered to be to be in the active volumes of the pool at the start of  
12 recirculation and be 100 percent transported by the active volumes of the pool to the sump. This  
13 is conservative, since debris from outside the ZOI is not considered to be transported to the  
14 inactive sump.

## 15 **3.6.3.3 Ice Condenser Containment**

### 16 **Fibrous Insulation in the ZOI**

17 The following guidance is provided for all types of fibrous debris in the ZOI.

#### 18 Blowdown Transport

19 Debris transport during blowdown is assumed to cause most of the small fines debris from the  
20 lower containment where the break is postulated to occur to be transported to the upper  
21 compartment and the dome through the ice condenser baskets. Ten percent of the small fines  
22 debris is retained in the upper compartment and the ice condensers, the rest returning back to the  
23 lower containment floor by the melting ice. Steam and water with entrained debris will pass  
24 through the ice condenser cavities. Some of the debris will be entrained in the baskets. At the end  
25 of blowdown, at least 50 percent of the ice will have melted. Ten percent is a conservative  
26 average value of the open area in the ice condenser. The large debris pieces from the ZOI are  
27 assumed to fall to the lower containment floor and not be transported.

#### 28 Washdown Transport

29 All the small fines that were transported to the upper containment by the blowdown will be  
30 conservatively assumed to be transported by the containment sprays from the upper containment  
31 to the lower containment bottom floor and be evenly distributed on the lower containment  
32 bottom floor. No transport of the large pieces is assumed to occur by containment spray.

## 1 Pool Fill Transport

2 Debris transport in the lower containment bottom floor pool during fill-up will transport all the  
3 small fines. Some of the small fines will be transported to the inactive volumes of the pool that  
4 will not participate in the recirculation flow, e.g., the cavity under the reactor vessel. The  
5 transport factor to the inactive pools is determined by calculating the ratio of the volumes of the  
6 inactive pool to the total pool volume. No transport of the large pieces is assumed to occur  
7 during pool fill-up.

## 8 Recirculation Transport

9 Debris transport in the containment bottom floor pool during recirculation is assumed to  
10 transport 100 percent of the small fines in the active volumes of the pool to the sump. No  
11 transport of the large pieces is assumed to occur during recirculation.

## 12 **RMI Insulation in the ZOI**

13 The following guidance is provided for all types of RMI debris in the ZOI.

## 14 Blowdown Transport

15 Debris transport during blowdown is assumed to cause most of the small RMI debris from the lower  
16 containment where the break is postulated to occur to be transported to the upper compartment and  
17 the dome through the ice condenser baskets. For conservatism, it is assumed that only 10 percent of  
18 the small RMI debris is transported to the upper compartment, the rest returning back to the lower  
19 containment bottom floor by the melting ice. Steam and water with entrained debris will all pass  
20 through the ice condenser cavities. Some of the debris will be entrained in the baskets. At the end of  
21 blowdown, at least 50 percent of the ice will have melted. Ten percent is a conservative average  
22 value of the open area in the ice condenser. The large debris pieces from the ZOI are assumed to fall  
23 to the lower containment bottom floor and not be transported.

## 24 Washdown Transport

25 Debris transport by the containment spray is assumed to cause none of the small RMI debris that  
26 is on the upper containment bottom floor and in the containment spray pathway to be transported  
27 to the containment bottom floor. The flow velocities and the very shallow pool depths in the  
28 upper containment floor are not conducive to transport of small RMI debris. No transport of the  
29 large pieces is assumed to occur by containment spray.

## 30 Pool Fill Transport

31 Debris transport in the lower containment bottom floor pool during fill-up will transport all the  
32 small RMI debris. Some of the small fines will be transported to the inactive volumes of the pool  
33 that will not participate in the recirculation flow, e.g., the cavity under the reactor vessel. The  
34 transport factor to the inactive pools is calculated by calculating the ratio of the volumes of the  
35 inactive pool to the total pool volume. No transport of the large RMI pieces is assumed to occur  
36 during pool fill-up.

## 1 Recirculation Transport

2 Debris transport in the containment bottom floor pool during recirculation is assumed to  
3 transport 100 percent of the small RMI debris in the active volumes of the pool to the sump. No  
4 transport of the large RMI pieces is assumed to occur during recirculation.

## 5 **Other Material in the ZOI**

6 All other material in the ZOI, including coatings within the coatings ZOI, will be assumed to  
7 transport similarly to the small fines of fibrous material.

## 8 **Debris from Materials Outside the ZOI**

9 All debris from materials outside the ZOI is considered to be in the active volumes of the pool at the  
10 start of recirculation and be 100 percent transported by the active volumes of the pool to the sump.  
11 Latent debris is also considered to be in the active volumes of the pool at the start of recirculation  
12 and be 100 percent transported by the active volumes of the pool to the sump. This is conservative,  
13 since debris from outside the ZOI is not considered to be transported to the inactive sump.

## 14 **3.6.4 Calculate Transport Factors**

15 The calculation of the transport factors for each type of debris is done by using the unquantified  
16 logic tree as a guide. A logic tree should be developed for each of the debris types and using the  
17 previously discussed values for the appropriate containment type. The summation of the two  
18 “Transport” branches is the cumulative transport fraction for the debris type.

### 19 **3.6.4.1 Sample Calculation**

20 The baseline sample plant is classified as a highly compartmentalized containment. From the  
21 post-DBA water level calculations, we have that the inactive pools account for 30 percent of the  
22 total post-DBA water volume in containment.

23 From the debris classification section, there are two types of debris from the ZOI for the baseline  
24 sample plant: Nukon and RMI. Using the recommended transport fractions, we have the following.

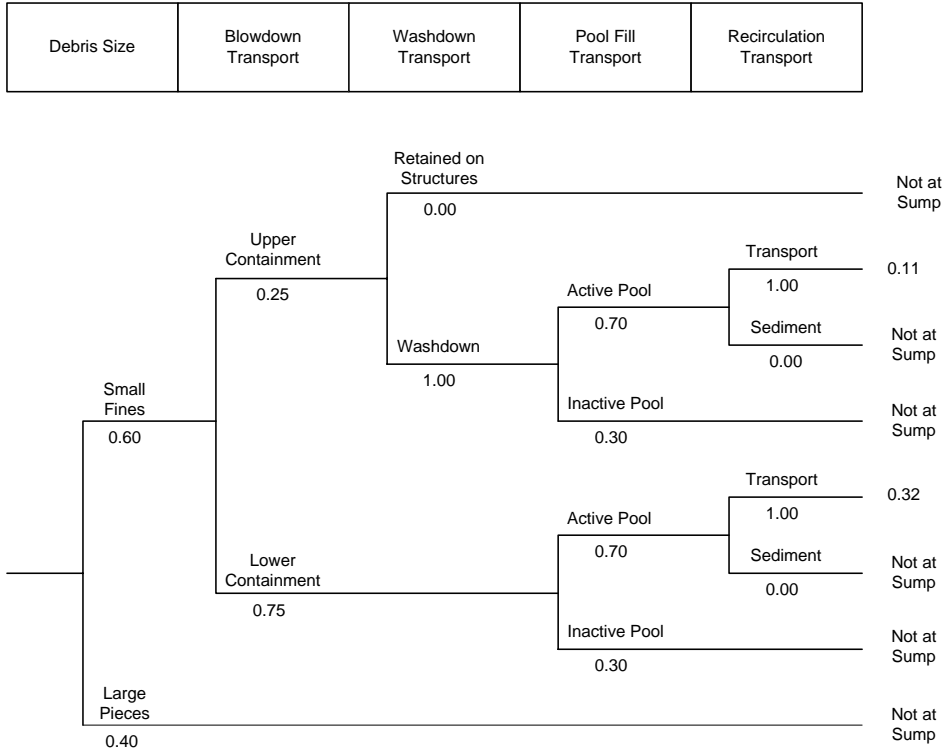
#### 25 **Nukon**

26 Figure 3-3 is a quantified logic tree for Nukon.

27 Adding the two paths that reach the sump, the total cumulative transport factor for Nukon fines  
28 reaching the sump is  $0.11 + 0.32 = 0.43$ . As such, 43 percent of the volume of Nukon in the ZOI  
29 reaches the sump in the form of small fines. No large pieces of Nukon will be transported to the sump.

#### 30 **RMI**

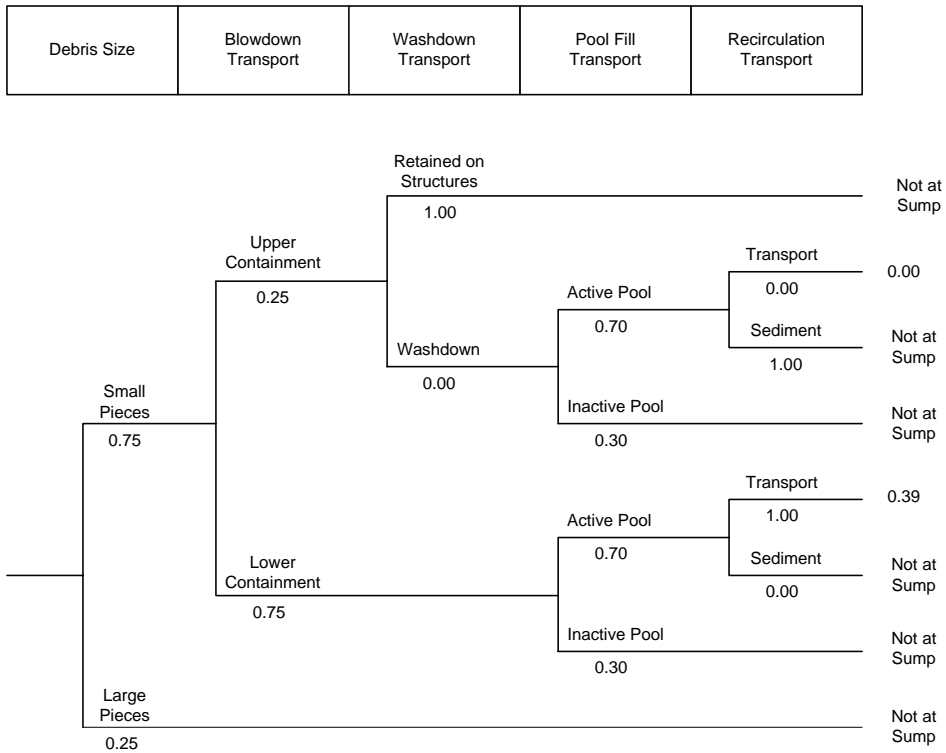
31 Figure 3-4 is a quantified logic tree for the RMI.



1

2

**Figure 3-3. Nukon Transport Logic Tree (Sample Problem)**



3

4

**Figure 3-4. RMI Transport Logic Tree (Sample Problem)**

1 From inspection of the logic tree, 0.39 is the transport factor for RMI. As such, 39 percent of the  
 2 volume of RMI in the ZOI reaches the sump in the form of small pieces. No large RMI pieces  
 3 will be transported to the sump.

4 Coating debris material from both from within the coatings ZOI and from outside the coatings  
 5 ZOI will all be transported to the sump. All debris material outside the ZOI, including latent  
 6 debris, will also be transported to the sump.

7 From the debris generation sample calculations, we have:

8 Total volume of Nukon blankets in ZOI:  $300 \text{ ft}^3$   
 9 Total quantity of RMI material in ZOI:  $15,000 \text{ ft}^2$

10 From the debris characterization section, we have:

11 Total Quantity of small fines coating:  
 12  $0.007 \text{ ft}^3$  from the ZOI +  $7.5 \text{ cu ft}$  from outside the ZOI =  $7.5 \text{ ft}^3$

13 From the latent debris section, we have:

14 Latent fiber:  $20.91 \text{ lb @ } 62.4 \text{ lb/ft}^3 = 0.34 \text{ ft}^3$   
 15 Latent particulates:  $33.51 \text{ lb @ } 100 \text{ lb/ft}^3 = 0.34 \text{ ft}^3$

16 Using the transport fractions derived above, the following quantities of debris are transported to  
 17 the sump:

18	Fibers: small fines:	$300 * 0.43 + 0.34$	$= 129.34 \text{ ft}^3$
19	RMI small pieces:	$15,000 * 0.39$	$= 5,850 \text{ ft}^2$
20	Coating small fines (IOZ equivalent):		$= 7.5 \text{ ft}^3$
21	Latent particulates:		$= 0.34 \text{ ft}^3$

## 22 3.7 HEAD LOSS

### 23 3.7.1 Introduction and Scope

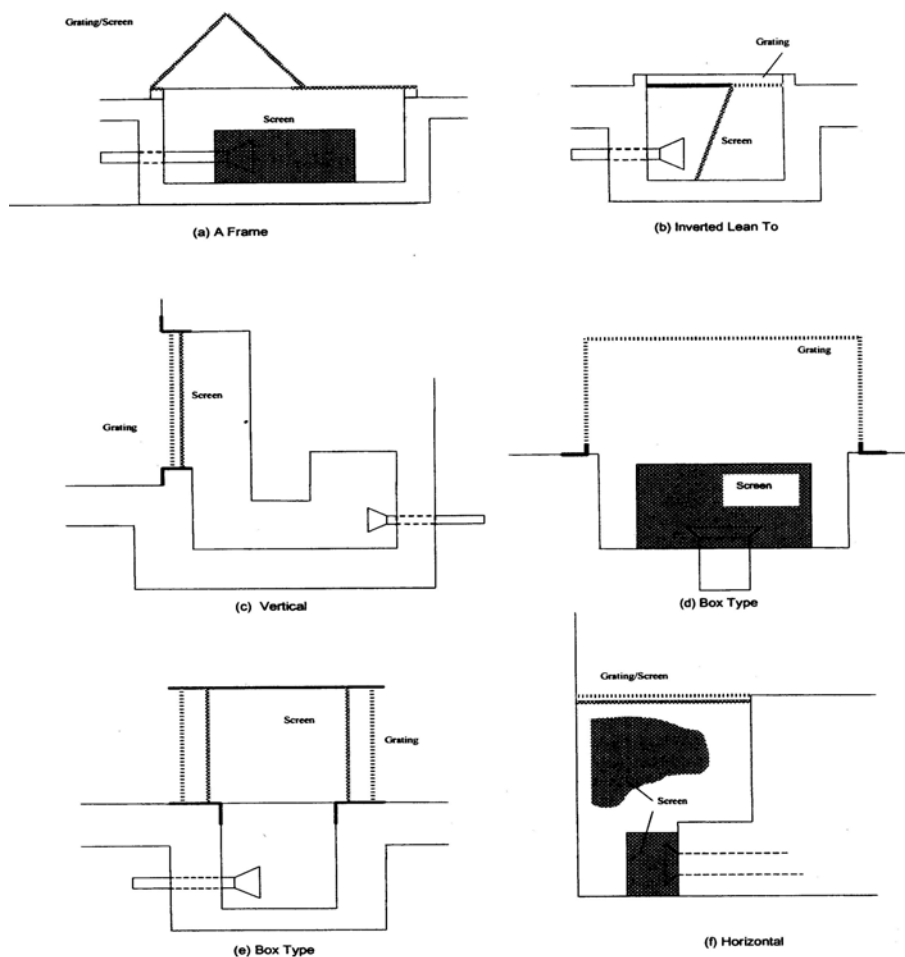
24 The methodology presented within this chapter details how to calculate the head loss from a  
 25 debris bed that could be formed on the ECCS sump screen(s). The sump screen parameters and  
 26 the thermal-hydraulic conditions required for this analysis will first be discussed. The types, total  
 27 quantities, and characteristics of debris that are generated in the containment and transported to  
 28 the sump screen are also primary design inputs for this methodology.

29 The methodology will provide the user with the head loss (feet of water) for the debris bed on the  
 30 sump screen. The user then has to add the estimated clean sump screen head loss to obtain the  
 31 total head loss across the sump screen. The ability to sustain this head loss is then assessed by  
 32 comparison to the NPSH margin. Sample problems are provided to illustrate the methodology.

## 1 3.7.2 Inputs for Head Loss Evaluation

### 2 3.7.2.1 Sump Screen Design

3 The sump screen design is an important consideration in the evaluation of debris head loss. Plant  
 4 drawings should provide details as to the screen construction, the orientation and the mesh size  
 5 (or hole size and pitch for perforated plates). Typical PWR sump screen configurations are  
 6 illustrated in Figure 3-5. Newer designs, such as those installed in the BWRs, typically have  
 7 more surface area and different geometries.



8

9

**Figure 3-5. Typical PWR Sump Screen Configurations**

10 Derived from plant drawings, the sump screen area ( $A$ ) is the total area of the sump screen  
 11 (without any correction for the solid area of the mesh or wire screen) over which debris  
 12 accumulates. Curbs are ignored when determining the screen area. For flat screens, the sump  
 13 screen is simply the total circumscribed area of the screen or perforated plate. Framing and/or  
 14 significant structures that block flow through the screen should be subtracted from the total area  
 15 to get a net screen area. For alternate geometries, particularly in the case of star or stacked-disc



1 designs, the initial strainer surface area available for debris deposition is the total perforated plate  
2 surface area, decreasing to the circumscribed area as debris fills in the voids and gaps between  
3 the ridges and disks.

4 If the screen is completely submerged, the net screen area is used. If the screen is partially  
5 submerged, the wetted area should be determined based on the height of the containment floor  
6 water pool at the time the head loss is calculated.

7 The sump screen opening size (or hole size and pitch for perforated plate screens) is obtained  
8 from plant drawings. The opening size is usually the size needed to keep out debris of a size  
9 greater than the minimum size of openings in the ECCS (e.g., spray nozzles, valve throats, and  
10 pump cooling lines). The sump screen opening size is used in determining the clean strainer head  
11 loss. The debris-bed head loss calculation methodology adopted in this chapter is largely  
12 independent of the sump screen opening size.

13 The clean strainer head loss (CSHL) is the head loss of the sump screen assembly in a clean,  
14 unfouled condition. The CSHL is a required input for the overall head loss evaluation and is  
15 highly dependent on plant-specific sump screen construction details and thermal-hydraulic  
16 conditions. Calculating the head loss of the sump screen assembly in a clean condition involves  
17 calculating the head loss across the screen itself taking submergence of the screen into  
18 consideration. The CSHL will mainly depend on the screen mesh size (or hole size and pitch for  
19 perforated plates), the flow through the screen, and the water temperature using standard  
20 methods of fluid mechanics. This baseline methodology does not provide details on how to  
21 calculate clean strainer head loss as this information is available from other sources. Clean sump  
22 screen head loss information is typically available from the manufacturer of the raw screen  
23 material itself. Note that existing plant calculations often document CSHL. In some cases, the  
24 head losses due to the attendant support structures, mechanical configuration of the bracing, and  
25 other structures in the sump (such as vortex suppressors) cannot be neglected, and these losses  
26 should normally be included in the CSHL calculation.

### 27 **3.7.2.2 Thermal-Hydraulic Conditions**

#### 28 **3.7.2.2.1 Recirculation Pool Water Level**

29 For conservatism, the minimum water level of the recirculation pool should be used to estimate  
30 the head loss across the debris bed accumulated on a screen. The minimum level will yield the  
31 smallest surface area (thus potentially greater head loss) for those screens that are not completely  
32 submerged in the pool as well as the lowest available NPSH to the ECCS pumps.

#### 33 **3.7.2.2.2 ECCS Flow Rate**

34 For conservatism, the highest flow rate ( $Q$ ) should be used in calculating the head loss across a  
35 screen. In this regard, the Baseline Methodology recommends that maximum pump flows, as  
36 identified in current NPSH calculations, be used for the ECCS flow rates. For multiple sump  
37 screens, the flow rate for the head loss calculation is the flow through each of the screens.

### 1 3.7.2.2.3 Temperature

2 The recirculation sump water temperature should be documented in the plant design basis  
3 calculations and is an important parameter in the head loss calculation.

4 The Baseline Evaluation Methodology recommends the following:

- 5 1. The temperature at which the head loss is evaluated should be consistent with the  
6 temperature used for the NPSH evaluation.
- 7 2. However, it is not clear which temperature is limiting overall; therefore, multiple  
8 times, temperatures, and flows during the accident may need to be evaluated. (For  
9 example, use of 250°F gives a head loss of 8.8 feet for the sample problem of this  
10 section, whereas using 120°F gives 33.9 feet).
- 11 3. As a conservative simplification, the maximum expected sump temperature may be  
12 used for the NPSH analysis, whereas the lowest expected temperature during ECCS  
13 operation may be taken for the head loss analysis.

### 14 3.7.2.2.4 Debris Types, Quantities, and Characteristics

15 Fibrous insulation debris, RMI debris, coatings debris, and miscellaneous debris such as concrete  
16 debris, dust, dirt, other latent debris, rust, etc. all have to be considered if they are present inside  
17 the containment. Therefore, the types, quantities (mass or volume), and characteristics of all  
18 potential debris materials need to be specified in the design input for a sump screen head loss  
19 evaluation. For fibrous materials, the insulation volume is the main parameter needed. For  
20 particulate materials, the mass and the density are the main parameters required. For RMI, the  
21 main parameter needed is the total foil area of the damaged RMI.

22 The composition and characteristics of the debris bed on the sump screen are important inputs  
23 into the head loss model. The debris types, quantities (i.e., mass or volume), and characteristics  
24 (e.g., shape and thickness) reaching the sump screen are needed to calculate the pressure drop  
25 across the debris bed. The debris types and potential quantities at the sump screen are determined  
26 by the debris generation and transport calculations.

### 27 3.7.2.3 Head Loss Methodology

28 The head loss model assumes that the screen is initially clean and that the floor pool contains a  
29 homogenous mixture and concentration of debris (i.e., fibrous, particulate, etc.). Upon  
30 switchover of suction from the refueling water storage tank (RWST) to the recirculation sump,  
31 debris begins to be transported to the sump and accumulates on the sump screen. Initially, some  
32 portion of the debris whose size is smaller than the screen mesh size (or hole-size of the  
33 perforated plate) passes through the sump screen. Fibers will quickly start to form a fiber mat in  
34 the cases where there is no RMI debris transported to the sump screen. (If RMI is present at the  
35 screen, refer to the mixed debris bed discussion in subsection 3.7.2.3.1.3). As the fiber mat  
36 forms, it will start trapping particulate debris reaching the sump screen. With sufficient fibers

1 reaching the screen, a uniform fiber mat bed will be formed, at which time the head loss across  
2 the debris will start increasing. The head loss across the debris bed will continue to rise as more  
3 debris is deposited on the screen, reaching steady state when all of the available debris is  
4 deposited on the screen.

5 Most analysts are interested in the head loss across the sump screen when all debris reaching the  
6 sump screen accumulates on the screen. The head loss methodology herein provides the ability to  
7 compute the sump screen head loss given the total quantity and type of debris over a specified  
8 surface area at a given ECCS pump flow.

### 9 **3.7.2.3.1 General Theoretical/Empirical Formulas**

#### 10 **3.7.2.3.1.1 Fibrous Debris Beds with Particulate**

11 For general use with fiber and particulate debris beds, the NUREG/CR-6224 correlation is  
12 recommended for determination of the head loss. The refinement guidance of Section 4 provides  
13 a discussion of factors associated with estimating debris head losses and presents several debris  
14 head loss correlations developed over the last few years.

15 The NUREG/CR-6224 head loss correlation is described and validated in detail in Appendix B of  
16 that report and is a semi-theoretical head loss model. The correlation is based on the theoretical  
17 and experimental research in head loss across a variety of porous and fibrous media carried out  
18 since the 1940s. The NUREG/CR-6224 head loss correlation has been thoroughly validated for  
19 fibrous debris and ferrous sludge found in BWRs for a variety of flow conditions, water  
20 temperatures, and in different experimental facilities. The types of fibrous insulation material  
21 tested include Nukon and Temp-Mat. The particulate matter debris tested includes iron oxide  
22 particles from 1 to 300  $\mu\text{m}$  in characteristic size, plus inorganic zinc and paint chips. In these  
23 cases, with the appropriate selection of particle sizes as described in Tables 3-2 and 3-3 of this  
24 document, the NUREG/CR-6224 head loss correlation bounds the experimental results.

25 U.S.NRC Regulatory Guide 1.82, Revision 3 states that estimates of head loss caused by debris  
26 blockage should be developed from empirical data based on the sump screen design (e.g., surface  
27 area and geometry), postulated combinations of debris (i.e., amount, size distribution, type), and  
28 approach velocity. Therefore, there may be materials and combinations of materials for which the  
29 empirical head loss data do not exist. In these cases, the following options are available:

- 30 • Characterization of the material with scanning electron microscopy (SEM)  
31 analysis, and establishing a size distribution.
- 32 • Choosing an alternative material that conservatively represents the material in  
33 question, via similitude arguments.
- 34 • Head loss testing of the particular material to establish a correlation or else validate  
35 an existing correlation for that material.

- 1           • Utilize other data that may exist to establish head loss for the material in question.  
 2           (The refinement guidance presented in Section 4 summarizes some of the industry  
 3           test data. More data are possibly available, some of which are currently the  
 4           property of individual utilities.)

5 The NUREG/CR-6224 head loss correlation, applicable for laminar, transient, and turbulent flow  
 6 regimes through mixed debris beds (i.e., debris beds composed of fibrous and particulate matter)  
 7 is given by:

$$8 \quad \Delta H = \Lambda [3.5 S_v^2 \alpha_m^{1.5} (1 + 57 \alpha_m^3) \mu U + 0.66 S_v \alpha_m / (1 - \alpha_m) \rho U^2] \Delta L_m$$

9 (Equation 3.7.2-1)

10 where:

11  $\Delta H$  is the head loss (feet of water)

12  $S_v$  is the surface-to-volume ratio of the debris ( $\text{ft}^2/\text{ft}^3$ )

13  $\mu$  is the dynamic viscosity of water ( $\text{lbm}/\text{ft}/\text{sec}$ )

14  $U$  is the fluid approach velocity (fps)

15  $\rho$  is the density of water ( $\text{lbm}/\text{ft}^3$ )

16  $\alpha_m$  is the mixed debris bed solidity (one minus the porosity)

17  $\Delta L_m$  is the actual mixed debris bed thickness (inches)

18  $\Lambda$  is a conversion factor –

19  $\Lambda = 1$  for SI units, and

20  $\Lambda = 4.1528 \times 10^{-5}$  ( $\text{ft-water}/\text{inch}/(\text{lbm}/\text{ft}^2/\text{sec}^2)$ ) for English units.

21 The fluid approach velocity,  $U$ , is given simply in terms of the volumetric flow rate and the  
 22 effective screen surface area as:

$$23 \quad U = \frac{Q}{A}$$

24 where:

25  $Q$  is the total volumetric flow rate through the screen ( $\text{ft}^3/\text{sec}$ ) and

26  $A$  is the effective screen surface area ( $\text{ft}^2$ ).

27 The screen surface area,  $A$ , is the submerged (wetted) effective surface area of the screen as  
 28 described in subsection 3.7.2.1 above. As noted previously, the available surface area may  
 29 change with time, particularly in the case of star or stacked-disc designs. For these particular  
 30 alternate geometry screens, given sufficient debris reaching the screen, the effective surface area  
 31 may eventually decrease to the circumscribed area. At the limit, the head loss for alternate  
 32 geometry screens may be calculated using the circumscribed area and the debris load equal to the

1 total debris load transported to the screen less the quantity of debris required to fill in the  
2 volumes and gaps of the alternate geometry screen.

3 The mixed debris bed solidity ( $\alpha_m$ ) is given by:

$$4 \quad \alpha_m = \left( 1 + \frac{\rho_f}{\rho_p} \eta \right) \alpha_o c \quad \text{(Equation 3.7.2-2)}$$

5 where:

6  $\alpha_o$  = the solidity of the original fiber blanket (i.e., the “as fabricated” solidity)

7  $\eta$  = mp/mf, the particulate-to-fiber mass ratio in the debris bed

8 mp =  $\Sigma m_i$  is the total particulate mass (lbm)

9  $\rho_f$  = the fiber density (lbm/ft<sup>3</sup>)

10  $\rho_p$  = the average particulate material density (lbm/ft<sup>3</sup>) =  $\Sigma \rho_i V_i / \Sigma V_i$

11 c = the head-loss-induced volumetric compression of the debris (inches/inch).

12 For debris deposition on a flat surface of a constant size, the compression (c) relates the actual  
13 debris bed thickness,  $\Delta L_m$ , and the theoretical fibrous debris bed thickness,  $\Delta L_o$  (inches), via the  
14 relation:

$$15 \quad c = \frac{\Delta L_o}{\Delta L_m} \quad \text{(Equation 3.7.2-3)}$$

16 Compression of the fibrous bed due to the pressure gradient across the bed is also accounted. The  
17 relation that accounts for this effect, which must be satisfied in parallel to the previous equation  
18 for the head loss, is given by (valid for ratios of  $\Delta H / \Delta L_o > 0.5$  ft-water/inch-insulation):

$$19 \quad c = 1.3 * K * (\Delta H / \Delta L_o)^{0.38} \quad \text{(Equation 3.7.2-4)}$$

20 Here, “K” is a constant that depends on the insulation type. It is 1.0 for Nukon fiber. Test data or  
21 a similitude analysis are required to determine “K” for fibrous materials that are dissimilar to  
22 Nukon. It should be noted that this formulation for debris bed compression may overpredict  
23 compression significantly in the case of very thick debris layers, roughly 6 inches or more. Thus,  
24 in these cases, it is conservative.

25 For very large pressure gradients and for cases where very little fiber is present, the compression  
26 has to be limited so that a maximum solidity is not exceeded. In NUREG/CR-6224, this  
27 maximum solidity is defined to be:

$$28 \quad \alpha_m = 65 \text{ lbm/ft}^3 / \rho_p \quad \text{(Equation 3.7.2-5)}$$

1 which is equivalent to having a granular debris layer with a bulk density of 65 lbm/ft<sup>3</sup>. Note that  
 2 65 lbm/ft<sup>3</sup> is the macroscopic, or bulk density of a granular media such as sand or gravel and clay  
 3 (Reference 6). Based on NUREG/CR-6224 (Reference 17), the above value is also appropriate  
 4 for ferrous sludge. For a sludge particle density of ~324 lbm/ft<sup>3</sup>, the maximum solidity is  
 5 ~20 percent, and this value has been determined from test data to yield acceptable results with  
 6 the NUREG/CR-6224 head loss correlation. In general, solidity is defined as:

$$7 \quad \alpha_m = \rho_b / \rho_p \quad \text{(Equation 3.7.2-5a)}$$

8 where  $\rho_b$  is the bulk, or macroscopic density, and  $\rho_p$  is the particle, or grain density. Since the  
 9 solidity depends on the material properties, different materials may require testing to establish  
 10 appropriate values. In practice, however, the limiting value of solidity specified above works  
 11 well for many particulate mixtures.

