U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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PNNL-17972

Evaluation of Treatment of Effects of Debris in Coolant on ECCS and CSS Performance in Pressurized Water Reactors and Boiling Water Reactors

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Prepared by
J.M. Cuta, B.E. Wells, C.H. Delegard and B.F. Saffell

Pacific Norhwest National Laboratory
902 Battelle Boulevard
Richland, WA 99352

J. Burke, NRC Project Manager

NRC Job Code N6636

Office of Nuclear Regulatory Research

ABSTRACT

This report identifies significant differences in the industry and regulatory guidance for the treatment of suction strainer performance in pressurized water reactors (PWRs) compared to that in boiling water reactors (BWRs) during operation of their respective emergency core cooling systems, containment spray systems, and residual heat-removal systems in postulated loss-of-coolant-accident events. These differences are evaluated for their technical significance, conservatism, and consistency. Recommendations are provided for appropriate guidance on technical requirements to address the issues in a consistent and conservative (or prototypic) manner for both reactor types.

FOREWORD

The objective of this report is to identify any significant disparities in the regulatory treatment of emergency core cooling system (ECCS) suction strainer performance for boiling-water reactors (BWRs) and pressurized-water reactors (PWRs), evaluate the technical significance of the differences, and provide recommendations on the path forward for handling the disparities. Differences are assessed in terms of their significance with regard to maintaining long-term core cooling in postulated design-basis accident conditions. Recommendations are provided to establish a conservative and appropriately consistent regulatory framework for both reactor types.

In the evolution of the technical knowledge base used to verify the adequate ECCS suction strainer performance for the currently licensed and operating nuclear reactors in the United States, differences have developed in the regulatory treatment of PWRs and BWRs. Some of the differences in the guidance for suction strainer performance analyses are due to technical differences in the basic design of the two reactor types. In many cases, however, the differences arose because of additional knowledge and changes in the regulatory focus in the time periods that the issues were addressed for each reactor type.

The disparities were identified by reviewing various reports from analytical and experimental studies, technical reports from industry groups such as the Boiling Water Reactor Owners Group (BWROG) and the Pressurized Water Reactor Owners Group (PWROG), associated NRC staff safety evaluations, and Regulatory Guide 1.82 revision 3. These differences were then grouped into five categories: debris characteristics, debris generation, debris transport, head loss on the suction strainers, and downstream effects of debris in the recirculation coolant. Recommendations are provided on changing the guidance for defining the technical requirements to address this issue in a consistent and conservative manner for both reactor types.

The NRC staff concurs with the majority of the recommendations for BWRs in this report such as the need to conduct plant-specific walkdowns to determine debris types, conduct chemical effects testing, evaluate downstream effects, and assess existing head loss test data for the suction strainers. The BWROG has begun to address these issues and has discussed its resolution strategies and associated schedules with the NRC staff in a series of public meetings starting in June 2008. However, the NRC staff disagrees with the following recommendations in this report that also apply to the current method of evaluating licensee responses to Generic Letter 2004-02 for PWRs:

- The report recommends that free-jet expansion of the zone-of-influence (ZOI) in a loss-of-coolant accident (LOCA) event be determined using an experimentally validated model applicable to both reactor types. This issue is concerned with the shape and extent of the high-energy jet ZOI in a LOCA (i.e., the ANSI/ANS-58.2 method). Current guidance in the Safety Evaluation for NEI-04-07 uses a spherical ZOI to encompass the effects of jet expansion resulting from impingement on structures and components. The spherical zone is a practical convenience that accounts for multiple jet reflections and mutual interference of jets from opposing sides of a guillotine break as well as pipe whip. It is important to note that when the spherical volume is computed using an acceptable approximation for unimpeded free-jet expansion, the actual energy loss involved in multiple reflections is conservatively neglected to maximize the size of the ZOI. The staff believes that this produces conservative results without an unnecessarily complex evaluation.

- Portions of two recommendations are concerned with the quantity of debris generated outside the ZOI from unqualified coatings in PWRs. Specifically, the report recommends that guidance for coating thickness and failure characteristics be developed. The current staff guidance for PWRs is that plant-specific values regarding the unqualified coating thicknesses and failure characteristics should be used. The NRC staff considers this approach adequate. Unqualified coatings consist of many different types of materials and are produced by many different manufacturers, so the staff believes generic guidance for failure characteristic is infeasable.

- Another recommendation is that the methods used for evaluation of downstream ex-vessel effects (i.e., erosion and abrasion of components) in PWRs be validated with more extensive testing. The staff considers the industry and staff guidance contained in WCAP 16406-P-A Rev 1 and the associated safety evaluation (SE) is adequate. As discussed in the SE, sufficient testing was done by NRC and industry to support the WCAP conclusions.

- Two recommendations are related to downstream in-vessel effects for PWRs. The recommendations are that prototypical testing be performed at post-LOCA temperatures, pressures, and flow conditions to evaluate blockage and debris deposition on the fuel. These issues are being addressed in WCAP 16793-NP-Rev 1, which is currently under review by the NRC staff. The PWROG has performed extensive testing and analyses for this topical report, and an SE is being prepared. The staff considers the test methodology used by the owners group at ambient temperatures to be conservative because it does not take advantage of the fluid viscosity change or higher flow turbulence that would exist at elevated temperatures. In addition, the methodology assumes all chemical precipitates formed in the containment pool pass through the strainer and into the reactor core. The LOCADM analysis also assumes all dissolved chemicals and suspended debris contained in the coolant are deposited as the coolant boils off.

NRC also notes the statement in the Executive Summary: "The debris generation methodology must be conservative if the overall analysis is to be conservative." The NRC position is that the overall evaluation of ECCS strainer performance should be conservative. An expectation of conservatism in each aspect of that evaluation could result in an overly conservative overall evaluation. Therefore, NRC disagrees with the referenced statement in the Executive Summary.

NRC has prepared a draft revision to RG 1.82 (DG 1234) that adopts the recommendations discussed in this report with the exceptions discussed above. This revision to the regulatory guide incorporates lessons learned from resolution of Generic Letter 2004-02 (GL 04-02) and from staff guidance contained in safety evaluations prepared for industry topical reports for GL 04-02. Upon publication of this revision, the regulatory guidance will be consistent for BWRs and PWRs except for guidance that is unique to each specific reactor type.

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EXECUTIVE SUMMARY

The U.S. Nuclear Regulatory Commission (NRC) licenses and regulates commercial nuclear power plants in the United States with the goal of ensuring the protection of public health and safety and of the environment. The specific regulatory positions relevant to the issues of sumps and suppression pools performing the functions of water sources for emergency core cooling, containment heat removal, and containment atmosphere cleanup are documented in Regulatory Guide 1.82, Revision 3, *Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident*. Guidelines for evaluating the adequacy of the sump and suppression pool for long-term recirculation cooling following a loss-of-coolant accident (LOCA) are also provided. The regulatory positions for the two types of reactors are similar, except for minor divergences due to differences in the basic designs. However, in the evolution of the regulatory process to verify the safety of the current licensed and operating Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs), differences have developed in the regulatory treatment of their respective emergency core cooling systems (ECCSs), containment spray systems (CSSs), and residual heat-removal systems (RHRSs) in postulated LOCA events. The differences arose mainly for historical reasons or because of the state of knowledge and regulatory focus at the time of the relevant reviews, and are not generally due to technical differences in the basic design of the two reactor types.

In a LOCA that could occur in a BWR or PWR, the postulated pipe break results in the rapid escape of high-energy liquid water or steam from the primary system. High-volume jets of coolant from the break can strike piping, walls, and equipment, stripping away insulation and surface coatings (e.g., paint, epoxy) and damaging or destroying other material (e.g., equipment labels, tags, tape) in the path of the jet. The energy of the jet generated by a postulated LOCA event is sufficient to reduce much of this material to fibers or fine particulate debris, which can be readily transported by the escaping coolant to the suppression pool (in BWRs) or the containment sump (in PWRs). In addition, chemicals in the coolant can interact with other materials (e.g., insulation, metal components) present in the containment environment to form chemical reaction by-products (e.g., corrosion products, solid precipitates) that constitute chemical debris. As emergency cooling water is drawn from the suppression pool or sump by the ECCS, the debris will be carried to the suction strainers, forming a debris bed that will result in an increased pressure drop (head loss) across the strainer or screen. This increase in pressure drop could potentially have adverse effects on short-term emergency cooling and long-term cooling of the reactor core in post-LOCA conditions, including loss of net positive suction head (NPSH) at the ECCS pumps, structural failure of strainers and supports, and flow blockages or equipment damage due to debris in the coolant.

Closure of the issues raised in the mid-1990s related to debris clogging of BWR suction strainers occurred in 2001 with the issuance October 18, 2001 of NRC Memorandum *Completion of Staff Reviews of NRC Bulletin 96-03 –* ***Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling Water Reactors****, and NRC Bulletin 95-02 –* ***Unexpected Clogging of a Residual Heat Removal (RHR) Pump Strainer while Operating in Suppression Pool Cooling Mode***, (ML0129702290). NRC staff concluded that BWR licensees were cognizant of the need to minimize latent debris sources by regular cleaning of the suppression pool and by developing and maintaining pro-active housekeeping procedures and Foreign Material Exclusion (FME) programs. NRC staff further concluded that installing large-capacity passive strainers provides assurance that NPSH can be maintained when operating the ECCS in recirculation mode during a LOCA.

The ECCS strainer performance has entered the "implementation phase" for PWRs with the dissemination of Regulatory positions provided in *NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Strainer Head Loss and Vortexing* (ML080230038), issued in March 2008. This document contains detailed guidance in the areas of test scaling, debris near-field settlement simulation, surrogate debris similitude requirements, testing procedures, post-test data processing, and extrapolation to conditions beyond the tested database. The specific issue of downstream effects on components, however, is still under review, with the submittal in April 2009 of Revision 1 of WCAP-16793-NP, *Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid*, by the PWR Owners Group (PWROG). The SE on this report is expected to be completed in 2010.

The objective of the work documented here is to evaluate the significance of disparities in the treatment of suction strainer performance for BWRs and PWRs. This report presents a technical evaluation of three main issues in which guidance is significantly different for BWRs and PWRs, and provides recommendations for appropriate treatment that is consistent for the two reactor types. The main issues are as follows;

- debris generation
    - definition of the zone of influence (ZOI) of the destructive effects of the high-energy water or steam jet due to the pipe break characerizing a particular LOCA scenario
    - definition of source terms due to chemical interactions in the coolant and with containment materials exposed to coolant during the LOCA
    - definition of source terms due to physical damage to containment materials, structures, and system components during the LOCA
- debris bed formation on suction strainers
- debris transport during the LOCA and post-LOCA long-term cooling of the core
    - in the suppression pool or sump
    - in the primary system downstream of the suction strainers

The general conclusion of this evaluation is that the two types of reactors should have the same or similar technical bases for ensuring adequate long-term cooling of the reactor core following a LOCA. The overall analysis for either reactor type should include the following elements:

1. a prototypic or conservative estimate of how much debris would be generated in a given LOCA event
2. a prototypic or conservative methodology for determining how much debris would reach the suction strainer(s)
3. a prototypic or conservative methodology for estimating how the debris bed forms, including effects of chemical debris

4. a prototypic or conservative methodology for estimating the head loss across the suction strainer(s) for all possible debris bed characteristics for a given plant
5. a prototypic or conservative methodology for estimating the amount of debris that could pass through the screens or strainers
6. a prototypic or conservative methodology for estimating the effects of debris in the coolant on downstream components, including the vessel and core (e.g., increased pressure loss, erosion, plugging)

The conservatism of the overall approach for determining NPSH margin depends primarily on developing a sound technical basis for defining the ZOI and the models for debris generation within the ZOI for a given LOCA event. This definition should be equivalent for both types of reactors (although dependent on jet specifics), and should be formulated to yield conservative estimates of the amount and specific types of debris generated. The debris generation methodology must be conservative if the overall analysis is to be conservative.

The debris transport methodology should be consistent between PWR and BWR systems, since the same type of hydrodynamic forces are involved. Differences should relate only to differences in details of containment configuration, sump or pool dimensions, and structural design of the strainers. Similarly, the methodologies for determining debris bed formation and head loss across the debris bed for the suction strainers should reflect similar hydrodynamic behavior, with differences reflecting differences in strainer geometries and support structures.

Table S.1 lists the specific recommendations developed to provide consistent guidance for analysis of the effects of debris on system performance during a LOCA and subsequently during post-LOCA recirculation cooling in PWRs and BWRs. The technical basis for these recommendations and the existing guidance on the related issues are discussed in detail in the body of this report.

Table S.1. Summary of recommendations for developing conservative and consistent guidance for analysis of post-LOCA recirculation cooling in PWRs and BWRs.

Index number	Recommendation
Debris Characteristics (see Section 2)	
2.1	*Plant-specific determination of the types, quantities, and distributions of physical debris, similar to the individual plant walkdowns for PWRs, is recommended for all commercial light water reactors, including BWRs. A sampling methodology, such as the guidelines offered through the SE to NEI 04-07, should be implemented across all plants to determine the relative quantity of fibrous debris. Methods to estimate the quantities and types of insulation debris, the largest contributor to the post-LOCA debris inventory, should be unified across BWRs and PWRs.*
2.2	*A determination of the effects of coolant, solutes, and insulation on the creation of chemical debris and the influence of the debris on head loss and downstream effect, along the lines of the ICET program and Westinghouse studies conducted for PWRs, is recommended for BWRs.*
Debris Generation (see Section 3)	
3.1	*The zone of influence (ZOI) of the high-energy jet of steam or saturated liquid water released in a LOCA should be determined using an experimentally validated free-jet expansion model that is applicable to both BWR and PWR conditions.*
3.2	*A validated basis that is consistent as applicable between reactor types for insulation material failure pressures should be developed for the range of thermodynamic conditions encountered in LOCA scenarios.*
3.3	*A validated basis consistent as applicable between reactor types for qualified and unqualified coatings thickness should be developed.*
3.4	*Reducing potential debris quantity by means of the definition of a specific ZOI extent, debris location, and contribution to subsequent head loss should only be considered after validated and consistent approaches for free-jet expansion, debris material failure pressure, and debris quantity are established.*
3.5	*A validated approach consistent as applicable between reactor types for the failure of insulation and coating systems outside of the ZOI is recommended.*
Debris Bed Formation on Strainers (see Section 4)	
4.1	*Evaluate the specific strainer designs currently installed in BWR plants, on a plant-by-plant basis (if necessary), with regard to test scaling, debris near field settlement simulation, surrogate debris similitude requirements, range of independent variables tested, and testing procedures, to determine if the tests and evaluations can be considered prototypic or conservative with respect to these parameters.*
4.2	*Apply the same standards and guidance to evaluations of submittals from BWR licensees regarding suction strainer head loss calculations, including the potential for thin bed effects, as are applied to submittals from PWR licensees.*

Table S.1. Summary of recommendations for developing conservative and consistent guidance for analysis of post-LOCA recirculation cooling in PWRs and BWRs.

Index number	Recommendation
Downstream Effects of Debris in Recirculating Coolant (see Section 4)	
4.3	*Require validation of debris ingestion models with experimental data obtained for conditions where the maximum amount of debris is able to pass through the suction strainers. This should include the evaluation of conditions where an incomplete debris bed might form, and generally corresponds to conditions where the effect of debris on strainer head loss may be relatively low.*
4.4	*Require validation of abrasion and erosion wear models for specific particulate materials and ranges of particle sizes postulated for debris generated in BWR and PWR LOCA scenarios.*
4.5	*Apply the same standards and guidance to evaluations of submittals from BWR licensees regarding effect of debris in the recirculation coolant on downstream components as are applied to submittals from PWR licensees.*
4.6	*Require prototypic testing of debris mixtures in core flow at pressures and temperatures corresponding to post-LOCA conditions to determine the effect of local blockages on local fuel rod cladding temperatures for postulated for BWR and PWR LOCA scenarios. Include testing to show the effects of debris left behind by core boil-off.*
4.7	*For PWRs, require testing to determine the effects on local fuel rod cladding temperatures of chemical plate-out (with and without trapped debris) for forced flow and core boil-off conditions in postulated for LOCA scenarios.*
4.8	*Apply similar standards and guidance to evaluations of submittals from BWR licensees regarding effects of debris in the reactor vessel and core as are applied to submittals from PWR licensees.*
Debris Transport in Sump or Suppression Pool (see Section 5)	
5.1	*Unless an assumption of 100% transport is employed, the approach used for flow field modeling in the sump and suppression pool should be validated and consistent in the basic approach and the degree of conservatism of assumptions.*
5.2	*Settling behavior of debris in the sump and suppression pool, if credited, should be based on the properties of the specific debris material, considering particle density, geometry, and size distribution.*

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ACRONYMS AND ABBREVIATIONS

ACRS	Advisory Committee on Reactor Safeguards
ANS	American Nuclear Society
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
BWR	boiling water reactor
BWROG	BWR Owners Group
CFD	computational fluid dynamics
CSHL	clean screen head loss
CSS	containment spray system
DBA	design basis accident
DBLOCA	design-basis loss-of-coolant accident
ECCS	emergency core cooling system
EOP	Emergency Operations Procedure
EPRI	Electric Power Research Institute
FME	Foreign Material Exclusion (program)
HEPA	high-efficiency particulate air (filter)
HVAC	heating, ventilation and air conditioning
ICET	integrated chemical effects testing
IOZ	inorganic zinc
LANL	Los Alamos National Laboratory
lbm	pounds, mass
LOCA	loss-of-coolant accident
M	molar
μm	micrometer
NDE	non-destructive evaluation
NEDO	Nuclear Energy Development Organization
NEI	Nuclear Energy Institute
NPSH	net positive suction head
NRC	U.S. Nuclear Regulatory Commission

PCI	Performance Contracting, Inc. (developer of stacked-disk suction strainer design for BWRs)
ppm	parts per million
psi	pounds per square inch
PWR	pressurized water reactor
PWROG	PWR Owners Group
QA	quality assurance
QC	quality control
RHR	residual heat removal
RHRS	residual heat removal system
RMI	reflective metal insulation
SE	safety evaluation
SLC	standby liquid control
SPB	sodium pentaborate
SSE	safe shutdown earthquake
TBE	thin bed effect
TSP	trisodium phosphate
wt%	weight percent
ZOI	zone of influence

1. INTRODUCTION

In the evolution of the technical knowledge base used to verify the adequate suction strainer performance for the currently licensed and operating nuclear reactors in the United States, differences have developed in the regulatory treatment of pressurized water reactors (PWRs) and boiling water reactors (BWRs). Some of the differences in the guidance for suction strainer performance analysis are due to technical differences in the basic design of the two reactor types, but in many cases, the differences arose for historical reasons or because of the state of knowledge and regulatory focus at the time of the relevant reviews.

The objective of this report is to identify any significant disparities in the treatment of suction strainer performance for BWRs and PWRs, and evaluate the technical significance of the differences, to provide a basis for evaluating the potential impact on safety. This work considers only currently licensed reactors and does not address the relevance of this issue to new reactor designs or advanced passive reactors. Differences are assessed in terms of their effects on maintaining long-term core cooling in postulated design-basis accident conditions. Recommendations are provided on appropriate guidance for defining the technical requirements to address this issue in a consistent and conservative manner for both reactor types.

Section 1.1 summarizes the current regulatory position on this issue and provides a brief historical timeline of relevant developments. Section 1.2 briefly describes the areas where treatment of the reactor types differs.

1.1 Background

The U.S. Nuclear Regulatory Commission (NRC) licenses and regulates commercial nuclear power plants with the goal of ensuring the protection of public health and safety and of the environment. The specific regulatory positions relevant to the issue of suction strainer performance are documented in Regulatory Guide 1.82, Revision 3, *Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident*. The issue is addressed in three main parts:

- strainer blockage, expressed primarily as the potential for loss of required net positive suction head (NPSH) at the inlet to the ECCS pumps
- availability of long-term recirculation cooling capability
- debris sources and generation

Appendix A provides a side-by-side listing of the relevant positions in Regulatory Guide 1.82, Revision 3 for BWRs and PWRs, in a table containing the full text of the guidance provided. The table also includes notes comparing each Regulatory Position for the two reactor types, pointing out differences and similarities.