12 Each constituent of debris has a surface-to-volume ratio associated with it based on the  
 13 characteristic shape of that debris type. For typical debris types, we have:

14 Cylindrically shaped debris:  $S_v = 4/\text{diam}$   
 15 Spherically shaped debris:  $S_v = 6/\text{diam}$   
 16 Flakes (flat plates):  $S_v = 2/\text{thick}$

17 where “diam” is the diameter in feet of the fiber or spherical particle, and “thick” is the thickness  
 18 in feet of the flake/chip. Other debris not listed above would have its surface-to-volume ratio  
 19 calculated similarly based on one of the above characteristic shapes. Clearly, the above relations  
 20 are simplified approximations. Generally, what is done is to select a characteristic size, for  
 21 example, small spheres to represent irregularly shaped particulate debris, small cylinders to  
 22 represent fiber, etc. Whatever modeling approach is used, a comparison to test data then has to be  
 23 made to assess the validity of the approximation for that particular material, with the  
 24 characteristic sizes adjusted as required for the head loss correlation to conservatively match the  
 25 data. For debris not yet tested and for which similitude arguments cannot be made, SEM analysis  
 26 and/or plant-specific testing may be required.

27 The following is a method for calculating the average surface to volume ratio for two different  
 28 types of debris constituents (Reference 22).

$$29 \quad S_v = \text{SQRT} [(S_{v1}^2 * v_1 + S_{v2}^2 * v_2)/(v_1 + v_2)] \quad \text{(Equation 3.7.2-6)}$$

30 where  $v_1$  and  $v_2$  are the microscopic volumes of constituents “1” and “2,” respectively.

31 Clearly, this result can be extended to more than two such fiber species as follows:

$$32 \quad S_v = \text{SQRT} [\Sigma(S_{vn}^2 * v_n)/\Sigma(v_n)] \quad \text{(Equation 3.7.2-7)}$$

33 where the subscript “n” refers to the nth constituent.

1 Averaging in the above manner will yield a higher pressure drop as more than one type of debris  
2 is added to the mixture.

3 Tables 3-2 and 3-3 list recommended values of fiber and particle sizes based on the data  
4 currently available, from which values of  $S_V$  may be derived. Where values are not given or  
5 where uncertainty otherwise exists, it is best to err on the low side for conservative values of  $S_V$ .  
6 In some cases, further measurements to establish debris sizes, SEM analysis, and comparisons to  
7 head loss correlations and test data may be required to establish appropriate values.

8 To obtain an aggregate density for both particulate and fibrous debris, a simple volume averaging  
9 procedure is appropriate, as indicated in association with Equation 3.7.2-2, since, for a well-mixed  
10 debris bed, the individual species can reasonably be expected to see the same porosity.

11 Summarizing the computation process:

12 • Fiber and particulate debris are handled with the general form of the NUREG/CR-  
13 6224 correlation, Equation 3.7.2-1.

14 • Material properties are necessary – see Section 3.4.3 (Debris Characteristics) for  
15 material properties of material commonly encountered in PWRs.

16 • Knowing the debris quantities that are calculated to reach the sump screen, the  
17 mass ratio of particulates-to-fiber ( $\eta$ ), the fiber density ( $\rho_f$ ), and the average  
18 particulate density ( $\rho_p$ ), and the theoretical bed thickness ( $\Delta L_o$ ) are determined.

19 • A compression factor [c] must be specified. This is an iterative process, with a  
20 value of 2.0 being a reasonable first approximation. (Adjust “c” thereafter in the  
21 direction of convergence. Alternatively, the bed thickness may be assumed and “c”  
22 derived from this.)

23 • The mixed-bed solidity ( $\alpha_m$ ) is next calculated from Equation 3.7.2-2.

24 • An overall, average value of  $S_V$  must be determined for the fibrous materials, each  
25 of the particulates and then an average for the overall debris mixture by  
26 Equation 3.7.2-7. If multiple fiber types are present, then each type should be  
27 included in the averaging process.

28 • The water properties ( $\rho$  and  $\mu$ ) are specified at the sump temperature at the time the  
29 head loss across the debris bed is calculated. Alternatively, a conservative approach  
30 would be to calculate the head loss using the lowest sump water temperature  
31 calculated over the entire time frame that the ECCS needs to function.

32 • The approach velocity will be known from the sump screen area and the ECCS  
33 flows through the screen.

- Substitution of all of the above information into Equation 3.7.2-1, in combination with iterative solution of Equations 3.7.2-3 and 3.7.2-4, yields the sump screen head loss and the actual debris-bed thickness,  $\Delta L_m$ .

The head loss across a debris bed consisting of fibrous debris (no particulates) can be calculated with the general form of the NUREG/CR-6224 correlation, Equation 3.7.2-1, where the mass ratio of particulates-to-fiber ( $\eta$ ) is set to zero. Given the presence of particulates from dirt/dust and possibly unqualified coatings, it would be unusual to have to analyze pure fiber bed head loss for a PWR. However, this case has application when interpreting experimental results, so it is mentioned for completeness.

### 3.7.2.3.1.2 RMI Debris Beds

The head loss for a RMI debris bed on the sump screen surface depends mainly on the accumulation at the sump screen and the type and size distribution of RMI debris. The key parameter needed to evaluate pure RMI head loss is the surface area of the RMI bed on the screen. The commonly accepted empirical correlation for RMI (Reference 6) is:

$$\Delta H = [1.56E-05/(K_t)^2] U^2 A_{\text{foil}}/A_c \quad \text{(Equation 3.7.2-8)}$$

where:

- $K_t$  is the interfoil gap thickness (ft)
- $\Delta H$  is the head loss, (feet-of-water)
- $U$  is the sump screen approach velocity (ft/sec)
- $A_{\text{foil}}$  is the RMI foil surface area (ft<sup>2</sup>)
- $A_c$  is the sump screen surface area (ft<sup>2</sup>)

Extracted from Table 7-2 of NUREG/CR-6808, some values of  $K_t$  are listed below in Table 3-5. Other values of  $K_t$  are listed in Appendix K of the SER to the URG.

**Table 3-5. Values of  $K_t$  from NUREG/CR-6808**

Foil Type and Bed Type	$K_t$ (feet)
2.5-mil SS (NRC large pieces)	0.014
2.5-mil SS (NRC small pieces)	0.010
1.5-mil Al (debris bed)	0.008
1.5-mil Al (debris bed)	0.006
2.5-mil SS (STUK flat pieces)	0.007
2.5-mil SS (1-mm dimple)	0.003

24



1 In Appendix K of the NRC SER to the BWROG URG, the NRC concluded that a value of  $K_t$  of  
2 0.012 in the above general equation bounds the head loss data reasonably well for 2.5-mil SS  
3 RMI. Substituting this value of  $K_t$  into Equation 3.7.2-8, one obtains:

$$4 \quad \Delta H = 0.108 U^2 A_{\text{foil}}/A_c \quad (\text{Equation 3.7.2-9})$$

5 Equation 3.7.2-9 accounts for experimental uncertainties, test repeatability variations, and  
6 variations in debris size and material types. As such, for 2.5-mil, SS foil, Equation 3.7.2-9  
7 predicts the head loss across a pure RMI debris bed for PWR sump screens. The refinement  
8 guidance given in Section 4 provides further discussion of RMI head loss correlations.

### 9 **3.7.2.3.1.3 Mixed Debris Beds (RMI, Fiber and Particulates)**

10 A mixed debris bed of RMI, fiber and particulates is handled by superposition (Reference 6).  
11 First, the fiber-and-particulate head loss is determined using the methodology for fibrous debris  
12 beds with particulate discussed earlier in subsection 3.7.2.3.1.1. Next, the RMI head loss is  
13 determined using the methodology for RMI debris beds discussed above. These two head losses  
14 are then added to estimate the total head loss of a RMI, fiber, and particulate bed. This procedure  
15 is conservative, and the user need not be concerned with how the debris bed is formed.

16 The superposition of RMI and fiber may be overly conservative for cases where relatively large  
17 amounts of RMI and trace amounts of fiber (e.g., latent fiber) are estimated to be transported to  
18 the sump screen. Experiments have shown that fiber can become caught either within the voids  
19 of the RMI bed or at the surface of the RMI bed (which can have a significantly larger surface  
20 area and a lower approach velocity than the sump screen itself). For plants that have essentially  
21 all RMI, a relatively small amount of latent fiber could provide the quantity necessary to develop  
22 a thin bed, causing unacceptable or unrealistic results when added algebraically to the RMI head  
23 loss. More realistic methods for trace amounts of either RMI or fiber will be addressed in the  
24 refinement guidance of Section 4.

### 25 **3.7.2.3.1.4 Calcium Silicate Insulation**

26 Calcium silicate (Cal-Sil) is a granular insulation. It consists of fine particulate material that is  
27 chemically bonded and is also held together by a fine fibrous matrix. Experiments thus far  
28 indicate that it is best treated as a particulate material for head loss calculations. Test data will be  
29 required for specification of the appropriate particle sizes and surface-to-volume ratios to use in  
30 head loss analysis. At present, most of the head loss test data for Cal-Sil are privately held, the  
31 exception being the NRC/LANL/UNM Cal-Sil Test Report whose issuance is pending. Based on  
32 current information, the NUREG/CR-6224 correlation can be used according to the methods for  
33 fibrous debris beds with particulate if the application is limited to particulate mixtures containing  
34 up to about 20 percent Cal-Sil by mass. Additional head loss data for Cal-Sil are anticipated to be  
35 released by the NRC in the near future.

36 Cal-Sil is used in many PWRs and has different compositions. For example, it may contain  
37 diatomaceous earths, perlite, and/or asbestos fibers, and plant-specific characterization (via SEM

1 analysis, at a minimum) is warranted to identify the specific composition, particle size range, and  
2 source of this material.

### 3 **3.7.2.3.1.5 Microporous Insulation**

4 Microporous insulation (e.g., MinK and Microtherm) is also a granular insulation and has been  
5 used in PWRs. The analyst is cautioned to ensure that the applicable material properties are used,  
6 since there may be significant variations in material properties from those suggested in the  
7 Debris Characteristics section. The Supplemental Guidance will provide additional background  
8 regarding the insights gained in the very limited series of head loss experiments available for  
9 review through May 2004.

### 10 **3.7.2.3.1.6 Microporous and Fiber Debris**

11 A limited series of head loss tests was performed with microporous debris in the presence of  
12 fibrous debris. These tests showed that the NUREG/CR-6224 correlation bounded the  
13 experimental data for all cases where the microporous-to-fiber mass ratio was less than about  
14 20 percent. For mass ratios higher than about 20 percent, the NUREG/CR-6224 correlation was  
15 found to be potentially non-conservative.

16 The computation of the head loss of mixed microporous and fiber debris beds (where the  
17 microporous to fiber mass ratio is less than 20 percent) is the same as described earlier for a fiber  
18 and particulate bed. The currently available experimental database does not support a correlation  
19 for estimating the head loss across a debris bed composed of microporous and fibrous insulation  
20 where the microporous-to-fiber-mass ratio is more than 20 percent.

21 In the event that a debris bed composed of microporous and fibrous insulation (or calcium  
22 silicate and fiber, where the microporous-to-fiber (or the Cal-Sil-to-fiber) mass ratio is more than  
23 20 percent), is calculated to form on the screens, the alternatives currently available for  
24 improving the sump screen performance include:

- 25 • Removal of microporous or calcium silicate insulation until the debris generation  
26 and transport analysis yields a debris mixture in which the particulate-to-fiber mass  
27 ratio is less than 20 percent.
- 28 • Use of a head loss correlation other than NUREG/CR-6224. (See the refinement  
29 guidance of Section 4 for potentially applicable head loss correlations.)
- 30 • Performance of head loss experiments using plant-specific debris mixtures, sump  
31 screen configuration, and thermal-hydraulic conditions.

### 32 **Microporous or Calcium Silicate Debris Only**

33 Based on results from a very limited series of experiments, microporous insulation debris or  
34 calcium silicate debris by itself has been shown to induce significant head losses. Tests have  
35 determined that the NUREG/CR-6224 correlation is unreliable for predicting the head loss of

1 microporous insulation debris alone. The currently available experimental database does not  
2 support a correlation for estimating the head loss across a debris bed composed solely of  
3 microporous insulation debris.

4 Calcium silicate by itself has also been shown to induce high head losses (Reference 23).  
5 Preliminary indications are that the NUREG/CR-6224 correlation may fit the data if appropriate  
6 physical parameters are used in the correlation.

7 The alternatives currently available for improving sump screen performance for a debris bed on  
8 the screen composed of only microporous or calcium silicate insulation include:

- 9       • Removal of all granular insulation (e.g., Cal-Sil, MinK, Microtherm, etc.).
- 10       • Use of a head loss correlation other than NUREG/CR-6224.
- 11       • Performance of head loss experiments using plant-specific debris mixtures, sump  
12       screen configuration, and thermal-hydraulic conditions.

### 13 **Granular Insulation and RMI Debris**

14 Reference 23 suggests that the head loss for an RMI and calcium silicate debris bed will be  
15 relatively low, with increased head loss as the quantity of Cal-Sil debris increases. The  
16 expectation is that the same would also occur for all types of granular insulation (Min-K,  
17 Microtherm, and calcium silicate) and RMI debris beds. Mixtures of granular insulation, RMI,  
18 fiber, and other debris should be treated the same as mixed debris bed treatment discussed earlier  
19 with the limitations noted for calcium silicate and microporous insulation above.

#### 20 **3.7.2.3.2 Methodology Application Considerations**

##### 21 **3.7.2.3.2.1 Total Sump Screen Head Loss**

22 The total strainer head loss (TSHL) is the sum of the debris-bed head loss (DBHL) and the clean  
23 strainer head loss (CSHL).

$$24 \quad \text{TSHL} = \text{CSHL} + \text{DBHL}$$

##### 25 **3.7.2.3.2.2 Evaluation of Breaks with Different Combinations of Debris**

26 It is important to identify the break location that produces the highest debris bed head loss, i.e.,  
27 the limiting break. The limiting break is not necessarily the break that generates the largest total  
28 quantity of debris. For example, a break that generates enough fiber and, after the transport  
29 considerations, deposits enough fiber on the screen to cause a thin bed may yield higher head  
30 losses in the presence of particulate than the break that generates more fiber (for the same  
31 quantity of particulate). As such, the analyst needs to evaluate a spectrum of breaks with different  
32 combinations of debris types to ensure that the mixture of debris on the screen that causes the  
33 highest head loss is identified.

### 1 **3.7.2.3.2.3 Thin Fibrous Beds**

2 For the reasons discussed in the preceding paragraph and as suggested in Revision 3 of RG 1.82,  
3 this methodology recommends that the head loss for a one-eighth-inch-thick fiber debris bed  
4 (including particulates) be evaluated for existing PWR sump screens.

5 For conditions of fiber and particulate present in the post-LOCA containment floor pool, as the  
6 fiber bed is deposited on the screen, particulate material will be trapped by the fiber, increasingly  
7 so as the fiber bed thickens. Once a fiber bed of approximately one-eighth-inch thickness is  
8 formed, if there is sufficient particulate debris, a low permeability granular layer of debris on top  
9 of the fiber bed will be formed. The head loss associated with the accumulation of mostly  
10 particulate debris on thin fibrous beds can be quite high, and surprisingly enough, greater than  
11 the head losses associated with much larger quantities of fiber and much thicker beds of debris.  
12 This apparently counterintuitive head loss phenomenon is known as the thin bed effect (TBE).  
13 The Supplemental Guidance will provide further discussions on the TBE.

14 It only takes a small quantity of fiber to facilitate TBE occurrence, and since it is difficult to  
15 make a defensible case that no fibers whatsoever are present in the containment, the possibility  
16 of forming a thin fibrous bed generally has to be evaluated for existing PWR screens.  
17 Additionally, given the uncertainties of debris generation and transport calculations, the total  
18 quantities of fiber calculated to reach the sump screens may be on the high side, hence the impact  
19 of a smaller quantity of fiber reaching the sump screen should be examined, i.e., the transport of  
20 only the fiber necessary to form a thin bed potentially being the limiting case. This methodology  
21 recommends that the head losses given a one-eighth-inch fiber bed (plus particulate) be  
22 calculated as a sensitivity analysis.

23 To analyze a thin fiber bed, a fiber quantity sufficient to form a bed one-eighth-inch thick should  
24 be determined to be available and if present could be deposited on the sump screen. The requisite  
25 quantity is easily calculated as 0.010-foot times the sump screen net area. The head loss  
26 computations are the same as described for fiber and particulate beds using the full value of  
27 particulate matter transported to the sump screen. (This would include latent debris such as dirt  
28 and concrete dust. It would also include any other fine particulate debris such as rust, inorganic  
29 zinc, epoxy fine material, etc.) It should be noted that the particulate layer is characterized by a  
30 very high sludge-to-fiber ratio; hence a limiting value for the compression is used. If under these  
31 conditions, the thin-bed head loss should exceed the NPSH margin, then the allowable particulate  
32 loading can be evaluated by reducing the particulate quantity until the calculated head loss is  
33 within the NPSH margin.

### 34 **3.7.2.3.2.4 Sump Screen Submergence**

35 For submerged screen sumps, the head loss computation methods presented herein are directly  
36 applicable. Submerged screens are characterized by having ambient pressure on one side of the  
37 screen, and the flow is driven by the pump. The limiting criterion for submerged screens occurs  
38 when the combined clean sump and debris bed head loss exceeds the NPSH margin.

1 For partially submerged screen sumps, the head loss computation methods presented herein are  
2 also directly applicable. Partially submerged screens are characterized by having the ambient  
3 pressure on both sides of the screen. In this case, the flow driver is the difference in fluid  
4 elevation between the two sides of the screen. As debris accumulates on the screen, the water  
5 level behind the screen falls and generates a pressure drop to allow the flow rate to be achieved.  
6 The limiting criterion for a partially submerged screen is when the debris bed accumulation on  
7 the screen reduces the flow to less than the flow requirements for the sump. Numerical  
8 simulations confirm that an effective head loss across a debris bed approximately equal to  
9 one-half of the pool height is sufficient to prevent adequate water flow. As such, for partially  
10 submerged sump screens, the methodology described herein should be used to estimate the  
11 pressure drop due to debris across the submerged sump screen area. The partially submerged  
12 sump screen will operate properly if the estimated head loss (in feet of water across the debris  
13 bed, when added to the clean screen head loss) is less than one-half the pool height.

#### 14 **3.7.2.3.2.5 Buoyant Debris**

15 For fully submerged screens, buoyant debris is not considered a problem since it would not reach  
16 the sump screens. However, for partially submerged screens, the effects of buoyant debris should  
17 be considered. Note that the transport analysis may indicate that the quantity of buoyant debris  
18 reaching the sump screen is negligible, since trash racks and gates may largely prevent this.

19 For buoyant debris that is determined to reach a partially submerged screen, this baseline  
20 methodology recommends that the effective screen area be reduced by the thickness of the  
21 buoyant debris layer times the length of the covered perimeter, to the extent that it fully  
22 envelopes the screen. This is very conservative, since floating debris will have gaps and large  
23 pore space among pieces that will admit flow.

#### 24 **3.7.2.3.3 Methodology Limitations and Other Considerations**

##### 25 **3.7.2.3.3.1 Flat Screen Assumption**

26 The NUREG/CR-6224 correlation adopted in this methodology was developed mainly using data  
27 obtained in a closed loop that contained a vertical pipe section that housed a horizontally  
28 mounted flat screen. The flat screens yielded conservative data for the development of the  
29 NUREG/CR-6224 correlation because all debris was forced onto a very small screen in a small-  
30 scale test apparatus. In the case of alternate design screens (stacked disc, star, large passive, etc.)  
31 direct application of the NUREG/CR-6224 correlation may yield overly conservative results  
32 (Reference 17). For these alternate geometry screens, independent head loss correlations should  
33 be developed based on actual design configurations, debris loads, and test data to reduce  
34 conservatism.

##### 35 **3.7.2.3.3.2 Non-Uniform Deposition on Sump Screen Surfaces**

36 PWR sump screens can have vertical and inclined orientation. On a vertical screen, there is  
37 greater chance for non-uniform deposition of debris, which will usually lead to lower head losses  
38 because of thin spots in the debris bed. Body forces also tend to shear the bed from the screen,

1 also a mitigating factor. For these reasons, using the uniform deposition assumption for vertical  
 2 screens is a conservative approach. Similar statements can be made for curved surfaces such as  
 3 horizontally oriented, cylindrical strainer designs, since body forces in the debris bed essentially  
 4 act in the opposite direction to the suction forces over a significant portion of the strainer area.  
 5 An inclined, flat surface is less limiting than a horizontal surface; therefore, the uniform  
 6 deposition assumption again should be conservative.

### 7 **3.7.2.3.3 Very Thin Fiber Beds**

8 This section pertains to the regime where fiber loading is less than that required to form a thin  
 9 bed. The NUREG/CR-6224 head loss correlation was developed and validated for debris that is  
 10 uniformly distributed on the screen surface. However, experiments have shown that very thin  
 11 fibrous beds (with a thickness of less than one-eighth inch) are characterized by large scale  
 12 non-uniformities on the screen and negligible head losses. For fibrous debris bed less than  
 13 one-eighth inch thick, the NUREG/CR-6224 head loss correlation significantly overpredicts the  
 14 experimentally determined head loss and should not be used. Instead, it is appropriate to consider  
 15 the head loss across fibrous debris beds of less than one-eighth inch to be negligible.

### 16 **3.7.2.3.4 Sample Calculations**

17 The following examples demonstrate the use of the head loss equations with the debris sources  
 18 specified in Section 3.4.3 of this document and typical plant conditions. These calculations  
 19 assume steady-state conditions at final debris loading with steady ECCS flows and a simple,  
 20 flat-plate strainer geometry.

#### 21 **3.7.2.3.4.1 Fiber and Particulate Debris Bed**

##### 22 Flow Conditions

23 These are obtained from plant design documents and NPSH calculations.

ECCS flow rate (Q)	=	<u>9000</u>	gpm
Temperature (T)	=	<u>170</u>	°F
Fluid density ( $\rho$ )	=	<u>60.80</u>	lbm/ft <sup>3</sup>
Fluid viscosity ( $\mu$ )	=	<u>2.51E-04</u>	lbm/ft/sec

24

##### 25 Screen Parameters

26 These are obtained from screen design drawings and ECCS flow rate.

Effective surface area (A)	=	<u>300</u>	ft <sup>2</sup>
Screen approach velocity (U)	=	<u>0.067</u>	ft/s

27

1 Debris Types/Quantities at Screen

2 These are obtained from Debris Characteristics (Section 3.4.3), Latent Debris (Table 3-4) and the  
3 Transport Analysis (Section 3.6).

Nukon fiber	=	$\frac{129}{1}$	ft <sup>3</sup>	
Latent fiber	=	$\frac{8.84}{1}$	ft <sup>3</sup>	← 62.4/2.4 * 0.34 ft <sup>3</sup>
Latent dirt-dust	=	$\frac{33.51}{1}$	lbm	
Qual-epoxy	=	$\frac{329}{1}$	lbm	
Unqual. coatings	=	$\frac{2625}{1}$	lbm	

4  
5 Debris Characteristics

## 6 • Nukon

Theoretical packing density ( $\rho_f$ )	=	$\frac{2.4}{1}$	lbm/ft <sup>3</sup>	
Fiber diameter (D)	=	$\frac{2.33 * 10^{-5}}{1}$	ft (use LDFG)	
Surface to volume ratio (Sv)	=	$\frac{1.717 * 10^5}{1}$	ft <sup>-1</sup>	← 4 / 2.33 * 10 <sup>-5</sup> ft <sup>3</sup>
Mass of fiber ( $m_f$ )	=	$\frac{309.6}{1}$	lbm	← 129 ft <sup>3</sup> * 2.4 lbm/ft <sup>3</sup>
Fiber density	=	$\frac{175}{1}$	lbm/ft <sup>3</sup>	
Fiber volume	=	$\frac{1.77}{1}$	ft <sup>3</sup>	← 309.6 lbm / 175 lbm/ft <sup>3</sup>

7  
8 • Latent fiber

Theoretical packing density ( $\rho_f$ )	=	$\frac{2.4}{1}$	lbm/ft <sup>3</sup>	
Fiber diameter (D)	=	$\frac{2.33 * 10^{-5}}{1}$	ft	
Surface to volume ratio (Sv)	=	$\frac{1.717 * 10^5}{1}$	ft <sup>-1</sup>	← 4 / 2.33 * 10 <sup>-5</sup> ft <sup>3</sup>
Mass of fiber ( $m_f$ )	=	$\frac{21.22}{1}$	lbm	← 8.84 ft <sup>3</sup> * 2.4 lbm/ft <sup>3</sup>
Fiber density	=	$\frac{62.4}{1}$	lbm/ft <sup>3</sup> (Table 3-1)	
Fiber volume	=	$\frac{0.34}{1}$	ft <sup>3</sup>	← 21.22 lbm / 62.4 lbm/ft <sup>3</sup>

9  
10 • Latent dirt/dust

Particle density	=	$\frac{100}{1}$	lbm/ft <sup>3</sup>	
Particle diameter (D)	=	$\frac{3.28 * 10^{-5}}{1}$	ft	
Surface to volume ratio (Sv)	=	$\frac{1.829 * 10^5}{1}$	ft <sup>-1</sup>	← 4 / 2.33 * 10 <sup>-5</sup> ft <sup>3</sup>
Particle volume	=	$\frac{0.335}{1}$	lbm	← 8.84 ft <sup>3</sup> * 2.4 lbm/ft <sup>3</sup>

11  
12 With respect to qualified coatings in the ZOI, a relatively high damage pressure was justified in  
13 earlier sections of this document. However, the demonstration calculations will use a spherical  
14 ZOI with radius of 10 feet, for a surface area of 1256.6 ft<sup>2</sup>. The qualified coatings thickness is  
15 taken to be 0.009 inch. For unqualified coatings, a thickness of 0.003 inch is used, and 30,000 ft<sup>2</sup>  
16 is the assumed coverage. In both cases, the coating particles are conservatively assumed to be  
17 spherical with diameter equal to 10  $\mu$ m. The coatings material is assumed to be inorganic zinc  
18 (IOZ) in both cases.

1       •     Qualified epoxy

Particle density	=	$\frac{350}{3.28 * 10^{-5}}$	lbm/ft <sup>3</sup> (IOZ-equivalent)
Particle diameter (D)	=	$\frac{3.28 * 10^{-5}}{1.829 * 10^5}$	ft
Surface to volume ratio (S <sub>v</sub> )	=	$\frac{1.829 * 10^5}{0.94}$	ft <sup>-1</sup> $\Leftarrow 6 / 3.28 * 10^{-5}$ ft <sup>3</sup>
Particle volume	=	$\frac{0.94}{350}$	lbm $\Leftarrow 329$ lbm / 350 lbm/ft <sup>3</sup>

2

3       •     Unqualified epoxy

Particle density	=	$\frac{350}{3.28 * 10^{-5}}$	lbm/ft <sup>3</sup> (IOZ-equivalent)
Particle diameter (D)	=	$\frac{3.28 * 10^{-5}}{1.829 * 10^5}$	ft
Surface to volume ratio (S <sub>v</sub> )	=	$\frac{1.829 * 10^5}{7.50}$	ft <sup>-1</sup> $\Leftarrow 6 / 3.28 * 10^{-5}$ ft <sup>3</sup>
Particle volume	=	$\frac{7.50}{350}$	lbm $\Leftarrow 2625$ lbm / 350 lbm/ft <sup>3</sup>

4

5       •     Average fiber

Total fiber volume	=	$\frac{2.11}{330.82}$	ft <sup>3</sup>
Total fiber mass	=	$\frac{330.82}{156.86}$	lbm
Ave. fiber density	=	$\frac{156.86}{1.717 * 10^5}$	lbm/ft <sup>3</sup>
Ave. surface to volume ratio (S <sub>v</sub> )	=	$\frac{1.717 * 10^5}{2.11}$	ft <sup>-1</sup>

6

7       •     Average particulate

Total particle volume	=	$\frac{8.775}{2987.5}$	ft <sup>3</sup>
Total particle mass	=	$\frac{2987.5}{340.46}$	lbm
Ave. particle density	=	$\frac{340.46}{1.829 * 10^5}$	lbm/ft <sup>3</sup>
Ave. surface to volume ratio (S <sub>v</sub> )	=	$\frac{1.829 * 10^5}{8.775}$	ft <sup>-1</sup>

8

9       •     Average debris

Total particle volume	=	$\frac{8.775}{1.829 * 10^5}$	ft <sup>3</sup>
Ave. surface to volume ratio (S <sub>v</sub> )	=	$\frac{1.829 * 10^5}{2.11}$	ft <sup>-1</sup>
Total fiber volume	=	$\frac{2.11}{1.717 * 10^5}$	ft <sup>3</sup>
Surface to volume ratio (S <sub>v</sub> )	=	$\frac{1.717 * 10^5}{1.8078 * 10^5}$	ft <sup>-1</sup>
Ave. debris surface to volume ratio (S <sub>v</sub> )	=	$\frac{1.8078 * 10^5}{2.11}$	ft <sup>-1</sup>

10

11     Debris Bed Equations:

12       •     Theoretical debris bed thickness (ΔL<sub>o</sub>)

13             Total volume of fiber divided by screen area     = 5.51 inches



1 • Particulate to fiber mass ratio ( $\eta$ )  
2 Mass of particles divided by mass of fiber = 9.03

3 • Actual bed thickness ( $\Delta L_m$ )= 2.72 inches

4 Assume a value for the bed thickness and iterate until Equations 3.7.2-3 and 3.7.2-4 converge on  
5 approximately the same number. Computer solution may be required.

6 Head loss across debris bed ( $\Delta H$ ) = 17.80 feet H<sub>2</sub>O (using Equation 3.7.2-1)

7 Mixed debris bed solidity ( $\alpha_m$ ) = 0.16 (using Equation 3.7.2-2)

8 Head loss volumetric compression (c)  $\approx$  2.03 (using Equation 3.7.2-3)

9 Head loss volumetric compression (c)  $\approx$  2.03 (using Equation 3.2.5-4)

10 Equations 3.7.2-3 and 3.7.2-4 have converged within ~1 percent of each other, which is  
11 considered acceptable convergence. Therefore, the head loss is calculated as 17.80 feet of  
12 water.

13 The mixed debris bed solidity should be less than or equal to 0.20, therefore OK.

14 **3.7.2.3.4.2 Fiber Debris Bed**

15 No sample calculation is provided since a pure fiber debris bed would be unusual, given the  
16 coatings particulate debris in the ZOI, latent debris, the presence of dirt/dust, and other possible  
17 sources of particulates such as ablated concrete. However, should a fiber-only debris-bed head  
18 loss need to be calculated, the process would be the same as for fiber and particulate except that  
19 the particulate quantities would be set to zero.

20 **3.7.2.3.4.3 RMI Debris Bed**

21 Flow Conditions:

22 These are obtained from plant design documents and NPSH calculations.

ECCS flow rate (Q)	=	<u>9000</u>	gpm
Temperature (T)	=	<u>170</u>	°F
Fluid density ( $\rho$ )	=	<u>60.80</u>	lbm/ft <sup>3</sup>
Fluid viscosity ( $\mu$ )	=	<u>2.51E-04</u>	lbm/ft/sec

23

1 Screen Parameters:

2 These are obtained from screen design drawings and ECCS flow rates.

$$\begin{aligned} \text{Effective surface area (A)} &= \frac{300}{0.067} \text{ ft}^2 \\ \text{Screen approach velocity (U)} &= \frac{0.067}{0.067} \text{ ft/s} \end{aligned}$$

3

4 Debris Types/Quantities:5 These are obtained from the Debris Characteristics (Section 3.4.3) and Debris Transport Analysis  
6 (Section 3.6).

$$2.5\text{-mil SS RMI} = \frac{4387.5}{0.067} \text{ ft}^2 \Leftarrow 11,250 \text{ ft}^2 * 0.39 \text{ T.F.}$$

7

8 Debris Bed Equations:9 The head loss correlation for RMI is taken from the RMI debris bed discussion in  
10 subsection 3.7.2.3.1.2.

$$11 \quad \Delta H = 0.108 U^2 (A_{\text{foil}}/A_c)$$

12 where,

13  $\Delta H$  = the head loss across the RMI bed (ft-water)14  $U$  = the approach velocity to the screen (ft/s)15  $A_{\text{foil}}$  = the surface area of the RMI foils (ft<sup>2</sup> – nominal)16  $A_c$  = the strainer circumscribed area (ft<sup>2</sup>)

17 Substituting the above plant-specific parameters

$$\begin{aligned} 18 \quad \Delta H &= 0.108 (0.067)^2 (4387.5/300) \\ 19 &= 0.007 \text{ ft-water} \cong 0.01 \text{ ft-H}_2\text{O} \end{aligned}$$

20 **3.7.2.3.4.4 Mixed Debris Beds (RMI, Fiber, and Particulates)**21 The head loss of a mixed fiber, particulate, and RMI debris bed is the addition of the fiber-and-  
22 particulate head loss to the RMI head loss. For example, if the quantities of debris were as in the  
23 totals of the two preceding calculations, then the total mixed RMI and fibrous debris bed head  
24 loss would be:

$$25 \quad \Delta H_{\text{RMI}} = 0.01 \text{ ft-water}$$

$$26 \quad \Delta H_{\text{Fiber + Particulate}} = 17.80 \text{ ft-water}$$

1 hence,

2  $\Delta H_{\text{RMI} + \text{Fiber} + \text{Particulate}} = 17.81 \text{ ft-water}$  (We can neglect the RMI in this case.)

### 3 **3.7.2.3.4.5 Thin-Bed of Fiber and Particulate Debris**

#### 4 Flow Conditions:

5 These are obtained from plant design documents and NPSH calculations.

ECCS flow rate (Q)	=	$\frac{9000}{170}$	gpm
Temperature (T)	=	$\frac{60.80}{2.51\text{E-}04}$	°F
Fluid density ( $\rho$ )	=	$\frac{300}{0.067}$	lbm/ft <sup>3</sup>
Fluid viscosity ( $\mu$ )	=	$\frac{7.5}{175}$	lbm/ft/sec

6

#### 7 Screen Parameters:

8 These are obtained from screen design drawings and ECCS flow rate.

Effective surface area (A)	=	$\frac{300}{0.067}$	ft <sup>2</sup>
Screen approach velocity (U)	=	$\frac{7.5}{175}$	ft/s

9

#### 10 Debris Types/Quantities:

11 As a starting point, use plant-specific quantities of fine particulate and latent debris.

12 Provided that sufficient fiber is available, the fiber quantity is specifically selected to create a  
13 thin bed. Nukon is assumed for this example, although latent fiber could be used if a sufficient  
14 amount is present.

Nukon fiber	=	$\frac{3.125}{33.51}$	ft <sup>3</sup> $\Leftarrow 0.125"/12 * 300 \text{ ft}^2$
Dirt Dust	=	$\frac{329}{2625}$	lbm
Qual-epoxy	=	$\frac{7.5}{175}$	lbm
Unqualified coatings	=	$\frac{7.5}{175}$	lbm

15

#### 16 Debris Characteristics:

- 17 • Nukon

Theoretical packing density ( $\rho_f$ )	=	$\frac{2.4}{2.33 * 10^{-5}}$	lbm/ft <sup>3</sup>
Fiber diameter (D)	=	$\frac{1.717 * 10^5}{7.5}$	ft
Surface to volume ratio ( $S_v$ )	=	$\frac{4}{2.33 * 10^{-5}}$	ft <sup>-1</sup> $\Leftarrow 4 / 2.33 * 10^{-5} \text{ ft}^3$
Mass of fiber ( $m_f$ )	=	$\frac{7.5}{175}$	lbm $\Leftarrow 3.125 \text{ ft}^3 * 2.4 \text{ pcf}$
Fiber density	=	$\frac{7.5}{175}$	lbm/ft <sup>3</sup>
Fiber volume	=	$\frac{7.5}{175}$	ft <sup>3</sup> $\Leftarrow 7.5 \text{ lbm} / 175 \text{ lbm/ft}^3$

18

1           •     Latent dirt/dust

Particle density	=	$\frac{100}{3.28 * 10^{-5}}$	lbm/ft <sup>3</sup>
Particle diameter (D)	=	$\frac{3.28 * 10^{-5}}{1.829 * 10^5}$	ft
Surface to volume ratio (S <sub>v</sub> )	=	$\frac{1.829 * 10^5}{0.335}$	ft <sup>-1</sup> ⇐ 6 / 3.28 * 10 <sup>-5</sup> ft <sup>3</sup>
Particle volume	=	$\frac{0.335}{33.51}$	lbm ⇐ 33.51 ft <sup>3</sup> / 100 lbm/ft <sup>3</sup>

2

3           •     Qualified epoxy

Particle density	=	$\frac{350}{3.28 * 10^{-5}}$	lbm/ft <sup>3</sup> (IOZ-equivalent)
Particle diameter (D)	=	$\frac{3.28 * 10^{-5}}{1.829 * 10^5}$	ft
Surface to volume ratio (S <sub>v</sub> )	=	$\frac{1.829 * 10^5}{0.94}$	ft <sup>-1</sup> ⇐ 6 / 3.28 * 10 <sup>-5</sup> ft
Particle volume	=	$\frac{0.94}{329}$	lbm ⇐ 329 lbm / 350 lbm/ft <sup>3</sup>

4

5           •     Unqualified coatings

Particle density	=	$\frac{350}{3.28 * 10^{-5}}$	lbm/ft <sup>3</sup> (IOZ-equivalent)
Particle diameter (D)	=	$\frac{3.28 * 10^{-5}}{1.829 * 10^5}$	ft
Surface to volume ratio (S <sub>v</sub> )	=	$\frac{1.829 * 10^5}{7.5}$	ft <sup>-1</sup> ⇐ 6 / 3.28 * 10 <sup>-5</sup> ft
Particle volume	=	$\frac{7.5}{2625}$	lbm ⇐ 2625 lbm / 350 lbm/ft <sup>3</sup>

6

7           •     Average particulate

Total particle volume	=	$\frac{8.775}{2987.5}$	ft <sup>3</sup>
Total particle mass	=	$\frac{2987.5}{340.46}$	lbm
Ave. particle density	=	$\frac{340.46}{1.829 * 10^5}$	lbm/ft <sup>3</sup>
Ave. surface to volume ratio (S <sub>v</sub> )	=	$\frac{1.829 * 10^5}{8.775}$	ft <sup>-1</sup>

8

9           •     Average debris

Total particle volume	=	$\frac{8.775}{1.829 * 10^5}$	ft <sup>3</sup>
Ave. surface to volume ratio (S <sub>v</sub> )	=	$\frac{1.829 * 10^5}{0.043}$	ft <sup>-1</sup>
Total fiber volume	=	$\frac{0.043}{1.717 * 10^5}$	ft <sup>3</sup>
Surface to volume ratio (S <sub>v</sub> )	=	$\frac{1.717 * 10^5}{1.82847 * 10^5}$	ft <sup>-1</sup>
Ave. debris surface to volume ratio (S <sub>v</sub> )	=	$\frac{1.82847 * 10^5}{1.82847 * 10^5}$	ft <sup>-1</sup>

10

11    Debris Bed Equations:

12           •     Theoretical debris bed thickness (ΔL<sub>o</sub>)

13                   Total volume of fiber divided by screen area                   = 0.125 inch

- 1           •     Particulate to fiber mass ratio ( $\eta$ )
- 2                   Mass of particles divided by mass of fiber                   = 398.34
- 3           •     Actual bed thickness ( $\Delta L_m$ ) = 1.764 inches
- 4                   Sum the fiber and particulate volumes. Multiply by 12
- 5                   and divide by the product of the (solidity \* screen net area)
- 6                   Limiting solidity value of 0.20 is recommended.
- 7           (Using Equation 3.2.5-1) Head loss across debris bed ( $\Delta H$ ) = 19.27 ft-H<sub>2</sub>O
- 8           (Using Equation 3.2.5-2) Mixed debris bed solidity ( $\alpha_m$ ) = 0.20

9     The calculated head loss is 19.27 feet of water via iterative solution. Computational tools may be  
 10    required. Since the calculated head loss of the thin bed exceeds the NPSH margin at most plants,  
 11    parametric calculations can be performed to determine the allowable particulate quantities at the  
 12    sump screen(s).

#### 13    **3.7.2.3.4.6 Microporous Insulation**

14    As noted in the microporous insulation discussion in subsection 3.7.2.3.1, the currently available  
 15    experimental data can only support the head loss calculations of microporous insulation debris in  
 16    the presence of fibrous debris provided the mass ratio of microporous insulation-to-fiber is less  
 17    than 20 percent. In these cases, the microporous insulation debris is treated as a particulate and  
 18    the equations and methods for fibrous and particulate head loss are used (see example of the  
 19    fibrous and particulate debris bed calculation above).

#### 20    **3.7.2.3.4.7 Determination of Requisite Sump Screen Size**

21    If, through the evaluation of the debris head loss, the existing screen does not provide sufficient  
 22    surface area, the calculations provided within this methodology can be utilized with little or no  
 23    modification to determine the amount of surface area required.

24    The key assumption in the head loss correlations provided is homogeneous debris accumulation  
 25    on a flat plate. As noted in the very thin fiber bed discussion in subsection 3.7.2.3.3.3, different  
 26    screen orientations and configurations can provide different debris accumulation profiles and  
 27    take advantage of uneven debris distribution and flow redistribution. In these cases, the head loss  
 28    correlations provided in this methodology may yield overly conservative results. As such,  
 29    adjustments to the head loss correlation could be made based on experimental test data  
 30    applicable to the actual sump screen orientation and configuration. Some test data exist for  
 31    vertical screens (see Reference 24), but applicability of the test data always has to be assessed. In  
 32    some cases, plant-specific testing may be required to reduce conservatism. Suggested  
 33    refinements are further outlined in the Supplemental Guidance.

#### 1 3.7.2.3.4.8 Calcium Silicate

2 Informal results on the NRC/Los Alamos National Laboratory (LANL) calcium silicate testing at  
3 the University of New Mexico (UNM) were presented in February 2003 (Reference 23). This  
4 presentation did not provide any quantitative guidance with respect to use of the  
5 NUREG/CR-6224 correlation with Cal-Sil debris mixtures. A recent LANL/NRC/UNM paper  
6 (Reference 23) has provided more detailed test results. The formal NRC test report on this  
7 program is not yet available.

8 Reference 23 has been reviewed, and some observations are provided. With respect to the  
9 calcium silicate tests with Nukon fiber, the principal comment is that these results will have to be  
10 applied very carefully on a plant-specific basis. For example, the researchers operated their test  
11 apparatus at very high flow rates, which induced high approach velocities that compressed the  
12 debris beds to the compression limit of the granular debris. When the flow was reduced, the  
13 compressed bed did not relax, nor did it release the trapped particles. Hysteresic effects were  
14 observed, for which head losses were actually greater at lower flows. Then, the surface-to-  
15 volume ratio was adjusted such that the NUREG/CR-6224 correlation conservatively predicted  
16 the hysteresic effects. For some plants, this testing does not represent prototypical behavior, and  
17 it is excessively conservative. It also suggests the troubling conclusion that there is no benefit to  
18 throttling the ECCS flows to reduce sump screen head loss with Cal-Sil, which for some plants  
19 again may not be true.

20 Based on the research procedures described above, Reference 23 concludes that  $S_v = 550,000 \text{ ft}^{-1}$   
21 is an appropriate value for the specific type of Cal-Sil that was tested. The researchers further  
22 recommend that this value be conservatively enhanced for safety analyses. Our observation is  
23 that this procedure will be excessively conservative for many plants, depending on the type(s) of  
24 Cal-Sil present in these plants and on the sump screen approach velocities. Therefore, the results  
25 of Reference 23 should be applied with extreme caution.

26 The researchers applied similar techniques to the test with fiber, dirt and concrete dust in  
27 Reference 23. Therefore, the recommended value of  $S_v = 190,000 \text{ ft}^{-1}$  is also considered too  
28 conservative.

29 Reference 23 itself mentions that the LANL Test Report, LA-UR-03-0471, should be consulted  
30 for final recommendations once it is issued. On April 17, 2004, the PWR Industry became aware  
31 that Los Alamos published LA-UR-04-1227, "GSI-191: Experimental Studies of Loss-of-  
32 Coolant-Accident-Generated Debris Accumulation and Head Loss with Emphasis on the Effects  
33 of Calcium Silicate Insulation." A review of that document has been initiated to help assess  
34 what, if any, further guidance regarding treatment of calcium silicate might be supported by the  
35 tests reported.

36

## 1    **4    ANALYTICAL REFINEMENTS**

2    The Baseline Methodology described in Section 3 incorporates conservatisms in the analytical  
3    approach to evaluating post-accident sump performance. Identified in this section are  
4    refinements that may be implemented to those analytical approaches to provide for more realistic  
5    but still conservative evaluations.

### 6    **4.1    INTRODUCTION**

7    To facilitate its applicability to all PWRs, the Baseline Methodology utilized conservative  
8    analytical approaches to evaluating the five main topics associated with post-accident sump  
9    performance:

- 10            1.    Break selection
- 11            2.    Debris generation
- 12            3.    Latent debris
- 13            4.    Debris transport
- 14            5.    Head loss

15    With the exception of latent debris, refinements to the analytical approaches have been  
16    developed that, if applied, provide for more realistic, but still conservative, post-accident sump  
17    performance evaluations.

### 18    **4.2    METHOD DESCRIPTION**

19    Described within this section are refinements to three of the five analytical topics that comprise  
20    the Baseline Methodology. Although no refinements to break selection and latent debris guidance  
21    are offered, they are included in this section for completeness.

#### 22    **4.2.1    Break Selection**

23    On July 19, 1987, the NRC issued Generic Letter 87-11, "Relaxation in Arbitrary Intermediate  
24    Pipe Rupture Requirements." The Generic Letter informed licensees that the NRC had finalized  
25    a revision to Branch Technical Position MEB 3-1 of the Standard Review Plan Section 3.6.2 in  
26    NUREG-0800. The revision eliminated all dynamic effects (missile generation, pipe whipping,  
27    pipe break reaction forces, jet impingement forces, compartment, subcompartment and cavity  
28    pressurizations, and decompression waves within the ruptured pipe) and all environmental  
29    effects (pressure, temperature, humidity, and flooding) resulting from arbitrary intermediate pipe  
30    ruptures.

31    Arbitrary intermediate pipe ruptures, which previously were specified in B.1.c.(1)(d) of MEB 3-1  
32    for ASME Code Class 1 piping and in B.1.c.(2)(b)(ii) of MEB 3-1 for ASME Code Class 2 and 3  
33    piping, are now no longer mentioned or defined in MEB 3-1. Besides the relaxation in  
34    requirements relating to arbitrary intermediate pipe ruptures, the revised Standard Review Plan  
35    Section 3.6.2 updated the citations to the ASME stress limits to achieve consistency with current  
36    practices, and introduced other minor changes. The requirements for postulated terminal end pipe

1 ruptures, postulated intermediate pipe ruptures at locations of high stress, and high usage factor  
2 for leakage cracks were retained in the revision to MEB 3-1.

3 Consistent with a plant's licensing basis, MEB 3-1 may be used to select break locations for  
4 evaluating post-accident sump operability. The application of MEB 3-1 is justified for this  
5 purpose as it focuses attention on high stress and fatigue locations, such as at the terminal ends of  
6 a piping system at its connection to the nozzles of a component. The junction of a steam  
7 generator and the primary system piping is included as such a location. It is the industry  
8 experience that the steam generator is the largest source of insulation debris from a postulated  
9 pipe rupture. Furthermore, if multiple insulation types are used inside containment, they are often  
10 used on steam generators. Therefore, the application of MEB 3-1 is considered appropriate and  
11 conservative for selecting break locations.

## 12 **4.2.2 Debris Generation**

### 13 **4.2.2.1 Zone of Influence**

14 The zone of influence (ZOI) is defined as the volume about the break in which the fluid escaping  
15 from the break has sufficient energy to generate debris from insulation, coatings, and other  
16 materials within the zone.

17 For the baseline calculation, it is recommended that the boundary of the ZOI be assumed to be  
18 spherical, with the center of the sphere located at the break site. The use of a spherical ZOI is  
19 intended to encompass the effects of jet expansion resulting from impingement on structures and  
20 components. Two analytical refinements to the definition of the ZOI for insulation materials are  
21 recommended, as documented below. No refinements are offered in the definition of the ZOI for  
22 coatings.

#### 23 **4.2.2.1.1 Method 1: Debris-Specific Spherical ZOIs**

24 This method is similar to that recommended in Section 3.4 of this document, in that the ZOI is  
25 defined as a sphere with its origin at the break site. However, Section 3.4 recommends defining  
26 one spherical ZOI for each break site, based on the insulation with the lowest destruction  
27 pressure.

28 It is recommended that the ZOI definition be refined by assigning multiple ZOIs to each break  
29 site, with each corresponding to the destruction pressure of one insulation species located near  
30 the break site. Using this method still incorporates the conservatism and ease of use of a  
31 spherical ZOI, but more realistically models the destruction of multiple insulation types.  
32 Calculations are performed in the same way as those recommended in Section 3.4, including the  
33 treatment of robust barriers.

### 34 **Definition of Spherical ZOI**

35 To determine the radius of the spherical ZOI needed to represent the effects of the jet originating  
36 from a postulated pipe break, the ANSI/ANS 58.2-1988 standard (Reference 3) was used, as



1 described in Section 3.4 of this document. The basis for the use of the equivalent spherical ZOI is  
2 also described in Section 3.4 of this document.

3 Equivalent spherical ZOI calculations were performed and documented for values of isobars  
4 corresponding to destruction pressures of several types of insulation. Table 3-1 summarizes these  
5 insulation types and the applicable ZOI, expressed as the ratio of the ZOI radius to the break  
6 diameter, for which the calculations were performed. The calculations summarized in Table 3-1  
7 make no changes in insulation destruction pressures based on the differences between dry or  
8 saturated steam jets and flashing, as described in Section 3.4 of this document.

## 9 **The ZOI and Robust Barriers**

10 The effects of robust barriers on the ZOI are modeled in the same way as recommended in  
11 Section 3.4.

## 12 **Evaluating Debris Generation Within the ZOI**

13 Once the ZOI for each insulation type has been determined, calculate the amount of debris  
14 generated within each ZOI, then sum the individual contributions to determine the debris source  
15 term. Information about the type, location and amount of debris sources within the containment  
16 is obtained from plant drawings and the results of a condition assessment walkdown such as  
17 described in NEI 02-01 (Reference 2). The characterization of the debris (transport  
18 characteristics) is evaluated using the debris transport guidance in Sections 3.6 and 4.2.4.

### 19 **4.2.2.1.2 Method 2: Direct Jet Impingement Model**

20 Whereas Section 3.4 and the refinement described above use a spherical ZOI to model the region  
21 of insulation destruction, it is also possible to define the ZOI by modeling two freely-expanding  
22 jets, each originating at one end of the DEGB. It is recommended that if this method is used, the  
23 ANSI/ANS 58.2-1988 standard be used to determine the jet geometry.

## 24 **Definition of ZOI**

25 The ANSI/ANS 58.2-1988 standard (Reference 3) provides the information necessary to map the  
26 constant-stagnation-pressure contours (isobars) for jets originating from a postulated pipe break.  
27 Appendices B, C, and D of Reference 3 provide the guidance necessary to determine the  
28 geometry of a freely-expanding jet. Guidance is provided for jets originating from a variety of  
29 reservoir conditions, including subcooled conditions. Using this method to define a ZOI requires  
30 a high degree of rigor in determining what stagnation pressure each insulation type is subjected  
31 to.

32 The guidance in Reference 3 was used to determine the geometry of a jet originating from a  
33 postulated break in a PWR piping system. A subcooled reservoir and flashing break flow were  
34 assumed for the calculations as detailed below. The following steps were followed in performing  
35 the calculations:

- 1           1.    The mass flux from the postulated break was determined using the Henry-Fauske  
2           model, as recommended in Appendix B, for subcooled water blowdown through  
3           nozzles, based on a homogeneous non-equilibrium flow process. No irreversible  
4           losses were considered.
- 5           2.    The initial and steady-state thrust forces were calculated based on the guidance in  
6           Appendix B of Reference 3, and the postulated reservoir conditions detailed below.
- 7           3.    The jet outer boundary and regions were mapped using the guidance in  
8           Appendix C, Section 1.1, of Reference 3 for a circumferential break with full  
9           separation. The input to the equations from Appendix C for the thermodynamic  
10          conditions at the asymptotic plane was calculated using principles of  
11          thermodynamics and the postulated conditions in the reservoir.
- 12          4.    A spectrum of isobars was mapped using the guidance in Appendix D of  
13          Reference 3.
- 14          5.    The volume encompassed by the various isobars was calculated using a trapezoidal  
15          approximation to the integral.

16    The jet expansion calculations were based on the following conditions:

- 17          1.    A circular break geometry was used for the calculations. This break geometry is  
18          representative of both a postulated DEGB of primary piping as well as the DEGB  
19          of piping attached to the RCS. The complete breaking of a pipe, either primary  
20          piping or piping attached to the RCS, provides for a maximum debris generation  
21          volume as there are two ends of the break to release fluid.
- 22          2.    Fluid reservoir conditions of 2250 psia and 540°F were used for the calculations.  
23          The corresponding stagnation enthalpy and subcooling used in the calculations are  
24          547.2 Btu/lbm and 102.7°F, respectively. These conditions are intended to represent  
25          a PWR cold leg at full power and provide for a conservatively large ZOI compared  
26          to hot-leg conditions at power operations.
- 27          3.    Ambient pressure of 14.7 psia was used. This is conservative as no credit is taken  
28          for containment backpressure (the increase in containment pressure that would  
29          result from the release of mass and energy into the containment as a result of the  
30          postulated break).

31    The results of the isobar mapping calculations as well as an example of a plotted isobar are  
32    contained in Appendix D. For both the plot and table, the radius of the isobar is defined as a  
33    function of the axial distance from the break site. Using symmetry about the longitudinal axis, it  
34    is possible to define the three-dimensional constant-stagnation-pressure surface.

## 1    **The ZOI and Robust Barriers**

2    The effects of robust barriers on the ZOI are modeled in the same way as recommended in  
3    Section 3.4.

## 4    **Evaluating Debris Generation Within the ZOI**

5    Once the ZOI for each insulation type has been determined, calculate the amount of debris  
6    generated within each ZOI, then sum the individual contributions to determine the debris source  
7    term. Information about the type, location, and amount of debris sources within the containment  
8    is obtained from plant drawings and the results of a condition assessment walkdown such as  
9    described in NEI 02-01 (Reference 2). The characterization of the debris (transport  
10   characteristics) is evaluated using the debris transport guidance in Sections 3.6 and 4.2.4.

### 11   **4.2.2.2 Debris Characteristics**

12   This section provides data that may be used with the logic and procedures presented in  
13   Section 3.4.3 to conservatively predict the characteristics of debris generated as a result of a  
14   LOCA.

#### 15   **4.2.2.2.1 Fibrous Insulation**

16   Physical characteristics of fibrous materials (except calcium silicate), are identified in Table 3-2.  
17   Destruction pressures for common insulation and coating materials are provided in Table 3-2.  
18   The damage characteristics of additional materials are based on extrapolation of test data that are  
19   provided in Table 3-1. Not all generated fibrous debris needs to be assumed to be of a  
20   transportable size. The specifics of transportability are discussed in the debris transport section.

21   Fire barrier materials are addressed separately in subsection 4.2.2.2.5.

22   For some plant sites, it may be desirable to use a bounding, simplifying assumption for the debris  
23   size distribution. It would always be acceptable to conservatively assume that all debris is  
24   reduced to fine particles. It is also acceptable to assume a more conservative (biased toward  
25   smaller pieces) distribution than that presented in Section 3.4.3.2.

26   Utilities should also review their design documentation for additional information regarding  
27   debris generation characteristics of insulation used in their plant. For example, the NRC has  
28   previously reviewed and issued an SER on Nukon insulation and its consequential effect on  
29   ECCS operation post-accident (Reference 26).

#### 30   **4.2.2.2.2 Reflective Metallic Insulation (RMI)**

31   RMI debris is assumed to be generated within the ZOI. Typically, RMI is installed in  
32   pre-fabricated cassettes that conform to the piece of equipment being insulated. Break jet  
33   impingement can dislodge RMI and possibly destroy cassettes, creating smaller pieces of debris.

1 The following information should be used to evaluate the potential for debris generation from  
2 RMI cassettes:

- 3 • Latch mechanism types and characteristics
- 4 • Pressure at which destruction of the cassettes will occur
- 5 • Differences in destruction pressure for different insulation brands and types
- 6 • Modes of insulation detachment and destruction
- 7 • Destruction of insulation adjacent to the break site

8 RMI destruction regimes are defined as:

- 9 • Dislodged cassettes
- 10 • Damaged cassettes (individual foils produced)
- 11 • Complete destruction (shredded and crumpled foils). This occurs for RMI located  
12 on the section of piping where the break occurs and on sections of pipe and  
13 components located within six pipe diameters of the break site.

14 The destruction pressures for RMI are given in Table 3-1. The recommended debris size  
15 distribution is given in Reference 27.

#### 16 **4.2.2.2.3 Coatings**

17 All coatings need to be identified as DBA-qualified/acceptable or non-DBA qualified/  
18 unacceptable. Guidance on evaluating coatings is given in Reference 27.

#### 19 **4.2.2.2.3.1 Coatings Within the ZOI**

20 Within the ZOI of the postulated break, all coating materials (DBA-qualified and non-DBA-  
21 qualified) will be assumed to fail and will therefore contribute to the debris source term.

- 22 • The type(s) of coating systems within the ZOI should be identified and  
23 documented. If multiple coating systems have been applied to surfaces within the  
24 ZOI, the properties of the coating system that produces post-accident debris most  
25 detrimental to the containment sump should be used in subsequent transport and  
26 sump clogging analyses. Representative physical characteristics of the failed  
27 coating materials within the ZOI are shown in Table 3-2

#### 28 **4.2.2.2.3.2 Coatings Outside the ZOI**

- 29 • DBA-qualified coatings outside the ZOI, when properly maintained, do not fail and  
30 therefore do not contribute to the debris source term.
- 31 • Non-DBA-qualified coatings outside the ZOI may disbond from the substrate and  
32 contribute to the debris source term.

- 1           –       Non-DBA-qualified coatings that are potential debris sources include  
2                    coatings on equipment permanently stored in containment or temporarily  
3                    left in containment after an outage.
  
- 4           –       In the absence of vendor-generated or plant-specific data, all non-DBA-  
5                    qualified coatings should be assumed to fail and therefore be considered in  
6                    the debris source term.
  
- 7           –       Vendor or plant-specific data or experience may support using less than  
8                    complete (100 percent) failure of non-DBA-qualified coatings in the  
9                    debris source term. Additionally, an industry research project is being  
10                   conducted by the Electric Power Research Institute (EPRI) PSE in  
11                   2003/2004 concerning the failure of original equipment manufacturer  
12                   (OEM) non-DBA-qualified/unacceptable coatings in the PWR DBA  
13                   environment to provide additional data on this topic.
  
- 14       •       The type(s) of coating systems outside of the ZOI should be identified and  
15                   documented. If individual non-DBA-qualified coating systems used outside of the  
16                   ZOI are not identified, the properties of the non-DBA-qualified coating system that  
17                   produces post-accident debris most detrimental to the containment sump should be  
18                   used in subsequent transport and sump clogging analyses. The following types of  
19                   coatings are commonly found within PWR containments: inorganic zinc (IOZ),  
20                   epoxy, epoxy phenolic, and alkyd. Representative physical characteristics of failed  
21                   coating materials outside of the ZOI are shown in Table 3-2.