The comparison shows that there are no significant differences in the regulatory positions for the two types of reactors, other than minor divergences due to differences in the basic designs. Based on Regulatory Guide 1.82 (Revision 3), it is clearly the intent of the NRC that there should be no significant differences in the requirements imposed on BWRs and PWRs in regard to demonstrating appropriate suction strainer performance in a LOCA event. However, this issue has been significantly re-evaluated three times in the past 30 years, and attention has been drawn to different aspects of the issue at different times. As a result, the issue has recently been examined independently for BWRs (in response to strainer plugging events at BWRs in the 1990s) and for PWRs (in the ongoing effort to resolve Generic Safety Issue 191). These factors all tend to result in different treatment between the two reactor types. A timeline of significant events related to strainer blockage is included in Appendix B. The timeline is intended to present an overall prespective on the evolution of this complex issue, but is not meant to be inclusive of every industry and regulatory report or action. The following discussion summarizes the major highlights of this history.

The initial regulatory guidance published in Regulatory Guide 1.82 in 1974 on ECCS intake blockage was relatively simple; the head loss across the suction strainer was required to preserve an adequate NPSH with the strainer surface area 50% blocked. This was considered a conservative assumption at that time. However, there were subsequent concerns about verifying adequate recirculation flow for the ECCS from the sumps in PWRs. These concerns were centered on problems with air entrainment, vortexing, and sump blockage due to fibrous debris, and resulted in the development of **Unresolved Safety Issue A-43**, *Containment Emergency Sump Performance*, published in January 1979. The principle focus of USI A-43 was on PWR designs, although analysis and experiments for BWRs were also conducted under this program.

The matter was considered resolved in 1985 by the publication of NUREG-0896, *USI A-43 Regulatory Analysis*, and NUREG-0897, *Containment Emergency Sump Performance*. Section 6.2.2 of the Standard Review Plan was revised, and Revision 1 was developed for Regulatory Guide 1.82 (published November 1985). The guidance specifying the assumption of a 50% flow area blockage was revised to recommend that a deterministic analysis of potential blockage of strainers be performed. In December 1985, NRC issued Generic Letter 85-22, *Potential for Loss of Post-LOCA Recirculation Capability Due to Insulation Debris Blockage*, notifying licensees of the USI A-43 evaluation results. This generic letter stated that, while a backfit would not be imposed on operating reactor licensees, licensees performing plant modifications such as insulation changeouts should conduct a strainer performance analysis as specified in Revision 1 of Regulatory Guide 1.82.

Attention later shifted to suction strainers in BWRs with the occurrence of strainer blockage incidents at four domestic power plants and one foreign BWR-type reactor:

- 1988, 1989; strainer blocking events at Grand Gulf Nuclear station (BWR/6, Mark III) during testing of residual heat removal (RHR) pump suction strainers[a]
- May 1992, March 1993; strainer blockage events[b] at Perry Nuclear station (BWR/6, Mark III)

(a) The RHR loop has separate suction strainers from those seen by the ECCS pumps, but of the same design.
(b) Strainers were deformed due to excessive head loss in one incident at the Perry plant.

- July 1992; strainer blockage incident at the Barsebäck Unit 2 BWR plant[c] in Sweden, resulting from fibrous debris blown into containment from damaged insulation due to opening of a relief valve
- January 1994; cloth-like material partially blocked the ECCS suction strainers at Browns Ferry Unit 2 (BWR/4, Mark I) (discovered by divers assessing conditions in suppression pool)
- September 1995; strainer blockage incident at Limerick Unit 1 (BWR/4, Mark II); pump cavitation in ECCS loop indicated

In response to these incidents, NRC began a re-examination of this issue for BWR systems. While taking interim steps to address the problem, NRC also initiated the following detailed studies of debris generation in postulated LOCA events, which defines the limiting case for debris in the suppression pool:

- In May 1993, issued Bulletin 93-02, *Debris Plugging of Emergency Core Cooling Suction Strainers,* to all nuclear power plant licensees, requesting interim actions to remediate potential problems related to debris in the suppression pool
- In February 1994, issued Supplement 1 to Bulletin 93-02, requesting further interim actions of licensees
- In October 1995, issued Bulletin 95-02, *Unexpected Clogging of a Residual Heat Removal Pump Strainer While Operating in Suppression Pool Cooling Mode*, to all operating BWR licensees, requesting that they take action to ensure that unacceptable build-up of debris in the suppression pool would not occur during normal operation
- In May 1996, issued Revision 2 of Regulatory Guide 1.82, altering the debris blocking evaluation guidance for BWRs, since it had become apparent that Revision 1 guidance was not comprehensive enough
- In May 1996, issued Bulletin 96-03, *Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling Water Reactors*, to all holders of operating licenses, requiring that they implement specific measures, as appropriate to plant-specific conditions, to ensure ECCS performance following a LOCA
- In October 1997, issued Generic Letter 97-04, *Assurance of Sufficient Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal Pumps*, to all nuclear power plant licensees, requesting current information on NPSH analyses
- In July 1998, issued Generic Letter 98-04, *Potential for Degradation of the Emergency Core Cooling System and Containment Spray System after Loss-of-Coolant Accident Because of Construction and Protective Coatings Deficiencies and Foreign Material in Containment*, to all licensees of operating nuclear power plants (BWR and PWR), requesting information on licensees' programs for ensuring that protective coatings do not detach from substrate during a design basis loss-of-coolant accident (DBLOCA).

(c) Plant configuration at Barsebäck is similar to a BWR/4 with Mark II containment.

In November 1996, the BWROG submitted Utility Resolution Guidance for NRC review and approval in NEDO-32686, Rev. 0, *Utility Resolution Guidance for ECCS Suction Strainer Blockage*. In August 1998, NRC published the Safety Evaluation (SE) on this document, granting approval of the guidance, but with some important reservations and limitations. Shortly thereafter, in October 1998, the BWROG published the approved guidance as NEDO-32686-A, *Utility Resolution Guidance for ECCS Suction Strainer Blockage*. This document consists of four volumes and contains the original[(d)] NEDO-32686, Revision 0 (including all references from subcontracted research), the SE document issued by NRC, and a summary of the specific elements NRC did not accept or approve.

Through continuing evaluation of operational events, various analytical and experimental studies, and other research work, the NRC developed a comprehensive technical basis for resolving the BWR strainer blockage issue. The NRC guidance, and the technical basis, was summarized in LA-UR-01-1595, *BWR ECCS Strainer Blockage Issue: Summary of Research and Resolution Actions*, in March 2001.

In 1996, during the investigation of the BWR strainer blockage issue, NRC initiated a study of Generic Safety Issue 191, *Assessment of Debris Accumulation on PWR Sump Performance*, to determine if debris in a PWR containment could impede ECCS or CSS operation. This work led to the development of the technical basis for the NRC position that sump blockage is a credible concern for PWRs. The NRC implemented the resolution stage of this issue in September 2001 and documented this position with the following actions:

- In September 2001, published NUREG/CR-6762, Volume 1, *GSI-191 Technical Assessment: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance*
- In August 2002, published three additional volumes of NUREG/CR-6762:
  - Volume 2, *Summary and Analysis of US Pressurized Water Reactor Industry Survey Responses and Responses to GL 97-04*
  - Volume 3, *Development of Debris Generation Quantities in Support of the Parametric Evaluation*
  - Volume 4, *Development of Debris Transport Fractions in Support of the Parametric Evaluation*
- In November 2003, issued Revision 3 of Regulatory Guide 1.82, expanding and clarifying the guidance for both BWRs and PWRs related to maintaining adequate recirculation coolant flow in a LOCA and post-LOCA environment
- In June 2003, issued Bulletin 2003-01, *Potential Impact of Debris Blockage on Emergency Sump Recirculation at Pressurized-Water Reactors*, to all PWR licensees, requesting that they implement interim measures to mitigate the potential impacts of post-LOCA debris on strainer performance.
- In September 2004, issued Generic Letter 2004-02, *Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized Water Reactors*, to

(d) The BWROG did not revise the original document to address the NRC concerns and specific limitations. The guidance on these issues consists of advising the BWR licensees that they must justify the approach used for such issues in their individual submittals.

all PWR licensees, requesting that they perform an analysis of their strainer performance using a mechanistic methodology and perform any necessary plant modifications (e.g., strainer replacement) that the analysis demonstrated to be necessary.

To develop an approved methodology for PWR licensees to use in responding to Generic Letter 2004-02, the PWR Owners Group (PWROG) sponsored guidance documents developed through the Nuclear Energy Institute and Westinghouse Electric Corporation. Documents submitted to the NRC for review and approval included:

- In April 2002, the PWR Owners Group submitted NEI 02-01, *Condition Assessment Guidelines: Debris Sources Inside PWR Containments*.
    - In September 2002, this submittal was superseded by Revision 1 to NEI 02-01 (ML030420318), in response to comments from member utilities and NRC staff, and to incorporate new information on latent debris.
    - In meetings with NEI in 2002 and 2003, NRC provided comments on NEI 02-01, indicating that the document provided reasonable overall guidance, but also recommended additional work.
- In May 2004, the PWROG submitted NEI 04-07, *Pressurized Water Reactor Sump Performance Evaluation Methodology*.
    - In December 2004, NRC issued the SE on NEI 04-07, approving the Baseline Methodology for sump performance issues, with certain limitations and modified positions. By direct reference, substantial portions of NEI 02-01 are included in the SE on NEI 04-07.
- In August 2006, the PWROG submitted technical report WCAP-16406-P, Rev. 1, *Evaluation of Downstream Sump Debris Effects in Support of GSI-191*, for review and approval.
    - In December 2007, NRC issued the SE of WCAP-16406-P, approving the guidance provided, but subject to limitations and conditions.
- In September 2007, the PWROG completed submittal of technical report WCAP-16530-NP, *Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191*, for review and approval.
    - In December 2007, NRC issued the SE of WCAP-16530-NP, approving the guidance provided, but subject to limitations and conditions.
- In June 2007, the PWROG submitted technical report WCAP-16793-NP, *Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid*, for review and approval.
    - In February 2008, the NRC developed a draft SE of WCAP-16793-NP, with the intention of releasing the final SE by the end of March 2008.
    - On March 7, 2008, the NRC transmitted the Revision 0 draft of the SE of WCAP-16793-NP, requesting comment on any factual errors or clarity concerns from the PWROG.
    - On July 24, 2008, the NRC issued a recision of the draft SE for WCAP-16793-NP, having determined that additional information is needed on certain subject areas in the report, which the PWROG agreed to address by submitting Revision 1 of TR WCAP-16793-NP.

- In April 2009, Revision 1 of TR WCAP-16793-NP was submitted for review.

As can be seen from the above timeline summaries, the issue of suction strainer clogging followed independent paths for BWRs and PWRs. This is a major reason for differences between the BWROG and PWROG guidance, and in the regulatory guidance. However, there are no significant technical reasons for treating the two types of reactors differently in regard to the general issue of ensuring adequate long-term cooling of the reactor core following a LOCA event. The following section summarizes the specific differences between the guidance provided for BWRs and PWRs with regard to this issue.

1.2 Differences in Guidance for PWRs and BWRs

The detailed comparison in Appendix A shows that there are no significant differences in the treatment of PWRs and BWRs in **Regulatory Guidance 1.82**, as of Revision 3. In both designs, a LOCA event is expected to generate debris in containment due to the high-energy jet of coolant escaping at the break location. The great majority of this debris has essentially the same characteristics in a PWR or BWR containment, with only a few exceptions specific to each design. In both designs, the escaping coolant, along with drainage from sprays and condensation, is expected to transport LOCA-generated debris and latent debris into reservoirs that supply long-term cooling water to the ECCS, CSS, and RHRS. In both BWRs and PWRs, the emergency coolant is drawn from the reservoir through suction strainers designed to filter the debris from the coolant. Both types of plants can experience blockage of the suction strainers due to debris build-up, and both can draw fine-scale debris through the suction strainers, introducing it into the recirculation loop, containment spray system, RHR system, and the reactor vessel and core.

Table 1.1 summarizes 12 technical issues where the guidance from industry groups and from NRC staff (as provided in SEs for specific submittals) for analyzing BWRs and PWRs has been identified as significantly different. This summary is based on the BWROG and PWROG guidance documents and the NRC SEs of these documents. Table 1.1 also notes similarities or differences in the relevant physical phenomena for BWRs and PWRs. These specific areas fall into four categories: debris characteristics, debris generation, debris bed formation on the strainers, and downstream effects of debris in the recirculating coolant. As shown in Table 1.1, in nearly all cases there are no significant differences in the relevant phenomena between BWRs and PWRs. They could, therefore, be dealt with in a consistent manner in analyses for the two types of reactors.

These issues are discussed in greater detail in the following sections, in terms of the BWR and PWR industry guidance and the NRC SEs of the formal documentation of this guidance. In each of these sections, specific recommendations are developed regarding appropriate treatment of the issues. Section 2 discusses issues related to debris characteristics with particular attention to debris generated by chemical reactions. Section 3 discusses debris generation in terms of the definition of the zone of influence (ZOI) of the jet from the break, and the mechanical response of containment material impacted by the jet. Section 4 discusses appropriate characterization of the head loss across the debris bed on the strainer and evaluating the effects of debris downstream of the sump screens or suction strainers. Section 5 addresses the issue of debris settling within the sump or suppression pool. Section 6 presents a detailed summary of the evaluations and recommendations developed for defining consistent guidance for analyzing PWRs and BWRs with respect to these technical issues.

Table 1.1. Summary of differences in guidance for PWRs and BWRs.

Technical Issue	Treatment in Guidance	Similar or Different Effects in BWRs and PWRs?
Debris Characteristics (see Section 2)		
Debris generation source terms include calcium silicate, Min-K, Microtherm insulation.	BWR: limited PWR: detailed	Similar. Debris generation from insulation (including calcium silicate) is due to mechanical and thermal effects of jet impact; physical effects are same for LOCA conditions in PWRs and BWRs; differences are only in pressure and temperature values, and in some cases, jet medium.
Debris generation source terms include latent debris.	BWR: limited PWR: detailed	Similar. Except for suppression pool sludge in BWRs, sources and types of latent debris are essentially the same in PWRs and BWRs.
Debris generation source terms include assessment of coatings.	BWR: limited PWR: more detailed than for BWRs, but still limited	Similar. Coatings are essentially the same materials in PWRs and BWRs.
Debris generation source terms include chemical effects.	BWR: not considered PWR: limited	Different in degree, similar in kind. For all PWRs, chemical additions are required for normal and emergency operations. Only some BWRs add chemicals to coolant, and in limited quantities; should be assessed on a plant-specific basis.
Debris Generation (see Section 3)		
Analysis includes ZOI adjustment for air jet testing, a separate ZOI for protective coatings, and includes option for a spherical ZOI approach	BWR: yes PWR: yes, but with different limitations and restrictions than for BWRs	Similar. In both BWRs and PWRs, LOCA break results in high-energy steam jet or saturated water jet that rapidly turns to steam during blowdown. Insulation and protective coatings are subjected to mechanical impact at high temperatures and pressures; the physical extent of conditions severe enough to destroy or damage these materials is a critical component in determining the total debris generation.
Debris Bed Formation on Suction Strainers (see Section 4)		

Table 1.1. Summary of differences in guidance for PWRs and BWRs.

Technical Issue	Treatment in Guidance	Similar or Different Effects in BWRs and PWRs?
Analysis considers head loss predictions for debris bed on suction strainers.	BWR: yes PWR: yes, but with more limitations and restrictions on experimental databases	Similar. In both BWRs and PWRs, the hydrodynamics of flow through the debris bed are essentially identical; only the geometries differ in different BWR and PWR plants.
Downstream Effects of Debris in Recirculating Coolant (see Section 4)		
Analysis considers erosion due to debris transport in the ECCS, CSS, and RHR system.	BWR: no PWR: yes	Similar. Except for suppression pool sludge, erosive debris sources are essentially the same for BWRs and PWRs.
Analysis considers effects of debris (e.g., wear and flow blockage) on downstream components.	BWR: no PWR: yes	Similar. BWR and PWR systems include pumps, valves, nozzles, orifices, and heat exchangers of similar size and for similar functions.
Analysis considers effects of debris (e.g., wear and flow blockage) on reactor vessel and fuel coolability.	BWR: no, except for active strainer designs PWR: limited	Similar. BWR and PWR fuel assemblies have similar geometry, with spacer grids, inlet orifice plates, etc., with similar ability to capture debris from flow field. Both designs utilize core boil-off for long-term core cooling in design basis LOCA events, in which debris in the coolant could be left behind in the core.
Debris Transport in Sump or Suppression Pool (see Section 5)		
Analysis considers effect of debris settling in the sump or suppression pool.	BWR: optional PWR: optional	Similar. Settling rates of particulate should be similar in PWR sumps and BWR suppression pools, since debris constituents are similar.

2. DEBRIS CHARACTERISTICS

In the event of a LOCA in a BWR or PWR, the postulated pipe break results in the rapid escape of liquid water and/or steam of high energy from the primary system. The ensuing pressure wave and high-volume flow of coolant outside its intended channel will impinge on installed materials, destroying or altering their original forms and displacing them from their original locations as debris. Such installed materials include pipe insulation, coatings (e.g., paint, epoxy), and other installed materials (e.g., equipment labels, tags, tape). Some of this material can be damaged to such a degree by the energy of the LOCA that it will be reduced to fibers or fine particulate, which is readily transported by the blowdown from the pipe rupture. The escaping coolant and other flowing water (e.g., from containment sprays) will carry the material fibers and particles to the suppression pool (in BWRs) or the containment sump (in PWRs). As emergency cooling water is drawn from the suppression pool or sump by the ECCS, the debris will be carried to the suction strainers.

Dirt, dust, and materials inadvertently left behind during outages and maintenance (e.g., rags, tools, HEPA filters, paper and plastic sheeting) are not installed (i.e., intentionally part of the BWR or PWR systems) but also exist within the region affected by post-LOCA coolant flows. Such materials, called transient or latent debris, also may be carried to the suction strainers or sump screens. These sources of debris are common to both BWRs and PWRs, although their quantities and distributions vary according to plant design (even within BWR or PWR groups), the applications of the materials, and differences in plant cleanliness and housekeeping procedures. The transient debris and the installed material will also be subject to damage and erosion both during the blowdown and during the long-term cooling period.

Other sources of debris exist that are unique to each reactor type. BWRs contain suppression pool sludge as a debris source that is not found in PWRs, which do not have a suppression pool. The suppression pool present in each BWR is constructed of mild carbon steel but may be lined with stainless steel or be coated on the wetted surfaces as a corrosion barrier. In addition to the materials collected in the suppression pools (dirt, debris), the sludge in the mild steel lined suppression pools contains steel corrosion products. PWRs produce debris under post-LOCA conditions from chemical effects (or reactions) that may occur to a lesser extent for BWRs. The difference lies in the fact that BWRs are cooled with essentially neutral demineralized water while PWRs are cooled with a dilute boric acid solution. During normal operations, the reactor coolant system (RCS) in PWRs has decreasing boron concentrations over the operating cycle. In the event of a LOCA, the refueling water storage tank (RWST) injects cool borated water into the RCS system. Typically, ~2800 parts of boron per million parts of water, or ~0.26 moles boron per liter (0.26 M), are present in the post-LOCA RCS, including the contribution from the RWST. The boric acid acts as a soluble neutron poison (“chemical shim”), to ensure that the reactor remains shutdown following a LOCA.

The chemical composition of the PWR boric acid coolant also is changed through the addition of chemicals to adjust to higher pH (i.e., neutral or greater) under post-LOCA conditions, primarily to aid in radioiodine control. The pH adjustment is accomplished in different ways in different plants, including the addition of

- sodium hydroxide (NaOH; to about 0.2 M)
- trisodium phosphate (TSP, $Na_3PO_4 \cdot 12H_2O$; to about 0.01 M)
- sodium tetraborate (STB, also known as borax, $Na_2B_4O_7 \cdot 10H_2O$; to about 0.028 M, or 0.11 M boron).

These dissolved chemicals can interact with other materials present in the post-LOCA PWR containment environment to form chemical reaction by-products.

Although the BWR cooling water does not contain dissolved boric acid during normal operation and therefore is immune from debris formation related to buffer additions/chemical reaction by-products, chemical reactions including metal and insulation corrosion and interactions of dissolved materials with each other and with solids are possible in post-LOCA BWR waters. Some BWRs also manually add a solution of sodium pentaborate (SPB; $Na_2B_{10}O_{16} \cdot 10H_2O$) to the post-LOCA coolant by way of the standby liquid control (SLC) system as a back-up reactivity control or for radioiodine control. The typical quantity[e] of SPB added to the post-LOCA coolant is equivalent to 600 lbm (pounds, mass) of boron (~3000 to 4000 gallons of 8 to 10 wt% SPB) and is sufficient to give a final boron concentration of ~1100 ppm or ~0.1 M.