#### 22   **4.2.2.2.4   Tape, Tags and Stickers**

23   All tape, tags and stickers located in the ZOI are assumed to fail and contribute to the debris  
24   source term. This includes, but is not limited, to materials that are qualified for service in DBA  
25   conditions. Duct, electrical, masking, and grip tape are potential debris sources but other types of  
26   adhesive tape can be used inside containment. Equipment labels and tags secured by adhesives or  
27   other means are also potential sources of debris. All tape and stickers located in the ZOI will be  
28   assumed to be destroyed, creating small pieces and or fibers.

29   Tape, tags and stickers should be incorporated in licensees' FME programs to minimize the  
30   amount present inside containment. A licensee's FME program should be considered when  
31   performing the plant-specific evaluation.

32   All non-qualified tape and stickers outside the ZOI are assumed to fail unless a technical  
33   justification to exclude them from the source term is available. Non-soluble tape, stickers, and  
34   tags secured by adhesives located outside the ZOI will be assumed to fail by peeling away from  
35   the surface to which they are attached. Soluble tape, stickers, and tags secured by adhesives or  
36   other means will be assumed to dissolve under the action of containment sprays or other sources  
37   of water.

1 The size distribution of the debris produced by tape, tags and stickers should be evaluated on a  
2 case-specific basis. The properties of the materials in question should be used to determine a  
3 conservative debris size distribution (i.e., biased toward smaller, transportable forms). It is  
4 conservative to assume that all debris created from tape and stickers is reduced into fine or small  
5 pieces or individual fibers.

6 It is noteworthy that for some plant-specific applications, the amount of debris produced by tape,  
7 tags and stickers will be quite small compared to the contributions from other materials inside  
8 containment. In these cases, it may be possible to neglect the contribution of tape, tags and  
9 stickers to the debris source term.

#### 10 **4.2.2.2.5 Fire Barrier Materials**

11 Fire barrier material may be a source of debris inside containment. This includes board material,  
12 blanket material, and foam material. Fire barrier materials within the ZOI are to be evaluated as  
13 potential debris sources.

14 Fire barriers consist of many types of insulation and other materials. Many of the materials are  
15 similar or identical to those used to insulate RCS piping and components. These fire barrier  
16 materials may be treated in the same way as their counterparts used in other applications inside  
17 containment (i.e., the same destruction pressures can be used). However, differences in  
18 attachment, encapsulation, and construction of the fire barrier materials compared to RCS  
19 insulation should be accounted for when determining the amount of debris generated from  
20 materials that are also used in other applications.

21 Fire barrier materials are typically unencapsulated. The destruction pressures for these  
22 non-encapsulated blanket materials will be lower than encapsulated RCS insulation of  
23 comparable composition.

24 For materials that are unique to fire barrier applications and do not have supporting test data, a  
25 destruction pressure equal to that of low-density fiberglass may be assumed. Available  
26 destruction information for fire barrier and other materials that might be found inside typical  
27 PWR containments is given in Table 4-1.

28 A ZOI for fire barrier materials can then be constructed. This ZOI will be conservative since  
29 many fire barrier materials, such as fibrous boards, will have a higher destruction pressure than  
30 low-density fiberglass.

31 As an alternative, engineering judgment can be used to assign destruction pressures based on  
32 similarities in material properties between the fire barrier materials and materials for which  
33 destruction pressures are known. There is little information available regarding the destruction of  
34 board-type insulation. In most cases, the destruction pressure for the blanket-type insulation can  
35 be assumed to be the same as for low-density fiberglass piping insulation.

1 Specific fire barrier materials include:

- 2 • Marinite board which may be included in the debris is generated within the ZOI.  
3 According to NUREG/CR-6772, a large amount of plastic deformation is necessary  
4 to break Marinite board apart. Therefore, Marinite board is assumed to be destroyed  
5 within the ZOI but left intact outside the ZOI. All destroyed Marinite board can be  
6 assumed to be broken into large chunks.
- 7 • Kaowool blanket and mineral wool debris are destroyed in the ZOI. Assume the  
8 same destruction data for fiberglass or Nukon.
- 9 • Silicone foam debris is assumed to be destroyed within the ZOI. As with some  
10 other types of fire barrier, destruction information is needed for silicone foam  
11 insulation.

#### 12 **4.2.2.2.6 Miscellaneous Debris Sources**

13 This section discusses the generation of debris from sources inside containment other than RCS  
14 and fire barrier insulations tape, tags, and stickers. There are many miscellaneous debris sources  
15 inside containment. Some common sources are discussed in the following sections. Due to the  
16 variations in containment design and size from unit to unit, many miscellaneous sources can be  
17 evaluated on a plant-specific basis. It is not appropriate for the licensees to use their FME  
18 programs to entirely eliminate sources of miscellaneous debris.

19 Candidate miscellaneous debris sources that should be evaluated on a plant-specific basis are  
20 listed below. For each potential debris type considered, debris generation resulting from jet  
21 impingement and washdown effects should be considered.

- 22 • Fabric equipment covers
- 23 • Fire hoses
- 24 • Ropes
- 25 • Ventilation system filters
- 26 • Cloth
- 27 • Wire ties
- 28 • Plastic sheeting
- 29 • Rust from unpainted surfaces
- 30 • Scaffolding
- 31 • Auxiliary equipment left inside containment
- 32 • Caulking
- 33 • Mastic or filler materials
- 34 • Fibrous material from lead blankets
- 35 • Radiation protection signage
- 36 • Operations tags

37 Consideration that should be given to tape, tags and stickers as debris sources is discussed in  
38 Section 4.2.2.2.4.

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**Table 4-1. Damage Characteristics of Common Fibrous Insulation Materials inside PWR Containments<sup>(Note 6)</sup>**

Insulation Type	Description	Destruction Pressure (psi)	Fabricated Density (lb/ft <sup>3</sup> )	Material Density (lb/ft <sup>3</sup> )	Characteristic Size	
					µm	Inch
Calcium Silicate	1. Al clad, SS banding seam @ 180° 2. Al clad, SS banding seam @ 0° 3. Al clad, SS banding seam @ 45°	1. 64 <sup>(Ref. 27)</sup> 2. 50 <sup>(Ref. 27)</sup> 3. 24 <sup>(Ref. 27)</sup>	14.5	144 <sup>(Ref.11)</sup>	5 µm mean particle size (2 to 100 µm range) <sup>(Ref.11)</sup>	20E-05
Calcium Silicate	Generic seam orientation	20	14.5	144 <sup>(Ref.11)</sup>	5 µm mean particle size (2 to 100 µm range) <sup>(Ref.27)</sup>	20E-05
Newtherm	Clad with either SS or aluminum with high-strength stainless steel bands and closures		16.2	144 <sup>(Ref.11)</sup>	5 µm mean particle size (2 to 100 µm range) <sup>(Ref.11)</sup>	20E-05
<b>Microporous Insulation</b>						
Min-K	1. Blanketed, unjacketed 2. Blanketed, jacketed w/SS band and latch and strike locks	1. 2.5 2. 6	20 <sup>(Ref.12)</sup>	NA	<0.2	4.0E-06
Microtherm	1. Blanketed, unjacketed 2. Blanketed, jacketed w/SS band and latch and strike locks	1. 2.5 2. 6	22 <sup>(Ref.13)</sup>	NA	<0.2	4.0E-06

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**Table 4-1. Damage Characteristics of Common Fibrous Insulation Materials inside PWR Containments<sup>(Note 6)</sup> (Cont'd)**

Insulation Type	Description	Destruction Pressure (psi)	Fabricated Density (lb/ft <sup>3</sup> )	Material Density (lb/ft <sup>3</sup> )	Characteristic Size	
					μm	Inch
<b>Fiberglass</b>						
Nukon	1. Jacketed with Sure Hold latches 2. Jacketed with standard bands/latches 3. Unjacketed	1. 150 <sup>(Ref. 29)</sup> 2. 10 <sup>(Ref. 6)</sup> 3. 10 <sup>(Ref. 6)</sup>	2.4	159	7.0 fiber diameter	28E-05
Knaupf	Knaupf ET Panel (LDFG similar to Nukon)	10 (Same as Nukon) <sup>(Ref. 6)</sup>	2.4	159	5.5 fiber diameter	22E-05
Generic	Blanketed with Velcro closures	10 (Same as Nukon & Knaupf) <sup>(Ref. 27)</sup>	3.0 +/- 10%	159	6.75 fiber diameter	27E-05
Knaupf	Fibrous preformed pipe insulation		4.0 +/- 10% or	159	7.5 fiber diameter	30E-05
Owens Corning	Fibrous preformed pipe insulation		3.5 to 5.5	159	8.25 fiber diameter	33E-03
Temp-Mat and Insulbatte	Heavy cloth blanket with stainless steel mesh	17 <sup>(Ref.6)</sup>	11.8 <sup>(Ref.6)</sup>	162 <sup>(Refs. 9 and 10)</sup>	9.0 fiber diameter	36E-05 max. average (Ref.14)
<b>Mineral Wool</b>						
K-Wool	Unjacketed w/wire mesh inner and outer surfaces, heavy cloth blanket with wire hooks at seams	40 <sup>(Ref.6)</sup>	10	90	5 to 7 fiber diameter	20 to 28 E-05

**Table 4-1. Damage Characteristics of Common Fibrous Insulation Materials inside PWR Containments<sup>(Note 6)</sup> (Cont'd)**

Insulation Type	Description	Destruction Pressure (psi)	Fabricated Density (lb/ft <sup>3</sup> )	Material Density (lb/ft <sup>3</sup> )	Characteristic Size	
					µm	Inch
Generic	Generic name for families of products made by Rock Wool Mfg., Roxul, Fibrex, IIG, and others	10 <sup>(Note 1)</sup>	4, 6, 8, 10 pcf are standard	90	5 to 7 fiber diameter	20 to 28 E-05
<b>Other</b>						
Asbestos (Unibestos)	Insulation is blanketed – blankets with Velcro closures or metal band closures	10 <sup>(Note 2)</sup>	7 to 10	153	1 to 8	4 to 32E-05
Koolphen-K	With thin fiber reinforced aluminum antisweat covering w or w/o aluminum jacketing – closed-cell phenolic foam	6	2.2 <sup>(Ref.30)</sup>			
<b>Reflective Metal</b>						
Transco RMI	Reflective metal insulation	190 <sup>(Ref.6)</sup>			See Ref.27 for size distribution	
Darchem DARMET	Reflective metal insulation	190 <sup>(Ref.6)</sup>			Same as Transco	
Diamond Power Mirror	Reflective metal with sure-lock bands and Camlock <sup>®</sup> strikers and locks	190 <sup>(Ref.6)</sup>			Same as Transco	
Mirror	Reflective metal insulation	4 <sup>(Ref.6)</sup>			Same as Transco	
<b>Fire Barrier Material</b>						
Marinite Board	Dense, heat-treated, inorganic calcium silicate board made of fibers, micro-silica, and binders. High-strength calcium silicate board	64 <sup>(Note 3)</sup>	46 – 65 <sup>(Ref.32)</sup>			

**Table 4-1. Damage Characteristics of Common Fibrous Insulation Materials inside PWR Containments<sup>(Note 6)</sup> (Cont'd)**

Insulation Type	Description	Destruction Pressure (psi)	Fabricated Density (lb/ft <sup>3</sup> )	Material Density (lb/ft <sup>3</sup> )	Characteristic Size	
					μm	Inch
3M Interam	Mat with 3-mil aluminum cover – alumina trihydrate	17 <sup>(Note 4)</sup>	54.3 – 56.8 <sup>(Ref.31)</sup>			
Kaowool	1. Mat or blanket 2. Mat or blanket with stainless steel mesh to provide reinforcement and enhance for wrapping.	1. 3 2. 5	9.4	160-161 <sup>(Ref. XX)</sup>	2.7 to 3.0 fiber diameter	10.8 to 120 E-05
Silicone foam	Silicone foam/LDSE elastomer	4	~55 <sup>(Note 5)(Ref.34)</sup>	~55 <sup>(Ref.34)</sup>		
Gypsum Board	Calcium sulfate dihydrate (gypsum)	10	60 <sup>(Ref.33)</sup>	60 <sup>(Ref.33)</sup>		

Notes:

1. Same material as K-Wool insulation but without wire mesh reinforcement of blanket. From AJIT testing (Test 11-4): even when blanket damaged (torn), most insulation remained in place. Without the wire mesh reinforcement, conservatively assume the same destruction pressure as fiberglass. Destruction pressure may be used for either jacketed or unjacketed fiberglass.
2. Asbestos characteristics are similar to fiberglass except material has greater internal cohesiveness (tensile strength); therefore, AJIT results for fiberglass would be conservative. Fines are smaller (shorter) for asbestos fibers than fiberglass. Destruction pressure may be used for either blanketed and jacketed or unjacketed asbestos.
3. High-strength calcium silicate board. The most applicable tested material is calcium silicate with seam orientation at 180 degrees, except that marine board has flexure strength approximately 14 times the insulation material. Conservatively assume destruction pressure of 64 psi.
4. Tensile strength: 110 psi; DBA LOCA testing: remains intact and does not dissolve or disintegrate. Dense, flexible ceramic fiber blanket/mat or rigid configuration. Assume strength equivalent to Temp Mat since material is much more dense and has high tensile strength.
5. Assume low destruction pressure. Regardless of size, debris floats.
6. For materials not listed, the manufacturer should be contacted to obtain the type of information listed.

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### 1 **4.2.3 Latent Debris**

2 There are no generic analytical refinements to the method used to quantify latent debris to be  
3 described in this section. However, this document does allow for plant-specific improvements to  
4 the evaluation of the latent debris source term. If plant-specific conditions justify these  
5 refinements, they may be used.

### 6 **4.2.4 Debris Transport**

#### 7 **4.2.4.1 Nodal Network**

##### 8 **4.2.4.1.1 Background**

9 In the event of a loss-of-coolant-accident (LOCA) within containment of a pressurized water  
10 reactor (PWR), there is the potential for generation of debris with the attendant concern of  
11 containment sump screen blockage. The debris, consisting of piping or equipment insulation,  
12 protective coatings or paints, concrete dust, or general containment housekeeping materials, may  
13 be transported to the containment sump during the recirculation phase of emergency core cooling  
14 system (ECCS) and containment spray system (CSS) operations.

15 The resolution of this issue will potentially require licensees to evaluate containment sump  
16 performance with a focus on the generation and transport of debris to the containment sump  
17 screens. The methodology presented here provides licensees with one means to analyze  
18 post-accident fluid velocities on the containment floor without the complexity and manpower  
19 investment required to perform a computational fluid dynamics (CFD) calculation.

##### 20 **4.2.4.1.2 Open Channel Flow Network Analysis Approach**

21 Integral to analysis of debris transport is the determination of fluid velocities from the cooling  
22 water sources to the containment sump following the accident scenario. One method of  
23 evaluating fluid transport velocities is to develop a CFD model and simulate break and spray  
24 flows to determine local velocities. Although the CFD analysis provides an accurate prediction of  
25 flow velocities, the manpower requirements to generate the model present an economic basis for  
26 pursuing other approaches. An alternative method for predicting flow velocities within  
27 containment flooded regions is the development of an open channel network model with the  
28 development of boundary conditions based on sources and sinks of cooling water as well as the  
29 physical configuration of the containment flooded regions.

30 Simplistically, the flooded containment floor flow path regions are modeled by open channels;  
31 channel flow resistances are calculated based on friction and form losses, sources and sinks of  
32 recirculation water are identified and then a network analysis software tool is employed to  
33 calculate the individual channel velocities.

34 To demonstrate the alternative method for predicting flow velocities within containment flooded  
35 regions, Westinghouse developed an open channel flow network analysis of the example plant  
36 containment floor. Previously the example plant had been modeled with a CFD tool utilizing the

1 same inputs, conditions, and configuration. The results of the model were presented in  
2 Reference 37 and a comparison of those results demonstrating reasonable agreement to the  
3 channel flow network is provided in Appendix C. The results of the CFD analysis assisted in  
4 developing an appreciation of containment channel flow and also served as the benchmark  
5 against which the analysis results could be compared. The mapping of the channels onto CFD  
6 analysis results is demonstrated in Figure 4-2.

#### 7 **4.2.4.1.3 Open Channel Flow Network Development**

8 Although the generation of an open channel flow nodal model requires a significant level of effort  
9 to develop, the basic understanding of water sources (location and magnitude), flow path  
10 definition and constraints, and recirculation water sinks (location and magnitude) and a network  
11 analysis tool are the extent of the requirements.

##### 12 **4.2.4.1.3.1 Model Inputs**

13 The prerequisites for successful open channel flow network modeling of the post-accident ECCS  
14 sump include the following inputs. The developer must confirm that the inputs are conservative  
15 to maximize the calculation of flow velocities. Sensitivities on input parameters will ensure that  
16 the assumptions are conservative.

#### 17 **Containment Configuration**

18 Floor plan and elevation configuration – It is essential that the containment flooded region  
19 configuration be accurately defined, including any major obstacles to flow (equipment, walls, or  
20 architectural features). Basically, an obstacle to flow will be any walls, architectural/structural  
21 feature, or major equipment that occupies sufficient space to represent an impediment to flow  
22 (additional details provided below). Typically, some or all of the following documents will  
23 provide the necessary details:

- 24 • General Arrangement Drawings of the Flooded Elevations: Plan, Elevation and  
25 Detail views
- 26 • Civil or Structural Drawings of the Flooded Elevations: Plan, Elevation and Detail  
27 views
- 28 • Architectural Drawings of the Flooded Elevations: Plan, Elevation and Detail views

#### 29 **Containment Water Source and Sink Definition**

30 Water sources – The developer must have an accurate knowledge of water sources to the flood  
31 plane (basically the same input requirement required to develop a CFD model). The example  
32 plant had defined 24 specific sources of post-accident water flowing into the flood plane to be  
33 used as the boundary conditions for the modeling. Water sources will likely be comprised of  
34 these three major contributors. Additional plant-specific contributions are possible.

1 Flow sources (magnitudes and direction of point sources to the flood plane):

- 2 • Cascaded water from upper floor levels (stairwells, walls, floor drains, etc.).
- 3 • Containment spray flow input (sprayed volume if any, wall drainage and inputs to
- 4 drainage from upper compartment levels).
- 5 • Break flow from loop compartment(s).

6 Conservative maximum flow rates should be assumed to maximize fluid velocities for the  
7 assumed accident scenario and debris transport analysis. This data may be extracted from  
8 existing containment sump flooding and/or pump NPSH calculations or new calculations of flow  
9 delivery to the containment flooded regions will need to be generated.

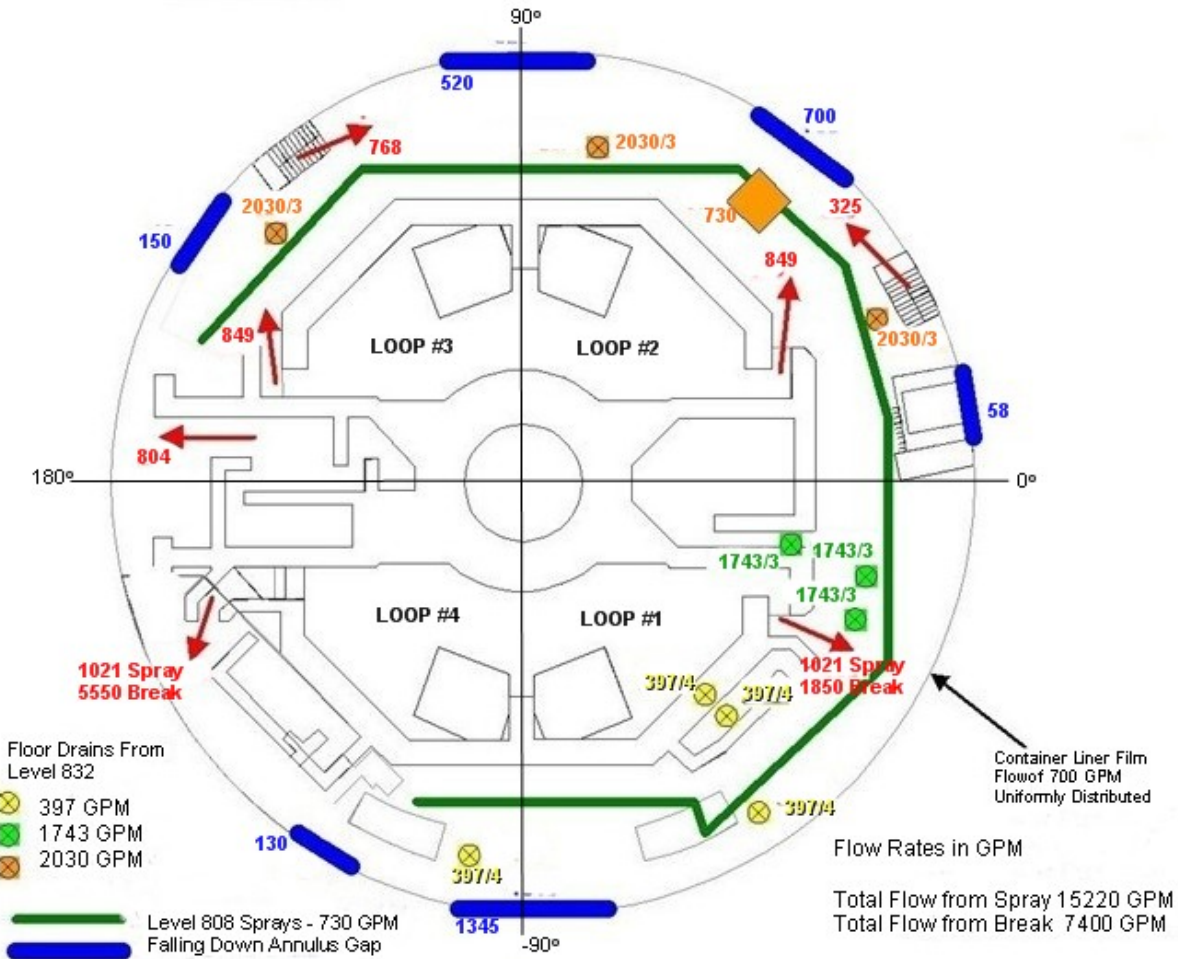
10 Water sinks – The developer assumes that the recirculation flow rate passes through the active  
11 sump(s). For those plants that have more than one sump, the active sump definition needs to be  
12 consistent with the scenario being evaluated. Differences in plant design may dictate multiple  
13 sump definitions. The selection needs to be consistent with the defined accident scenario or  
14 alternately in the conservative direction to limit the number of scenario cases. Contributors to the  
15 sump flow will include scenario-specific ECCS flows and containment spray flow rates or  
16 bounding values.

17 For the example plant, the specification of water sources and sinks have been summarized in  
18 Figure 4-1. A similar drawing should be developed for the licensee's plant design.

## 19 **Channel Definition**

20 Channel boundaries – The developer will define channel segments at essentially any point where  
21 there is a significant change in flow area (increase or decrease). At such points, the channel  
22 should be terminated and a new one defined until the next structural or flow area change. The  
23 same approach is taken at points of significant flow input (or output in the case of the sump) to  
24 the network. The open channel specification is based on identifying major flow areas from the  
25 various sources to the final destination, i.e., the sump.

26 The developer will begin the channel definition process at the major point source of water that is  
27 farthest from the containment sump(s). The defined channel continues until a significant change  
28 in flow area or flow rate occurs. A significant flow area change is considered to be in the range of  
29 15 percent based on the relative magnitude of the impact of additional flow resistance ( $K$  for  
30 form) and magnitudes of the calculated resistances ( $f(L/D)$ ) of individual channels for the  
31 example plant. Major obstacles that permanently or temporarily divide the flow analysis can  
32 result in the generation of parallel path channels in the analysis. Obstacles that cause minor  
33 interruption to flow, including structural supports, piping, or smaller equipment such as pumps  
34 and valves, can be ignored. These obstacles are acknowledged to cause higher local turbulences  
35 but can be assumed to be accommodated within the conservatism or sensitivities performed.



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**Figure 4-1. Example Plant Water Sources**

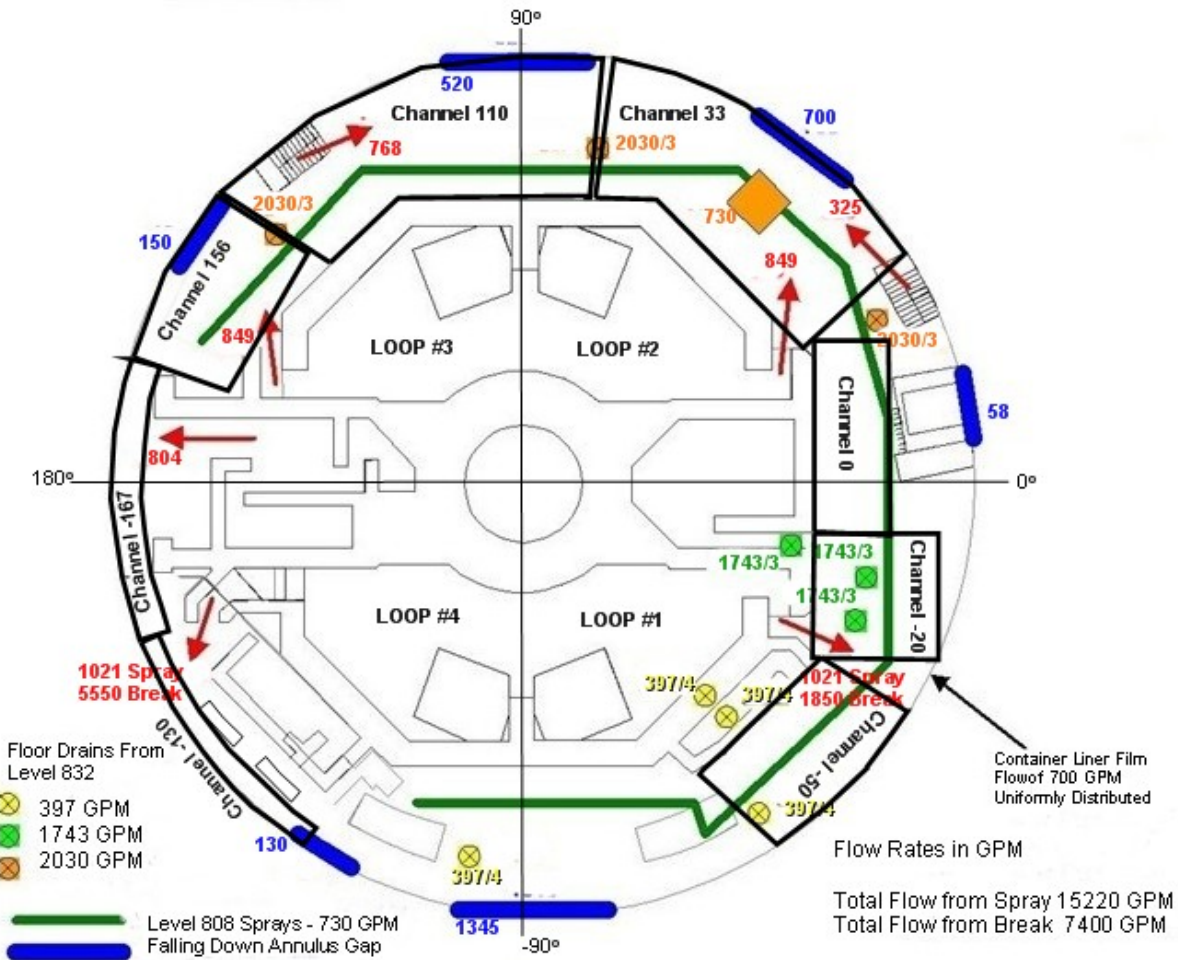
3 Portions of the containment floor may not be active in the transport of debris in the steady-state  
 4 analysis. Once the major channels are defined, the construction of smooth velocity vectors will  
 5 assist in the definition of major active flow paths, and thereby channel definition or refinement  
 6 versus reasonably still pool areas. For the most part, dead-end compartments such as loop  
 7 compartments that are separated from the break, equipment rooms, and passages to these areas as  
 8 well as regions blocked by architectural features can be considered dead-ended and excluded  
 9 from the channel flow analysis.

10 A change in flow rate magnitude of approximately 10 percent is considered significant and will  
 11 be used to define channel boundaries. Since the channel frictional losses are proportional to the  
 12 square of the flow, the effect is not a linear function and is therefore more sensitive to flow than  
 13 changes in friction factors. Plant general arrangement drawings with major equipment  
 14 documented may be necessary in addition to the structural and architectural drawings identified  
 15 above.

16 In the case of the example plant, the containment flood plane is basically a ring of channels  
 17 around the containment floor with sources defined along the ring header and a destination of the

1 containment sumps. Although most containments are expected to contain a similar contiguous  
 2 ring from sources to destinations, it is not essential to the modeling. The channel definition is  
 3 illustrated in Figure 4-2 and superimposed on the water source general arrangement drawing.  
 4 For illustrative purposes and as a guide in defining channels the above defined channel outlines  
 5 have also been superimposed on the CFD velocity profile drawing in Figure 4-3. This schematic  
 6 of channels and velocity profiles should help to provide an appreciation of the above guidelines.

7 The developer must assume a minimum flooded containment level based on plant calculations  
 8 maximizing water holdup in flooded compartments as well as any other phenomenon or  
 9 locations that would minimize level. Minimizing level serves to maximize recirculation flow  
 10 velocities and the consequential effects including debris transport and debris erosion.



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**Figure 4-2. Example Plant Network Channel Definition and Water Sources**

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**Channel Loss Calculation**

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Form and channel frictional losses are to be included in channel resistance to flow. Form losses are primarily based on the reduction or increases in flow areas from channel to channel but may include other changes in velocity head, flow turns, or even obstructions. Open channel flow K

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1 factors should be based on data from Crane Technical Paper 410 (Reference 35), Idelchek  
2 (Reference 39), Miller (Reference 40), or other accepted sources of loss coefficients.

3 Open channel frictional losses are calculated based on Altsul's Formula as presented in  
4 Reference 36 and then may be verified with the Colebrook-White formula, also from  
5 Reference 36.

6 Altsul's Formula

$$7 \quad f = 0.1 \left[ 1.46 \frac{k_s}{D_H} + \frac{100}{R_e} \right]^{\frac{1}{4}}$$

8 Colebrook-White Formula

$$9 \quad \frac{1}{\sqrt{f}} = -2.0 \log_{10} \left[ \frac{k_s}{3.71 D_H} + \frac{2.51}{R_e \sqrt{f}} \right]$$

10 where,

11  $f$  is the Darcy friction factor coefficient

12  $R_e$  is the Reynolds number

$$13 \quad R_e = \rho \frac{V \times D_h}{\mu_e}$$

14 where,

15  $\rho$  is fluid density lb/ft<sup>3</sup> (ASME Steam Tables)

16  $V$  is flow velocity in ft/sec (since Reynolds number is based on velocity, it may be  
17 necessary to assume a value and then iterate the value after the initial model is run)

18  $\mu_e$  is the absolute viscosity in lbm/ft-sec

19  $D_H$  is the hydraulic diameter of the subject channel and for open flow channels

20  $D_H = 4A/P_w$  where  $A$  is the flow channel area and  $P_w$  is the wetted perimeter or base +  
21 2 x height. The base will change with each channel and is included in the summary  
22 below.

23  $k_s$  is the roughness height. From Reference 36. For smooth concrete, a range of values  
24 from 0.3 to 3.0 mm is given. Based on the walls being painted with nuclear-grade

1 coatings and often topcoated, the roughness height is expected to be somewhat attenuated  
2 and closer to the 0.3 than 3.0 value. If a value of 0.5 mm is used, then

$$3 \quad k_s = 0.5 \text{ mm}(0.00328 \text{ ft/mm}) = 0.00164 \text{ ft}$$

4 Figure 4-3 provides the resulting network channel definition and includes the calculated friction  
5 and form resistances, flow area and hydraulic diameter for each channel for the example plant.  
6 Figure 4-4 superimposes the channel network defined on the basis above onto a XY plot of the  
7 CFD model results. The CFD plot of velocity profiles providing the basis for Figure 4-4 is a  
8 composite of the results presented at the NRC public meeting of March 5, 2003 in Albuquerque,  
9 NM (Reference 37).

## 10 **Channel Definition Refinement**

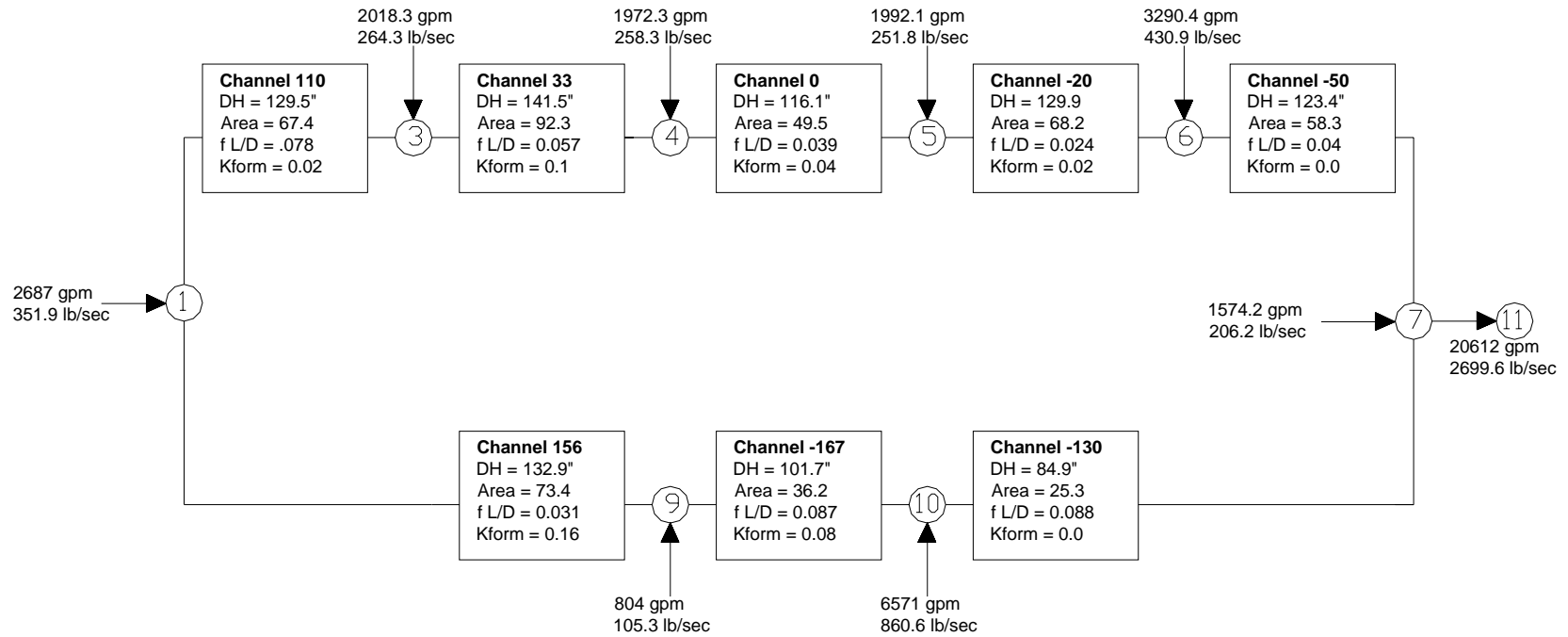
11 Based on the results of the network nodal analysis, it may be necessary to refine the channel  
12 definition and the points at which the flow is introduced into the network. The developer must  
13 evaluate the results against assumptions and refine and rerun the analysis as necessary.

### 14 **4.2.4.1.4 Results**

15 The network nodal mode results for the example plant compare very favorably with the CFD  
16 analysis, generally providing an error of less than 10 percent of the total flow. It is recommended  
17 that, as a minimum, 10 percent should be added to the calculated flow channel flow calculated  
18 rates and sensitivity calculations should be used to identify particular aspects that could  
19 significantly influence the results. Finally, in regions with major flow inputs (for example, in this  
20 configuration, where the loop compartments empty into channels -130 and -50), turbulence will  
21 be created as the flow turns to align with channel flow. For these regions, the calculated velocity  
22 must be increased based on the amount of expected turbulence. An examination of the CFD  
23 results (Figure 4.2.4.1-2) indicates the effects are fairly localized and, since the channels are  
24 defined based on the narrowest cross-section of the region, the bulk effect is expected to be  
25 limited in terms of transport. Additional discussion of these factors is provided in Appendix C.

26 The major discrepancy between the CFD and channel flow results is in the low-flow regime  
27 channels. This seems logical since the flow rates are low and the calculated resistances  
28 downstream are what actually drive the flow in one direction versus another. The concern that  
29 arises is that the debris transported from these areas may experience a limiting obstacle in one  
30 direction. This concern is, however, mitigated by the fact that the velocities are sufficiently low  
31 in these low-flow regions that the debris that will be transported from these regions will be  
32 mostly suspended and not typically susceptible to obstacle holdup. Therefore, it is judged  
33 acceptable that these low-flow channels may be calculated to be flowing in the reverse direction.  
34 A detailed comparison of channel flow versus CFD analysis is provided in Appendix C.

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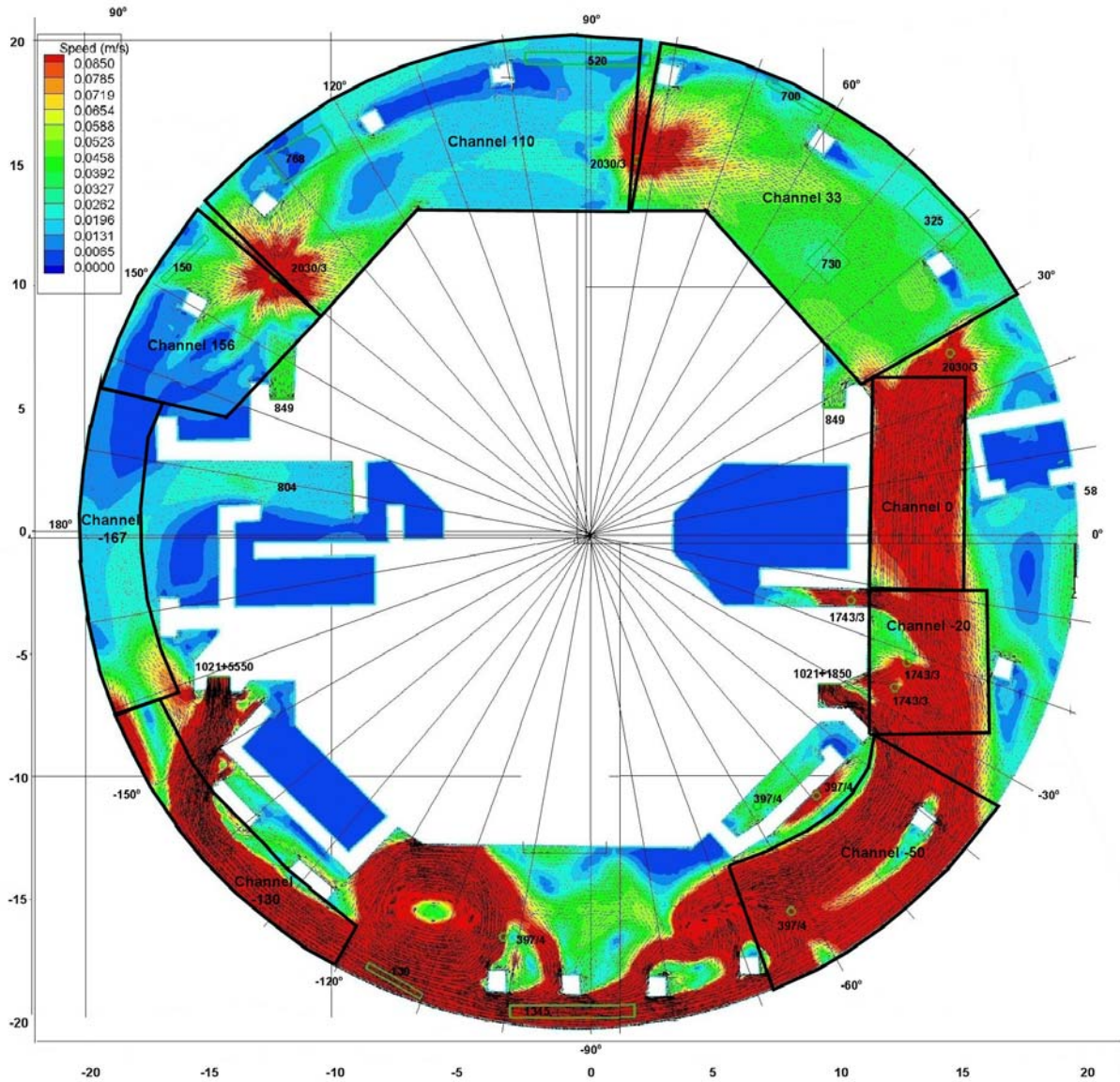


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Figure 4-3. Example Plant Network Channel Definition

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3 **Figure 4-4. Channel Network Superimposed onto yx Plot of the CFD Model Results**

#### 1 4.2.4.2 Three Dimensional Computational Fluid Dynamics (CFD)

2 Once the containment recirculation pumps are activated and the ECCS flow is drawn from the  
3 recirculation sump, detailed flow patterns in the containment pool can be obtained using state-of-  
4 the-art 3D computational fluid dynamics (CFD). The flow is quasi-steady or steady at this stage  
5 of the ECCS operation. Several commercially available CFD software applications (FLUENT,  
6 FLOW3D) can be used for the flow simulation and analysis, which essentially solve the full set  
7 of the conservation of mass and momentum equations (Navier-Stokes equations) as well as  
8 turbulence equations for each of the computational elements in the domain of interest. Thus,  
9 fully three-dimensional (3D) flow patterns can be obtained, which in turn can be used to predict  
10 the various flow paths to the recirculation sump(s), including detailed 3D velocities for the debris  
11 transport analysis. The flow velocities and turbulent kinetic energy can be compared to the  
12 debris-specific settling velocities, incipient and bulk transport velocities to determine the  
13 percentage of debris expected to transport to the sump screen.

14 The guidance relative to the use of CFD should address:

- 15 • Key considerations in defining the containment geometry to be modeled by the  
16 CFD code
- 17 • Establishment of the water level for these calculations
- 18 • Treatment of flow paths to the containment floor
- 19 • Treatment of flow paths to and out of the active sump regions
- 20 • Treatment of transport restrictions such as curbs and trash racks
- 21 • Determination of key transport metrics that include both local velocities (floor  
22 transport) and turbulent kinetic energy (debris suspension)
- 23 • Comparison of calculated transport metrics to threshold quantities for various  
24 debris types, and the resulting determination of overall pool transport fraction for  
25 various debris types

26 The value of performing such detailed transport analyses will depend on several factors  
27 including:

- 28 • Predominant debris types for a given plant
- 29 • Quantity of such debris
- 30 • ECCS flow rates

- 1 • Containment characteristics that influence velocity and Turbine Kinetic Energy  
2 (TKE) profiles in the pool
- 3 • Floor pool water level
- 4 • NPSH margin versus potential calculated reduction in head loss due to enhanced  
5 transport analysis.

6 Generally it is necessary to provide a qualitative assessment of the benefit to be derived from a  
7 CFD analysis to determine the cost-benefit associated with such an undertaking.

#### 8 **4.2.4.2.1 Selection of CFD Software and CAD Package**

9 As a minimum, the CFD software used for performing 3D flow simulations shall have the  
10 following features:

- 11 • Solves the full set of Navier-Stokes equations
- 12 • Turbulence closure options, such the typical k-  $\epsilon$  equations with the standard wall  
13 function
- 14 • Incompressible fluid flow solution
- 15 • Modern mesh generator
- 16 • Modern preprocessor for specifying fluid property and boundary conditions, such  
17 as non-slip walls, inflows, outflows, etc.
- 18 • Modern postprocessor or compatibility with independent modern postprocessor for  
19 analyzing CFD results

20 The computer-assisted design (CAD) package used for preparing the 3D geometry of the  
21 containment sump shall be capable of performing 3D solid modeling and have a compatible  
22 interface with the selected CFD software, i.e., the CAD files shall be imported by the CFD mesh  
23 generator.

#### 24 **4.2.4.2.2 Building the CAD Model**

25 The 3D geometric model of the containment pool shall cover the entire volume that forms the  
26 pool after a LOCA, i.e., all the open space from the containment floor (and the containment  
27 sump floor) to the potential maximum water level, including a short length (at least five  
28 diameters) of the suction pipes from the recirculation sump(s). A detailed review of the  
29 containment civil and mechanical pipe drawings, and any available photographs, shall be made  
30 to identify major flow obstructions, such as structures, equipment, pipes, etc. that will be

1 submerged in the pool. Obstructions less than 6 inches in diameter or the equivalent may be  
2 omitted.

3 If available, use an existing electronic 3D solid model (file) of the containment as a basis for the  
4 geometric model. If a CAD file is unavailable or is not used, the containment geometry and  
5 details of obstructions shall be obtained from as built drawings and/or a containment walkdown.

#### 6 **4.2.4.2.3 Building the CFD Model**

##### 7 **Computational Mesh Generation**

8 The 3D geometric CAD model is imported into the mesh generator. The geometric model needs  
9 to simulate the actual pool water level and break location, thus requiring separate meshes for  
10 each of the LOCA break locations and water levels to be analyzed. For better accuracy of the  
11 CFD solution, meshes shall be clustered around the break inflow, sump intake(s), and other areas  
12 of interest where high velocities and gradients are expected. Hexagonal meshes shall be used as  
13 much as possible. Computational meshes shall be of good quality, i.e., the “skew angle” shall be  
14 less than 0.85.

##### 15 **Specification of Material Properties and Boundary Conditions**

16 The computational meshes are read into the selected CFD package and preprocessing of the CFD  
17 model is performed. Preprocessing includes the following:

- 18 • Specify the properties of water in the containment pool.
- 19 • Specify boundary conditions. The types of boundary conditions associated with the  
20 containment pool flow simulations are “non-slip” walls for solid surfaces, a zero-  
21 stress lid for the water surface, inflows for the break and core spray flow and  
22 outflows for the suction pipes of the recirculation sump(s). It may be conservative  
23 to assume that the break flow falls freely by gravity onto the water surface from the  
24 break location without interruption by any structures. Knowledge of plant-specific  
25 spray flow path(s) shall be obtained to determine the proper location(s) and method  
26 for introducing spray flow into the pool. The water surface may be treated either as  
27 a zero-stress rigid lid or a free surface, depending on the capability of the CFD  
28 software used. Outflow or pressure is generally specified at the recirculation sump  
29 suction pipe outlet.
- 30 • Specify the accuracy of discretization schemes. Generally, a second-order accuracy  
31 for discretization schemes shall be used in the CFD analyses.

##### 32 **4.2.4.2.4 CFD Analysis**

33 A converged CFD solution shall be obtained by running the CFD model for a sufficient time. If  
34 the velocity components, turbulent kinetic energy and turbulent energy dissipation rate do not  
35 change appreciably with subsequent iterations, it is an indication that a converged solution has

1 been achieved. The generally acceptable convergence criterion is that the residuals of these  
2 pertinent flow parameters should be less than 10. Other equivalent criteria may be used if  
3 properly justified.

#### 4 **4.2.4.2.5 CFD Results for Debris Transport**

5 The CFD results shall be post-processed to produce meaningful plots that assist in debris  
6 transport analysis. Types of useful plots are as follows:

- 7       • For a given type and size of debris, plot velocity magnitude contours for the  
8       minimum bulk transport velocity (from available experimental data, see Table-4-1)  
9       at a selected elevation(s) within the containment pool using the CFD software's  
10       built-in post-processor or an independent post-processor. Conservative results are  
11       obtained if the elevation selected for analysis gives the maximum area under the  
12       bulk velocity contour. The area within the velocity magnitude contour connected to  
13       the recirculation sump is determined, and it may be conservatively assumed that  
14       debris in this area (of the given type and size being analyzed) will be transported to  
15       the sump screen. Refinements based on the flow pattern may be incorporated.
  
- 16       • The effects of turbulence level may be taken into account by assessing whether  
17       debris particles or fibers will stay suspended due to the instantaneous vertical  
18       velocity component being equal to or greater than the settling velocity of the debris  
19       particles. The maximum instantaneous vertical velocity is calculated by adding the  
20       fluctuating vertical velocity to the (CFD) computed mean (time average) vertical  
21       velocity. The fluctuating velocity is determined from the computed turbulent  
22       kinetic energy,  $k$ . Contours within which the instantaneous vertical velocity  
23       component is equal to or greater than the settling velocities of different type and  
24       size of debris being analyzed may be used to assess if this debris may become or  
25       stay suspended.
  
- 26       • Velocity vectors and flow streamlines may also be used to assist the analysis of  
27       debris transport.

#### 28 **4.2.4.2.6 Example of a CFD Simulation**

##### 29 **Assumptions**

30 An example PWR containment is shown in Figure 4-1. The flow patterns are calculated with  
31 FLUENT software. The containment has a diameter of about 100 feet and has structures in the  
32 pool as shown. There are two recirculation pumps with suction pipes of 1-foot diameter. It is  
33 assumed that spray flow enters the water surface from a 6-inch annular gap on the outsider  
34 perimeter and two rectangular stair wells (shown in solid color). It is assumed that the break jet  
35 (shown as a small circle of solid color) has a diameter of 10 inches when it free-falls from its  
36 break location. Flow conditions being simulated are as follows:

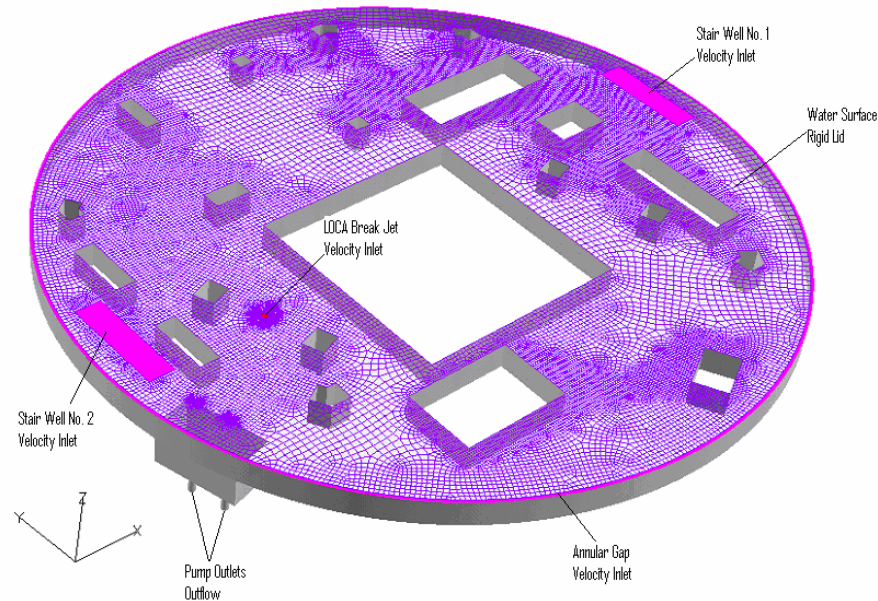
- 37       • Water depth: 3.5 feet



- 1       • Break flow: 2,000 gpm
- 2       • Containment spray flow: 1,000 gpm (60 percent of the spray flow is assumed to
- 3       enter into the water surface from the annular gap)
- 4       • Two recirculation pumps are in operation with 1,500 gpm each
- 5       • Fluid medium is water

## 6 Model Setup

7 A total of 1.2 million hexagonal computational meshes were generated as shown in Figure 4-1. It  
 8 can be seen that meshes are clustered around the LOCA break, spray flow inlets (the annular gap  
 9 and two stairwells), recirculation pump intake and the structures.

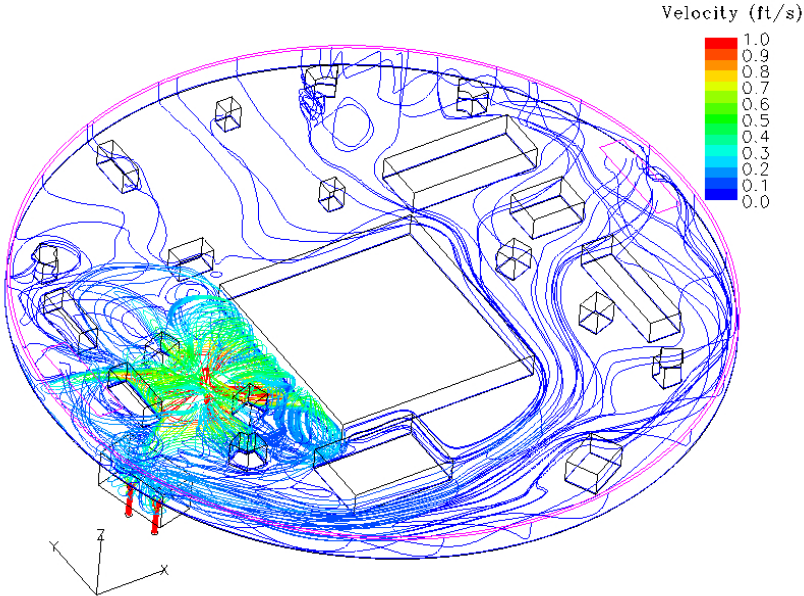


10

11       **Figure 4-5. Containment Geometry and Computational Meshes**

## 12 CFD Calculation Results

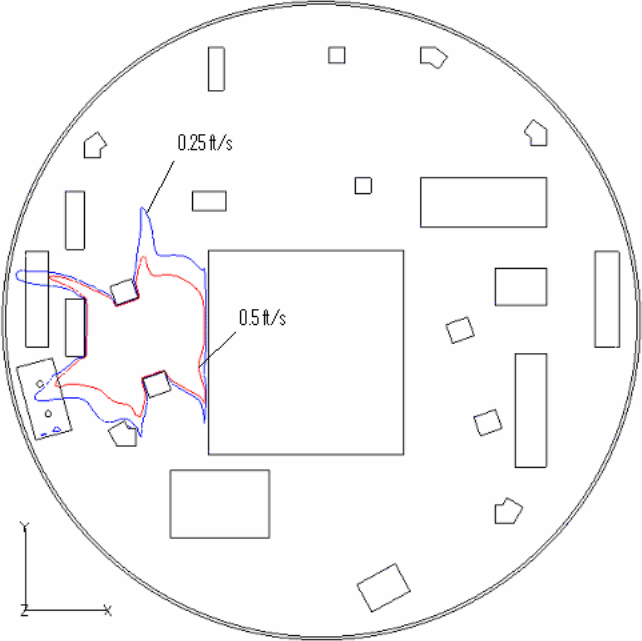
13 Figure 4-2 plots streamlines of the flow field that illustrates the general flow patterns in the  
 14 containment. These streamlines are colored by velocity magnitudes. Figure 4-3 shows two  
 15 velocity magnitude contours (0.25 ft/sec in blue and 0.5 ft/sec in red). These contours are used to  
 16 calculate the areas in which the debris with the corresponding bulk transport velocities are  
 17 assumed to be transported to the sump screens.



1

2

**Figure 4-6. Streamlines Illustrating Flow Patterns**



3

4

**Figure 4-7. Velocity Magnitude Contours near the Containment Floor**

1

**Table 4-2. Debris Transport Reference Table**

Debris Category/Type	Size	Density (lbm/ft <sup>3</sup> )	Terminal Settling Velocity (ft/sec)	Minimum TKE Required to Suspend (ft <sup>2</sup> /sec <sup>2</sup> )	Flow Velocity Associated with Incipient Tumbling (ft/sec)	Lift-Over-Curb Velocity (ft/sec)	Comment	Reference(s)
<b>A. Fibrous Insulation</b>								
1. Fiberglass – Generic								
2. Fiberglass – Nukon	a. 6"	a. 2.4	a. 0.41	a. 0.084	a. 0.12	a. 0.25 (2" curb) 0.34 (6" curb)	Min. TKE to suspend calculated from settling velocity for sizes a, b, c, and e	a. NUREG/CR-6772
	b. 4"	b. 2.4	b. 0.40	b. 0.080	b. 0.12			b. NUREG/CR-6772
	c. 1"	c. 2.4	c. 0.15	c. 0.011	c. 0.12	b. 0.25 (2" curb) 0.34 (6" curb)		c. NUREG/CR-6772
	d. 1/4"x 1/4" clumps	d. 2.4	d. 0.175	d. 0.14	d. 0.16	c. 0.25 (2" curb) 0.34 (6" curb)		d. NUREG/CR-6369, NUREG/CR-6808
	e. loose fibers	e. 175	e. 0.008	e. 3E-05	e. NA	d. ? e. NA		e. NUREG 6808
3. Fiberglass – High Density					0.2 (shreds) 0.3 (4 x 4 x 1 in. and 4 x 1 x 1 in.) 0.9 (whole pillow)		NUREG-0897, Rev. 1	
4. Fiberglass – Temp-Mat		11.3 macro	See comment.		See comment.	See comment.	No data specifically for Temp-Mat. Conservatively use data for NUKON (NUKON has a lighter macroscopic density).	NUREG-6808, Section 3.2.1.2

2

**Table 4-2. Debris Transport Reference Table (Cont'd)**

Debris Category/Type	Size	Density (lbm/ft <sup>3</sup> )	Terminal Settling Velocity (ft/sec)	Minimum TKE Required to Suspend (ft <sup>2</sup> /sec <sup>2</sup> )	Flow Velocity Associated with Incipient Tumbling (ft/sec)	Lift-Over-Curb Velocity (ft/sec)	Comment	Reference(s)
5. Fiberglass – Transco (Thermal Wrap <sup>®</sup> ) a. Shredded b. 4-in. x 6-in. pieces			a. 0.13 b. Not Tested		a. 0.07 b. 0.12	a. 0.22 (2-in. curb) b. 0.25 (6-in. curb)	Most limiting transport velocities were taken from NUREG/CR-6772. Transco tested various sizes of debris for transport velocities. Submersion of floating samples occurs within seconds for high temperatures (~90°C). Settling velocity weakly dependent on temperature (higher velocities for higher temps)	a. NUREG/CR-6772 b. NUREG/CR-6772
6. Mineral Wool a. 4-in. x 4-in. x 1-in. b. Shreds					a. 0.4 b. 0.3		Mineral Wool floats unless forced to sink.	NUREG/CR-2982 and NUREG-0897
7. Miscellaneous Fibrous a. Asbestos b. Unibestos								

**Table 4-2. Debris Transport Reference Table (Cont'd)**

Debris Category/Type	Size	Density (lbm/ft <sup>3</sup> )	Terminal Settling Velocity (ft/sec)	Minimum TKE Required to Suspend (ft <sup>2</sup> /sec <sup>2</sup> )	Flow Velocity Associated with Incipient Tumbling (ft/sec)	Lift-Over-Curb Velocity (ft/sec)	Comment	Reference(s)
<b>B. Calcium Silicate Insulation</b>								
Generic - Chunks with dust + fibers			Not tested: see comment on dissolution		0.10 (dust + fibers) 0.25 (small chunks) 0.30 (larger chunks)	Not tested: see comment on dissolution	Tests performed at ~20°C. Chunks were almost fully dissolved after immersion in near-boiling water for 20 min. 10-g pieces lost 50 to 75% of weight after immersion in 80°C water for 20 min.	NUREG/CR-6772
<b>C. Reflective Metallic Insulation</b>								
1. Stainless Steel	a. 1/2" square crumpled foils b. 2" square crumpled foils c. half cassette d. cover		a. 0.37 b. 0.48	a. 0.068 b. 0.115	a. 0.28 b. 0.28 c. 1.0 d. 0.7	a. 0.84 b. 0.84 (2" curb)	Min. TKE to suspend calculated from settling velocity	a. NUREG/CR-6772 b. NUREG/CR-6772 c. NUREG/CR-3616 d. NUREG/CR-3616