The debris generated by the physical destruction of materials or the mobilization of latent and transient materials in BWRs and PWRs in the post-LOCA environment within containment is considered in Section 2.1. The debris generated by chemical reactions in BWRs and PWRs in the post-LOCA coolant and its interactions with the wetted materials, both other debris and fixed hardware, are considered in Section 2.2. These sections also include assessment of the comparative scope of knowledge of debris sources and generation in both PWRs and BWRs.

2.1 Physical Debris

The primary source of physical debris in both BWRs and PWRs is thermal insulation on piping, vessels, and other components of the system. Other significant contributors are transient debris (i.e., foreign materials), fixed debris (e.g., coatings), and latent debris (e.g., dirt, dust, and [for BWRs only] suppression pool sludge). The characteristics and sources of BWR physical debris are considered in Section 2.1.1. Physical debris sources and characteristics in PWRs are discussed in Section 2.1.2.

2.1.1 Physical Debris in BWRs

Debris for BWRs is categorized according to its genesis within the drywell or the wetwell (or Mark III containment), including the suppression pool. The primary source of drywell debris is thermal insulation materials. The primary source of wetwell debris is the suppression pool sludge. Section 2.1.1.1 describes pipe insulation sources, and Section 2.1.1.2 describes other drywell debris. Section 2.1.1.3 describes wetwell debris.

(e) For specific examples, see Columbia Generating Station, Calculation, “Dose Calculation Database.” Calculation Number NE-02-04-1, Revision 2. Energy Northwest. Richland, WA. 2004. ADAMS accession number ML042930379, or Nuclear Engineering Calculation EC-059-1041, Rev. 02, “Suppression Pool pH Post LOCA.” Susquehanna Steam Electric Station, Berwick, PA. 2006. ADAMS accession number ML063060122.

2.1.1.1 BWR Pipe Insulation

The BWROG guidance[1] offers four methods for determining the quantity of pipe insulation subject to destruction in a LOCA in a ZOI of the pipe break. (The definition of the ZOI obviously has a very important influence on the amount of debris generated. This issue is discussed in detail in Section 3. In Section 2, the topic is confined to a discussion of the characteristics of the debris only.) In all four methods, the fraction of the insulation located within the ZOI assumed to be destroyed into "fines" is determined. A methodology for determining the actual degree of damage to various insulation materials within the ZOI (e.g., from complete destruction as fines to partially shredded into larger mats) is specified in Table 4 of the guidance.

2.1.1.2 Other BWR Drywell Debris

Transient debris is non-permanent plant material (tools, rags, temporary filters, dirt, and dust) brought into the drywell, often during an outage. Routine housekeeping and Foreign Material Exclusion (FME) programs are used to control transient debris. Fixed debris is non-insulation material that becomes debris by being dislodged during a LOCA. Paints and coatings or concrete fragments displaced by direct jet impingement are considered to be fixed debris. Other fixed debris that can become dislodged by a LOCA stream flow includes tape and wire ties. Fixed debris also arises after long exposure to LOCA conditions and might originate from coatings not qualified to withstand the environmental conditions (e.g., temperature, humidity, radiation) associated with design basis accidents (DBAs). Drywell debris sources and bounding quantities for some of these sources defined in the BWROG guidance are summarized in Table 2.1.

Table 2.1. Non-insulation drywell debris sources and quantities in BWRs.

Transient	Fixed	Latent
Dirt/dust (incl. ablated concrete)—150 lbm	Paint/coatings—47 lbm inorganic zinc (IOZ), 85 lbm IOZ top-coated with epoxy, 71 lbm epoxy	Unqualified coatings*
Other—not quantified (e.g., tools, rags, temporary filters)	Concrete – included with transient dust/dirt	Degraded qualified coatings*
	Fabric equipment covers (e.g., for fire hose reel)	Adhesive backed tags or labels
	Permanent tags/stickers	
	Cloth equipment bags	
	Fire hoses	
	Ropes	
	Ventilation system filters	
	Cloth	
	Non-piping thermal insulation	
	Tape	
	Wire ties	
	Paper (signs, postings, diagrams)	
	Plastic laminate and sheeting	
	Rust from unpainted steel—50 lbm	
	Other material stored in the drywell	

* Note that the Safety Evaluation of the BWROG guidance does not accept the URG position that unqualified coatings will fail later in the LOCA event after the pressure is reduced. The SE implies that the unqualified coatings should be assumed to fail early in the event.

2.1.1.3 BWR Wetwell Debris

Wetwell debris consists largely of suppression pool sludge, but also includes LOCA-generated debris (dirt and dust in the wetwell that is above the normal suppression pool level, corrosion products from unpainted steel, and unqualified paint), and any transient debris that had been dropped or introduced into the suppression pool such that, at LOCA initiation, it was already present.

The transient debris sources identified in the BWROG guidance document for the wetwell are somewhat more extensive than the transient debris defined in the drywell. Besides tools, rags, and temporary filters, the wetwell debris includes ropes, fiber or paper mats placed over gratings during outages, plastic sheeting, cloth-based duct tape, and anti-contamination clothing. Active FME and housekeeping programs, including surveillance and cleaning of the suppression pool, are designed to limit the amounts of transient debris present at the time of the LOCA. The transient debris is categorized as fibrous and non-fibrous. Some non-fibrous transient debris, including plastic sheeting, plastic clothing, plastic tags and step-off pads, and rubber gasket materials, pose another hazard to strainer clogging because of their potential to block large cross-sectional areas. Two other types of transient debris pose little risk to strainer clogging: very heavy or very light materials. Tools and metallic hardware constitute non-fibrous transient debris that is dense, sinks rapidly in the suppression pool, and is not readily moved by stream currents. Transient debris that can float on the pool surface (e.g., foam insulation) cannot reach the submerged inlet strainers unless it degrades to lose its buoyancy or the suppression pool stream flows become sufficiently turbulent to entrain the debris.

Suppression pool sludge is primarily carbon steel corrosion products and dirt/dust. The balance between the sludge generation rate and the pool cleaning thoroughness and frequency controls the quantity of suppression pool sludge. A survey of 12 BWRs of various ages and all three containment types (Mark I, II, and III) showed a median value of dry sludge generation rate at 88 lbm per year (Section 3.2.4.3.2 of Reference 1). The amount of sludge present at a given time in the suppression pool is greater than the annual sludge generation rate, however. The largest load was reported for the Duane Arnold plant in 1985, conservatively estimated as ~1350 lbm of sludge. The sludge load in the 15 other plants (excluding the Duane Arnold measurement) averaged ~300 lbm, with a maximum of about 510 lbm (Appendix J of the SE of Reference 1).

The BWROG guidance suggests that an accumulation rate of 150 lbm per year could be assumed to be conservative, but each plant should estimate its individual rate based on experience. Then, some margin should be added to account for uncertainties in operation variation and sampling and analysis. The BWROG guidance also recommends measurement considerations for determining the sludge generation rate. The guidance recommends a bounding value of 300-lbm annual sludge generation rate if plant-specific measurements are not available.

The sludge particle size distribution in the BWROG guidance was determined in two separate surveys (Section 3.2.4.3.1 of Reference 1). The particle size distributions were in three particle size bins – 0 to 5 μm, 5 to 10 μm, and 10 to 75 μm. The combined results of the first (five plant) and second (an additional nine plant) surveys, which included all three containment types and a range of plant ages, closely matched the results of the first testing set alone. Based on the similarity of the results for the sampled plants, the BWROG guidance recommends assuming that the measured distribution can be applied to all plants.

The size distribution on a particle number basis was 83% in the range 0 to 5 μm (2.5 μm average), 11% in the 5- to 10-μm range (7.5 μm average), and 6% in the 10- to 75-μm range (42.5-μm average). The initial (five plant) survey showed 81% in the 0 to 5 μm range, 14% in the 5- to 10-μm range, and 5% in the 10- to 75-μm range. The air-dried weight of this debris was estimated as 0.385 times the water-saturated sludge weight. Further details of sludge characteristics (phases, chemical composition) are not specified in the guidance document. Its origin as a steel corrosion product and dirt/dust led to the presumption that the sludge is composed of iron oxides/hydroxides (rust), silicate minerals (dirt), and cellulose (dust from paper and fabrics). Confirmation of the sludge material composition is needed to predict, more accurately, the potential for the material to be transported to the strainers and, at the strainers, model their impact in contributing to blockage.

2.1.2 Physical Debris in PWRs

Guidance on physical debris sources in PWRs is provided in NEI 02-01[2] and NEI 04-07[3] guidelines and in the NRC SE of NEI 04-07.[4] The debris sources within PWRs are similar to many of those identified for BWRs, except that PWRs do not have a wetwell and therefore do not accumulate the associated sludge debris found in BWRs. However, the guidance identifies sources of latent debris that include dirt, dust, and fibers in the dry containment. LOCA-generated debris in PWRs is defined as broken or dislodged materials (such as insulation, coatings, tape, and dust) due to the action of fluid released from a postulated break of a high-energy water line inside containment.

The debris sources in operating PWRs have been assessed in each plant by facility walkdowns (see Section 5.1 of NEI 02-01).[2] The facility walkdowns were performed to determine the locations and amounts of insulation materials, unqualified coatings, and foreign materials present within containment. The extents of such walkdowns were plant specific due to plant design and to the extents of prior and ongoing individual assessment programs.

The walkdowns typically were conducted by personnel familiar with the equipment installation and by the ECCS systems engineer. The guidance recommends that they be conducted in the brief interval after the containment building has been cleaned following a refueling outage but prior to restart. This is suggested primarily to provide a good assessment of transient materials. Insulation and coatings could presumably be assessed earlier during the outage, as these plant features are unlikely to change as a result of outage activities.

2.1.2.1 NEI 02-01 Guidance for PWRs

The purpose of the guidance in NEI 02-01[2] is to provide the plant operators with a consistent and systematic approach to gather information on the sources, types, and locations of potential debris that could be transported to the strainer in the event of a LOCA. Appendix A of NEI 02-01 provides summary descriptions of the nature of information that should be collected in PWR plant walkdown surveys, the types of personnel necessary, preparations needed for walkdowns, and other considerations. Results that should be obtained are specified to include the types and quantities of the various insulation, insulation samples, piping layout drawings, cable tray layout drawings, assessments of plant housekeeping, and FME. The walkdowns may also serve as confirmation of the plant design configuration, and can help ensure that as-built drawings are available to assess GSI-191 issues. Details of the guidance with respect to pipe insulation, coatings, and foreign materials are discussed in Sections 2.1.2.1.1, 2.1.2.1.2, and 2.1.2.1.3, respectively.

2.1.2.1.1 PWR Pipe Insulation

The guidance notes that investigating the insulation, particularly the fibrous insulation, is a key part of the walkdown. One objective of the walkdown is to update as-built knowledge of the insulation distribution (i.e., identifying and documenting any insulation that may have been replaced during plant operations because of piping changes or insulation removal and replacement in the course of weld inspections). Other fibrous materials, such as filter media, fire barrier materials, and fibrous cable insulation, should be catalogued since these materials have been identified as potential sump screen blockage sources. The guidance lists 12 types of insulation (including Nukon®, calcium silicate [Cal-Sil], and Min-K) that are routinely used in PWR containments. Although the guidance emphasizes fibrous insulation over other types of insulation, it is known that relatively small amounts of particulate or microporous insulations can have significant effect on sump strainer head loss. These other types of insulation must also be carefully identified and quantified.

The guidance recommends that the type and distribution of the insulation, the thickness and size, the physical condition, the types of fastening, and other details should be mapped, beginning with the primary system and extending to other piping, equipment, temporary equipment, and structures. Penetrations within the crane wall and bioshield wall, which could potentially be influenced by a high-energy line break, are to be surveyed as well.

During the survey, other sources of fibrous materials, such as insulated equipment, penetration insulations, fire barriers, heating, ventilation and air conditioning (HVAC) air cleaning filter media, electrical cable trays, and electrical cables within containment should be logged. In addition, piping insulation that might be eroded and transport due to the impingement from containment spray should be considered. Because the size and location of regions affected by a LOCA can vary greatly over the large range of postulated events, the guidance recommends that the entire inventory of insulation should be surveyed.

2.1.2.1.2 PWR Coatings

The quantities and distributions of coatings within containment also were surveyed by walkdown during PWRs' refueling outages. The guidance recommended that walkdowns to survey coatings be performed by a coatings specialist or other personnel familiar with the application and maintenance of coatings. Consistent with the NRC position, the guidance assumes that all coatings within the ZOI of a given LOCA, whether DBA-qualified or unqualified, are expected to fail. The coatings outside of the ZOI that are DBA-qualified are not expected to contribute to the coatings debris unless current information from plant walkdowns (as discussed in Section 2.1.2.1 above) shows them to be degraded. The unqualified coatings also may be assumed to fail even if outside the ZOI.

The DBA-qualified coatings commonly used in PWR containments are listed in Section 5.2.2.3 of NEI 02-01 according to their application to concrete or steel substrates. Surfaces that may have unqualified coatings are listed in Section 5.2.2.4 of NEI 02-01 and generally include installed equipment (e.g., accumulator tanks, valves, manipulator crane, electrical cabinets, instrumentation, pump motors) as opposed to structural elements.

The objective of the coatings walkdown is to map the locations and class (DBA-qualified or unqualified) of all coatings. The approximate areas and thicknesses of the coatings also are to be mapped. Documentation of the coatings surveys is part of the program.

2.1.2.1.3 PWR Foreign Materials

Walkdowns are also recommended in the NEI guidance for assessing foreign materials in the plant. Foreign materials include tape, equipment labels, construction and maintenance debris, temporary equipment, dirt, dust, and lint that may be transported to the strainers after an accident or block water flow into the sump. By their nature, the surveys for dirt, dust, and lint should be more regionally directed such that areas where this type of material builds up (e.g., in cable trays, corners, floor recesses, ledges) are identified as well as the general distribution of the material. The guidance recommends that foreign material should be minimized by FME and housekeeping practices. The nature and quantity of buildups of dust and dirt are to be recorded or logged in some manner, and, if possible, samples of the dust and dirt should be collected to assess particle size and density.

2.1.2.2 NEI 04-07 Guidance for PWRs

The guidance in NEI 04-07[3] recommends determining debris quantities based on the results of the containment walkdown and information on the debris properties. The physical properties of many of the debris materials are provided in NEI 04-07. The debris characteristics for PWRs are described in Section 3.4.3 of NEI 04-07 for insulation and coatings, and in Section 3.5 for latent debris. The associated NRC SE[4] provides further guidance on the debris characteristics.

Relevant debris characteristics include the size distribution, particle shape, micro-density (particle density), and macro-density (as-fabricated bulk density) of the material. The PWR guidance relies on the BWROG destruction testing done as described in the BWR guidance document.[1] However, that destruction testing did not generate all data needed for either BWR or PWR conditions and variety of materials. Therefore, the industry guidance for PWRs recommends adopting a two-regime size distribution for materials within the ZOI; small fines (which are smaller than 4 inches by 4 inches and can pass through gratings, trash racks, or radiological fences), and large pieces (which consist of all fragments larger than 4 inches by 4 inches.) The portion of fibrous or particulate (e.g., calcium silicate) debris classified as fines is assumed to exist as individual fibers or particles as a result of break flow impact. While the fiber in the fines cannot be further reduced by water-flow erosion, the particulate fines still are susceptible to erosive comminution.

In the baseline methodology, the large pieces of fibrous debris are assumed not to be subject to further size reduction and therefore are not transported to the sump. For purpose of performing a refined debris transport analysis that credits debris settlement, the NRC SE[4] indicated further refinement was necessary. Although the SE found that the transport guidance for small debris fines was acceptable, the guidance for the large pieces of debris was not acceptable because of the unrealistic assumption that large pieces of debris could not be transported particularly for plants whose configurations lead to fast pool velocities. The SE also found that the method recommended for determining the quantity of fine debris trapped in inactive pools based on the volume ratio of inactive pools to the total pools was unrealistic for plants with large inactive pools. Therefore the SE recommended that licensees limit the maximum fraction of fine debris being trapped in inactive pools to 15 percent to avoid non-conservative results. The NRC evaluation recommends a further subdivision of small fines into suspended fines (which largely remain suspended in the sump pool flows) and small pieces (which will transport along the floor in the water-stream flow). Section VI.3.2.1, Fibrous Insulation Debris-Size Categorization, of Appendix VI of the SE recommends a path forward to determine the physical qualities and distributions of the suspended fines and small pieces with respect to the other two classifications of fibrous debris, large pieces and intact insulation.

In the same manner as for insulation, coatings within the ZOI are considered to be fines of the dimensions of the original pigments. The coatings particle dimensions were conservatively assumed to be 10 μm.

The guidance recommends assuming that all jacketed insulation outside of the ZOI remains intact and is not eroded or disintegrated by any impinging flow (i.e., containment spray or flow from the break.) The behavior can be inferred by the lack of further destruction of damaged jacketed material from within the ZOI during transport to the sump. Testing has confirmed this behavior with Nukon blankets (Section 3.4.3.3.4 of Reference 3). The testing also showed that as much as 52% of the mass of Nukon within the ZOI was reduced to fragments that could be classified as small fines (Section 3.4.3.2 of Reference 3). Based on these results, the guidance recommends assuming, as a measure of conservatism, that the fibrous insulation within the ZOI breaks up into 60% small fines. The NRC SE[4] took issue with the methodology used to arrive at the 60% figure, but accepted the recommendation as conservative. The guidance recommends assuming similar size-distribution values as those obtained with Nukon for many other materials, based on BWROG testing. For fibrous materials that were not tested, the recommendation is to assume 100% reduction to small fines as a conservatism.

The guidance recommends assuming all reflective metal insulation (RMI) within the ZOI fails as 75% small fines and 25% large pieces. This is based on BWROG testing of a single RMI type and observation of larger destructive pressures for other RMI types.

For particulate insulation and other containment materials for which destruction test results were limited or unavailable, the guidance recommends assuming 100% destruction to small fines within the ZOI. Such materials include Cal-Sil, Microtherm, Min-K, Koolphen, fire barrier, and lead wool. Materials outside of the ZOI are by definition not affected by the break jet, but may be damaged by water flows from the containment spray or water draining to the containment sump. Jacketed materials (insulations, fire barriers, lead wool) can be expected to remain undamaged under such conditions. Unjacketed materials are conservatively considered to fail completely to small fines.

The DBA-qualified coatings are expected to remain intact, but the non-qualified, indeterminate, or unacceptable coatings are assumed to fail completely outside of the ZOI.

In Section 3.4.3.5 of the NEI 04-07 [3] guidance, a sample calculation is provided to determine the quantity of debris materials (insulation and coatings) generated in the ZOI and the contribution by the total quantity of unqualified coatings outside of the ZOI. NRC [4] takes issue with the estimate of the quantity of insulation based on the testing which was limited to one insulation type (NUKON) and particularly coatings debris. The NRC recommendation is that assessments be made based on plant-specific characterization and not default coatings thicknesses.

2.1.2.2.1 Insulation and Coatings Debris Characteristics

Section 3.4.3.6 of NEI 04-07 [3] provides tabulated information on debris characteristics of 15 types of insulation (fibrous and particulate) and 5 types of coatings. The associated SE report[4] discussion takes issue with some of the values and ranges of values presented in the guidance. Where large ranges are given, the SE[4] recommends that as-installed plant-specific values be used. Of greater concern for the SE[4] is the use of characteristic sizes (fiber or particle diameters) rather than specific surface areas for head loss correlations (this objection may be moot, however, because, in practice, essentially all PWRs perform testing to validate the strainer designs and do not rely on correlations). The SE agrees with the recommendations for assumed size of the coatings debris. Overall, the SE[4] recommends that insulation qualities be assessed in each plant and that specific surface areas be properly determined for use in head loss calculations.

2.1.2.2.2 Latent Debris Quantities and Characteristics

The latent debris inside containment is characterized and quantified by

- estimating the horizontal and vertical surfaces areas
- evaluating the rate of debris buildup in those areas
- defining the observed debris characteristics
- determining the fraction of the surface area that is susceptible to debris buildup.