**Table 4-2. Debris Transport Reference Table (Cont'd)**

Debris Category/Type	Size	Density (lbm/ft <sup>3</sup> )	Terminal Settling Velocity (ft/sec)	Minimum TKE Required to Suspend (ft <sup>2</sup> /sec <sup>2</sup> )	Flow Velocity Associated with Incipient Tumbling (ft/sec)	Lift-Over-Curb Velocity (ft/sec)	Comment	Reference(s)
2. Aluminum	Mix of flat, crumpled, & semi-crumpled foils up to 2" square		0.11	0.0061	0.20		Min. TKE to suspend calculated from settling velocity	NUREG/CR-6772
<b>D. Fire Barrier</b>								
1. 3M Interam								
2. Fiberglass blanket			Same as Nukon		Same as Nukon	Same as Nukon	Since no data for "generic fiberglass" is available, it is recommended that the data for Nukon be used to represent low-density fiberglass.	
3. Kaowool a. Shredded b. 4-in. x 6-in.			a. 0.21 b. Use value from (a) above		a. 0.09 b. 0.12	a. 0.25 b. 0.25 (2-in. or 6-in. curb for both debris types)	Based on similarity of other hydraulic transport characteristics, suggest using same settling velocity for shredded and cut Kaowool.	NUREG/CR-6772

**Table 4-2. Debris Transport Reference Table (Cont'd)**

Debris Category/Type	Size	Density (lbm/ft <sup>3</sup> )	Terminal Settling Velocity (ft/sec)	Minimum TKE Required to Suspend (ft <sup>2</sup> /sec <sup>2</sup> )	Flow Velocity Associated with Incipient Tumbling (ft/sec)	Lift-Over-Curb Velocity (ft/sec)	Comment	Reference(s)
4. Marinite board a. 1-in. x 1-in. b. 4-in. x 4-in. Three values for density: Marinite-23 =23 lb/ft <sup>3</sup> Marinite-36 =36 lb/ft <sup>3</sup> Marinite-65 =65 lb/ft <sup>3</sup>			a. 0.59 - 0.63 b. 0.42 - 0.60		a. 0.77 b. 0.77	a. Not tested b. Not tested		NUREG/CR-6772
5. Silicone foam			--		--	--	Floats – Readily transports at any velocity	NUREG/CR-6772
<b>E. Other</b>								
1. Koolphen (closed cell phenolic)								
2. Min-K (microporous)								
3. Lead Wool Macroscopic Density = 10-15 lb/ft <sup>3</sup>								
4. Dirt/Dust	10 μ particulate	156						

**Table 4-2. Debris Transport Reference Table (Cont'd)**

Debris Category/Type	Size	Density (lbm/ft <sup>3</sup> )	Terminal Settling Velocity (ft/sec)	Minimum TKE Required to Suspend (ft <sup>2</sup> /sec <sup>2</sup> )	Flow Velocity Associated with Incipient Tumbling (ft/sec)	Lift-Over-Curb Velocity (ft/sec)	Comment	Reference(s)
5. Sludge (Iron)	Particulate	324	N/A		N/A	N/A	No credible source of iron sludge identified for PWR's	
<b>F. Coatings</b>								
1. Epoxy	15-mil thick chips	94	0.15	0.0113	0.4	0.5 (2-in. curb)	Min. TKE to suspend calculated from settling velocity	NUREG/CR-6772
2. Alkyd	10 μ particulate	98	2.25E-04	2.53E-08	NA	NA	Settling velocity calculated per Stokes' Law Min. TKE to suspend calculated from settling velocity	
3. Inorganic Zinc	10 μ particulate		6.74E-04	2.27E-07	NA	NA	Settling velocity calculated per Stokes' Law Min. TKE to suspend calculated from settling velocity	

1  
2



## 1 4.2.5 Head Loss

### 2 4.2.5.1 Thin-Bed Effects

3 No refinements are offered for the evaluation of this bed effects beyond those given in  
4 Section 3.7.2.3.2.3.

### 5 4.2.5.2 Alternative Methods for Head Loss Calculations

6 Although there are no analytical refinements recommended for the head loss correlation for flat  
7 screens (the NUREG/CR-6224 correlation), this section presents information that may be helpful  
8 in refining the head loss analysis as a whole or useful in the development of correlations for  
9 alternate strainer designs. The following information is presented in this section:

- 10 • Background information on the development of head loss correlations
- 11 • A summary of head loss tests performed to date
- 12 • The currently available head loss correlations
- 13 • Discussion of possible analytical refinements
- 14 • Discussion of head loss correlations for alternate strainer designs

## 15 Background

16 The head loss across a screen is highly dependent on the size and shape of the insulation debris  
17 reaching the screen. These debris characteristics depend on a variety of factors, including the  
18 type and manufacturer of the material (e.g., Nukon versus mineral wool versus Thermal-Wrap);  
19 plant aging effects such as the duration of exposure to high temperatures; the mode of transport  
20 (blowdown or washdown) to the recirculation pool; and the recirculation pool agitation at the  
21 time of the materials transport (e.g., chugging or falling water). For example, fiber debris may  
22 vary in size from individual fibers, typically a few millimeters in length, to shreds or small pieces  
23 that retain some of the original structure of the insulation blankets.

24 Nearly all of the suspended fibrous and metallic insulation debris approaching the strainer will be  
25 trapped by the strainer, except for a small quantity of finely destroyed debris (e.g., small  
26 individual fibers) that may pass through the strainer during the early stages of bed formation.  
27 During these early stages, the debris beds would be very thin and have a nonuniform thickness.  
28 In extreme cases, the debris bed may result in a partially covered strainer with open voids until  
29 more debris materials are transported. Initially, such beds may not possess the required structure  
30 or strength to filter the particulate debris, especially particulates that are a few microns in size.  
31 As a result, the majority of the particulate debris approaching the strainer during these early  
32 stages will most likely penetrate the strainer and circulate through the reactor core region. The  
33 concerns arising from this consideration are known as “downstream effects” and are addressed in  
34 Section 7.3.

35 The non-uniformity of the bed during its initial formation may result in a redistribution of  
36 incoming flow, with more flow through the open areas where the flow resistance is lower. As a  
37 result of this redistribution, the newly arriving debris will be carried to the open areas of the

1 strainer where they would be deposited. With time, continuous addition of debris in this manner  
2 will ultimately lead to formation of a thin, uniform debris bed on the strainer surface.

3 Some PWRs have quiescent pools (i.e., low-turbulence pools) and low approach velocities so  
4 that some or all of the material may not be transported to the screens. The material (particularly  
5 paint and RMI) that is transported near the floor may tend to accumulate near the front of the  
6 vertical or inclined screens. These factors should be considered in the development of the actual  
7 debris loads to which the screen will be subjected.

8 As the debris bed thickness increases, it acquires the required structure to commence filtering  
9 particulate debris passing through it. Filtration efficiencies close to 100 percent may be possible  
10 for larger particulates such as paint chips and concrete dust, but efficiencies on the order of 25 to  
11 50 percent have been reported for filtration of particles ranging in size from 1-10  $\mu\text{m}$ . As such,  
12 the quantity of particulate debris filtered by the fiber bed and, consequently, the head loss across  
13 the strainer (which is an increasing function of both the amount of debris trapped on the strainer  
14 and its geometry) are strong functions of the size distribution of the particulate debris reaching  
15 the strainer. This also brings into focus the important role played by filtration efficiency in  
16 estimating the head loss.

17 The head loss incurred during the debris bed buildup and the time at which such head loss may  
18 exceed the available NPSH margin are important factors in design considerations and in planning  
19 for mitigating actions. The rate and magnitude of head loss increase and will be influenced by the  
20 following factors:

- 21 • Amounts of various types of debris reaching the strainer and their rate of transport  
22 at any given time.
- 23 • Size distribution and type of debris reaching the strainer.
- 24 • Filtration efficiency of the fibrous bed to trap particulate matter.
- 25 • ECCS flow rate and approach velocity.
- 26 • Recirculation pool temperature.
- 27 • Plant-specific considerations such as screen/strainer area, hole or mesh size, design,  
28 arrangement and flood height.

29 The detail to which such phenomena are modeled can significantly affect the calculated head loss  
30 at any given time. Experience has shown the need to adopt a plant-specific transient analysis  
31 model that incorporates all these considerations for performance evaluations. Moreover, mixtures  
32 of fibrous materials and microporous insulation or calcium silicate may exhibit significantly high  
33 head loss for relatively low amounts of fibrous material. Consequently, it is not appropriate to  
34 extrapolate head loss obtained for one mixture of debris to another without taking into account  
35 the debris characteristics. Any predictive calculations should be based on test data that provide

1 accurate debris characteristics of the constituents of the debris beds. Extrapolation of correlations  
2 that do not factor the debris characteristics explicitly should not be practiced.

### 3 **4.2.5.2.1 Summary of Significant Head Loss Tests**

4 Table E-2 in Appendix E provides a compilation of the testing and data, results, and pressure  
5 drop relationships developed by several organizations that have issued publicly available head  
6 loss test information. In addition, Table E-2 provides a summary of experiments and tests. The  
7 insulating materials used or simulated in these experiments consisted of:

- 8 • Mineral wool (rockwool)
- 9 • Low-density fiberglass (Nukon, Transco Thermal-Wrap)
- 10 • High-density fiberglass
- 11 • Caposil (Unibestos) (calcium silicate containing asbestos fibers)
- 12 • Calcium silicate (diatomaceous earth, "Newtherm," "Calosil")
- 13 • Insulation particulates (e.g., calcium silicate and alumina)
- 14 • Reflective metallic insulation with stainless steel foils
- 15 • Reflective metallic insulation with aluminum foils
- 16 • Microporous insulation, including Min-K and Microtherm

17 Other debris materials included in some tests were:

- 18 • Paint chips
- 19 • Rust (iron oxide corrosion products)
- 20 • Metallic particulates

### 21 **Early Tests**

22 Various techniques were used to generate insulation debris of representative sizes. For fibrous  
23 insulation, these included manual (hand) shredding, mechanical shredding (meat mincer, leaf  
24 shredder) and jet fragmentation (steamjets, waterjets, and airjets). The actual size class of the  
25 fibrous debris varied from as-fabricated blankets (without covers or scrims) to finely destroyed  
26 debris consisting of a significant quantity of individual fibers. Production techniques such as  
27 manual shearing and jet fragmentation were used for generation of nonfibrous insulation  
28 fragments used in the experiments (e.g., metallic insulation).

29 U.S. boiling water reactor (BWR) corrosion products were initially simulated using iron oxide  
30 particles that are larger than 75  $\mu\text{m}$  owing to the lack of information related to size  
31 characteristics of the rust particles usually found in the BWR suppression pools. The U.S. BWR  
32 Owners' Group (BWROG) later provided the information in Table 4-1 that was used to size the  
33 corrosion products.

1

**Table 4-3. Size Distribution of Suppression Pool Sludge**

Size, mm	% by weight
0-5	81
5-10	14
10-75	5

2

3 The paint chips varied from 0.125 to 0.25 inches in size; and from 0.02 to 0.16 grams in weight.

4 The size of the paint chips used in the experiments was based on engineering analyses provided

5 by the BWROG for BWR containment coatings.

6 The head loss experiments listed in Table 4.2.5.2-2 can be broadly categorized as 1) separate

7 effects experiments, and 2) small-scale strainer qualification tests. The focus of the separate

8 effects tests was to develop relationships that correlate strainer head loss to flow velocity and the

9 amount of debris on the strainer. The intent of the investigators was to use these relationships,

10 together with engineering judgment and assumptions regarding the debris generation and

11 transport, to provide the basis for design and sizing of the strainers. Typically, these tests

12 employed a flat-plate strainer and a closed test loop to conduct experiments. Note that the results

13 from a once-through column and closed-loop and open-loop recirculating experiments can

14 produce significantly different results if these experiments are not preplanned to separate such

15 effects.

16 Typical data reported by the closed-loop experiments included head loss as a function of strainer

17 approach velocity and the quantity and type of debris added to the test loop. Some of the

18 European experimental data were reported in the form of coverage ( $\text{kg}/\text{m}^2$ ) of insulation material

19 required to produce a head loss of 2 meters of water across the strainer as a function of velocity.

20 The material in Table 4.2.5.2-2 includes the parameters and range studied in each experiment.

21 The head loss data were reported for theoretical bed thicknesses in the range of 3 mm to about

22 25 cm; approach velocities in the range of 1 to 0.5 m/sec; at temperatures of 20°-25°C and

23 50°-55°C; and for nominal sludge-to-fiber mass ratios in the range of 0 to 60. Considerable

24 scatter exists in head loss data from different sources. Careful examination of the experimental

25 data suggests that scattering can be attributed to the following:

26 • Variation in size classes of debris used in the experiments to simulate LOCA-

27 generated debris. (Typically, debris produced by manual methods is larger, that is,

28 NUREG/CR-6224 Classes 6 and 7, and resulted in lower pressure drops. On the

29 other hand, debris produced by mechanical methods and jet fragmentation was

30 much smaller and resulted in higher pressure drops. Further discussions related to

31 the effect of size class on the head loss across the strainer are presented in previous

32 sections.)

33 • Variation in the age of the fibrous insulation debris.

34 • Differences in experimental test loops.

- 1       • Differences in the range of experimental parameters. (For example, European  
2 experiments were conducted at very low velocities, 1-10 cm/s, while the U.S.  
3 experiments were conducted at much higher velocities, 5-50 cm/s.)
  
- 4       • The chosen method of correlating the data. (In most cases, purely empirical  
5 relationships were sought to correlate the head loss data that were obtained for a  
6 limited range of experimental parameters. This seriously limited extendibility of  
7 these individual correlations beyond their original range of study.)

## 8   **Testing Performed After ~1995**

9   More recent tests and experiments were performed by different organizations either to provide a  
10 basis for design of ECCS recirculation strainers and screens or a basis for regulation. The  
11 organizations recognized the major shortcomings and limitations in the early testing programs  
12 and devised the more recent ones to provide sufficiently detailed and proven information for the  
13 intended purposes. Documents such as NUREG-6224 and the BWROG Utility Resolution Guide  
14 (URG) are based on and/or refer to these recent investigations. Following are some of the  
15 functional areas investigated:

- 16       • Head loss characteristics of various types of fibrous insulation by itself and in  
17 combination with particulate matter (sludge).
  
- 18       • Head loss characteristics of other less common materials, such as containment  
19 coatings, microporous insulation debris (Min-K and calcium silicate), in  
20 combination with fibrous insulation debris.
  
- 21       • Head loss characteristics of reflective metallic insulation debris, by itself and in  
22 combination with other debris such as fibrous and particulate matter.
  
- 23       • Head loss characteristics of insulation debris deposited on specific strainer or sump  
24 designs.

25   Some of the previous difficulty in obtaining repeatable and comparable results lay in the testing  
26 methodology. Having results that can be directly correlated with the realistic plant configurations  
27 and arrangements, or that can be properly scaled to these, is important.

### 28   **4.2.5.2.2 Head Loss Correlations**

29   Several different approaches and methodologies have been employed for predicting head loss  
30 across debris beds. These approaches include theoretical or semi-theoretical relationships and  
31 empirical relationships. As discussed below, some of the early empirical relationships, while  
32 adequate for their intended purpose of predicting pressure drop across a single media debris bed,  
33 are inadequate for predicting pressure drop across mixed debris beds. This inadequacy may have  
34 contributed to some of the events challenging ECCS recirculation capability. It is important to  
35 anticipate what debris may be transported to an ECCS screen, and to employ head loss  
36 correlations valid for the combination of materials, anticipated debris characteristics, and

1 conditions expected. Different forms and approaches for head loss correlations are described in  
2 the following paragraphs.

### 3 **Empirical Correlation for Fiber-Only Beds**

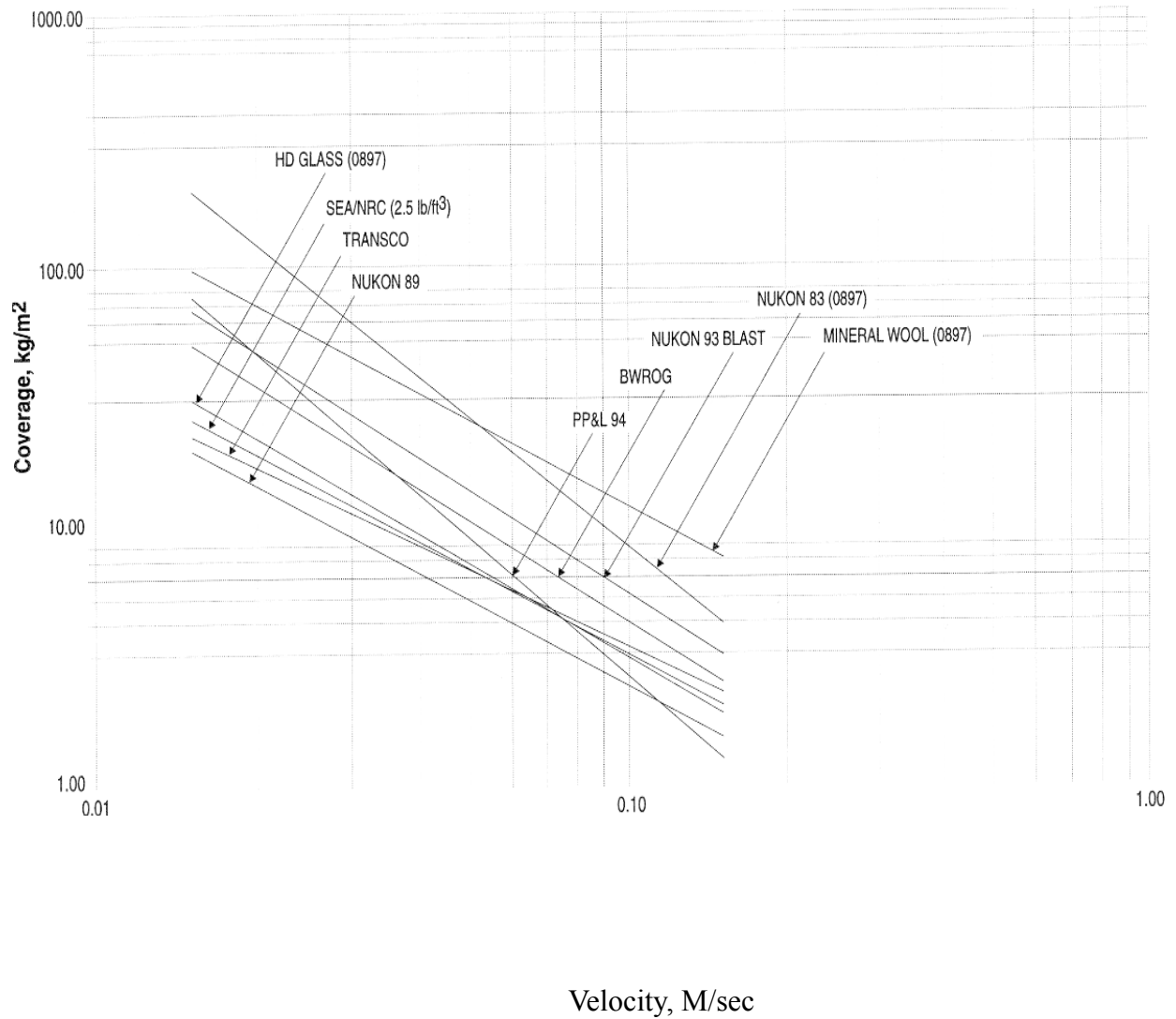
4 Early strainer or screen design methods typically assumed that the screen/strainer pressure drop  
5 was primarily due to an accumulation of fibrous debris. For pure fiber beds, most studies  
6 developed empirical relationships to relate velocity and bed theoretical thickness or fibrous  
7 debris accumulation to strainer pressure drop. The relationships were usually of the following  
8 form:

$$9 \quad \Delta H = aV^b e^c \quad (1)$$

10 where

11	$\Delta H$	is strainer head loss (ft)
12	$V$	is strainer approach velocity (ft/sec)
13	$e$	is debris bed theoretical thickness (ft)
14	$a, b, \text{ and } c$	are empirical constants determined in experiments

15 These relationships, together with engineering judgment and assumptions regarding the debris  
16 generation, debris characteristics, and transport, provided the basis for design and sizing of the  
17 strainers. Some attempts were also made to employ similar relationships to correlate  
18 experimental data obtained for mixed beds. The various correlations developed for debris beds  
19 formed of pure mineral wool beds, pure low-density fiberglass beds, and mixed beds formed of  
20 fiber and sludge mixtures are contained in the summary material of Table 4.2.5.2-2. The  
21 predictions of the correlations for low-density fiberglass are illustrated in Figure 4.2.5.2-1, which  
22 clearly illustrates the variabilities and uncertainties associated with early correlations that apply  
23 only to the low-density fiberglass tested. Other insulation materials may exhibit different head  
24 loss characteristics.



1

2 **Figure 4-8. Comparison of Available Head Loss Correlation for Low-Density Fiberglass**  
3 **Material Plotted as Strainer Coverage Required to Develop 2 Meters Water  $\Delta P$  for Various**  
4 **Fibrous Materials**

## 1 U.S. NRC NUREG/CR-6224 Head Loss Model

2 To minimize some of the shortcomings previously listed, the U.S. NRC sought a semi-theoretical  
3 approach for correlating the experimental data. Equation 2 is of a form containing two terms that  
4 account for head loss in the laminar and turbulent flow regimes, derived from the  
5 Kozeny-Carman and Ergun Equations as explained in Table 4.2.5.2-2.

$$6 \quad \frac{\Delta P}{t} = 3.55 S_v^2 (1 - \varepsilon)^{1.5} \left[ 1 + 57(1 - \varepsilon)^3 \right] \mu V + \frac{0.66 S_v (1 - \varepsilon)}{\varepsilon} \rho V^2 \quad (2)$$

7 where,

8	$\Delta P$	is the pressure drop that is due to flow across the bed (dynes/cm <sup>2</sup> )
9	t	is the height or thickness of the fibrous bed (cm)
10	$\mu$	is the fluid dynamic viscosity (poise)
11	$\rho$	is the fluid density (g/cc)
12	V	is the fluid velocity (cm/sec)
13	$\varepsilon$	is the bed porosity
14	$S_v$	is the specific surface area (cm <sup>2</sup> /cm <sup>3</sup> )

15 This correlation has the following salient features:

- 16 • Head loss dependence on the type of fibrous insulation material (e.g., mineral wool  
17 versus low-density fiberglass) can be handled directly by varying material  
18 properties (fiber-specific surface area, fiber strand density, and material packing  
19 density) in the equation. This eliminates the need for developing a separate  
20 equation for each debris type.
- 21 • Head loss dependence on particulate can be handled directly by varying the bed  
22 porosity.
- 23 • The same equation is valid for laminar, transitional, and turbulent flow regimes,  
24 which maximizes its usage in the plant analysis.
- 25 • Head loss dependence on water temperature can be handled explicitly through the  
26 use of flow viscosity in the equation.
- 27 • Compressibility effects can be handled by analysis.

28 A series of experiments was conducted by the U.S. NRC to obtain head loss data that can be used  
29 to validate the correlation previously listed. The experimental data obtained from these tests  
30 formed the most comprehensive head loss database for debris beds formed of Nukon and  
31 corrosion products, encompassing an experimental parameter range of 3 mm to 10.2 cm for  
32 thickness; 5 to 50 cm/sec for approach velocity; 0 to 60 for sludge-to-fiber mass ratios; and at  
33 temperatures of 24° and 52°C. Detailed comparison of the correlation predictions with these



1 experimental data is presented in NUREG/CR-6224. This correlation was used for the plant  
2 evaluation reported in NUREG/CR-6224 and has also been incorporated into the BLOCKAGE  
3 computer code developed by the U.S. NRC.

4 The following limitations of this correlation are identified for the potential user:

- 5 • The correlation may not be applicable for nonuniform debris beds since the  
6 correlation is developed based on the assumption that the debris forms a uniform  
7 bed. This may limit equation applicability to very thin beds or thin beds formed on  
8 specialized strainers.
- 9 • The correlation may not be applicable to thin fiber beds coupled with high sludge-  
10 to-fiber mass ratios since nonuniform debris bed thicknesses, including open  
11 spaces, were observed in the ARL experiments.
- 12 • Although this correlation is expected to provide an upper-bound estimate for the  
13 head loss, these limitations and other factors presented in NUREG/CR-6224 should  
14 be reviewed before using this correlation.
- 15 • As explained in subsection 5.1.6.3, debris bed loadings of microporous insulation  
16 debris exceeding microporous-to-fiber mass ratio of 0.2 may result in somewhat  
17 nonconservative results from the above NUREG-6224 correlation.

18 These limitations should be considered for plant-specific applications of the NUREG/CR 6224  
19 head loss correlations.

## 20 **Impact of Microporous Insulation Debris**

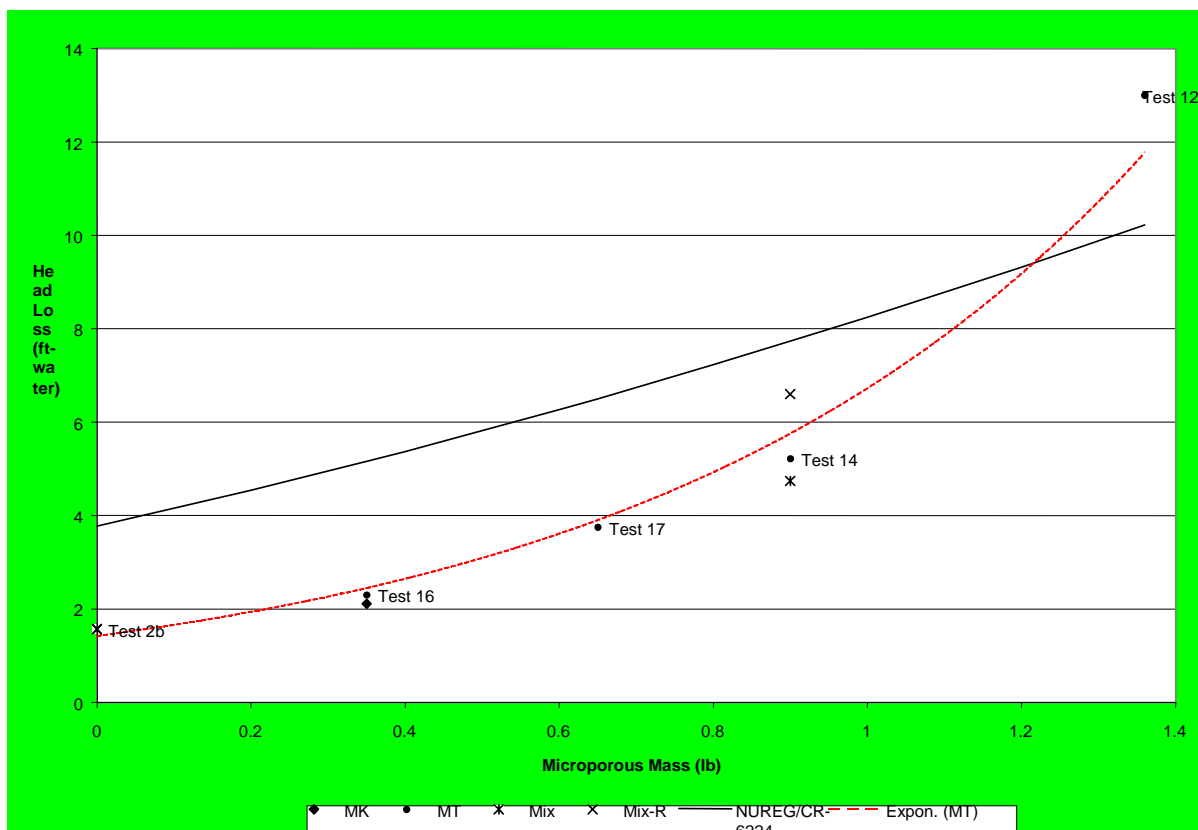
21 A postulated LOCA due to a high-energy pipe break could generate a mixture of fibrous and  
22 microporous insulation debris that may be potentially transported to the ECCS pump intake  
23 screens. Experiments were conducted to address the head loss behavior due to mixtures of  
24 fibrous and microporous debris. In particular, these experiments considered several combinations  
25 of microporous insulation debris (i.e., Min-K, Microtherm, Cal-Sil) mixed with fibrous  
26 insulation debris and particulate debris.

27 The microporous tests showed that the contributions to head loss of microporous insulation could  
28 be neglected when conditions yielded a microporous mass to strainer surface area ratio of  
29  $0.02 \text{ lb/ft}^2$ . Scaling of the experimental results to the prototypical conditions can be accomplished  
30 by scaling to the actual installed strainers apportioning the microporous loads in the ratio of the  
31 flows when more than one strainer is operational.

32 The microporous tests also showed that it is possible to use the NUREG/CR-6224 head loss  
33 correlation to bound the observed test results for mixtures of fibrous and microporous insulation  
34 debris when the microporous-to-fiber mass ratio is less than 0.2. For quantities of debris for  
35 which the microporous-to-fibrous mass ratio exceeds 0.2, the head loss behavior appears to be

1 dominated by the microporous component, and the NUREG/CR-6224 head loss approximation is  
 2 no longer applicable.