Based on these prior estimates, the quantity and composition of latent debris can be calculated. The guidance provided in Section 3.5.2 of NEI 04-07[3] details the specific steps to be taken to perform these evaluations. The associated SE[4] offers additional suggestions on how to perform these evaluations. Among the suggestions is the use of lint-free Masolin cloths or high-efficiency particulate air (HEPA) vacuuming with mild brushing as a means to assess debris deposits on vertical surfaces (both provide readily quantifiable debris mass measurements).

The guidance in Section 3.5.2.3 of NEI 04-07 describes two alternative methods for defining latent debris characteristics. The first method is a strict analysis of collected latent debris samples to determine compositions and physical properties. The second method is to assume compositional and physical properties of the debris based on conservative values. The latter method is recommended due to the probable prohibitive cost of exhaustive characterization testing, the impracticality of separating particles from fibers, and the likelihood that the bulk densities of fibrous debris would be altered in the process of collecting and handling. To pursue the latter method, a reasonable estimate of the relative mix of particles to fibers must be obtained.

Material density and particle size also are important physical characteristics for debris. The bulk fiber density is assumed to be that of water to make the fiber particulate neutrally buoyant. The particle bulk density is assumed to be 100 lbm per cubic foot, slightly above that for dry sand or packed earth (95 lbm/ft^3). Finally, the particle diameter is assumed to be 10 μm.

The associated SE[4] recommends that, in the absence of measurements to the contrary (i.e., the first method or observation of an inordinate amount of paint chips), fiber would constitute 15% of the latent debris mass. The SE further states that fiber bulk density is not the value of merit for transportability to the sump screen, but it is conservative to assume that all fiber is transported to the sump screen. The assumed particle density of the fiber should be 1.5 g/cm^3. Similarly, the particle density of the particulate material ("dirt"), 2.7 g/cm^3, is the value of merit, not the bulk density. Finally, the SE[4] accepts the assumed particulate particle diameter of 10 μm as being conservative, but perhaps overly so, as much of the particulate latent debris mass could be due to hardware and larger paint chips and sand grains. The SE provides alternative and more refined means to estimate the hydraulic properties of the particulate debris.[4]

The NRC SE[4] points out two additional values that are not addressed in the NEI guidelines. These are the dry bed (i.e., in the absence of associated water) accumulation of latent fibers and the fiber-specific surface area, both of which are needed for head loss calculations. NRC recommends either experimental measurement of these values or using the dry-bed values for fiberglass as being conservatively bounding.

2.1.3 Evaluation of BWR and PWR Guidance on Physical Debris

The sources of many types of physical debris at BWRs and PWRs are similar or identical, including primarily insulation materials and coatings, but also installed materials (e.g., labels, tags, tape) and non-installed transient materials such as dirt, dust (both particulate and fibrous), and maintenance debris (e.g., rags, tools, filters). BWRs also have the suppression pool sludge (steel corrosion products plus dirt and dust), which is not found in PWRs. Table 2.2 summarizes the types of physical debris found in BWRs and PWRs as reflected in the guidance documents showing the expected numerous similarities and differences, largely in the presence and characteristics of suppression pool sludge in BWRs and in the emphases placed on the materials.

Table 2.2. Physical debris evaluated in PWRs and BWRs.

PWR	BWR
Primary Insulation on Piping and Vessels:	
Fiber blanket, reflective metal, particulate, microporous	Fiber blanket, reflective metal, particulate, microporous particulate
Installed Materials:	
Filters, fire barrier materials, fibrous cable insulation, insulation in wall penetrations, coatings (paint), labels, tags, tape	Coatings (paint), fabric, permanent tags, ropes, filters, tape, wire ties
Latent Materials:	
Unqualified coatings, degraded qualified coatings, dirt, dust, lint, tape, labels	Unqualified coatings, degraded qualified coatings, tags, labels, dirt and dust in wetwell, fibers, suppression pool sludge (carbon steel corrosion products)
Transient Materials:	
Construction and maintenance debris, temporary equipment, dirt, dust, lint	Tools, rags, filters, ablated concrete, dirt and dust in drywell; ropes, fiber, paper mats, plastic sheeting, rubber gasket materials in wetwell; paper, plastic sheets in both

The BWR determinations of physical debris types generally pre-date those of the PWRs. The types and quantities of certain types of debris for BWR plants was based on values derived from surveys of a number of plants at different times and over various plant operating cycles. The recommended assumed quantities for debris types other than insulation identified in the BWROG guidance include the following;

- from the drywell:
  - 150 lbm of dirt and dust
  - 47 lbm of inorganic zinc coating

- 85 lbm of inorganic zinc with epoxy top coat
- 71 lbm of epoxy
- 50 lbm of rust from unpainted steel

- in the suppression pool:
  - 150 lbm per year sludge generation rate.

The insulation contributions were determined by ZOI calculations. The above recommendations are assumed in the URG to be bounding values, but the guidance advises that licensees should verify that these values are bounding for their particular plant. The guidance document recommends that licensees develop plant-specific estimates for the items in the drywell. The guidance also recommends that plant-specific sludge generation rates should be based on experience, or determined with conservative sludge estimation techniques. Table 2.3 compares the PWR and BWR approaches in summary form, showing the similarities and differences.

Table 2.3. Comparison of BWR and PWR guidance on physical debris.

<table>
<tr><th>PWR</th><th>BWR</th></tr>
<tr><td>Determine inventory of debris by quantities and types based on walkdowns of plant; update records such that “as built” documentation reflects actual plant conditions; systematic guidance provided for walkdown procedures, which defines the expertise required, the methodologies, and the approaches used to survey debris sources and distributions</td><td>1.) Use generic/representative values developed by BWROG based on plant surveys and recommended as applicable to all plants
2.) Alternative recommendation; determine quantities and types of debris based on plant-specific conditions (procedure to be devised and defended by licensees) for insulation debris defined by ZOI</td></tr>
<tr><td>Material properties (geometry, size, density) of debris determined from direct measurement of sampled species or from recommended values from guidance documents</td><td>Material properties of debris determined from direct measurement of sampled species, or from recommended values from guidance documents</td></tr>
<tr><td>ZOI spherical</td><td>ZOI spherical, except below as used for coatings</td></tr>
<tr><td>Within ZOI, RMI fails as 75% small fines (fines and pieces <1-inch), 25% larger pieces</td><td rowspan="3">Fraction of the insulation located within the ZOI assumed to be destroyed into “fines” is determined. Methodology for determining the actual degree of damage to various insulation materials within the ZOI (e.g., from complete destruction as fines to partially shredded into larger mats) is specified in Table 4 of the guidance.</td></tr>
<tr><td>Within ZOI, tested fibrous insulation breaks up with 60% small fines, the remainder of larger fragments; assume 100% small fines for untested materials.</td></tr>
<tr><td>Within ZOI, particulate insulation and other materials with limited or no test results (Cal-Sil, Microtherm, fire barriers, etc.) fail 100% as small fines</td></tr>
</table>

Within ZOI, all coatings (qualified and unqualified) assumed to fail as 10-μm particles	Within ZOI, all coatings assumed to fail on a projected surface (base of expanding cone) located 10D from a nominal-sized break (bounding value of 20 ft for 24-inch pipe break), doubled to account for intervening structures; generic to all BWRs.
Outside of the ZOI, all jacketed insulation assumed to remain intact	Not specified, but presumed to remain intact.
Outside of the ZOI, all non-qualified coatings assumed to fail as fine particulate; qualified coatings remain intact, unless current walkdown evaluations show that they have become degraded	Outside of the ZOI, non-qualified coatings must be evaluated for detachment or their susceptibility to detach after prolonged exposure to post-LOCA environment within containment. Form of failed coatings not specified.
1.) Latent debris inside containment estimated by detailed measurement and assessment methodologies to determine density and particle size (some plants use default <200 lbm; 15% fibrous) 2.) Assume bounding values of 62 lbm/ft^3 bulk density (water density) for fiber debris; 100 lbm/ft^3 and 10 μm particle size for particulate debris	1.) Assume suppression pool sludge accumulates at rate of 150 lbm/year (must justify this as bounding for specific plant) 2.) Assume suppression pool sludge accumulates at rate of 300 lbm/year (bounding; no plant-specific justification needed) 3.) Sludge particle-size distribution determined from test sampling reported in BWROG document; assumed applicable to all plants 4.) Latent debris; e.g., dirt and dust in the wetwell that is above the normal suppression pool level, corrosion products from unpainted steel, and unqualified paint and any transient debris that had been dropped or introduced into the suppression pool such that, at LOCA initiation, it was already present.

2.1.4 Recommendations for BWR and PWR Guidance on Physical Debris

The PWR guidance for estimating the quantities and properties of physical debris is provided by the Nuclear Energy Institute,[2] in NEI-04-07,[3] and the associated NRC Safety Evaluation.[4] For PWRs, individual facility walkdowns are directed to obtain and confirm information on debris types and quantities. For BWRs, estimates of quantities based on generalizations derived from plant surveys were done for certain types of debris. Information on physical properties of debris for PWRs can be based on plant-specific observations or may be based on generalized data obtained as consensus values. Such consensus values are provided by the guidance documents and associated NRC staff evaluation. For example, unless evidence to the contrary is observed during plant walkdowns, fiber is assumed to constitute 15% of the latent debris, the fiber particle density is 1.5 g/cm^3, and the particulate matter density is 2.7 g/cm^3 with an assumed particle diameter of 10 μm noted by the SE to be conservative. Information on insulation and coatings properties likewise are provided.

Systematic direction on performance of the PWR plant walkdowns also is provided in the guidance document. This direction is prescriptive, thus guiding the various PWR operators to apply similar expertise, methodologies, and approaches to survey physical debris sources and distributions.

Recommendation 2-1: Plant-specific determination of the types, quantities, and distributions of physical debris, similar to the individual plant walkdowns for PWRs, is recommended for all commercial light water reactors, including BWRs. A sampling methodology, such as the guidelines offered through the SE to NEI 04-07, should be implemented across all plants to determine the relative quantity of fibrous debris. Methods to estimate the quantities and types of insulation debris, the largest contributor to the post-LOCA debris inventory, should be unified across BWRs and PWRs.

2.2 Chemical Debris

Solutes in post-LOCA PWR coolant can react with materials exposed to the coolant under post-LOCA conditions to create precipitates. Solutes in post-LOCA PWR coolant include boric acid (used in the reactor coolant system during normal plant operation as well as in the water injected by the ECCS), and chemical buffers (trisodium phosphate, sodium hydroxide, or sodium tetraborate) added to adjust pH to a neutral value or greater to inhibit iodine volatility and limit corrosion under post-LOCA operations. Solutes also can arise from partial dissolution of solids (e.g., aluminum, calcium silicate insulation, concrete) into the coolant. The reactions of the PWR solutes with each other and with the post-LOCA debris are referred to as chemical effects, and the solid precipitates arising from these reactions are termed chemical debris in the present discussion. The reactions include interactions of the solutes with other materials in the circulating post-LOCA coolant (e.g., insulation), interactions of the solutes with other fixed materials (e.g., metals to form corrosion products), or interactions of the solutes derived from fixed materials with themselves (e.g., from dissolution of calcium silicate insulation to form other precipitates).

Although all BWRs operate without solutes in their normal coolant (i.e., the coolant is essentially pure water), some BWRs inject the SPB in the standby liquid control system in the event of a LOCA. Like the PWRs, solutes also can arise for BWRs by the partial dissolution of solids, such as metals (including aluminum RMI), other insulation, or concrete, in the released coolant. Thus, the interactions of the post-LOCA debris, the fixed materials, and the neutral water or water plus the SPB solute may also create chemical debris or precipitates in the BWR post-LOCA system. Table 2.4 summarizes the chemical additions that can lead to chemical debris generation in PWRs and BWRs.

Table 2.4. Contributors to chemical debris in PWRs and BWRs.

PWR	BWR
Primary Coolant:	
Boric acid (varies from nominally 2800 ppm to near 0 ppm boron depending on time in cycle)	Water
Secondary Sources of Water:	
RWST boric acid	Suppression pool
Chemical Additions to Post-LOCA Coolant:	
One of the following: • sodium hydroxide (NaOH) up to ~0.2 M • TSP ($Na_3PO_4 \cdot 12H_2O$) up to ~0.011 M as phosphate • STB ($Na_2B_4O_7 \cdot 10H_2O$) up to 0.11 M as boron	Generally none; some plants add SPB; $Na_2B_{10}O_{16} \cdot 10H_2O$) up to ~0.2 M as boron
Dissolved Solids:	
Insulation, concrete, metals	Insulation, concrete, metals

The chemical effects discussed herein are based on the outcomes of chemical effects testing and other work done for PWRs in prior extensive testing programs. Similar considerations or testing programs on chemical effects in generating post-LOCA debris in BWRs have been done on only a limited basis. Chemical debris in PWRs is considered in Section 2.2.1; chemical debris in BWRs is discussed in Section 2.2.2. The different treatments of chemical debris for BWRs and PWRs are evaluated in Section 2.2.3. Based on this assessment, recommendations for uniformly addressing chemical debris for commercial light water reactors are provided in Section 2.2.4.

2.2.1 Chemical Debris in PWRs

In the research activities associated with the resolution of GSI-191, the NRC Advisory Committee on Reactor Safeguards (ACRS) raised a concern that chemical interactions between the ECCS containment spray water and exposed material surfaces (such as metals, paint, and insulation debris) could impede water recirculation in a post-LOCA PWR. As part of the response to this concern, the Integrated Chemical Effects Testing (ICET) program[5] was performed at the University of New Mexico under the direction of Los Alamos National Laboratory (LANL). The objectives of the ICET program were to determine, characterize, and quantify chemical reaction products that might arise in a post-LOCA PWR environment and to determine and quantify gelatinous materials that might arise during post-LOCA recirculation.

The concerns about chemical effects arise because of the ~2800 ppm boric acid in the post-LOCA sump fluid and the post-LOCA upward pH adjustment to decrease radioiodine volatility, which is accomplished by injecting sodium hydroxide (NaOH), TSP ($Na_3PO_4 \cdot 12H_2O$), or STB (sodium tetraborate; $Na_2B_4O_7 \cdot 10H_2O$). These chemicals in the coolant can interact with materials (e.g., insulation, metal, concrete, and coatings) present in containment.

Five sets of post-LOCA coolant and insulation compositions were investigated under the ICET program, as shown in Table 2.5. Tests 1 through 4 comprise a 2×2 matrix that varied the insulation materials (fiberglass only or a fiberglass/Cal-Sil combination), and the buffer (NaOH or TSP). The fifth test simulated the conditions of an “ice condenser” PWR, which uses STB as the additive for the upward pH adjustment, and fiberglass insulation.

Table 2.5. Test conditions for ICET experiments.

Test	$[H_3BO_3]$, mg/L	[Buffer], mg/L			$[B_{total}]$, mg/L	pH	Insulation, mg/L	
		$Na_2B_4O_7 \cdot 10H_2O$	NaOH	$Na_3PO_4 \cdot 12H_2O$			Fiberglass	Cal-Sil
1	16000	0	7677	0	2800	9.3–9.5	5270	0
2	16000	0	0	4000	2800	7.1–7.4	5270	0
3	16000	0	0	4000	2800	7.3–8.1	1050	20800
4	16000	0	9600	0	2800	9.5–9.9	1050	20800
5	6850	10580	0	0	2400	8.2–8.5	5270	0

- Adjustments of pH in Tests 1 and 4 represent PWRs using NaOH spray injection, Tests 2 and 3 represent PWRs using dry $Na_3PO_4 \cdot 12H_2O$ for pH adjustment, and Test 5 represents PWRs using $Na_2B_4O_7 \cdot 10H_2O$ within melting ice for pH adjustment.
- All tests also contained 90 mg/L pulverized concrete plus “dirt” debris in a 1:3 weight ratio, 43 to 100 mg/L HCl, and 0.3 to 0.7 mg/L LiOH.
- Each test conducted at 60°C for 30 days with 59 aluminum 3003 alloy coupons, 134 galvanized steel coupons, 100 copper coupons, 3 uncoated mild steel coupons, 77 mild steel coupons coated with inorganic zinc, and 1 concrete coupon.

As shown in Table 2.5, the cooling water used in PWRs contains up to 2400 to 2800 ppm (~0.22 to 0.26 M) total boron. The pH of the PWR boric acid coolant is adjusted upward in post-LOCA conditions. This is accomplished by adding NaOH to about 0.2 M in sodium, or TSP to about 0.011 M in phosphorus and 0.032 M in sodium, or STB to about 0.056 M in sodium (see Table 2.5).

The ICET experimental findings are presented comprehensively in the original NUREG report[5] and summarized concisely with additional interpretation in a subsequent journal article.[6] A general overview of the observations made in the five ICET experiments is presented in Table 2.6. These general observations and the more detailed data descriptions and interpretations based on the ICET experiments suggest that significant chemical interactions would be expected in some post-LOCA PWR environments, with the interactions varying according to the insulation type and the buffering system.

The results summarized in Table 2.6 show that the primary impact of the chemicals in the post-LOCA coolant is the possible formation of chemical precipitates that may increase head loss more than other types of particulates. A large amount of sediment was present in ICET 3 and ICET 4 due to the large quantity of calcium silicate insulation (Cal-Sil) used in these tests. Some of this debris may remain unaltered but a significant amount of the Cal-Sil dissolves in water and then re-precipitates to form much finer solids that, with fibrous debris, pose risk to strainer flow. Thus, the relative change in solids quantity from the Cal-Sil reactions likely is small but the character of the resulting solids may change significantly. The sediment quantities are much lower for Tests 1, 2, and 5, which have no Cal-Sil. In these cases, the sediment material is composed of fiberglass and “dirt” (i.e., a mixture of soil and crushed concrete). Table 2.6 shows that Cal-Sil is not only the predominant source of debris solids, but is also the origin of significant dissolved calcium and silicon (silicate). Test 4, the case with the higher pH of the two tests with Cal-Sil, also has the higher silicate concentration.

Table 2.6. Results for ICET Experiments.

Test	Insulation	Buffer	Al Corr., g	Steel Corr., g	Sediment		Precipitates	Particulate Deposits on Fiberglass	Final Conc., mg/L			pH
					Type	Wt., g			Al	Ca	Si	
1	Fiber-glass	NaOH	-98.6	-23.3	Fiber-glass, "dirt"	292	Al, B as $Al(OH)_3$	Al corrosion product deposits	350	12	14	9.3–9.5
2	Fiber-glass	TSP	-0.9	1.4	Fiber-glass, "dirt"	256	None	Small amount of phosphate deposits	<0.5	8	89	7.1–7.4
3	Fiber-glass & Cal-Sil	TSP	0.6	-1.1	Cal-Sil	78,000	Ca, P as Ca phosphates	TSP reacted with Ca from Cal-Sil to form Ca phosphates; Cal-Sil deposits	<0.5	105	86	7.3–8.1
4	Fiber-glass & Cal-Sil	NaOH	0.0	0.2	Cal-Sil	86,000	None	Cal-Sil deposits	<0.5	46	180	9.5–9.9
5	Fiber-glass	STB	-11.2	0.0	Fiber-glass, "dirt"	89	Al, B as $Al(OH)_3$	Low amounts of chemical deposits	50	32	8	8.2–8.5

The tests with Cal-Sil or TSP or both (Tests 2, 3, and 4) have the lowest aluminum corrosion rates. This is probably because both phosphate and silicate are known to provide corrosion protection to aluminum. Subsequent analyses of the aluminum coupons exposed to Cal-Sil showed a silicate passivation layer composed of Al_2OSiO_4.[7] Of the tests without Cal-Sil or phosphate (Tests 1 and 5), aluminum corrosion is higher for Test 1 than for Test 5, probably because Test 1 has the higher (more alkaline) pH, which favors aluminum corrosion. The amorphous aluminum hydroxide corrosion product was assumed to be a form of $Al(OH)_3$ but also contained significant associated boron. The aluminum hydroxide solids were very fine and were largely observed upon cooling the 60°C fluids to room temperature at the completion of testing. Another source of fine precipitate was calcium phosphate, which arose from the interaction of the added TSP with the calcium dissolved from Cal-Sil in Test 3. No separate precipitates were observed in Tests 2 and 4.

The loading of water-borne solids onto fibrous mats is of great concern in sump screen clogging. The observations of particulate deposits onto fiberglass (present in all ICET experiments) are summarized in Table 2.6. Not surprisingly, the deposit quantities are highest for Tests 3 and 4, which contained Cal-Sil. Aluminum corrosion products were found in Test 1, which also had the greatest amount of aluminum corrosion. Although Test 3 was the only experiment that combined phosphate with Cal-Sil, and thus produced observable calcium phosphate precipitates, small amounts of phosphate-bearing solids were found embedded in the fiberglass in Test 2, which contained added TSP. The calcium source, presuming the solids contained calcium, could have arisen from the concrete debris added to this (and every) test or from the fiberglass itself. Separate brief (30, 60, and 90-minute contact time) dissolution studies of individual solids in PWR coolant solutions show much greater calcium dissolution from concrete than from fiberglass at all temperatures (~88 and 129°C) and pHs (~4.1, 8, and 12) studied[7].

The susceptibility or resistance of fiberglass fibers to corrosion is also influenced by the solution composition. The primary agent of fiberglass corrosion is high pH, while the presence of dissolved aluminum likely helps the glass fibers resist corrosion.[9, 10] The effect of dissolved aluminum on fiberglass leaching is demonstrated by the measured silicon concentrations in the ICET 1 and ICET 2 test fluid. Although the significantly higher pH in ICET 1 should have resulted in much greater dissolution of fibers, the Si concentration is approximately 6-fold greater in ICET 2.

Subsequent studies were conducted by Westinghouse Electric Company LLC to supplement the ICET program. The testing had the following objectives:[7]

- identify quantities of containment material classes (structural materials such as aluminum, carbon steel, concrete, and zinc, and insulations such as aluminum silicate, calcium silicate, E-glass, amorphous silica, Interam E class, and mineral wool) and the potential of each to cause chemical effects
- perform dissolution testing of 11 specific materials (aluminum sheet, carbon steel, galvanized steel, powdered concrete, Cal-Sil, Nukon fiberglass, high density fiberglass, mineral wool, Min-K, E-glass, Interam foil-backed insulation, and FiberFrax fire retardant material), based on further consideration of the material classes, for a total of 66 tests, at the following conditions:
    - at three pH levels (4.1, 8, and 12)
    - two temperatures (190 and 265°F, ~88 and ~129°C) characteristic of the early post-LOCA thermal excursion
    - with material to coolant ratios scaled based on industry survey
- perform precipitation testing for a total of 60 tests, consisting of
    - the high temperature (265°F) tests during cooling of the solutions (33 tests)
    - the pH 4.1 tests for all 11 materials adjusted to pH 8 with TSP (11 tests)
    - the pH 4.1 tests for all 11 materials adjusted to pH 8 with STB (11 tests)
    - five dissolution mixtures;
        - pH 4.1 Interam with pH 12 aluminum
        - pH 4.1 CalSil with pH 12 aluminum
        - pH 4.1 concrete with pH 4.1 galvanized steel
        - pH 4.1 concrete with pH 12 carbon steel
        - pH 4.1 CalSil with pH 12 high density fiberglass
- develop chemical models for the aluminum, calcium, and silicon solution concentrations and masses of the three observed precipitate types (aluminum oxyhydroxide, aluminum silicates such as sodium aluminum silicate, and calcium phosphate, for plants using TSP for pH control)
- testing and demonstration of particulate generators to prepare representative precipitates for use in sump screen head testing.

The dissolution tests were sampled after 30, 60, and 90 minutes of contact and analyzed for aluminum, calcium, silicon magnesium, phosphorus, sulfur, iron, zinc, and titanium concentrations. Dissolved mass values were negligible for phosphorus, magnesium, and titanium for the ten material classes tested; aluminum, calcium, and silicon gave the highest concentrations and thus were most likely to form precipitates. Dissolution rates were determined based on the three sample analyses obtained for each of the 66 test solution and temperature combinations. Based on these observations, the model assumed that all of the aluminum and calcium, when calcium was present with phosphate, would precipitate. The model also assumed that dissolved aluminum, sodium, and silicate would precipitate as $NaAlSi_3O_8$, with the amount limited by the silicate. As a simplifying but unproven assumption, any excess aluminum was assumed to precipitate as AlOOH, the net effect being that all of the aluminum would precipitate as a fine particulate posing similar risks to strainer blockage.

Of the 33 precipitation tests from the high temperature material dissolutions, 10 formed precipitates. These included all three of the aluminum tests (all three pH levels tested) to give hydrated AlOOH, the fiberglass test at pH 12 to give $NaAlSi_3O_8$ (albite), the concrete tests at pH 4.1 and 8 (calcium aluminum silicates), mineral wool at pH 4.1 (hydrated AlOOH), FiberFrax at pH 4.1 (hydrated AlOOH) and 12 ($NaAlSi_3O_8$), and galvanized steel at pH 12 (the zinc silicate, Zn_2SiO_4). Two of the TSP tests, with CalSil and with concrete, gave precipitates, each with calcium phosphate and with accompanying silicate and AlOOH, respectively. None of the tests with added pH 8 STB yielded a precipitate. For the five dissolution test mixtures, only the last one with pH 4.1 CalSil and pH 12 fiberglass gave solids (a sodium calcium aluminum silicate).

Of the 33 precipitation tests from high temperature dissolutions, the solids quantities were greatest, in decreasing order, for the pH 12 aluminum test (AlOOH), the pH 12 FiberFrax test ($NaAlSi_3O_8$), the pH 8 concrete test (calcium aluminum silicate), and pH 12 high-density fiberglass test ($NaAlSi_3O_8$). The solids amounts in the mixtures with TSP and the solution mixtures were not measured.

These precipitation studies showed that the solids of most concern are AlOOH, various calcium or sodium aluminosilicates, and calcium phosphate. Recipes to prepare such solids for strainer testing were developed and the product filtration qualities determined. Overall, the results of the Westinghouse testing[7] support and broaden the findings of the ICET experimentation.

Researchers in the Japanese Nuclear Energy Safety (JNES) organization[11] recently performed tests simulating the containment vessel of a PWR and a single test under simulating BWR conditions. These ~800-hour (~33 day) integrated chemical assessment tests, dubbed ICAN, were performed to examine flow rate pressure losses (net pump suction head, NPSH) and dissolved element concentrations in recirculating 60°C coolant accompanied by spray flow in gas spaces. Other test parameters such as scale (1,000 liters) and types, quantities, and placements of material surfaces were patterned on the ICET experiments. Two types of insulation materials were tested under ICAN – calcium silicate and rock wool. Eight ICAN experiments have been performed. The experiments are outlined in Table 2.7.

Table 2.7. ICAN experimental matrix.

Test, ICAN	Insulation	Coolant	Buffer	pH		Wt. Lost, g		Comments
				(a)	(b)	Al	Fe	
-1	Rock wool	H_3BO_3	?	?	?	?	?	Dry condenser
-2	Rock wool, calcium silicate	H_3BO_3	?	?	?	?	?	
-3	Rock wool, calcium silicate	H_3BO_3	?	?	?	?	?	With added heating and cooling
-4	Rock wool	H_3BO_3	$Na_2B_4O_7$	8.3	8.4	-0.05	6.60	Ice condenser
-5	Rock wool	H_3BO_3	N_2H_4, NaOH	7.5	7.0	0.67	18.53	
-6	Rock wool	none	none	3.2	5.9	0.67	59.0	Like BWR; galvanized steel also tested
-7	Rock wool	H_3BO_3,	NaOH	9.9	9.9	0.44	0.63	Dry condenser to repeat ICAN 1
-8	Rock wool	H_3BO_3	N_2H_4, NaOH	7.5	7.3	0.02	9.50	Like ICAN 5 but galvanized steel added in place of some of the carbon steel

(a) At the end of spray cycle.
(b) At end of 33 days of testing.

Details on the configurations of the prior ICAN experiments numbered 1 though 3 were sparse and no references were provided in JNES-SS-0804[11] to describe this earlier work. The dissolved concentrations of aluminum, silicon, iron, and copper were found to roughly match the solubilities of the corresponding oxides and hydroxides observed in the testing [i.e., gibbsite, $Al(OH)_3$, and amorphous $Al(OH)_3$, quartz, SiO_2, and amorphous silica, $SiO_{2\,(am)}$, hematite, Fe_2O_3, goethite, FeOOH, cupric oxide, CuO, and zinc oxide, ZnO]. The changes in the pressure losses with time were complex for these tests and the report provided observations but little overall interpretation of the pressure loss testing.

A third set of integrated tests under PWR conditions was performed by Framatome in Germany[12]. The testing was performed in a loop tank with 50°C (122°F) solution containing 2200 ppm boron as (unbuffered) boric acid and mineral wool insulation for 140 hours (almost 6 days). Neither the use of buffering agents (e.g., STB) nor pH monitoring was mentioned in the article. Some neutralization of the boric acid would occur by interaction with the mineral wool insulation. The testing showed dissolution of zinc from galvanized surfaces. No zinc oxide particle erosion was noted in areas of low velocity recirculation but zinc oxide erosion was seen in high velocity regions. Pressure loss at the strainer caused by accumulation of zinc oxide and iron corrosion products on the insulation was observed to commence after about 10 hours. It was shown that the pressure loss could be avoided if the pump flow rates were restricted to minimum rates in the first 10 hours after the LOCA.

2.2.2 Chemical Debris in BWRs

The chemical effects arising from interactions of solutes in the post-LOCA coolant with other materials in BWRs have to date not been a subject of study in the United States. Unlike the PWR coolant and the contained boric acid chemical shim, the BWR coolant is essentially pure water and does not contain solutes. However, some BWRs add SPB, sodium pentaborate, to the post-LOCA coolant and the SPB additions may lead to chemical effects similar to those observed in the PWRs. Although the BWR coolant is chemically simpler than that of the PWRs, chemical reactions in BWRs are still possible in the interaction of the post-LOCA coolant (water) with various materials contacted by that coolant. As in the case with the PWRs, the temperature, pH profiles, and plant-specific BWR materials will impact the chemical effects that may occur in post-LOCA situations.

A recent Japanese study has investigated the corrosion of rock wool (Thermboard 1080, Nippon Rockwool Corporation) and calcium silicate (Nippon Keical Limited) insulation materials in PWR and BWR coolant compositions.[11] The rock wool and Keical calcium silicate insulation materials are used in Japan. The two insulation materials were both contacted with sodium tetraborate solution (2312 ppm in boron), a hydrazine-bearing boric acid solution (2800 ppm boron), and a dilute (0.002 M; pH ~3) hydrochloric acid (HCl) solution. The last was stated by the researchers to model BWR coolant with the HCl arising from decomposition of cable insulation. The leaching tests were run at 60°C (140°F) and samples drawn at 3, 6, 24, 120, and 480 hours (20 days). Dissolution weight losses also were measured for each material/solution combination as a function of time.

The most evident instance of chemical reaction in the BWR post-LOCA coolant is the interaction of water with calcium silicate insulation. Phases such as tobermorite $[Ca_4(Si_6O_{15}(OH)_2)(H_2O)_5]$, and various carbonates (e.g., $CaCO_3$; $NaHCO_3$) are the primary constituents in Cal-Sil, with sodium, iron, and magnesium also present (Dallman et al. 2006; Volume 5).[5] Upon contact with water, the Cal-Sil will partially dissolve to add calcium, silicate, sodium, carbonate, and other solutes to the post-LOCA coolant. This is shown by the JNES tests of Keical (the calcium silicate insulation).[11] Dissolution of the Keical in the dilute HCl solution (pH ~3) increased the pH to 9.21 after 3 hours and the pH crept to 9.66 after 480 hours. Calcium concentrations reached ~26 ppm after 3 hours and were ~36 ppm (~0.001 M) after 480 hours, while silicon was about 19 ppm at 3 hours, rising to ~64 ppm (0.0023 M) after 480 hours.

With the pH controlled to lower values (~8.4) by sodium tetraborate, the dissolved calcium concentration rose from 63 to 138 ppm over the 3 to 480-hour test interval for the Keical calcium silicate product. The silicon concentration likewise was higher in the pH ~8.4 sodium tetraborate solution than in the unbuffered HCl solution, rising from ~12 to 83 ppm. With the pH ~7.6 boric acid solution, both calcium and silicon showed concentrations that were higher yet (86 to 227 ppm calcium as contact time increased from 3 to 480 hours and ~20 to 117 ppm silicon as time increased from 3 to 480 hours). Overall, the concentrations of the calcium and silicon decreased as pH increased from about 7.6 to 9.7. It is also clear from these tests that the calcium silicate insulation, in the absence of significant buffering, will drive the pH to fairly alkaline levels (pH ~9.7) as would be expected by its likely complement of contained sodium and calcium carbonates.

The pH values observed for the dissolution tests with the rock wool were about 4.2 in the unbuffered HCl solution (much lower than the pH ~9.7 observed with Keical), 7.6 in the boric acid solution (similar to that observed with Keical), and 8.4 in the sodium tetraborate solution (again similar to Keical). The most prominent solutes from the rock wool dissolution again were calcium and silicon. The calcium and silicon concentrations were lower for the rock wool than for the calcium silicate (Keical).

The solutes derived from Cal-Sil or the Japanese equivalent Keical can react with each other and also interact with components within the containment. For example, the dissolving Cal-Sil provides significant alkalinity, which can act to increase aluminum metal corrosion. In an opposite effect, however, the silicate present from dissolving Cal-Sil in a simulated post-LOCA coolant in the ICET experimentation conducted at the University of New Mexico has been credited with decreasing the corrosion of aluminum in post-LOCA PWR chemical systems.[5, 13]

The corrosion of aluminum present in the containments of BWRs is further complicated for those BWRs having dissolved SPB added to the post-LOCA coolant by means of the standby liquid control (SLC) system. The boron is added to provide nuclear reactivity control, and some SPB formulations are enriched in ^{10}B. The SPB addition also provides pH buffering to decrease iodine fission product release. About 600 lbm of boron is added as SPB ($Na_2B_{10}O_{16}\cdot 10H_2O$) to the post-LOCA coolant via the SLC system. The SPB addition, in the form of about 3000 to 4000 gallons of solution that is 8 to 10 wt% in SPB, is sufficient to give a final boron concentration of ~1100 ppm or ~0.1 M to the circulating post-LOCA coolant. The initial suppression pool pH is 5.3 (i.e., in equilibrium with atmospheric carbon dioxide), and the pH after injection of the SPB is greater than 7 (Table 15 of Gallagher 2004).[14]

In the absence of SPB, the BWR coolant has negligible buffering capacity. Therefore, the coolant is expected to assume the pH imposed by its interactions with the water-exposed solids surfaces (insulation, concrete, metal, and coatings). As shown by the Keical calcium silicate testing, exposure of the nominal BWR coolant (0.002 M HCl) to this insulation caused the initial pH of ~3 (the measured pH in the ICAN-6 test was 3.2) to rise to about 9.7 while exposure of the same coolant to rock wool insulation raised the pH only to about 4.2.

Dissolved borate significantly increases aluminum corrosion,[13] probably because of the formation of stable aluminate-borate complexes.[15] Thus, the rate of aluminum corrosion at pH 10 increases by a factor in the range of 25 to 64 in the presence of ~0.25 M borate. This increases the corrosion rate from 0.019 $g/m^2\cdot hour$ in water[16] to values in the range 0.459 to 1.22 $g/m^2\cdot hour$ in 0.236 to 0.259 M borate.[17] Although the studied borate concentrations are typical of PWRs, similar aluminum corrosion rates are observed in 0.1 M borate solution that would be typical in BWRs that use SPB addition.[13]

In a survey of 69 PWRs, all plants reported aluminum surfaces to be present in the containment. Of these 69, the maximum reported ratio of aluminum surface area to coolant volume is 5.42 ft^2 of aluminum surface area per ft^3 of coolant (~177 cm^2/liter). The prevalence of aluminum at some BWRs that have installed aluminum-based reflective metal insulation is probably greater than in PWRs because the hydrogen generation associated with aluminum does not impact the inert gas filled BWR containments (i.e., Mark I and Mark II designs). The corroded aluminum largely would precipitate to form aluminum hydroxides [e.g., $Al(OH)_3$ or, at higher temperatures, AlOOH as seen in the Westinghouse studies]. Because of the larger exposed aluminum surface area in some BWRs with aluminum RMI as compared to PWRs, greater quantities of corroded aluminum could form for these BWRs if post-LOCA manual SLC injection is used (i.e., dissolved borate is present in the coolant).

For BWRs that do not inject SPB during a LOCA (i.e., in the absence of dissolved borate), aluminum corrosion could be high, depending on the quantity of HCl formed by cable insulation decomposition. Weight losses of immersed aluminum coupons were measured in the ICAN tests. The test results (Table 2.7) show aluminum weight losses as great in the acidic simulated BWR system (ICAN-6) as in any of the simulated PWR systems (all other ICAN tests) with dissolved borate.

In Test 5 of the ICET experimental program executed to study PWR chemical effects, the conditions investigated were akin to the conditions that could be obtained in BWRs using SPB in the SLC system. Test 5 of the ICET series for PWRs studied the chemical effects of a system that contained shredded fiberglass insulation, concrete, metal coupons (mild steel, steel coated with inorganic zinc paint, galvanized steel, copper, and aluminum), concrete powder, and soil. These materials are also present in BWRs. In this test, the total boron concentration was 2400 ppm, or 0.22 M, which is about double the concentration available in the post-LOCA coolant of a BWR using SPB. The pH of Test 5 ranged from 8.2 to 8.5; the pH of the post-LOCA BWR coolant using SPB is expected to be greater than 7.[7] Test 5 of the ICET series thus provides useful information for understanding chemical effects in BWRs.

As already noted, the test ICAN-6 (Table 2.7) was designed to emulate the pure water BWR coolant amended by the hydrochloric acid generated by cable deterioration. Accordingly, the test system containing 7.8×10^{-4} M HCl, with calculated pH of 3.1, had a measured pH of 3.2. It is seen that the low pH (probably abetted by chloride) led to significantly greater carbon steel (Fe) corrosion compared with the parallel ICAN-4, -5, -7, and -8 tests buffered by borates to much higher pH (ranging from 7.5 to 9.9). If such high initial and unbuffered HCl concentrations do, indeed, exist in post-LOCA BWRs, high carbon steel corrosion should be expected. The depletion of acid strength exhibited over the duration of the ICAN-6 testing, and likely to occur over the course of the post-LOCA period, will lead to formation of flocculent iron hydroxide precipitates and significant solids loading. If, however, the HCl is neutralized as soon as it forms by interaction with calcium silicate insulation (a condition not tested), much less carbon steel corrosion would be anticipated.

2.2.3 Evaluation of Chemical Debris in PWRs and BWRs

Chemical debris concerns are more complicated for PWRs than for BWRs, given the varied chemical constituents and their diverse combinations found across PWR plants. Experimentation under the ICET program was performed by LANL and the University of New Mexico to understand interactions of PWR coolants with construction and insulation materials. Five different sets of coolant composition, all based on borate but with three different buffers, and insulation (two combinations, with and without added Cal-Sil) were required to address the varied systems available. The ICET experimentation indicated influences on chemical debris quantity and quality arose from

1. simple dissolution and fragmentation of the Cal-Sil,
2. the effects of borate, phosphate, and silicate on aluminum corrosion,
3. the nature of the aluminum hydroxide product from aluminum corrosion (and the interaction of the corrosion product with borate),
4. the interaction of calcium with phosphate to produce a fine precipitate,

5. the effects of the solution composition on fiberglass corrosion, and
6. the collection of the various chemical debris solids onto fiberglass.

Of the five ICET experiments, only one experiment (ICET-5) provided information that would be useful for BWRs. The usefulness, however, would be limited to BWRs using SLC systems to inject borate into the post-LOCA coolant and having fiberglass but no calcium silicate insulation.

Westinghouse performed subsequent studies of the influences of pH, time, and temperature on the dissolution in PWR coolant of 11 different containment construction and insulation materials (and the ensuing precipitation).[7] The precipitating solids found to be most prominent were AlOOH, various calcium or sodium aluminosilicates, and calcium phosphate. The rates of precipitation were modeled, the product filtration qualities were determined, and recipes to prepare these solids for strainer testing were developed. The Westinghouse studies were designed for PWR application but also would be useful for those BWRs having borate in the post-LOCA coolant (i.e., SLC systems inject during a LOCA).

A set of testing analogous to the ICET experiments was conducted by the Japanese Nuclear Energy Safety organization.[11] Eight so-called ICAN experiments were performed with one of the ICAN tests being done under nominal BWR conditions (i.e., borate-free coolant) in the presence of rock wool insulation and various materials of construction (e.g., mild steel, aluminum, copper, concrete). In the same report, the JNES also described dissolution kinetics testing of rock wool and calcium silicate insulation materials with two borate solutions (modeling post-LOCA PWR coolant) and a dilute hydrochloric acid solution (modeling post-LOCA BWR coolant).