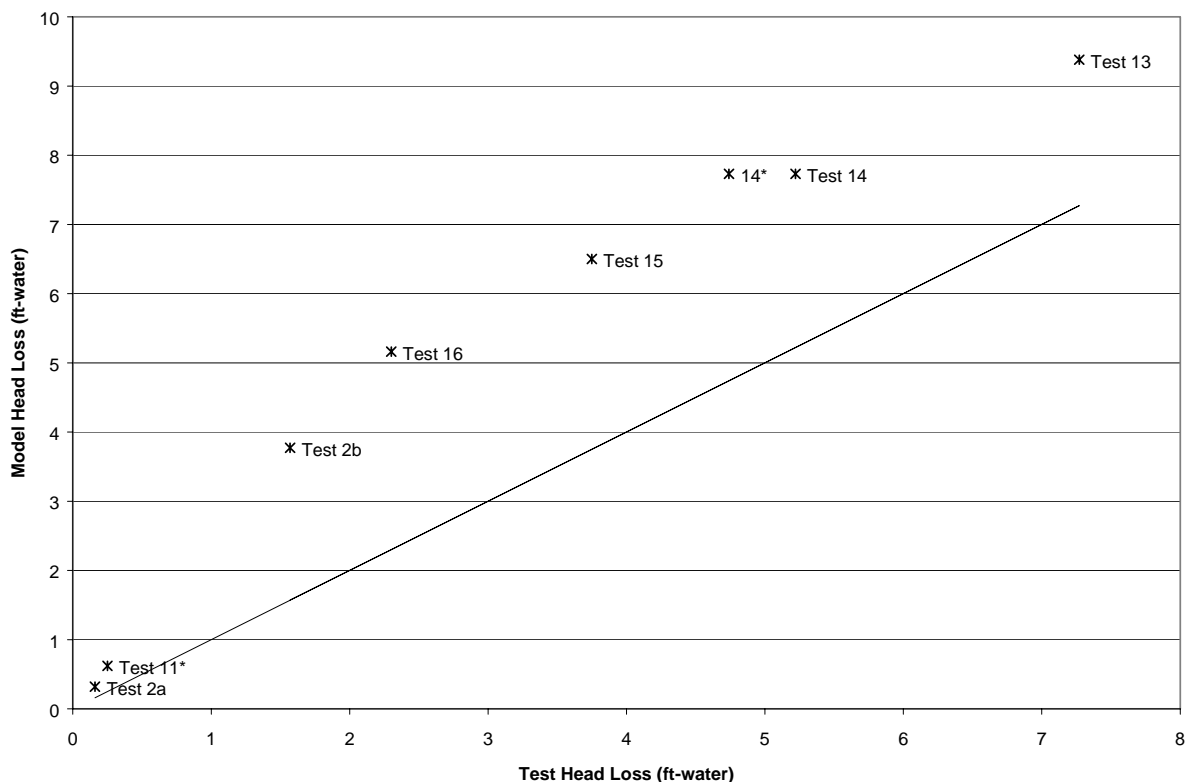
3 Use of the NUREG/CR-6224 head loss correlation to approximate the observed head loss  
 4 behavior due to fibrous and microporous insulation debris requires the specification of a  
 5 characteristic size and density of the microporous particles. Reasonable agreement with the  
 6 observed head loss results is obtained when the microporous particulate matter debris is assumed  
 7 to be in spherical particles, with a characteristic size of 5  $\mu\text{m}$  and a density of 140  $\text{lb}/\text{ft}^3$ . With  
 8 these parameters to characterize microporous particles, the NUREG/CR-6224 head loss  
 9 correlation adequately bounds the observed test data when the microporous-to-fiber mass ratio is  
 10 less than approximately 0.2. This comparison is shown in Figure 4.2.5.2-2, which presents the  
 11 NUREG/CR-6224 head loss correlation and the measured head loss results for 6 pounds of fibers  
 12 at a flow rate of 200 gpm (equivalent to an approach velocity of 0.09 ft/sec) and a water  
 13 temperature of 60°F.



14  
 15 **Figure 4-9. Comparison between the NUREG/CR-6224 Head Loss Correlation and the**  
 16 **Test Data for 6.0 lb of Fibrous Insulation Debris in the Test Tank**

17 As indicated in the figure, the NUREG/CR-6224 head loss correlation adequately bounds the test  
 18 data when the microporous-to-fiber mass ratio is less than 0.2 and when the aforementioned  
 19 parameters are used to characterize the microporous debris (i.e., size and density).

1 A comparison of the NUREG/CR-6224 head loss correlation with the test data for a  
 2 microporous-to-fiber mass ratio less than 0.2, including a medium fiber load as well as the  
 3 applicable test with simulated sludge, is presented in Figure 4.2.5.2-3.



4  
 5 Note: The straight line corresponds to an ideal agreement with the test results.

6 **Figure 4-10. Comparison between the NUREG/CR-6224 Head Loss Correlation and the**  
 7 **Test Data when the Microporous-to-Fiber Mass Ratio in the Test Tank is Less than 0.2**

8 As indicated in Figure 4.2.5.2-3, the proposed model of considering that microporous insulation  
 9 debris may be treated as particulate matter debris, with the NUREG/CR-6224 head loss  
 10 correlation, bounds the test data when the microporous-to-fiber mass ratio in the tank is less than  
 11 0.2. Consequently, estimation of head losses due to mixtures of debris with microporous  
 12 insulation debris can treat the microporous insulation as a particulate matter debris in the  
 13 NUREG/CR-6224 head loss correlation for fibrous debris, provided that the microporous-to-  
 14 fiber mass ratio in the debris bed does not exceed 0.2.

15 **U. S. BWROG Characterization of Combined Debris Head Loss**

16 The U.S. BWROG, while conducting combined debris testing to establish the bases for resolution  
 17 of the ECCS suction strainer plugging issues, has observed phenomena that may have significant  
 18 implications for potential resolutions of the ECCS suction strainer issue. In general, the BWROG  
 19 observations indicate increasing head losses when both fiber loading and corrosion product

1 loading on the strainer are increased together, which is what would be anticipated. A second and  
 2 more significant observation was not initially expected. If the amount of fibrous debris in the bed  
 3 is decreased while the amount of particulate material is held constant, the head loss could  
 4 increase (depending on the ratio of the mass of corrosion products to the mass of fiber) rather  
 5 than decrease as might be initially thought. This behavior was previously suggested by  
 6 Vattenfall.

7 While this phenomenon seems counterintuitive, this finding is consistent with other European  
 8 experiments. As demonstrated during the Perry events and confirmed by subsequent testing, only  
 9 a thin bed of fiber is required on the surface of a flat-plate strainer to effectively filter out fine  
 10 particulate materials that would have otherwise passed through the strainer. The BWROG testing  
 11 program demonstrated that the highest head losses occur with thin layers of fiber and high ratios  
 12 of corrosion product mass to fibrous debris on flat-plate strainers.

13 Physically, a given amount of particulate material results in debris beds that can become  
 14 increasingly compact and decreasingly porous as the amount of fiber present in the bed  
 15 decreases. The end result is that a fiber bed just thick enough to bridge all of the strainer holes  
 16 combined with an inventory of fine particulate materials can result in a very large head loss.  
 17 Based on the testing performed and current understanding of the likely physical causes, these  
 18 phenomena would not be expected to proceed beyond the point where the layer of fibrous  
 19 material is insufficient to fully bridge all of the strainer holes. These observations were made  
 20 during extensive testing both on fiber only and on debris beds comprising fiber and corrosion  
 21 products. The iron oxide corrosion products used for these tests had a larger average particle size  
 22 than that typically present in U.S. BWR suppression pools. Use of the larger-size particulate  
 23 material was shown to result in a conservative estimate of the combined debris head losses, as  
 24 larger particles are more likely to be captured in the fibrous bed. The following head loss  
 25 correlation was documented in the BWROG URG (Reference 41) (Note: Other correlations  
 26 were developed by replacement strainer vendors.)

$$27 \quad \Delta h = K_h \mu U t / (\rho g d^2) \quad (3)$$

28 where,

29	$\Delta h$	is strainer head loss, ft of water
30	$\mu$	is viscosity, lb-sec/ft <sup>2</sup>
31	$U$	is strainer approach velocity, ft/sec
32	$t$	is fiber bed thickness, ft
33	$\rho$	is water density slug/ft <sup>2</sup>
34	$g$	is gravitational constant, 32.2 ft/sec <sup>2</sup>
35	$d$	is inter-fiber spacing, ft

36 This equation has been simplified to:

$$37 \quad \Delta h = a + bU \quad (4)$$

1 where a and b are coefficients dependent on the ratios (Ms/Mf) of different masses of solids (e.g.,  
 2 corrosion products, paint chips, rust flakes, sand, cement dust, calcium silicate, etc.) and fibrous  
 3 materials assumed to collect on the debris bed.

4 A significant aspect of this section is that a large head loss can occur with relatively small fibrous  
 5 loading in combination with a particulate inventory, and that the resolution options must be able  
 6 to manage or prevent unacceptable strainer head losses. Equations 3 and 4 and the BWROG  
 7 URG methodology were developed by the U.S. BWROG for specific conditions and should,  
 8 therefore, be used with caution and reviewed for applicability by the user.

## 9 **Characterization of Head Loss Due to Reflective Metallic Insulation**

10 Many plants have some reflective metallic insulation (RMI) installed, and there has been  
 11 significant interest in the behavior of this material. Experiments have been performed to  
 12 determine how it and other materials react to blast and jet forces, and its transport characteristics.  
 13 Head loss testing of debris beds comprising RMI, or of mixed beds containing RMI, has been  
 14 conducted by several organizations, as described in detail in Table 4.2.5.2-2. The topic of RMI  
 15 debris bed head loss has initiated some disagreement, and it would appear that much of the lack  
 16 of agreement stems from RMI debris shape, bed morphology, and transport characteristics  
 17 fundamental to the head loss experiments. For one to evaluate the effect of RMI, the shape and  
 18 form of RMI reaching the bed, and the predicted morphology of the bed under accident  
 19 conditions should be carefully evaluated to ensure that the testing and derived relationships  
 20 properly represent the real situation.

21 The following observations provide the basis for the method of accounting for RMI contribution  
 22 to debris bed head loss in the U.S.:

- 23 1. The transport characteristics for RMI may be different than other debris, and must  
 24 be accounted for in predicting the debris bed formation. Depending on the pool  
 25 turbulence and approach velocities, RMI deposition may not be uniform.
- 26 2. If RMI does transport and is deposited on screens/strainers, it will produce head  
 27 loss. The head loss developed is highly dependent on the type of RMI debris. For  
 28 example, if a large, intact sheet of metallic foil is deposited over the screen or  
 29 strainer, it will reduce the flow area significantly and increase the velocity and head  
 30 loss in the remaining flow area. Based on various results from debris generation  
 31 testing, RMI debris is expected to be small and crumpled in form, as opposed to  
 32 large, intact sheets. The head loss characteristics of this type of RMI debris range  
 33 from benign to small in comparison with that expected from combined  
 34 fiber/particulate beds.

35 The BWROG has recommended, in its URG, use of the following equation for determining RMI  
 36 bed head loss (the equation is valid for head losses under ~ 10 feet H<sub>2</sub>O):

$$37 \quad \Delta h = K_p U^2 t_p \quad (5)$$

1 where,

2  $\Delta h$  is head loss, ft of water  
 3  $K_p$  is a constant depending on the type of RMI and strainer  
 4  $U$  is the approach velocity, ft/sec  
 5  $t_p$  is the projected RMI debris bed thickness

6 A similar relationship has been suggested by the NRC:

$$7 \quad \Delta P \propto \frac{S_v(1-\epsilon)}{\epsilon^2} U^2 \quad N \propto \frac{L_1 * L_2}{K_t^2} U^2 \quad (A_{\text{foil}}/A_{\text{str}}) \quad (6)$$

8 where,

9  $\Delta P$  is head loss  
 10  $L, S$  are foil dimensions  
 11  $K$  is inter-foil channel size  
 12  $U$  is approach velocity  
 13  $N$  is number of foil layers

14 Where there is combined debris consisting of fibrous material, particulate matter or sludge, and  
 15 RMI, the head loss due to the fibrous and particulate material are expected to dominate. Testing  
 16 of BWR prototypic strainers has indicated that RMI does not cause significantly different head  
 17 losses than those caused by fibrous debris and sludge only. The NRC and BWROG research does  
 18 not indicate the presence of an autocatalytic or synergistic effect between RMI and other debris  
 19 beds similar to combined fibrous and particulate beds. For mixed RMI and fiber beds, the NRC  
 20 approach to consideration of RMI head loss is that it should be added (summed) to the head  
 21 losses expected from other (fibrous and particulate) debris unless it can be demonstrated that this  
 22 conservative approach is not appropriate.

23 Other investigators have reported results and conclusions that differ from the above due to  
 24 considerations associated with the structure of metallic debris beds. The bed structure, as alluded  
 25 to before, will have a significant impact on the head loss. For example, consider a bed of metallic  
 26 foils where most of the foils are arranged parallel to the flow direction. One might expect that  
 27 relative head loss resulting from this configuration with or without other material would be less  
 28 than other configurations. Consider a bed where most of the foils are deposited perpendicular to  
 29 the flow. This type of bed configuration will be subject to compression effects, and combined  
 30 debris would also tend to increase the head loss and bed compression. The realistic situation  
 31 would probably exist between these two extremes. As previously stated, the bed structure  
 32 depends on many factors including its shape as generated during the LOCA event, how it is  
 33 transported (tumbling on floor versus mid-stream suspension), and its formation sequence  
 34 (mixed deposition of insulation and other debris, tumbling up from bottom or curb, etc.). Again,  
 35 it is important to carefully consider the plant-specific situation to develop realistic models.

1 Another form of RMI head loss correlation takes into consideration the pressure drop in RMI  
2 debris beds with gap or bypass:

$$3 \quad \frac{\Delta p}{\frac{\rho w_o^2}{2}} = f_{(R)} \frac{nW}{D} \quad (7)$$

4 where,

5	$\Delta p$	is the pressure drop
6	$\rho$	is the fluid density
7	$w_o$	is velocity
8	$f_{(R)}$	is friction factor
9	$n_w$	is path length of fluid traveled in the bed; n is the number of foil layers and
10		W the foil lateral length
11	D	is the width of the flow channel; depth of foil crumpling

12 This relationship assumes that pressure drop in a metallic bed behaves analogously to pipe flow.  
13 The friction factor, f, depends on bed morphology (structure), and may also contain dependency  
14 on debris surface characteristics such as relative roughness, in addition to the Reynolds number,  
15 and must be determined experimentally. The correlation is presently limited by the following  
16 assumptions:

- 17 • The debris has uniform dimensions.
- 18 • The debris bed area is independent of thickness.

19 While investigating the RMI debris head losses, it was observed that the ratio of maximum to  
20 minimum head loss for different configurations (flatter RMI debris perpendicular to flow versus  
21 parallel to flow) can vary by two or three orders of magnitude.

22 It should be noted that the variability of different vendor products (e.g., dimpled foils, waffle  
23 patterns, or smooth patterns) suggests caution and review of product lines before extrapolating  
24 results. In addition, some experimental results indicate that mixtures of foil pieces and fibrous  
25 debris can result in significantly higher head losses than would be derived from summing the  
26 individual contributions.

## 27 **Related Methodologies**

28 Several companion methodologies have been developed utilizing the research results and  
29 methods discussed above. These methods have been primarily developed for use in calculating  
30 the pressure drop across replacement suction strainers, and are discussed in Table 4.2.5.2-2.  
31 Typical of these methodologies is one developed that utilizes dimensional analysis for  
32 determination of head loss and has been further enhanced to account for bed compression and  
33 different strainer geometrical configurations such as would be present in a stacked disc or star  
34 strainer. The basic equation is of the following form:

$$\Delta H A_s^2 \rho / QM \left( v / d_{if}^2 \right) [1 + k Re] = f(\eta) \quad (8)$$

2 where,

3	$\Delta H$	is the head loss
4	$A_s$	is the surface area
5	$\rho$	is the bed density
6	$Q$	is volume flow
7	$M$	is mass of fiber $M_f$ and mass of sludge
8	$M_s$	is kinematic viscosity
9	$d_{if}$	is inter-fiber spacing
10	$k$	is a constant
11	$Re$	is the Reynolds number, $Re = (Q/A_s)d_{if}/v$
12	$\eta$	is $M_s/M_f$

### 13 4.2.5.2.3 Refinements and Recommendations

14 Although there are no refinements recommended to reduce the conservatism of the  
15 NUREG/CR-6224 correlation itself, there exist potential improvements in head loss modeling:

- 16 1. Flat screen assumption – Section 3.7 recommends using the assumption of a flat  
17 screen for the head loss analysis. For most screen designs, there is little or no  
18 improvement to be had by changing to another assumption. However, for some  
19 screen designs, alternate geometry is used and conservatism could be reduced by  
20 modeling the screen geometry more accurately.
- 21 2. Uniform debris deposition – Section 3.7 recommends using the assumption of  
22 uniform debris deposition for the head loss analysis. For most screen designs, there  
23 is little or no improvement to be had by changing to another assumption. However,  
24 for some screen designs, debris will not be deposited in a uniform manner. If the  
25 uniform debris deposition assumption is not used, the screen design being  
26 evaluated will need to be tested or analyzed to determine the actual debris  
27 deposition. Using this information, more realistic assumptions can be made  
28 regarding the screen area available and the thickness of the resulting debris bed.

29 It is noteworthy that the two refinements discussed above are two of the areas in which alternate  
30 strainer designs offer an advantage over standard screen designs. Typically, alternate strainer  
31 designs are not flat screens. If this is the case, depending on the geometry, uniform debris  
32 deposition will not occur. In these cases, using the NUREG/CR-6224 correlation will be overly  
33 conservative.

34 For alternate strainer designs, new head loss correlations will have to be developed. These  
35 correlations should be developed by the designer and/or vendor of the new sump screen, and  
36 should be used when performing the head loss analysis.



## 1    **5    REFINEMENTS IN ADMINISTRATIVE CONTROL AND DESIGN**

2    In addition to analytical refinements, licensees may choose to consider administrative control  
3    refinements, design refinements, or a combination of administrative control and design  
4    refinements, to enhance post-accident sump performance. This section describes some of these  
5    refinements that are generically applicable to all PWRs. Licensees may identify additional design  
6    or operational refinements that are applicable to their specific plant.

### 7    **5.1    DEBRIS SOURCE TERM**

8    A number of design and operational refinements can contribute to the improvement of the debris  
9    source term, with a consequential reduction in head loss across the sump screen resulting from  
10    debris accumulation. Five categories for design and operational refinements are examined.

11            1.    Housekeeping and FME programs – Implementing or improving housekeeping and  
12                    foreign material exclusion (FME) programs has the potential to reduce the debris  
13                    source term. This operational refinement primarily addresses latent debris concerns  
14                    (as described in Section 3.5).

15                    Housekeeping and FME programs reduce the amount of latent debris inside  
16                    containment by removing as much foreign material as possible between the end of  
17                    outage activities and plant startup. Many FME programs that are in place at plants  
18                    focus on exclusion of foreign materials from the reactor itself and supporting  
19                    systems located inside and outside containment. Since the containment is a system  
20                    in itself and is directly connected to the ECCS during the recirculation mode, it is  
21                    reasonable to include containment housekeeping as part of a plant FME program.

22                    Housekeeping and FME programs should remove all foreign materials from  
23                    containment that have the potential to be transported to the sump. These materials  
24                    include, but are not limited to:

- 25                    •    Dirt and dust
- 26                    •    Tape
- 27                    •    Temporary-use outage equipment
- 28                    •    Temporary-use signs
- 29                    •    Protective clothing
- 30                    •    Trash bags
- 31                    •    Cable ties
- 32                    •    Rope
- 33                    •    Tarps

34                    Refer to NEI 02-01 (Reference 2) for a more complete list of these items.

35                    A significant reduction in the amount of foreign material can be accomplished by  
36                    simply picking up (by hand) and removing foreign material at the end of the

1 outage. Large-scale cleaning activities such as pressure washing, vacuuming, and  
2 mopping are effective at removing dust and dirt from surfaces inside containment  
3 such as floors, walls, junction boxes, and other equipment. A subsequent  
4 cleanliness walkdown is recommended, to verify that foreign materials have been  
5 removed and perform final cleaning activities.

6 It is recommended that, if housekeeping or FME programs are implemented,  
7 appropriate procedures be designed to ensure a high level of performance from the  
8 programs. Of course, it is necessary to integrate FME and housekeeping activities  
9 into outage schedules.

- 10 2. Change-out of insulation – Change-out of insulation is a highly effective method to  
11 improve the debris source term and the resulting head loss across the sump screen  
12 when sufficient quantities of problematic insulation are located inside containment.  
13 A generic strategy is to remove problematic insulation types and replace them with  
14 reflective metallic insulation (RMI). Therefore, it is unlikely that plants using all  
15 RMI on the RCS would have a significant benefit from change-out of insulation.  
16 One exception for these plants would be if problematic insulation types are used on  
17 components besides the RCS. Problematic insulation types include, but are not  
18 limited to the following:

- 19 • Calcium silicate  
20 • Microporous  
21 • Fibrous insulation (all types)

22 Although this refinement is highly effective in reducing the debris source term,  
23 there are significant drawbacks to its implementation. Some of these concerns are  
24 described below:

- 25 • Other analyses may need to be evaluated, as pipe stress and seismic analysis,  
26 heat loads, etc.
- 27 • There is a direct cost associated with the disposal of used insulation  
28 materials.
- 29 • There are possible health hazards associated with removing insulation  
30 materials such as asbestos. Materials such as this present both biological and  
31 radiological hazards and must be dealt with accordingly.
- 32 • It may be necessary to extend a plant outage to remove the problematic  
33 materials, depending on the quantity and composition of the insulation.
- 34 • Consequences of insulation change-out, such as thermal performance  
35 reduction and changes to pipe stress and seismic analyses, must be evaluated.

- 1                   • The new insulation materials must be consistent with the plant’s licensing  
2                   basis, or the licensing basis must be modified.

3                   The effectiveness of change-out of insulation should be quantified by analyzing the  
4                   changes in sump screen head loss using the methods presented in this document.

5                   3.   Modify existing insulation – Modifying the existing insulation may reduce the  
6                   debris source term by increasing the destruction pressure of the insulation and  
7                   reducing the propagation of damage. Typically, modification is accomplished by  
8                   adding metal encapsulation or jacketing, while leaving the insulation in place.  
9                   While this method does offer the possibility of reducing the debris source term  
10                  while reducing the cost and some potential hazards associated with debris change-  
11                  out, there are elements to this approach that should be considered carefully. These  
12                  include, but are not necessarily limited to:

- 13                  •   Review available and applicable test data.
- 14                  •   Additional testing may be performed to determine the destruction pressure of  
15                  insulation with protective jacketing or encapsulation.
- 16                  •   Other analyses may need to be addressed, such as, pipe stress and seismic  
17                  analysis, heat load, etc.

18                  4.   Modify other equipment or systems – Some benefit may be gained in the debris  
19                  source term for some plants by modifying other equipment or systems. This option  
20                  will be less effective than change-out or modification of existing insulation  
21                  systems. However, in some cases it may be worthwhile to remove or modify  
22                  equipment such as:

- 23                  •   Equipment tags and other signs  
24                  •   Sealants (e.g., silicone)  
25                  •   Fire and radiant barriers  
26                  •   Elastomer-coated conduit  
27                  •   Other materials, such as Teflon-coated light bulbs

28                  The list above is not an exhaustive list. Plants should review their containments for  
29                  possible debris source modifications.

30                  Changes to non-insulation systems should be examined on a plant-specific basis  
31                  and should be considered in the context of the entire sump performance evaluation.  
32                  For example, it is unlikely that items such as light bulb covers would be major  
33                  contributors to the debris source term, when considered along with insulation  
34                  debris.

- 1           5.    Modify or improve coatings program – Coating systems used inside containment  
2           can be divided into two categories: DBA-qualified/Acceptable coatings and  
3           unqualified coatings. DBA-qualified coatings have very high destruction pressures  
4           and the corresponding zone of influence is relatively small as compared to the ZOIs  
5           for insulation. Since DBA-qualified/Acceptable coatings should make a very small  
6           contribution to the debris source term, modifying this type of coating system would  
7           have no benefit.

8           Non-DBA-qualified coating systems are used extensively in some containments.  
9           Since these coatings are assumed to fail when subjected to the post-accident  
10          environment, they can be a significant contributor to the debris source term. In all  
11          cases, replacing DBA-unqualified/Unacceptable coatings with a DBA-qualified/  
12          Acceptable coating system will be of benefit to the sump performance analysis. The  
13          benefit of replacing non-qualified coatings with qualified coatings should be  
14          quantified based on plant-specific information and compared to other approaches to  
15          determine which is most cost-effective.

## 16   **5.2    DEBRIS TRANSPORT OBSTRUCTIONS**

17   This section provides mechanical design information for physical debris barriers that may assist  
18   in the mitigation of debris movement to the containment sump.

### 19   **5.2.1   Floor Obstruction Design Considerations**

20   The introduction of physical barriers on the floor will help reduce total debris movement toward  
21   the containment sump. Introduced floor barriers (curbs) are capable of stopping or redirecting  
22   floor debris in such a manner that the debris loading on the recirculation sump can be reduced  
23   (Reference 54). Curbs may be incorporated in the design at or near the sump or may be utilized  
24   to isolate debris closer to its source. Debris stopped behind a barrier is likely to remain there if  
25   flow velocities and turbulence are insufficient to lift it over the barrier. If the barrier does not  
26   cover the entire cross-section of the flow, its effectiveness may be reduced significantly.

#### 27   **5.2.1.1   Test Results**

28   Tests were conducted to ascertain the required velocity and turbulence necessary to lift debris  
29   over curbs with the results reported in Reference 55. Reference 55 documents that, assuming a  
30   2-inch curb is introduced (although a higher curb increases conservatism and the ability to trap  
31   additional material), for the insulation materials listed in Table 5-1, the velocities shown are  
32   required at the curb to lift the debris to pass over the curb. Three different turbulence-producing  
33   configurations were tested and the lowest, “Lift at Curb Velocity,” is reported in Table 5-1. The  
34   velocities listed are typically for the smallest debris size tested and are specified in the tabulation.

1

**Table 5-1. Test Results for “Lift at Curb Velocity”**

<b>Insulation Type</b>	<b>Size or Description</b>	<b>Lift at Curb Velocity (ft/sec)</b>
Nukon	1 in.	0.22
Thermal Wrap (Fiberglass)	4 in x 6 in	0.22
Kaowool	4 in x 6 in	0.25
Stainless Steel RMI	1/2 x 1/2 in.	0.30
Paint Chips	From 1 x 1/2 to 1/8 x 1/8 in. and 15-mil thickness	0.5
Marinite	1 x 1 in.	Not measured but expected to be > 0.5

2

3 Based on the inventory of insulation types and calculated post-accident flow velocities, the  
4 placement of a curb will be optimized in locations where the local velocity is less than in the test  
5 results above. Alternatively, the location of curbs in flow regimes of less than 0.20 ft/sec will  
6 limit movement of all expected debris types.

## 7 **5.2.2 Debris Obstruction Rack Design Considerations**

8 The placement of physical barriers within the flow path, when done correctly, may assist in the  
9 mitigation of total debris movement without impeding water flow to the containment sump.  
10 Debris racks may be incorporated in the design at or near the sump or may be utilized to isolate  
11 debris closer to its source. If the barrier does not cover the entire cross-section of the flow, its  
12 effectiveness will be reduced significantly. A permanent or a moveable design may be used,  
13 depending on the expected personnel traffic and accessibility limitations introduced by the  
14 design. A debris rack may also be used in lieu of a curb within the flow path to minimize the  
15 potential trip hazard or to better accommodate expected equipment maintenance and movement  
16 requirements. To be effective, the location of the barrier must be within a region where local  
17 velocities exceed the incipient tumbling velocity of the debris inventory. Debris  
18 obstructions/interceptors should be designed to the same structural considerations as the sump  
19 strainer. These barriers should take into account water hold-up behind the barriers. See the test  
20 results below.

### 21 **5.2.2.1 Test Results**

22 Tests were conducted with the results reported in Reference 55. The value listed in Table 5-2 for  
23 each insulation type is the lowest tumbling velocity recorded from the University of New Mexico  
24 floor transport tests for which there was debris movement. The “Incipient Tumbling Velocity”  
25 refers to the minimum fluid velocity (averaged over the flume cross-section) required to induce  
26 tumbling or sliding of the debris fragments on the flume bottom. Three different turbulence-  
27 producing configurations were tested and the lowest incipient tumbling velocity is reported. The  
28 velocities listed are typically the smallest debris size tested as indicated in Table 5-2.

**Table 5-2. Test Results for a Floor Transport**

<b>Insulation Type</b>	<b>Size or Description</b>	<b>Incipient Tumbling Velocity (ft/sec)</b>
Nukon	1 in.	0.06
Thermal Wrap (Fiberglass)	Fragments, smaller than 4 in x 6 6 in	0.07
Kaowool	Fragments, smaller than 4 in x 6 6 in	0.09
Aluminum RMI	2 in <sup>2</sup> crumpled or flat	0.2
Stainless Steel RMI	1/2 x 1/2 in.	0.2
Paint Chips	From 1 x 1/2 to 1/8 x 1/8 in. and 15-mil thickness	0.4
Marinite	1 x 1 in.	0.77

1  
2 Based on the inventory of insulation types and calculated post-accident flow velocities, the  
3 placement of a debris rack will be optimized in locations where the local velocity is greater than  
4 the test results above.

#### 5 **5.2.2.2 Debris Rack Grating Size**

6 Too large an opening will not capture significant debris and thus be ineffective. As concluded in  
7 Reference 55, large debris will probably not be transported and therefore, little debris would be  
8 expected to be captured. Too small an opening will potentially cause a debris bed buildup,  
9 leading to a decrease in flow-through rates and consequently either increasing local flow  
10 velocities in other regions (and picking up settled debris) or damming upper levels, causing a  
11 drop in downstream levels.

12 Typically, debris racks in the range of 1 x 4 inches to 1 x 1 inch have been used. Based on the  
13 debris generation tests conducted and documented in Reference 54, a high percentage of the RMI  
14 debris exceeded these sizes. For fibrous debris, Reference 54 tests indicated that the amount of  
15 debris characterized as large generally had an equivalent weight to the amount of fines and small  
16 fibers generated. Thus, there is potential for collecting significant debris.

### 17 **5.3 SCREEN MODIFICATION**

18 In evaluating post-accident sump screen performance, a licensee may determine that it is  
19 desirable to modify their existing sump screen. There are several general sump screen designs  
20 that a utility may consider for implementation. Factors to be evaluated and features of the  
21 designs are discussed below.

### 1 **5.3.1 Considerations for Passive Strainer Designs**

2 A passive strainer design is one that requires no movement or actuation to perform its design  
3 function. Typically, strainers of this design have large surface areas. The large surface area  
4 provides the ability to collect large amounts of debris on the strainer face, while sustaining a  
5 sufficiently low head loss across the sump screen/debris bed combination that  $NPSH_{AVAILABLE}$  is  
6 greater than  $NPSH_{REQUIRED}$ .

7 Passive strainer designs have several favorable technical considerations.

- 8 1. There is an existing body of head loss test data that may be conservatively applied  
9 to most hardware designs for several types of debris and debris combinations.
- 10 2. Sizing of passive strainers is a relatively straightforward application of existing  
11 head loss correlations, such as those given in NUREG/CR-6224.
- 12 3. Structural evaluations also involve a relatively straightforward application of  
13 standard structural analysis methods and techniques.
- 14 4. The design may be modular, facilitating both manufacturing and installation of the  
15 modules. Also, a modular design allows expansion of strainer surface area, should  
16 the need arise.
- 17 5. The applicability of available test data, sizing criteria, commonly accepted  
18 structural analysis techniques and modular design, coupled with the passive nature  
19 of the design, provide high reliability. Passive strainers will work anytime that flow  
20 is initiated through the strainer.