Overall, there is limited test data that is relevant to BWR post-LOCA chemical debris effects. Although the chemical system for BWRs is simpler than for PWRs, at least in the number of solutes, the JNES study and related insights gained from ICET experiment 5, applicable to BWRs using SLC systems during a LOCA, show that the formation of chemical debris in post-LOCA BWR coolants cannot be ignored. The ICAN tests and the ICET experimentation, particularly Test 5, suggest the scope of chemical interactions that might be anticipated. However, the potential post-LOCA chemical debris-forming situations studied for BWRs have hardly been exhausted. In particular, integrated testing of BWR post-LOCA conditions with calcium silicate insulation is recommended.

2.2.4 Recommendations for Guidance on Chemical Debris in PWRs and BWRs

In light of the test matrix conceived and executed for the PWRs under the ICET program, similar experimental studies for BWRs could be proposed following survey of the BWR plants and the identification of materials of concern. For example, and paralleling the design of the ICET program, a 2×2 test matrix could be advanced for an ICET-type experimental program for BWRs. The testing would examine the effects of the presence and absence of SPB in the presence and absence of Cal-Sil insulation with background fiberglass insulation, representative or bounding aluminum RMI, and representative quantities of other materials of construction. The post-LOCA coolant composition in BWRs also should be determined. The ICAN testing posited a nominal pH ~3 hydrochloric acid solution but the evolution of this degree of acidity immediately after the LOCA may be unduly conservative. Directed single component insulation and construction material dissolution studies, along the lines the testing reported for PWR coolants by Westinghouse,[7] and solution mixing tests also are recommended for BWR coolant compositions. It is believed that the outcomes of the proposed studies would raise the understanding of chemical debris generation effects in the post-LOCA BWR system to be equivalent to the PWR understanding. Efforts similar to those conducted for PWRs into head loss studies also are recommended.

Recommendation 2-2: A determination of the effects of coolant, solutes, and insulation on the creation of chemical debris and the influence of the debris on head loss and downstream effect, along the lines of the ICET program and Westinghouse studies conducted for PWRs, is recommended for BWRs.

3. INSULATION AND COATINGS DEBRIS GENERATION

Debris is generated inside the reactor drywell/containment during a LOCA as high-energy fluid is released from a pipe rupture. Damge to containment materials occurs as the result of the impinging steam jet or saturated liquid jet that becomes two-phase because of rapid depressurization to containment ambient. The high-energy fluid can damage adjacent equipment and material, particularly insulation and coatings, creating debris that can be transported to the suppression pool or containment sump. In addition, debris may be generated in regions not directly impacted by the high-energy fluid due to the harsh post-LOCA containment environmental conditions (e.g., temperature, pressure, humidity, radiation).

The basic methodology for determining the amount of debris generated in a given LOCA event consists primarily of determining the zone of influence (ZOI) of the high-energy jet resulting from the pipe break. The ZOI is by definition the volume within which the jet is expected to generate debris from the insulation, coatings, and other materials typically present on reactor system equipment or containment walls. In some approaches recommended in the guidance documents, the ZOI is defined one way for determining insulation debris generation and in a different manner for coatings debris generation. The ZOI for various materials is different based on the ability of the specific material to withstand a LOCA jet.

Regulatory Guide 1.82, Rev. 3 [18] provides the NRC staff regulatory positions for insulation and coatings debris generation. The full text of the relevant sections of the Regulatory Guide is included in Appendix A.

The BWROG and PWROG guidance on specific issues of insulation debris generation during a LOCA event is summarized in Section 3.1. Section 3.2 contains similar summaries for coatings debris generation. These sections also include summaries of the NRC staff Safety Evaluations of the industry guidance documents, and additional NRC staff review guidance. The guidance for BWRs and PWRs on these issues is compared and evaluated in Section 3.3. This subsection also includes recommendations to clarify and reconcile the guidance provided determining debris generation for BWRs and PWRs.

3.1 Insulation Debris Generation

Insulation within the reactor containments is manufactured from materials that may fail due to a LOCA event, either as fibrous or particulate debris, depending on insulation type. The amount of insulation debris generated in a given LOCA event depends on the amount and type of insulation material within the ZOI defined for the particular pipe break of the LOCA event. The BWROG guidance on defining the ZOI for generation of insulation debris is summarized in Section 3.1.1. The PWROG guidance on this issue is summarized in Section 3.1.2. In both sections, the NRC staff evaluations of the respective guidance are also summarized.

3.1.1 BWR Guidance and NRC Staff Evaluation on ZOI for Insulation Debris

This section summarizes the BWR guidance and NRC staff evaluation for insulation debris ZOIs. No interpretation of the guidance or the evaluation has been made here. Section 3.3 contains comparisons and evaluations of the guidance provided.

In BWRs, the coolant lost from the primary system in a LOCA event can be a single-phase steam jet or a saturated liquid water jet that expands very rapidly to a two-phase jet because of the large difference between the primary system operating pressure and ambient pressure in the containment. The approach recommended in the BWR guidance for defining the ZOI for insulation debris generation is to determine the volume of the region where the pressure of the jet exceeds the material failure pressure of the insulation. This region is assumed to be equal in volume to the region within the dynamic pressure surface of a freely expanding steam jet where the dynamic pressure is equal to the material failure pressure of the insulation.[1] As an analytical simplification, the volume of the region defined by the material failure pressure is assumed to be a sphere centered on the break location, rather than a pair of truncated cones (typical of a double-ended pipe break) or a thickening disk (typical of a simple pipe separation).

The material failure pressure for a given insulation is determined empirically. The BWR guidance document provides tables of the free space expansion of a jet as a function of break geometry, based on the Continuum Dynamics Report 96-01 Rev. 3.[19] [(f)] Insulation material failure pressures for types of insulation found in BWR containments are also provided in the guidance document, based on the Continuum Dynamics Report 96-06 Rev. A.[20] [(g)] For LOCA events where the jet is saturated water/two-phase (rather than a pure steam jet), correction factors are provided in NEDO-32686,[1] to adjust the material failure pressure for a steam jet to the failure pressure for a saturated water jet. These empirical correction factors are based on the General Electric report DRF A74-00004.[27] [(h)] Thus, for the BWR approach, insulation ZOI volumes are functions of the material failure pressure of the insulation, the break configuration, and the jet medium (i.e., a steam jet or a saturated water/two-phase jet).

In the SE of NEDO-32686, Rev. 0 (which is included in the BWR guidance document NEDO-32686-A[1]), NRC staff noted concerns about scaling the results of air jet testing for damage or failure of insulation to BWR drywells. NRC staff also had concerns about relating the measured pressures to the pressure distribution in the free space expansion of a steam or saturated-liquid water jet. However, the staff found the jet medium correction factors acceptable.

The BWR guidance document[1] provides four methods for determining the ZOI. These methods, in decreasing level of conservatism, can be summarized as:

- Method 1, the entire drywell constitutes the ZOI, and all insulation materials therein fail.
- Method 2, target-based analysis using limiting (i.e. largest ZOI) double-ended guillotine break ZOIs in which individual insulation debris volumes are determined by the lowest insulation failure pressure and largest break diameter (using the approach summarized above).
- Method 3, break-specific analysis using break-dependent ZOIs; similar in approach to Method 2, but break-specific ZOI shape and insulation material quantities within the ZOI from a specific break location are considered.

(f) Reference 4 of NEDO-32686, Rev. 0; this report appears in Volume 3 of the guidance document.
(g) Reference 6 of NEDO-32686, Rev. 0; this report appears in Volume 3 of the guidance document.
(h) Reference 30 of NEDO-32686, Rev. 0; this report appears in Volume 4 of the guidance document.

- Method 4, direct scaling from computational fluid dynamics (CFD) modeling of the measured data, as presented in Continuum Dynamics Report, Rev. 3.[19] The calculated dynamic pressures from the jet expansion data are used to determine debris quantities; the analysis then continues as per Method 3.

All of these methods include consideration of the location of the insulation materials relative to the lowest elevation of gratings in the drywell. This is significant, because it affects the transportability of the failed insulation.

The NRC staff concluded in the SE of the BWROG guidance that Method 1 is clearly a bounding and conservative method. Regarding the spherical ZOI of Methods 2 and 3, the NRC staff concluded that the volume of the ZOI would be "...sufficiently large to envelop the entire zone over which destruction would actually occur."[1] Further, the SE notes that Methods 2 and 3 are "...sufficiently conservative to compensate for..." concerns about the air jet scaling issues and jet pressures noted above and are considered acceptable for use with insulations with low dynamic pressures (i.e., low failure pressures). For insulations with noted high dynamic pressures, the staff recommended that licensees consider the concerns related to the jet pressures on a plant-specific basis.

The NRC staff did not consider Method 4 acceptable without further detailed justification, citing:

- lack of "...the details of the analysis and how the code would be benchmarked..."
- "...BWROG has not yet demonstrated...that a CFD code can accurately predict the specific ZOI for a pipe break...," and
- the "...BWROG has not yet provided sufficient detail for the staff to reach any specific conclusions relative to the adequacy of using a CFD model for the purpose of determining the ZOI for a pipe break...."

Regarding insulation materials beyond the jet impingement, the BWR guidance states that "...it has been determined that additional transportable debris would not be generated as a result of bulk flow velocities in the drywell...for the materials evaluated."[1] No NRC staff response is identified from NEDO-32686-A.[1]

3.1.2 PWR Guidance and NRC Staff Evaluation on ZOI for Insulation Debris

This section summarizes the PWR guidance and NRC staff evaluation for insulation debris ZOIs. No interpretation of the guidance of the evaluation has been made here. Section 3.3 contains comparisons and evaluations of the guidance provided.

The PWR guidance for determining the insulation debris ZOI is provided in NEI 04-07.[3] For the baseline calculation, the guidance document recommends defining the ZOI as a sphere with the center at the location of the break. The debris generation region is determined through the described analytical calculations via ANSI/ANS-58.2-1988.[22] The radius of the spherical ZOI is defined such that its volume is twice the volume around the break in which the escaping fluid in the form of a freely expanding jet has sufficient energy to generate debris. The factor of two is included to account for a double-ended guillotine break (i.e., assuming a jet issues from each end of the break). The spherical ZOI radius is a function of the insulation failure pressure of interest, and is expressed in terms of the break diameter.

The baseline ZOI is selected based on the location of insulation with the lowest destruction pressure inside the containment that could potentially be affected by the LOCA. Walls and robust boundaries that could deflect the jet may be accounted for by assuming that insulation behind such barriers will be free from damage. The ZOI determination may be simplified for some breaks by assuming that the entire subcompartment becomes the ZOI.

The NRC staff concluded that the baseline ZOI calculation was acceptable but provided comments regarding the methodology that should be considered and implemented.[4] These details included determination of the mass flux from the break, irreversible losses, equivalent insulation damage pressures, and conditions of jet expansion. The NRC staff compared the jet expansion results of NEI 04-07 [4] to those of the NEDO-32686, Rev. 0 [1] (i.e., Continuum Dynamics Report[19]) and concluded that the Continuum Dynamics Report[19] approach is "a more capable method of modeling steam jets than the ANSI (ANSI/ANS-58.2-1988 [22]) model." Further, the NRC staff accepted the baseline calculation approach of defining the ZOI based on the insulation type with the lowest destruction pressure provided that

1. no other potential debris generation sources with a lower destruction pressure exist
2. defensible destruction pressure values are available for all materials of concern.

Given the NRC staff concerns related to the ZOI model and insulation failure pressures, the staff recommended that, for all material types characterized by air jet testing, the destruction pressures should be reduced by 40%. This reduction is imposed to "...account for potentially enhanced debris generation in a two-phase PWR jet." [4]

Two refinements to the baseline spherical ZOI determination are provided in the PWROG guidance document. The first method uses debris-specific spherical ZOIs. That is, the failure or destruction pressure of the specific insulations is considered such that there are multiple ZOIs for a single break. For the second method, the use of the freely expanding jet models, which were employed for the spherical ZOI determination, is recommended. In each method, fixed boundaries are accounted for as in the baseline calculation.

The NRC staff agreed that both the first and second ZOI refinement methods are appropriate[4] with the inclusion of the 40% reduction in destruction pressures noted above. The staff provided three additional refinements related to the application of worst-case thermal hydraulic conditions to every break location, the equivalent mass flux application to both ends of a guillotine break (i.e., the factor of two for the equivalent volume), and reduction of the effective total pressure at the break due to friction losses in lines leading to the break.

Covered (jacketed) insulation material outside of the ZOI is considered undamaged insulation, and will not generate transportable debris. As a conservatism, all unjacketed insulation outside of the ZOI is presumed to fail (NEI 04-07).[3] Per SE NEI 04-07,[3] the NRC staff agreed that covered insulations will not form significant debris outside of the ZOI.

3.2 Coatings Debris Generation

Primary coatings typically found in BWR containments include untopcoated inorganic zinc, inorganic zinc with epoxy topcoat, epoxy primer/topcoat for steel and concrete, and epoxy surfacer systems for concrete (Bechtel Report 22754094.12A).[23] The coatings in PWR containments are system-specific combinations of epoxy surfacers, inorganic zinc primers, epoxy and phenolic primers, and epoxy and epoxy phenolic topcoats.[3]

The coatings are designated as either as "qualified" or "non-qualified" (unqualified) for BWRs.[23] For PWRs, the equivalent terms are "DBA-qualified and acceptable" or "DBA-unqualified and unacceptable."[3] The coatings types will subsequently be referred to herein as qualified or unqualified regardless of reactor type. For both reactor types, the qualified coatings are differentiated as such by acceptable performance at DBA conditions and in radiation tolerance testing. Qualification is also dependent on factors such as surface preparation, coating preparation and application methods, and curing conditions as well as quality assurance/quality control (QA/QC) documentation thereof, in addition to coating type (ASTM D5144-00).[25]

Summaries of the BWR and PWR guidance for coating material debris generation are provided in Sections 3.2.1 and 3.2.2, respectively. These sections also summarize the NRC staff evaluations of this guidance.

3.2.1 Summary of BWR Guidance and NRC Staff Evaluation for Coatings Debris

This section summarizes the BWR guidance and NRC staff evaluation for coatings debris. No interpretation of the guidance or the evaluation has been made here. Section 3.3 contains comparisons and evaluations of the guidance provided.

The BWR guidance for coating material debris generation is provided in NEDO-32686, Rev. 0.[1] Paint/coatings on walls and equipment are classified as fixed debris, i.e., material that is part of the permanent plant that becomes a debris source only after exposure to the effects of a LOCA. Concrete floor coatings are assumed not to be a debris source because thay are located in the bottom of the drywell and should not be subjected to jet impingement (Bechtel report 22754094.12A).[22]

The guidance document states that "Where a LOCA jet directly impacts a coated surface it is conservatively assumed the jet will strip off all the applied coating in the affected area without regard to the coating qualification." The jet impingement area is defined in Bechtel Report 22754094.12A, [23] referencing ANSI/ANS-58.2-1988,[22] as bounded by a 24-inch unrestrained pipe break with an impingement range to the drywell wall of 10 pipe diameters, or 20 feet. The diameter of the jet at 20 feet is 19.6 feet, which is then doubled to account for pipe hangers, structural steel, valves, or other coated items in the jet path.

Generic values, intended to be bounding, for the maximum amount of particulate debris from different coatings are provided in the guidance document, based on the impingement area and coating thickness, as shown in Table 3.1. In the SE of this document, the NRC staff did not identify any concerns relative to the information shown in Table 3.1.

Table 3.1. BWR values of coating debris, Table 3 of NEDO-32686, Rev. 0. [1]

Coating	Thickness	Max Debris Volume	Max Debris Weight
Inorganic Zinc (IOZ)	0.005 inches	0.2516 ft^3	47 lb.
IOZ Top Coated with Epoxy	0.008 inches (epoxy topcoat)	0.6500 ft^3	85 lb.
100% Epoxy Coating	0.015 inches	0.7550 ft^3	71 lb.

Latent drywell debris sources are considered as "...debris which would not be present until later in the LOCA event and includes unqualified coatings as well as other material which may become debris after exposure to a LOCA environment." Qualified coatings that are not subject to the direct jet impact are not considered as a possible latent debris source. The Bechtel Report 22754094.12A[23] states that "...the properly applied qualified coatings...can all be expected to survive a LOCA intact beyond the jet impingement zone."

Regarding unqualified/indeterminate paint/coatings beyond the jet impingement, the BWR guidance advises licensees to determine if unqualified coatings are present in the drywell and to consider whether a qualified coating may have degraded such that its qualification is in doubt. The guidance states further,

> "If indeterminate or unqualified coatings are present, an evaluation should be conducted to establish the quantity of this latent particulate debris assumed to be available for transport from the drywell to the wetwell. Dependent on several plant-specific factors, it may be possible to show that the failure of indeterminate/unqualified coatings would not occur until late enough in the LOCA progression that there would is no transport mechanism available...The Bechtel report provides helpful information for evaluating this situation."

The NRC staff position regarding the BWR guidance for unqualified/indeterminate coatings beyond the jet impingement is that the guidance is "...incomplete and unsupported."[1] Licensees are cautioned by the NRC staff to carefully evaluate the potential impact of unqualified and indeterminate coatings on ECCS suction strainer head loss and are encouraged to support their evaluations with test data.[1]

3.2.2 PWR Guidance and NRC Staff Evaluation for Coatings Debris Generation

This section summarizes the PWR guidance and NRC staff evaluation for coatings debris. No interpretation of the guidance or the evaluation has been made here. Section 3.3 contains comparisons and evaluations of the guidance provided.

PWR guidance for coating material debris generation is provided in NEI 04-07.[3] DBA-qualified and acceptable protective coatings have a recommended ZOI radius of one break diameter (i.e. 1D) based on an assigned destruction pressure and pressure isobars obtained using the spherical ZOI approach (based on ANSI/ANS-58.2-1988 [22]) described in Section 3.1.2.

In SE NEI 04-07,[4] the NRC staff supports the position that all coatings, regardless of their qualification, fail within the ZOI. However, the NRC staff position in SE NEI 04-07 regarding the ZOI is that "...licensees should use a coatings ZOI spherical equivalent determined by plant specific analysis, or 10D...," where D is equal to the break diameter. As reported in NRC Staff Review Guidance 08,[26] the staff positions for licensees who use the reduced ZOI value rather than the default 10D are that ZOIs of 4D or greater should be used for qualified epoxy coatings and 5D or greater for qualified untopcoated inorganic zinc coatings.[(i)]

Material outside of the ZOI can be subjected to containment spray and/or be immersed in the post-DBA pool. The PWR guidance is to assume that DBA-qualified and acceptable coatings outside of the ZOI do not fail. However, all exposed DBA-unqualified and unacceptable coatings (e.g., coatings on piping that is not shielded by undamaged insulation) are assumed to fail.

The NRC staff agreed with the assumption that DBA-qualified and acceptable coatings outside of the ZOI do not fail.[4] The staff noted, however, that periodic assessments of the DBA-qualified and acceptable coatings must be conducted to ensure that degradation has not occurred such that those coatings are no longer qualified or acceptable. All DBA-qualified and acceptable coatings that have degraded are to be treated per the guidance for unqualified coatings. Per NRC Staff Review Guidance 08,[26] licensees should not reduce the unqualified coatings failure percentage below 100%. It is noted in Review Guidance 08[26] that if licensees are able to specifically determine their unqualified coatings types and align those types with specific tests, the licensees may be able to credit a reduction in failure of those coatings types.

To determine the quantity of coating particulate generated, NEI 04-07 specifies that plant-specific information should be used to estimate the thickness of the coatings. If insufficient information is available, guidelines for both in and out of the ZOI are provided. Within the ZOI, the thickness is specified by the coating system:

- 0.003 inches, inorganic zinc primer
- 0.006 inches epoxy/epoxy phenolic topcoat.

Outside of the ZOI, the DBA-unqualified and unacceptable coatings thickness is specified as "...the worst case of 3 mils (0.003 inch) inorganic zinc primer."

The staff concluded that "...the baseline alternatives to plant-specific data for the determination of the coating thickness may not be conservative and are not acceptable without plant specific justification."[4] In addition, the NRC staff concluded that the DBA-unqualified and unacceptable coating equivalent thickness of 0.003 inches is "...not acceptable without plant-specific justification".

(i) Recent work has suggested that ZOI for inorganic zinc coatings may need to be revised. This is documented in "Interim Report of the Evaluation of a Deviation Pursuant to 10CFR21.21(a)(2)" dated 2/12/10. ADAMS ML100480138. As a result, NRC staff guidance on this issue is being revised.

3.3 Comparison and Evaluation of Guidance for Insulation and Coating Debris Generation

The BWR and PWR guidance and NRC staff evaluations summarized above are compared in this section. The basic approach in both guidance documents is to determine the extent of the effect of the high-energy fluid expelled from a LOCA break (i.e., the ZOI) for a specific insulation or coating, and then quantify the amount of debris generated within and outside of the ZOI. The high-energy fluid expelled from a LOCA break acts as a jet. The jet behavior in the containment environment establishes isobars in the containment, which are dependent on the jet medium. ZOIs for specific insulations and coatings are established from the jet isobars, dependent on the material type. The quantity of debris can thus be estimated, based on the volume of material within the ZOI.

The guidance methodologies of ZOI determination are compared in Section 3.3.1 with respect to the jet pressure field and jet medium. In Section 3.3.2, the guidance on determining debris generation inside the ZOI is compared via insulation failure pressure, and coatings qualification and type. The guidance on the effect of the extent of the ZOI is also considered. Approaches to considering insulation and coatings debris generation outside of the ZOI are compared in Section 3.3.3.

3.3.1 ZOI Determination

Industry has established methodologies for determining ZOIs for insulation and coating materials. The influence of the basis of the jet pressure field on the ZOI is discussed in Section 3.3.1.1, and a recommendation is provided in Section 3.3.1.2.

3.3.1.1 Jet Pressure Field

The BWR and PWR guidance documents both use the concept of a freely expanding jet to define the ZOIs and thereby debris generation, which is the fundamental issue of post-LOCA coolant flow. The methodology for determining the region of influence for the freely expanding jet is therefore critical.

The methodologies recommended in the PWR and BWR guidance documents establish jet pressure-field ZOIs for insulation and coatings debris generation. Table 3.2 summarizes these methodologies and the NRC staff responses for both types of ZOI definitions, as discussed in Sections 3.1 and 3.2.

There are basic differences for determination of the ZOI volume within the BWR guidance and between the BWR and PWR guidance. The BWR guidance specifies three possible methods that use of the results of anaysis with the CFD code NPARC (as provided in the Continuum Dynamics Report 96-01 Rev. 3 [19]) to determine the insulation ZOI. The coatings ZOI, however, is defined based on a conical jet, as per ANSI/ANS-58.2-1988 [22]. The PWR guidance uses ANSI/ANS-58.2-1988 for both the insulation and coatings ZOIs.

In SE NEI 04-07,[4] the NRC staff compared the jet expansion results of ANSI/ANS-58.2-1988 in the PWR guidance (as applied in NEI 04-07) to the results in the BWR guidance (i.e., from the Continuum Dynamics Report 96-01 Rev. 3 [19] (NEDO-32686, Rev. 0 [1])) and concluded that the approach in the BWR guidance was “a more capable method of modeling steam jets than the

ANSI (ANSI/ANS-58.2-1988 [22]) model." However, the NRC staff did not fully endorse the BWR guidance for determining the ZOI based on the Continuum Dynamics Report 96-01, Rev. 3. Methods 2 and 3 (as the basis for the insulation ZOI) were generally accepted, but the NRC staff did not accept Method 4, in which the ZOI is based directly on Continuum Dynamics Report 96-01, Rev. 3. Method 4 would require further justification, particularly in regard to the uncertainty of the CFD model (see Section 3.1.1).

The BWR coatings ZOI definition references Appendix C of ANSI/ANS-58.2-1988,[22] while the PWR insulation ZOI and coatings ZOI definitions reference Appendices B, C, and D of this standard. These appendices each have the disclaimer "This appendix is not part of American National Standard Design Basis for Protection of Light Water Reactor Nuclear Power Plants Against Effects of Postulated Pipe Rupture, ANSI/ANS-58.2-1988, but is included for information only."

NRC staff discussions regarding acceptance/rejection of the ZOI definitions are essentially focused on the accuracy of the free jet expansion model, the application thereof either directly or via a spherical equivalent, and the effect of plant specifics on the ZOI (e.g., break configuration, drywell geometry, impingements, debris location and quantity, etc.). Concerns about the PWR approach using ANSI/ANS-58.2-1988, which focused on the accuracy of the methodology, were addressed via the methodology for application of the results. Specifically, the SE[4] states "The staff's position is that the overall approach to determining ZOI is sufficiently conservative (by conserving the volume of a freely expanding jet to isobars of demonstrated destruction pressure) to allow use of the ANSI/ANS standard for determining ZOI."

3.3.1.2 Recommendations for ZOI Determination

As described above, ZOI determination is based on the approach for modeling the free jet expansion in both the BWR and PWR guidance. The treatment of free jet expansion should be similar in both approaches because the physical behavior of a steam or saturated water jet is not dependent on the reactor type.

The BWR and PWR insulation and coatings ZOI bases are not consistent. As described previously and summarized in Table 3.2, the basis accepted by the NRC staff for BWR insulation ZOIs using Methods 2 and 3 is Continuum Dynamics Report 96-01 Rev. 3 [19], but the staff specified Method 4 as unacceptable without futher justification because it is based directly on Continuum Dynamics Report 96-01 Rev. 3 [19]. The NRC staff accepted the BWR use of ANSI/ANS-58.2-1988 [20] for the coatings ZOI. For the PWRs, the NRC staff used Continuum Dynamics Report 96-01 Rev. 3 [19] to help establish the acceptability of ANSI/ANS-58.2-1988.[20]

As noted, the NRC staff discussions regarding acceptance/rejection of the ZOI definitions are essentially focused on the accuracy of the free jet expansion model, and the application thereof either directly or via a spherical equivalent. However, the NRC staff judged the acceptability of the free jet expansion models by considering the conservatism of the overall approach to determining the ZOI. Determination of whether one approach for modeling the free jet expansion for the ZOI is more technically valid than another is not possible based on the available analyses.

Table 3.2. ZOI as a function of reactor type and debris material.

Reactor Type	Debris Material	ZOI (Basis Reference)	NRC Staff Position
BWR	Insulation	Method 1, Entire Drywell	Accepted
		Method 2, Spherical with Bounding Radius (Continuum Dynamics Report 96-01 Rev. 3)[18]	Accepted with Clarification
		Method 3, Spherical with Break and Insulation Specific Radii (Continuum Dynamics Report 96-01 Rev. 3)	Accepted with Clarification
		Method 4, Non-Spherical Free Jet Expansion, Direct CFD Application (Continuum Dynamics Report 96-01 Rev. 3)	Not Accepted without Further Justification
PWR	Insulation	Baseline, Spherical with Bounding Radius (ANSI/ANS-58.2-1988)[20]	Accepted with Modification(a)
		Refinement 1, Spherical with Insulation Specific Radii (ANSI/ANS-58.2-1988)	Accepted with Modification(a)
		Refinement 2, Non-Spherical Free Jet Expansion (ANSI/ANS-58.2-1988)	Accepted with Modification(a)
BWR	Coating	Generic value (Bechtel Report 22754094.12A, ANSI/ANS-58.2-1988)	Accepted
PWR	Coating	Spherical (ANSI/ANS-58.2-1988)	Accepted with Modification(b)

(a) Reduction of insulation failure pressures by 40% for all material types characterized with air jet testing.
(b) Expansion of ZOI to default value of 10D or depending on coating type.

Recommendation 3.1 *The zone of influence (ZOI) of the high-energy jet of steam or saturated liquid water released in a LOCA should be determined using an experimentally validated free-jet expansion model that is applicable to both BWR and PWR conditions.*

3.3.2 Debris Generation Within the ZOI

The determination of debris quantity with respect to the region of the ZOI and the effect of debris type are discussed in Section 3.3.2.1. Direct comparisons of the BWR and PWR industry approaches to insulation and coatings debris generation are made in Sections 3.3.2.1.1 and 3.3.2.1.2, respectively. The insulation comparison addresses failure pressure, and the coatings comparison considers the guidance for qualified and unqualified coatings, as well as coating types. Industry guidance for the effect of the ZOI extent on debris generation is discussed in Section 3.3.2.2.

3.3.2.1 Quantity of Debris Generation

Table 3.3 provides the BWR and PWR guidance for the extent of insulation and coating debris generation within the ZOIs, which are defined as summarized in Sections 3.1 and 3.2. The differences within the BWR guidance and between the BWR and PWR guidance for the region of ZOI effect and quantity of debris are apparent.

The BWR guidance for determining insulation debris generation requires specific licensee evaluation, depending on the applied method and the specific LOCA scenario (e.g., break location, break type, insulation type and quantity, etc.). In contrast, fixed generic quantities are defined for the coatings debris. The insulation debris generation is a direct function of the insulation material's failure pressure (excepting Method 1, in which all insulation is assumed to fail), while the coating debris generation is not. This approach is inconsistent and complicates the separate determination of debris generation within and outside of a ZOI. In addition, as noted in Section 3.3.1.1, the free jet expansion models for determining the insulation and coatings debris quantities are different.

Table 3.3. Debris generation as a function of reactor type and debris material.

Reactor Type	Region of ZOI Effect		Quantity of Debris	
	Insulation	**Coatings**	**Insulation**	**Coatings**
BWR	Isobar Volume[a, b]	Generic Surface Area[c]	Volume within ZOI	Fixed Generic Volume
PWR	Isobar Volume[d]	Isobar Volume[e]	Volume within ZOI	Volume within ZOI

(a) Method 1 includes entire drywell as ZOI.
(b) Methods 2 through 4 use insulation specific failure pressure; break specific jet.
(c) Specified as area of a 24-inch-diameter jet at 20 feet with 10-degree half angle.
(d) Baseline ZOI based on insulation inside containment with minimum destruction pressure. Refinements 1 and 2 use insulation specific failure pressures.
(e) Coating specific or default ZOI.

The guidance from the PWROG for determining the insulation and coatings debris generation relies on the material failure pressure. However, the baseline insulation ZOI is determined from the insulation inside containment with lowest destruction pressure.

3.3.2.1.1 Insulation Failure Pressure

Except for the BWR coatings ZOI, all ZOIs in Table 3.2 are based on the pressure at which the insulation or coating materials fail. The approaches to determining the pressure at which the materials fail are functions of the jet medium (i.e., steam or saturated water). As noted above in Section 3.1, the NRC staff cited concerns with the approaches to determining insulation failure pressures for both the BWR and PWR industry guidance.

The staff accepted the jet medium insulation failure correction factors provided by the BWR guidance. As noted in Section 3.1.1, the correction factors for the jet medium are taken from

DRF A74-00004.[27] Table 3.4 lists the BWR correction factors, and Figure 3.1 is also taken directly from DRF A74-00004.

The jet volume differences of Figure 3.1 are computed via the ANSI/ANS-58.2-1988 model.[22] These results are applied to the BWR insulation ZOIs, which are based on the Continuum Dynamics Report 96-01, Rev. 3 as discussed in Section 3.3.1.1. Comparing the correction factors from Table 3.4 and Figure 3.1 clearly indicates that the Table 3.4 values are conservative with respect to Figure 3.1 (however, evaluation of the conservatism or accuracy of Figure 3.1 is neither indicated nor implied by this comparison). The saturated water ZOI determined using the correction factors in Table 3.4 will be larger than indicated by Figure 3.1. The conservatism of Table 3.4 relative to Figure 3.1 may be very significant for materials with failure pressures greater than 60 psi, assuming the trend of decreased correction factor with increased failure pressure shown in Figure 3.1 is extrapolated beyond the conditions evaluated, i.e., above 60 psi.

The NRC staff did not accept the PWR guidance insulation ZOIs, and reduced the insulation damage pressure by 40%, thereby increasing the ZOIs to account for the two-phase PWR jet. As reported in Section 3.1.2, SE NEI 04-07 stated that the failure pressure reduction is to "...account for potentially enhanced debris generation in a two-phase PWR jet." This approach is in disagreement with the BRW guidance, which has equivalent or decreased ZOIs for saturated water jets (i.e., see Table 3.4). Additionally, large-scale jet impact testing with insulation has demonstrated that saturated water jets are less destructive than steam jets (NEA/CSNI/R (95)11).[28] It is reasonable to expect that the same debris materials may have different failure pressures, depending on the jet medium.

Table 3.4. Material Failure Pressure Correction Factors
(NEDO-32686, Rev. 0, from DRF A74-00004 [27])

Material Failure Pressure (psi)	Correction Factor
>60	0.4
50-60	0.5
40-50	0.7
30-40	0.8
20-30	0.9
0-20	1.0

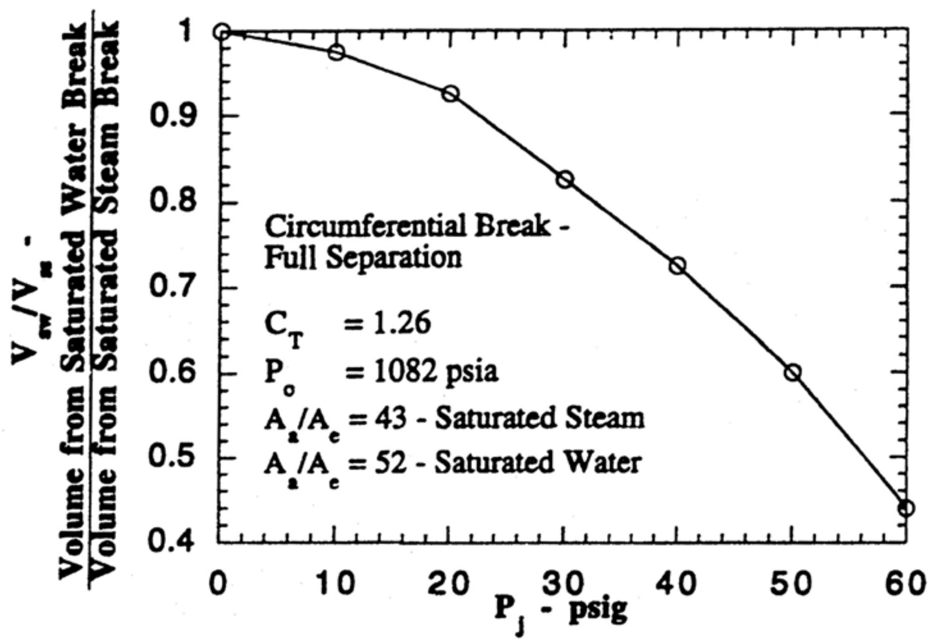

Figure 3.1. Comparison of the Volume of a Jet With Pressure Greater than or Equal to Pj (the material failure pressure) from Saturated Water and Steam Breaks (Figure 2 of DRF A74-00004 Appendix)[27]

The insulation failure pressures provided by the PWR and BWR industry guidance are compared in Table 3.5 for the same insulation types. The BWR guidance for steam jets is taken from NEDO-32686, Rev. 0 and and the PWR guidance is from NEI 04-07. The failure pressures for saturated water jets are determined via the BWR guidance for BWRs and the NRC staff position on the PWR guidance for PWRs, Section 3.3.1.2.

The failure pressures due to steam jets have the same or similar values in the BWR and the PWR guidance (with the notable exception of the value for calcium silicate [CaSil], which is from two-phase testing in the PWR guidance). However, the values for failure pressures due to a saturated water jet are significantly different, with the PWR failure pressures significantly lower than those for BWRs. For example, the saturated water jet failure pressure for PWR reactors for NUKON®, a fiber insulation, is 40% to 80% lower than the BWR values, and for Calcium Silicate, which will fail as particulate, up to 95% lower. This difference is due in large part to differences in regulatory guidance provided for the different reactor types. As referenced in Section 3.3.1.2 in the summary of guidance for PWRs, the NRC staff reduced the experimentally determined insulation damage pressure by 40% to "...account for potentially enhanced debris generation in a two-phase PWR jet." This is in direct disagreement with the BWR guidance, which has equivalent or decreased ZOIs for saturated water jets (see Table 3.4), thereby effectively increasing the insulation damage pressure (Table 3.5).

While increasing the debris generation (by defining a decreased failure pressure relative to measured values) is obviously a more conservative approach, it is not necessarily more technically valid than relying directly on measured values. This is particularly the case when test results are not consistent with the imposed conservatism, and the conservatism is not uniformly applied to both reactor types. The same types of insulation are used for containment components in BWRs and PWRs. Thus, insulation material failure pressure is not a direct function of reactor type, even though it may be affected differently by different thermodynamic conditions during a LOCA blowdown. However, the differences in the PWR and BWR guidance can be expected to result in significant differences in the quantity and type of debris predicted to be generated for the same or similar conditions in a LOCA scenario.

Recommendation 3.2 *A validated basis that is consistent as applicable between reactor types for insulation material failure pressures should be developed for the range of thermodynamic conditions encountered in LOCA scenarios.*

Table 3.5. Insulation failure pressures.

Material[a]	BWR Failure Pressure (psi)		PWR Failure Pressure (psi)	
	Steam Jet[b]	Saturated Water Jet[c]	NEI 04-07[d]	Saturated Water Jet SE NEI 04-07[e]
Darchem DARMET®	190	246, 363, 458	190	114
Transco RMI	190	246, 363, 458	190	114
Jacketed NUKON® with modified "Sure-Hold" Bands, Camloc® Strikers and Latches[f]	190	246, 363, 458	150	90
Diamond Power MIRROR® with modified "Sure-Hold" Bands, Camloc® Strikers and Latches[f]	190	246, 363, 458	150	90
Calcium Silicate with Aluminum Jacketing[g, h]	160	234, 355, 446	24	24
K-wool	40	78, 115, 144	40	24
Temp-Mat™ with Stainless Steel Wire Retainer	17	17	17	10.2
Knaupf®	10	10	10	6
Jacketed NUKON® with standard bands	10	10	10	6
Unjacketed NUKON®	10	10	10	6
Koolphen-K®	6	6	6	3.6
Diamond Power MIRROR® with standard bands	4	4	4	2.4
Min-K	4	4	4	2.4

(a) Only the same or similar materials listed from each source.
(b) NEDO-32686, Rev. 0, Table 2.
(c) The three values are minimum, median, and maximum failure pressures as functions of radial offset and axial separation, determined from NEDO-32686, Rev. 0, Table 1 data. Failure pressures determined by adjusting NEDO-32686, Rev. 0, Table 1 "A" values by the correction factor (Table 3.3, Section 3.3.1.2) and linearly interpolating to the pressure corresponding to the "corrected A" value.
(d) NEI 04-07, Table 3-1.
(e) SE NEI 04-07, Table 3-2. See Section 3.3.1.2. Failure pressure for saturated water jet.
(f) PWR listing does not specify "modified" "Sure-Hold" bands nor Camloc® Strikers and Latches.
(g) PWR listing includes stainless steel bands.
(h) PWR failure pressure for saturated water jet.

3.3.2.1.2 Coatings Qualification and Type

Comparison of the BWR and PWR industry approaches to coatings debris generation is made with regard to the guidance for qualified and unqualified coatings as well as coating types.

3.3.2.1.2.1 Effect of Coating Qualification

Both the BWR and PWR industry guidance specify that all coating material within the zone of direct LOCA influence fails, regardless of its qualification. The NRC staff supports this position. This approach is conservative, and has a justifiable technical basis.

3.3.2.1.2.2 Coatings Types

The quantity of coating debris generated is a function of the coating thickness. The BWR guidance provides generic values for coatings debris quantities (as shown in Table 3.1; see Section 3.2.1), based on the ZOI area and the coating thickness as described in Bechtel Report 22754094.12A.[23] The specific coating thicknesses from Bechtel Report 22754094.12A are provided in Table 3.6, in comparison with values defined in the PWR guidance. Comments, as discussed below, are also included in Table 3.6.

Table 3.6. Coating thicknesses for BWR and PWR.

	BWR[(a)]		PWR	
Coating	Coating Thickness (inch)	Notes	Coating Thickness (inch)	Notes
Inorganic Zinc (IOZ)	0.005	-	0.003	Default value
Epoxy	0.013	0.005 inch IOZ, plus 0.008 inch epoxy topcoat	0.006	Default value; epoxy or epoxy pheloic topcoat
100% Epoxy	0.015	Up to 0.024 inches possible	-	No information provided
Other[(b)]	-	Up to 0.006 inches possible, depending on coating type	-	No information provided
Unqualified	-	No information provided	0.003	inorganic zinc primer

(a) BWR reference source is Bechtel Report 22754094.12A.
(b) Other coatings include alkyd, vinyl, silicone, silicone alkyd, and silicone acrylic.