21 Additional considerations for passive strainers, particularly large passive strainers, include:

- 22 1. The containment design may limit the surface area of a passive strainer that can be  
23 installed without containment modifications.
- 24 2. Large passive strainers may infringe on and limit use of floor space previously used  
25 for other purposes.

### 26 **5.3.2 Considerations for a Backwash Strainer Design**

27 A backwash strainer is a design that allows for self-cleaning by reversing water flow to dislodge  
28 debris from the strainer face, thereby reducing the head loss when recirculation flow is  
29 reinitiated. Self-cleaning is a desirable feature.

1 Additional considerations for backwash strainers include:

- 2 1. This design requires a source of fluid, and its associated motive force, to perform  
3 the backwash function. This fluid may be either water or air. The motive force may  
4 be provided by a pump, compressor, or pressurized tank.
- 5 2. A power source is needed to support the operation of this design. A power source is  
6 needed to actuate valves, pumps, or compressors to initiate and/or terminate the  
7 backwash sequence.
- 8 3. As with all strainers, backwash strainers require structural evaluations. In addition  
9 to the seismic loading that all strainer designs must be designed to withstand,  
10 backwash strainers must withstand loads associated with normal (recirculation)  
11 flow and debris loading, as well as the reverse flow and impulse loading associated  
12 with shedding of debris.
- 13 4. Since there are moving parts in a backwash strainer design, the failure of critical  
14 components should be addressed in the design; redundancy and separation of trains  
15 should be considered.
- 16 5. Since backwashing of the strainer is based on the head loss across the debris  
17 bed/strainer reaching a predetermined value, instrumentation is needed to determine  
18 when that value is reached. This necessarily involves calibration and uncertainty  
19 analysis to ensure that adequate margin is available to initiate backwash before  
20 sump blockage affects either ECC or CS operation.
- 21 6. A backwash strainer may be required to undergo surveillance testing to demonstrate  
22 that it will work as designed. This testing would require planning, procedures, and  
23 personnel to conduct the surveillance. Also, surveillance testing may impact  
24 ALARA dose.
- 25 7. Reliability of active components is a design concern for backwash strainers. The  
26 inadvertent or spurious actuation of components of a backwash strainer may result  
27 in a forced shutdown. Similarly, the failure of a component to operate during an  
28 at-power surveillance test may cause a plant to shut down.

### 29 **5.3.3 Considerations for an Active Strainer Design**

30 An active strainer is a design that incorporates active components to maintain flow to the sump.  
31 Typically, this design has some components that are powered continuously once recirculation  
32 flow is initiated. Continuous cleaning of the strainer surface area is a desirable feature of an  
33 active strainer design.



1 Active self-cleaning strainers have several favorable technical considerations.

- 2 1. Active self-cleaning strainers may be relatively small compared to passive systems  
3 and therefore minimize the impact on containment floor space.
- 4 2. Active self-cleaning strainer head loss and performance may be independent of  
5 debris type and quantity.
- 6 3. Active self-cleaning strainers may avoid uncertainties related to water chemistry,  
7 chemical effects, debris, transportability, and long term bed compaction and  
8 erosion.

9 Additional considerations for active strainers include:

- 10 1. Currently, there are no active strainer applications for either BWRs or PWRs. It  
11 may be expected that several experimental studies will need to be undertaken to  
12 support the implementation of an active strainer design.
- 13 2. The design of the active strainer will need to account for characteristics of PWR  
14 insulation debris.
- 15 3. A power source may be needed to support the operation of this design. The power  
16 source may be external to the strainer, such as a motor, or internal to the strainer,  
17 such as a turbine that uses the water flow through the strainer to drive the strainer  
18 cleaning mechanism.
- 19 4. As with all strainers, active strainers require structural evaluations. In addition to  
20 the seismic loading that all strainer designs must be designed to withstand, active  
21 strainers must withstand loads associated with the normal (recirculation) flow,  
22 loads imposed on the strainer structure by the cleaning mechanism, and debris  
23 loading.
- 24 5. Since there are moving parts in an active strainer design, reliability of active  
25 components is a design concern. Specifically, redundancy and separation of trains  
26 of the cleaning mechanisms should be considered.
- 27 6. An active strainer is actuated upon a signal that the strainer is required to be in  
28 operation. An actuation signal or an instrument output signal is needed to initiate  
29 the active portion of the strainer cleaning mechanism. This necessarily involves a  
30 signal analysis and uncertainty evaluation to ensure that adequate time is available  
31 between identification of need for the strainer and actuation of the cleaning  
32 mechanism. Margin must be available to initiate backwash before sump blockage  
33 affects either ECC or CS operation.

- 1           7.    The cleaning action of active strainers may induce ingestion of debris into the  
2           recirculating flow that otherwise might be captured on the debris bed. This ingested  
3           debris may present additional considerations for downstream effects evaluations.
- 4           8.    An active strainer may be required to undergo surveillance testing to demonstrate  
5           that it will work as designed. This testing would require planning, procedures, and  
6           personnel to conduct the surveillance. Also, surveillance testing may impact  
7           ALARA dose.

#### 8   **5.3.4 Summary**

9    In assessing post-accident sump screen performance, licensees may choose to change the sump  
10   screen. Three possible sump screen designs were identified, along with their potential benefits  
11   and related concerns for their design, installation, and operation. It is expected that licensees will  
12   conduct a design review as an integral step in their sump screen modifications. The benefits and  
13   concerns listed in this section are useful in considering strainer design options, and provide an  
14   initial set of criteria for conducting a design review. NRC review of new strainer designs may  
15   require experimental data demonstrating performance of the design.

16

## 1   **6     RISK-INFORMED EVALUATION**

### 2   **6.1    INTRODUCTION**

3       In SECY-02-0057, “Update to SECY-01-0133, ‘Fourth Status Report on Study of Risk-  
4       Informed Changes to the Technical Requirements of 10 CFR Part 50 (Option 3) and  
5       Recommendation on Risk-Informed Changes to 10 CFR 50.46 (ECCS Acceptance  
6       Criteria),” the staff recommended the development of risk-informed approaches to  
7       technical requirements in 10 CFR 50.46 (and related provisions) concerning LOCA  
8       acceptance criteria and evaluation models. In its March 31, 2003 SRM, the Commission  
9       directed the staff to undertake rulemakings, one of which would develop a proposed rule to  
10      allow, as a voluntary alternative, a redefinition of design basis maximum break size.

11      The NRC supports consideration of licensee requests for exemptions to these requirements,  
12      as allowed by 10 CFR 50.12, as a means to facilitate the rulemaking process. In a March  
13      4, 2004 letter to NEI, NRC opened the possibility for risk-informing portions of the  
14      evaluation process for addressing GSI-191 concerns.

15      “...the NRC staff plans to discuss, in public meetings, the use of current or planned work to risk-inform Title  
16      10, *Code of Federal Regulations* Section 50.46, “Acceptance criteria for emergency core cooling system for  
17      light-water nuclear power reactors,” as a suitable technical basis for defining a spectrum of break sizes for  
18      debris generation and containment sump strainer performance.”

19      A risk-informed option for GSI-191 resolution is discussed in this section. This process  
20      (Option B of Figure X) allows for use of an alternate maximum break size in analyses that  
21      demonstrate compliance with the long-term cooling requirement of 10 CFR 50.46.

22      Implementation of Option B involves two separate analysis steps:

- 23      1) Design Basis Analysis using Alternate Break Size
- 24      2) Demonstration of Beyond-Design-Basis Mitigation Capability

25  
26      The design basis analysis under Option B is performed in the same manner as that called  
27      for under Option A and described in Sections 3, 4 and 5 with the exception that the  
28      maximum break size considered in the design basis analysis is less than the double-ended  
29      rupture of the largest pipe in the reactor coolant system called for in 10 CFR 50.46.  
30      Section 6.2 provides additional guidance on performance of the design basis analysis  
31      under Option B. Table 6.2-1 provides a summary of modifications to guidance in Sections  
32      3, 4 and 5 to perform the design basis analysis under Option B.

33      In implementing the Option B approach and use of an alternate break size, it is necessary  
34      to demonstrate that some degree of mitigation capability is retained for break sizes  
35      between the new maximum break size and the double-ended guillotine break of the largest  
36      pipe in the reactor coolant system. This “beyond-design-basis” analysis is performed using  
37      more realistic analysis methods and assumptions and allows credit to be taken for non-  
38      safety SSCs and operator actions. In addition, relaxation of the acceptance criteria

1 applicable to design basis analyses is acceptable. Section 6.3 provides guidance on an  
2 appropriate set of modifications to the analysis methods and assumptions described in  
3 Sections 3, 4 and 5 for use in the Option B analysis to demonstrate mitigation capability.  
4 These modifications are summarized in Table 6.3-1.

5 In addition to the analysis steps described in this section, the preparation of a separate  
6 regulatory basis document will be necessary to support the application of the Option B  
7 approach. Guidance for preparation of the regulatory basis will be provided in a separate  
8 document.

## 9 **6.2 RISK-INFORMED DESIGN BASIS ANALYSIS**

10 The analysis of recirculation system performance under Option B is performed in the same  
11 manner as described in Sections 3, 4 and 5 of this document, except that the maximum size  
12 of RCS breaks to be considered is set by the “Alternate Break Size.” The range of  
13 secondary side break sizes that should be considered is unchanged under Option B. The  
14 “Alternate Break Size” for use under Option B is described in section 6.2.1.

### 15 **6.2.1 Alternate Maximum Break Size**

16 (Alternative break size, established as effective flow area, to be determined)

### 17 **6.2.2 Modification of Break Locations to be considered**

18 The use of an alternate maximum break size has no impact on the range of break  
19 locations to be considered. As discussed in Section 3, a full range of break locations  
20 should be assessed to determine the limiting location. The use of an alternate maximum  
21 break size could impact the limiting location of the break compared to analyses  
22 performed under Option A.

### 23 **6.2.3 Modification of Break Configuration**

24 The maximum break size to be considered for a given primary-side piping location is the  
25 minimum of either the Alternate Break Size established in section 6.2.1 or the maximum  
26 attainable effective break area.

#### 27 **Example:**

28 Consider a 6” schedule 160 pipe. The transverse internal area of this pipe is 21.15 in<sup>2</sup>.  
29 The maximum attainable effective break area for this pipe is 2 times this value, or 42.30  
30 in<sup>2</sup> (assuming a source high-energy flow from both directions). This value would be used  
31 for the postulated break locations in this pipe in lieu of the alternative maximum break  
32 size.

33

## 1   **6.2.4 Modifications to Zone of Influence Calculations**

2       The guidance in Section 3.4.2 on determination of the zone of influence for debris  
3       generation presumes a DEG break. For DEG breaks, a spherical zone of influence is  
4       conservatively postulated.

5       For large bore piping, postulation of a break size less than the DEG break area would  
6       indicate a limited-displacement circumferential break or a longitudinal break, i.e., “split  
7       break”. This difference can be accounted for in one of the following ways.

### 8       a)   ZOI Based on a Hemisphere

9               The zone of influence for split breaks can be simulated as a hemisphere with  
10              radius determined by the destruction pressure of the insulation that would be  
11              affected by the postulated break. From Table 3.4.2-1, for unjacketed Nukon  
12              insulation<sup>1</sup>, the hemisphere would have a radius of 12.1 times the effective  
13              diameter,  $D$ , of postulated break or  $12.1D$ .

### 14      b)   ZOI Based on a Sphere

15              Because a worst-case break orientation can be difficult to determine, an  
16              alternative to assuming a hemispherical ZOI is to translate the hemispherical  
17              volume into an equivalent volume sphere. For the case of unjacketed Nukon  
18              insulation, this translation leads to a sphere with a radius of  $9.6D$ .

19       Additional guidance is provided in Section 4 for the use of the following refinements to  
20       the guidance given above:

- 21           1. The use of debris specific zones of influence, and,
- 22           2. The use of directed jets to evaluate damage to insulation and coatings

23  
24       As noted above in item (a), however, for large bore piping and a postulated break size  
25       less than the DEG break area, the use of a directed jet for debris generation may require  
26       the determination of a worst-case break orientation.

## 27   **6.2.5 Modifications to Event Timings and Conditions**

28       Consideration should be given to the potential impact of the Alternate Break Size on  
29       event timings, thermal/hydraulic conditions and NPSH requirements. Use of the

---

<sup>1</sup> As described in Section 3.4.2.2, “Selecting The value of the ZOI,” the ZOI value used in a plant-specific calculation depends upon the destruction pressure of the insulation in the region of the break. Nukon insulation is used as an example here as this was the insulation type that was used to define the sample calculation described in Section 3.4.2.6, “Sample Calculation”, of the Baseline Evaluation.

1 Alternate Break Size in lieu of a full DEG break on the main loop piping will affect key  
 2 event timings, such as lower containment fill-up and the timing of transfer to  
 3 recirculation from RWST injection.

4 **Table 6.2-1**

5 **Design Basis Analysis Methodology**

6 **Comparison between Option A and Option B**

	<b>Option A</b>	<b>Option B</b>
<b>Maximum Break Size</b>	Up to full DEG of largest pipe in reactor coolant system	Up to Alternate Maximum Break Size as defined in Section 6.2.1
<b>Break Locations</b>	No Change	
<b>Break Configuration</b>	Full DEG	Minimum of full DEG or Alternate Maximum Break Size

7  
 8 **6.3 ANALYSIS TO DEMONSTRATE MITIGATION CAPABILITY**

9 In implementing the Option B approach and use of an alternate break size, it is necessary  
 10 to demonstrate that some degree of mitigation capability is retained for break sizes  
 11 between the new maximum break size and the double-ended guillotine break of the  
 12 largest pipe in the reactor coolant system. This analysis to demonstrate mitigation  
 13 capability (DMC) is performed using more realistic analysis methods and assumptions  
 14 and credit can be taken for operation of non-safety systems, structures and components as  
 15 well as expected operator actions. In addition, modification of the acceptance criteria  
 16 applicable to design basis analyses is allowed.

17 The list of potential modifications to the set of conservative methods and assumptions  
 18 used in the design basis analysis is large. In order to simplify the DMC analysis process  
 19 the following sections identify a recommended set of modifications to methods and  
 20 assumptions described in Section 3 through 5.

21 **6.3.1 Break Sizes**

22 Break sizes that need to be considered in the DMC analysis cover the range from  
 23 “Alternate Break Size” identified in Section 6.2.1 up to a full DEGB of the largest  
 24 attached piping.

1

### 2 **6.3.2 Break Locations**

3 Primary side piping whose maximum attainable break area is less than or equal to the  
4 “Alternate Break Size” will have already been addressed as part of the design basis  
5 analysis and can be excluded from further consideration as part of the DMC analysis.  
6 Any postulated secondary side break locations will also have been addressed as part of  
7 the design basis analysis and can be excluded from the DMC analysis. Consequently, all  
8 high energy piping locations except for main loop piping are fully addressed as part of the  
9 design basis analysis.

10 For the remaining break locations, guidance provided in Standard Review Plan 3.6.2,  
11 *Determination of Rupture Locations and Dynamic Effects Associated with the Postulated*  
12 *Rupture of Piping*, and MEB 3-1, *Postulated Rupture Locations in Fluid System Piping*  
13 *Inside and Outside Containment*, should be used to identify postulated primary side break  
14 locations.

### 15 **6.3.3 Break Configuration**

16 Circumferential breaks should be assumed to result in pipe severance and separation  
17 amounting to at least one-diameter lateral displacement of the ruptured piping sections  
18 unless physically limited by piping restraints, structural members, or piping stiffness as  
19 may be demonstrated by limit analysis. Limited pipe displacement at the break location,  
20 line restrictions, flow limiters, positive pump-controlled flow, and the absence of energy  
21 reservoirs may be taken into account, as applicable.

22 Existing plant-specific dynamic loads analyses for postulated primary side breaks should  
23 be utilized to assist the DMC analysis.

### 24 **6.3.4 Analysis Assumptions**

25 In performing the DMC analysis, consideration should be given to relaxation of analysis  
26 assumptions used in the design basis analysis. In general, the DMC analysis can use  
27 nominal expected conditions in lieu of bounding values used in DBA calculations.

28 For simplicity and ease of calculation, DBA analysis assumptions and guidance in  
29 Sections 3, 4 and 5 may be used. Any modifications to DBA analysis assumptions for use  
30 in the DMC analysis, to account for nominal expected conditions, should be identified.

31 Key DBA assumptions that can be considered for modification and use in the DMC  
32 analysis include:

- 33 • No coincident loss of offsite power
- 34 • No assumed limiting single failure

35

1 In addition, nominal expected conditions can be considered in a number of areas,  
2 including:

- 3 • RCS initial power and temperature
  - 4 • Decay heat
  - 5 • ECCS flow and temperature
  - 6 • Containment spray flow and temperature
  - 7 • Latent debris source term
  - 8 • More realistic assumptions for debris transport to the sump
- 9

10 An important allowance in the DMC analysis is credit for operation of non-safety  
11 equipment and for expected operation actions taken to mitigate the postulated LOCA  
12 event. The actions and operations that can be credited will be plant-specific, but could  
13 include:

- 14 • Credit for non-safety active screens, screen backwash systems or similar  
15 modifications to containment sump screen design
  - 16 • Operator actions, as directed by emergency procedures (e.g., termination of  
17 containment spray flow, ECCS flow adjustments)
- 18

### 19 **6.3.5 Applicable Success Criteria**

20 Breaks greater than the maximum break size considered in the design basis analysis are  
21 “beyond-design-basis.” The applicable criteria to demonstrate retained mitigation  
22 capability for long-term cooling capability in the DMC analysis are:

- 23 1. Positive NPSH margin is maintained for the minimum number of ECCS pumps  
24 necessary to demonstrate adequate core cooling flow
  - 25 2. Demonstration of adequate containment cooling capability to provide  
26 assurance that the containment boundary remains intact
- 27

28 The first criterion can be met by demonstrating that adequate flow to the core is  
29 maintained to remove decay heat. This demonstration can be met by ensuring NPSH  
30 margin is maintained for one or more moderate to high-capacity ECCS injection pumps  
31 (e.g., low-head RHR pumps). A single-failure of ECCS trains does not need to be  
32 considered.

33 The time-variable nature of required and available NPSH can be considered. Limited  
34 operation in cavitation (negative NPSH margin) can be considered.

35 In the calculation of available and required NPSH, the following should be considered:



- 1           -    Nominal containment sump temperatures and levels
- 2           -    Nominal Containment backpressure
- 3           -    Nominal ECCS flow (credit may be taken for operator actions to control
- 4           ECCS flow and match decay heat removal requirements)
- 5

6           The second criterion can be met through credit taken for one or more heat-removal  
7           pathways, including containment fan coolers.

8

## 1 7 ADDITIONAL DESIGN CONSIDERATIONS

2 There are additional considerations beyond head loss that are to be taken into consideration when  
3 evaluating the post-accident performance of the containment sump screen. These considerations  
4 include:

- 5 1. Structural analysis of the containment sump
- 6 2. Upstream effects
- 7 3. Downstream effects
- 8 4. Chemical effects

9 Guidance is given in the following sections for evaluating each of these considerations.

### 10 7.1 STRUCTURAL ANALYSIS OF CONTAINMENT SUMP

11 Following the analysis of the debris generation, debris transport, and debris head loss across the  
12 strainer screen, a structural evaluation of the strainer screen assembly shall be performed based  
13 on the predicted debris head loss. Using the strainer flow rates and the debris loading, the clean  
14 strainer head loss combined with the debris head loss will predict the maximum differential  
15 pressure across the strainer screen assembly. This head loss is less than or equal to the allowable  
16 head loss at which the ECCS pumps and CS pumps would be credited to deliver the required  
17 cooling water flow. Many existing PWR strainer screen assemblies have a geometry of a  
18 rectangular box, with essentially four vertical flat screens, constructed of grating and wire mesh  
19 screening. Most of the existing PWR strainers were designed for 50 percent blockage with  
20 essentially no differential pressure across the screen assembly. As such, many of these simple  
21 rectangular strainer assemblies were not designed to accommodate any significant differential  
22 pressure. Along with the evaluation of the overall structural integrity of the strainer assembly, it  
23 is very important to evaluate the attachment of the wire mesh screen to the strainer assembly  
24 frame. The wire mesh tends to stretch and, depending on the attachment method, gaps could  
25 form during debris loading that would allow the debris to bypass the wire mesh. It should be  
26 noted that all of the replacement BWR strainers used perforated plate material instead of the  
27 original wire mesh.

28 Materials selected for fabrication of new strainers should take into account the post-accident  
29 environment in which they will be required to operate. Corrosion-resistant materials are  
30 recommended.

31 The existing strainers should have been designed to the specific plant seismic requirements. The  
32 seismic design is typically a pre-LOCA environment with no debris loading and a dry  
33 containment. As stated in Regulatory Guide 1.82, Revision 3, subsection 1.1.1.8, hydrodynamic  
34 loads on the strainer may need to be evaluated. A review of the design basis of the containment  
35 should provide guidance in the design requirements of the strainer in the long-term post-LOCA  
36 environment. When evaluating long term, many days or months, operation of the strainer in a  
37 submerged environment with debris loading, a seismic event could introduce sloshing of the  
38 water within the flooded containment. This could introduce additional structural loading onto the  
39 strainer.

1 In addition to the above structural issues, one may wish to allow for structural margin in the  
2 strainer design. If additional NPSH margin is gained by a combination of changes in the ECCS  
3 pump requirements, CS pump requirements, containment water level, containment overpressure,  
4 or debris source term, this could result in an increase in the differential pressure across the  
5 strainer. A plant would not want structural design of the strainer to be the weak link in resolving  
6 the GSI-191 issue.

7 Finally, the replacement BWR ECCS strainers that were installed during the 1990s were  
8 designed to different structural requirements than would be required for the PWRs. In BWRs,  
9 very large hydrodynamic loads are created in the suppression pool during the LOCA blowdown  
10 and safety relief valve discharges, resulting in long-term chugging in the suppression pool. As  
11 such, the BWR strainer designs incorporated structural features that may not be applicable or  
12 needed in the PWR design.

## 13 **7.2 UPSTREAM EFFECTS**

14 Evaluation of the containment sump should include a review of the flow paths leading to the  
15 sump screen itself. The containment condition assessment as described in NEI 02-01 provides  
16 guidance on this review. The concern to be addressed for upstream effects is the hold-up of  
17 inventory away from the containment sump, possibly “starving” the sump of flow. Thus, this  
18 review should look for locations where debris might collect and either retard or block the flow to  
19 the sump.

20 The following parameters are important to the evaluation of upstream effects:

- 21 1. Both the containment design and the postulated break location. These two items  
22 determine the flow path and the hydraulic characteristics of the flow path to the  
23 containment sump.
- 24 2. The postulated break size and insulation materials in the ZOI about the break.  
25 These two items determine the debris characteristics to be considered, as well as the  
26 flow rate to the sump.

27 The parameters identified above provide a basis to evaluate hold-up or choke points in the flow  
28 field within containment upstream of the containment sump.

29 Examples of locations to look for and evaluate for hold-up of liquid upstream of the sump screen  
30 include:

- 31 1. Narrowing of hallways or passages. Large pieces of debris may gather on the floor  
32 in these areas and form a debris “mound.”
- 33 2. Gates or screens that restrict access to areas of containment such as behind the  
34 bioshield or crane wall. Again, medium- to large-sized debris may form behind the  
35 screen or grate, restricting flow to the containment sump from behind the bioshield  
36 or crane wall.

- 1           3.    Refueling canal drain to lower containment. Most plants have a drain path from  
2           upper containment to the refueling canal to the elevation of the containment sump.  
3           Depending on break location and insulation materials used at a plant, significant  
4           debris may be generated from a postulated break, then transported to the upper  
5           containment and on to the refueling canal to be collected on the refueling canal  
6           floor drain. The collection of debris on the floor drain should be evaluated to  
7           determine if this path to the containment sump may be blocked.

8    The items listed above are typical areas of concern that are generally applicable to all  
9    containments. As noted previously, however, each containment design has unique geometric  
10   features, as well as a plant-specific insulation installation. An upstream effects evaluation should  
11   include and address these plant-specific features.

### 12   **7.3    DOWNSTREAM EFFECTS**

13   Evaluation of the containment sump should include a review of the flow paths downstream of the  
14   emergency core cooling (ECC) and containment spray (CS) systems. The concerns to be  
15   addressed for downstream effects are:

- 16           1.    Blockage of flow paths in equipment; for example, containment spray nozzles or  
17           tight-clearance valves.
- 18           2.    Wear and abrasion of surfaces; for example, pump running surfaces, heat exchanger  
19           tubes and orifices.
- 20           3.    Blockage of flow clearances through fuel assemblies.

21   In general, a downstream review should broadly consider flow blockage in the ECC and CS flow  
22   paths, as well as examining wear and abrasion in systems, structures, and components in the  
23   ECC and CS flow paths that are important to the long-term cooling function.

24   A logical start for the evaluation is to consider the flow clearance through the sump screen. This  
25   determines the maximum size of particulate debris that will pass through the sump screen and  
26   enter the ECC and CS flow paths. If passages and channels in the ECC and CS downstream of  
27   the sump screen are larger than the flow clearance through the sump screen, blockage of those  
28   passages and channels by ingested debris is not a concern. If there are passages and channels  
29   equal to or smaller than the flow clearance through the sump screen, then the potential for  
30   blockage exists and an evaluation should be made to determine if the consequences of blockage  
31   are acceptable, or if design modifications are warranted.

32   Similarly, wear and abrasion of surfaces in the ECC and CS should be evaluated, based on the  
33   flow rates to which the surfaces will be subjected and the grittiness or abrasiveness of the  
34   ingested debris. The abrasiveness of the debris is plant-specific and depends on the insulation  
35   materials that become debris. For example, fiberglass is a known to be an abrasive material.

1 Wear and abrasion of pumps due to ingestion of debris may have been addressed by the pump  
2 manufacturer. Licensees should request information and/or test data from the pump vendor  
3 regarding the ability of specific pumps to perform with debris in the pumped flow. Other sources  
4 of information may include information generated to support the closeout of USI A-41 such as  
5 NUREG/CR-2792 (Reference 58).

#### 6 **7.4 CHEMICAL EFFECTS**

7 Pressurized water reactor (PWR) containment buildings are designed to both contain radioactive  
8 material releases and facilitate core cooling in the event of a loss-of-coolant accident (LOCA).  
9 The cooling process requires water from the break and from containment spray to be collected in  
10 a sump and recirculated through the emergency core cooling (ECC) and containment spray (CS)  
11 systems. The containment sump design incorporates a screen that protects systems, structures,  
12 and components in the CS and ECC system flow paths from the effects of debris that could be  
13 washed into the sump. There has been concern that fibrous insulation could form a mat on the  
14 screen that would obstruct flow.

15 Concerns have been raised about the potential for corrosion products to significantly block flow  
16 across a fiber bed and therefore increase the head loss across the bed. Among the materials that  
17 are found inside containment and are susceptible to chemical reactions with the post-LOCA  
18 solution are aluminum, zinc, carbon steel, copper and non-metallic materials such as paints,  
19 thermal insulation (e.g., cal-sil, fiberglass), and concrete.

20 Industry, with support from the NRC and EPRI, has developed a test plan to study possible  
21 interaction between the corrosion products (e.g., gelatinous material, agglomerates, etc.) and the  
22 effects of those products on filtration. The test plan addresses two objectives:

23 Guidance to address the effects of corrosion products on head loss is deferred until the testing is  
24 completed and the data have been appropriately evaluated.

## 1   **8   SUMMARY**

2   The purpose of this document is to provide licensees with a guidance for evaluating the post-  
3   accident performance of the containment sump screen for a pressurized water reactor (PWR).  
4   The approach taken in developing this guidance was to define a common and consistent approach  
5   that was applicable to all PWRs. This common and consistent method is termed the “*Baseline*  
6   *Evaluation Method.*” Above and beyond the Baseline Evaluation Method, refinements to the  
7   analytical methods and design considerations are defined. Also, additional design considerations  
8   that should be accounted for in evaluating current or future designs are identified. Finally, a risk-  
9   informed approach to break size selection is also provided.

10   PWRs vary greatly in containment size, floor layout, sump configuration, required ECCS flows,  
11   insulation types and location, and post-LOCA operational requirements. Since it was evident that  
12   one guideline could not encompass all PWRs, this methodology document provides basic  
13   guidance on approach and various methods available, but recognizes that the best strategy for  
14   each plant could involve a combination of methods and refinements. Each PWR operator, having  
15   unique knowledge of specific plant design and operation, is best qualified to determine the  
16   optimum solution strategy. As such, this document does not prescribe a specific combination of  
17   methods to the user.

18   The Baseline Evaluation Method, and the guidance to perform the Baseline Evaluation Method,  
19   provides a conservative approach for evaluating the generation and transport of debris to the  
20   sump screen, and the resulting head loss across the sump screen. If a plant uses this method and  
21   guidance to determine that sufficient head loss margin exists for proper long-term Emergency  
22   Core Cooling (ECC) and Containment Spray (CS) function, no additional evaluation for head  
23   loss is required.

24   Given is Section 1 is an introduction to the PWR strainer debris issue, including a historical  
25   review describing the steps that led to the current understanding. Section 2 is a high-level  
26   summary of the overall process considerations that need to be addressed during the evaluation  
27   process, while Section 3 describes a Baseline Evaluation Method that may be applied to all  
28   PWR’s and provides sample calculation using the Baseline Evaluation Method. In Section 5,  
29   refinements in administrative control and design are discussed. Section 6 provides a guidance on  
30   a risk-informed evaluation. Section 7 provides guidance for additional design considerations.

31   The current document has several open areas that require either more study or testing to address.  
32   They include the treatment of long-term chemical effects and calcium silicate head loss  
33   correlations. This document also does not address the implementation and/or licensing of any  
34   design or operational changes resulting from the use of the evaluation methodology.

35

36

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