Bechtel Report 22754094.12A indicates that some metal surfaces have a three-coat epoxy system, where each coat may be 0.004 to 0.008 inches thick. Thus, the Table 3.6 thickness for 100% epoxy coating is indicated to be low by possibly 0.009 inches. Further, Bechtel Report 22754094.12A indicates that additional coatings (alkyd, vinyl, silicone, silicone alkyd, and silicone acrylic) may be present and have a thickness of up to 0.006 inches, depending on coating type. These coatings are unqualified.[24] No information (i.e., typical maximum thickness) is provided directly to enable the contribution to the debris loading of unqualified coatings to be determined.

The PWR guidance provides default values that are recommended for use, in lieu of plant specific information. The recommended coating thicknesses provided are listed in Table 3.6, for direct comparison to the BWR recommended values. The NRC staff does not accept the PWR guidance provided in NEI 04-07, and recommends that licensees should perform plant-specific evaluations of existing coatings and their current condition.

The NRC staff also recommended increases in the PWR coatings ZOI, as summarized in Section 3.2.2. These recommendations were made due to the different temperature responses of different coatings systems, and because the coatings testing referenced in NEI 04-07 was not performed at conditions replicating the effects of LOCA jet pressures and temperatures. Pressure by itself is not as detrimental to coatings as the synergistic effect of pressure and temperature, as noted in NEDO-32686, Rev. 0.[1]

BWR and PWR coatings types and coatings requirement/standards are specified in Bechtel Report 22754094.12A[23] and ASTM D5144-00 [25] (per NEI 04-07), respectively. Comparison of these two documents provides no indication that coating variations may be expected between reactor types. For example, an inorganic zinc coating in a BWR would be expected to have the same thickness as in a PWR, although, as addressed in the NRC staff recommendation for plant specific evaluations, variations in the actual application both in and between the reactor types are expected.

The greater default thickness of the BWR coatings may result in a more conservative coatings debris quantity, but the "fixed bounding volume" may be nonconservative. No guidance for the determination of the thickness of unqualified coatings is provided for BWRs.

Recommendation 3.3 *A validated basis consistent as applicable between reactor types for qualified and unqualified coatings thickness should be developed.*

3.3.2.3 Effect of ZOI Extent

The BWR guidance (specifically, Methods 2, 3, and 4 for defining the ZOI) and the PWR guidance (specifically, the Baseline ZOI, including Refinements 1 and 2, and the coatings ZOI) result in the potential exclusion of debris sources, depending on the break location, drywell component configuration, and the extent of the ZOI. This issue is expected to be of particular significance for those approaches that rely on a spherical equivalent ZOI (see Table 3.2).

The simplification of defining a spherical ZOI of equivalent volume to the destructive volume of a free jet is assumed to be conservative in the BWR and PWR guidance documents and is accepted as such in the NRC staff evaluations of this approach. This assumption is based on qualitative arguments on the possible dissipation of the energy of the jet due to reflections and deflections from drywell equipment, possible interference from opposing jets, etc. These arguments ignore the long reach of the jet cone, which could carry pressures above the material destruction pressures much farther from the break than would be reached by the spherical ZOI, and the possibility that deflections of the jet could also extend the destruction pressures beyond the reach of the spherical ZOI. Without careful evaluation of specific plant layouts and break locations, it is not clearly demonstrable that the spherical ZOI would in all cases be conservative, compared to a more physically realistic determination of the actual ZOI of the jet(s) that could be generated in a given LOCA.

3.3.2.4 Recommendations for Determining ZOI Extent

Approaches that make use of simplifications (e.g., impingement with barriers, extent of ZOI with regards to debris location, significance of debris source to subsequent head loss, etc.) intended as conservatisms may not in all cases result in conservative estimates of debris quantities. The recomendations in the preceeding sections address the free jet expansion modelling for the ZOI (Recommendation 3.1), the failure pressure of the insulation material (Recommendation 3.2), and the quantity of coating debris in terms of coating thickness (Recommendation 3.3). These recommendations address aspects of debris generation that may significantly alter the quantity of debris generated by a LOCA.

The simplification of relating the extent of the ZOI to the location of debris-generating material is specifically affected by Recommendations 3.1 and 3.2. If the flow field of the LOCA break jet and the material failure pressure(s) are not technically valid, it is not possible to determine that the estimated volume of the zone of influence of the jet is conservative. If this volume is then approximated by a spherical region, there is no assurance of conservatism in the assumption that material outside of the artificially defined spherical ZOI can be excluded as debris sources.

Establishing 1) consistent and validated fundamentals of free jet expansion, 2) the effect of the jet medium, 3) the pressures at which debris-generating materials fail, and 4) the quantity of debris generated (as addressed in Recommendations 3.1 through 3.3) would allow for increased confidence in the conservatism of potentially reducing the quantity of debris generation by means of defining a specific ZOI extent relative to the location of debris-generating material.

Recommendation 3.4 *Reducing potential debris quantity by means of the definition of a specific ZOI extent, debris location, and contribution to subsequent head loss should only be considered after validated and consistent approaches for free-jet expansion, debris material failure pressure, and debris quantity are established.*

3.3.3 Comparison of Debris Generation Outside of the ZOI

The BWR and PWR guidance for insulation and coatings debris generation inside of the ZOI is summarized in Sections 3.1 and 3.2 above. Comparison of the guidance for debris generation outside of the ZOI is made for insulation material in Section 3.3.3.1 and coatings in Section 3.3.3.2.

3.3.3.1 Insulation Debris Generation

The BWR industry position for insulation debris generation outside of a ZOI is that no additional transportable debris would be generated. The PWR guidance specifies that jacketed insulation that is undamaged will not generate transportable debris, but that all unjacketed insulation is presumed to fail. Thus, depending on the ZOI extent and plant-specific quantity of unjacketed insulation, there may be significant additional potential debris sources accounted for in the PWR guidance.

3.3.3.2 Coatings Debris Generation Outside of the ZOI

The BWR industry guidance for coatings debris generation outside of a ZOI is that all unqualified or sufficiently degraded coatings may be available for transport (i.e., will fail and become debris) but allows for licensees to negate its contribution due to a lack of transport mechanism. The NRC staff does not support the latter approach.

The PWR guidance for coating debris generation outside of a ZOI specifies that all exposed DBA-unqualified and unacceptable coatings fail. The NRC staff agrees with this position, but specifies that licensees must periodically assess the DBA-qualified and acceptable coatings to ensure that degradation has not occurred to render them a debris source.

The general BWR and PWR guidance is similar, but the lack of specific details for unqualified coatings (see Section 3.3.2.1.2.2) may allow for differences in debris generation per unit area.

3.3.3.3 Recommendations for Debris Generation Outside of the ZOI

Failure of insulation material and coating systems outside of the ZOI are functions of the post-LOCA environment within containment and the material's properties. Differences in debris generation outside the ZOI for BWRs and PWRs should be due only to differences in the post-LOCA environment.

The PWR position for insulation debris outside of the ZOI, which is to assume that all unjacketed insulation will fail, is clearly more conservative than that of the BWR guidance, which specifies that no additional transportable insulation debris will be generated. However, the difference is impossible to quantify given the disparate ZOI development and debris generation parameters.

The lack of specific details for coatings debris generation (e.g., no BWR guidance is provided for unqualified coatings thickness, so the quantity is indeterminant), confounded in the same manner as with the insulation debris by the disparate ZOI development and debris generation parameters, makes it impossible to determine the conservatism of one approach for coatings debris generation with regards to the other.

The quantity and type of debris generated by a LOCA is impacted by debris generation outside of the ZOI.

Recommendation 3.5	*A validated approach consistent as applicable between reactor types for the failure of insulation and coating systems outside of the ZOI is recommended.*

4. EFFECTS OF DEBRIS IN RECIRCULATION LOOP COOLANT

This section discusses guidance for determining the effects of debris in the recirculation loop coolant. Guidance for BWRs, from the BWROG, is documented in NEDO-32686-A,[1] *Utility Resolution Guidance for ECCS Suction Strainer Blockage*, Volumes 1, 2, 3, and 4, prepared by the BWROG (NEDO-32686-A). Guidance for PWRs, from the Nuclear Energy Institute, is documented in NEI 04-07,[3] *Pressurized Water Reactor Sump Performance Evaluation Methodology*[3] and WCAP-16406-P (Revision 1), *Evaluation of Downstream Sump Debris Effects in Support of GSI-191*. NRC guidance is documented in the SE reports on the BWROG document and on the documents presenting industry guidance for PWRs. Additional guidance is also provided in evaluations of responses to GL 2004-02, NRC Bulletin 95-02, and NRC Bulletin 96-03.

The general structure of this section presents industry guidance, then regulatory guidance, then provides an evaluation and recommendations to reconcile guidance for the two reactor types. First, the relevant points of industry guidance from the listed documents are summarized, with separate subsections for BWRs and PWRs. In these subsections, specific guidance that was not acceptable to NRC is noted. These subsections are followed by a summary of the relevent guidance from NRC, including guidance related to issues not accepted in the industry guidance. Differences in the guidance provided for BWRs and PWRs are then summarized, and finally, specific recommendations are presented to unify and reconcile the guidance provided for both types of reactors. The specific topics discussed are listed below.

1) Section 4.1 discusses guidance for determining the amount of debris captured on the suction strainers.
2) Section 4.2 discusses guidance for determining the amount of debris that passes through the suction strainers. (This section also discusses guidance for determining effects on downstream components.)
3) Section 4.3 discusses guidance for evaluating the effects of debris in the reactor vessel and core.

4.1 Debris Captured on Suction Strainers

This subsection is concerned with guidance provided for examining what happens when the suction strainers capture debris, as they are designed to do. The pressure drop (also expressed as head loss) across the strainer will be greater than it would be if the water were clean (or if all debris were fine enough to simply pass through the screen.) Regulatory Positions 1.1 (PWRs) and 2.1 (BWRs) from Regulatory Guidance 1.82, Revision 3, specify that net positive suction head (NPSH) must be maintained, to ensure the availability of the sump (PWRs) or the suppression pool (BWRs) water supply for long-term cooling of the reactor core in post-LOCA conditions.

Determining the pressure drop across a suction strainer is a relatively straightforward problem in hydraulics when the coolant does not contain debris. The manufacturer generally has performed experimental measurements of pressure loss across the strainer for a range of flow velocities at the conditions of interest, so that the “clean” loss coefficient for a particular plant’s suction strainer design is known from plant-specific analyses and design requirements. It can be presumed that the suction strainers are designed such that this loss coefficient will yield an acceptably low pressure drop for clean fluid. However, the purpose of the suction strainers is to prevent debris from entering the recirculation loops, containment spray loops, and residual heat removal loops, so it must be expected that they could capture a significant amount of debris material in the course of a LOCA event. This will result in an increased pressure drop (or head loss) across the suction strainer, if the ECCS pumps are to maintain the required flow rate of cooling water from the sump or suppression pool.

Determining what the increased head loss will be as a function of debris loading is an issue that must be satisfactorily resolved to show that NPSH can be maintained throughout the LOCA and post-LOCA recirculation cooling. Section 4.1.1 describes the approach recommended by the BWROG for suppression pool suction strainers. Section 4.1.2 describes the approach recommended by the Nuclear Energy Institute (NEI) and Westinghouse Electric for PWR systems. Section 4.1.3 describes the guidance provided by NRC for resolution of this issue. The differences between the guidance developed for BWRs and PWRs are summarized in Section 4.1.4. Recommendations for developing consistent guidance for the two systems are provided in Section 4.1.5.

4.1.1 Guidance from BWROG for Suction Strainer Head Loss Calculations

Guidance for calculating the head loss due to a debris bed on the ECCS suction strainers in a BWR is provided in NEDO-32686-A,[1] in Section 3.2.6.2.2 *Total Strainer Debris Loading.*[(j)] The general approach is as follows:

1. Determine the debris source terms for each of the debris species in the suppression pool (including latent debris and debris generated by the LOCA).
2. Assume that the debris present in the suppression pool accumulates on the functioning strainers in amounts proportional to the flow rate through each strainer, and determine the limiting quantity of debris for each strainer.
3. Calculate the head loss for each functioning strainer, following the methodology and calculational procedures documented in NEDO-32686-A,[1] using plant-specific debris source terms as input. (The methodology is based on evaluation of strainer head loss data obtained at the EPRI/NDE facility in Charlotte, North Carolina, and is documented in Appendices A and B of C.D.I. Report No. 95-09,[(k)] *Testing of Alternate Strainers with Insulation Fiber and Other Debris*, Revision 4, prepared by Continuum Dynamics, Inc,. Princeton, New Jersey,[29] This report is contained in the BWROG guidance document.)

Appendix A of C.D.I. Report No. 95-09 in the BWROG guidance document provides guidance for determining strainer head loss due to fibrous debris in combination with sludge and other miscellaneous debris. The guidance document notes that this evaluation must be conducted for

(j) This is part of Subsection *3.2.6 Verification of Adequate ECCS Pump NPSH*, in Section *3.2 Methodology for Sizing Passive ECCS Suction Strainers*.

(k) The C.D.I report is Reference 3 of NEDO-32686-A and appears in Volume 2 of the Utility Resolution Guidance document.

every plant, since it is assumed that some quantity of fiber will in every case be present in the suppression pool post-LOCA, even for plants that have primarily reflective metal insulation. Appendix B of C.D.I. Report No. 95-09 in the BWROG guidance document provides guidance for determining strainer head loss due to RMI debris. For plants with both types of insulation, the guidance document recommends that the higher of the limiting strainer head loss values determined from these two approaches should be used as the input for determining ECCS pump NPSH. (The SE issued by NRC on this document does not endorse this recommendation. See Section 4.1.3.)

The experimental data used to develop the BWROG guidance for determining strainer head loss consists of testing with five[(l)] full-size passive strainers of different designs. These included a truncated cone, a 20-point star, two stacked-disk designs (prototypes #1 and #2 from Performance Contracting, Inc.), and a 60-point star design. Of these alternative strainer designs, only the stacked-disk configuration has been developed and installed in BWR plant suppression pools as part of the response to the strainer clogging issue. (It should be noted, however, that none of the specific designs tested are directly prototypic of new strainers installed in operating plants.)

The passive strainer designs were tested with varying quantities of debris consisting of fibrous insulation, RMI, corrosion products, and miscellaneous debris, over a range of flow rates. For plants with debris species that were not included in the testing (as documented in Reference 3 of NEDO-32686-A), the guidance document recommends that the licensee develop the necessary "estimated adjustments" to the model developed from the test data, to calculate the head loss due to the untested debris species. Precisely how this could be done in a physically correct manner is not specified.

The test results are presented in the BWROG guidance document as non-dimensional head loss curves correlated to the ratio of the fiber bed thickness and the strainer diameter, which is defined as the diameter of the (uniform) stacked discs. The maximum fiber bed thickness-to-diameter ratio obtained in the testing is assumed bounding. Without presenting any dimensional analysis to justify this ratio as a physically meaningful scaled relationship, the BWROG guidance document asserts that a lower fiber bed thickness-to-diameter ratio "assures applicability of the existing non-dimensional head loss correlation." For strainers with higher fiber loadings, however, the document notes that strainer-specific testing may be required. The guidance document also notes that it is the responsibility of the licensee to develop documentation supporting any adjustments in the head loss calculation.

If the head loss calculation shows that adequate NPSH is available to the ECCS pump, then the strainer design is assumed to be acceptable (provided all other strainer design requirements not related to NPSH are also satisfied). If the analysis shows that adequate NPSH is not available for the worst-case conditions, further guidance is provided on ways to reduce the calculated strainer head loss. The following subsections describe the detailed guidance provided for each step in the analysis.

(l) The document describes seven strainer designs tested, but one was an "active" strainer, and another was only a 2/3[rd] segment of a particular design. So in effect, the testing included only five prototypic passive suction strainer types.

4.1.1.1 Passive Strainer Head Loss with Fibrous Debris and Pool Sludge

In Appendix A of C.D.I. Report No. 95-09 in NEDO-32686-A, the BWROG guidance document presents a step-by-step procedure for calculating passive strainer head loss across a fibrous debris bed with corrosion products and other debris. The strainer geometry must scale uniformly to the geometry of one of the tested strainers (i.e., all dimensions match the tested strainer dimensions if multiplied by a single constant). This approach uses a relationship fitted to the test data by least-squares approximation to express the head loss across the debris bed on a given strainer as a function of

- the Reynolds number of flow through the bed (defined using the inter-fiber spacing as the characteristic length)
- the ratio of the mass of corrosion products to the mass of fiber debris
- the approach velocity to the strainer
- the nominal thickness of the fiber bed
- the inter-fiber spacing
- the viscosity and density of the water in the pool
- the acceleration of gravity
- empirical coefficients from the data-fitting process.

The BWROG guidance document notes that in applying this procedure, the licensee must determine the appropriate plant-specific input values for the mass of corrosion products in the suppression pool and the volume and mass of fiber debris generated in a given LOCA. The approach velocity must also be calculated based on required ECCS flow rates. The inter-fiber spacing of the intact insulation, which defines an upper bound on the size of fiber debris, must be determined for the plant-specific fibrous insulation. (Appendix E of C.D.I. Report No. 95-09 in the BWROG guidance document provides values for Nukon®, Kaowool®, and Tempmat®.)

For plants with no other debris sources than fibrous insulation and the sludge in the suppression pool, the BWROG guidance document asserts that this is all that needs to be done to determine the strainer head loss. For most plants, however, it is expected that there will be other types of debris, such as RMI particulate or other miscellaneous debris, and the analysis must continue to follow the procedural steps for determining the possibly greater head loss due to the presence of these materials.

4.1.1.2 Passive Strainer Head Loss with Fiber, Pool Sludge, and Miscellaneous Debris

In this context, "miscellaneous" debris refers specifically to paint chips, rust flakes, cement dust, sand, zinc, and calcium silicate. These are the materials that were tested in the experiments reported in C.D.I. Report No. 95-09 in the guidance document (NEDO-32686-A),[1] and have empirical coefficients listed for use in the head loss calculation. However, the testing to obtain information on the head loss effects of this material was not performed in the same manner as the testing with fibrous debris and corrosion products (pool sludge) only.

In the tests with fibrous debris and pool sludge, a pumped loop drove the required flow rate through the strainer, simulating the effect of flow drawn into the ECCS recirculation loop. For the miscellaneous debris, the testing was performed in a "gravity head" apparatus. This consisted of a vertical pipe containing a static column of water supported from below, with the strainer being tested inserted near the bottom of the column. A predetermined load of miscellaneous debris was placed on the strainer or suspended in the column of water, and at the appropriate time, a trap door was opened suddenly at the base of the pipe. The head loss was determined by measuring the fall in the water level in the pipe, and the time required for the level to travel a specified distance.

The effect of this debris on the overall head loss for the strainer is accounted for with a factor, K_{bu}, termed the "bump up" factor, which is multiplied by the head loss due to fiber and pool sludge only. The recommended procedure is to define K_{bu} as the ratio of the head loss calculated for all debris sources over the head loss for the fiber and pool sludge only (calculated as described in Section 4.1.1.1 above.) That is,

$$K_{bu} = \frac{\Delta H_{all\,debris}}{\Delta H_{fiber+sludge}}$$

The ΔH terms in the above ratio are simplified to linear functions of the approach velocity, $\Delta H = a+b\mathrm{U}$, and the coefficients a and b are defined from the test data for the debris material tested. The coefficients consist of empirically determined weighted summations of the mass fractions of the various components present in the debris. The strainer head loss is calculated as the value obtained for the fiber and sludge alone (as described in Section 4.1.1.1), times the "bump up" factor.

4.1.1.3 Passive Strainer Head Loss with RMI Debris

In Appendix B of C.D.I. Report No. 95-09 in NEDO-32686-A, the guidance document presents a step-by-step procedure for calculating passive strainer head loss across a debris bed that includes RMI fragments. The basis for the recommended approach is the full-scale testing at the Electric Power Research Institute (EPRI) Non-Destructive Evaluation (NDE) center (documented in C.D.I. Report No. 95-09 in NEDO-32686-A) and blast-test RMI samples obtained in another test program. Only three of the five strainer designs were tested with RMI debris in the testing at the EPRI facility: the truncated cone, the 20-point star, and the 60-point star designs. Test measurements were obtained for the three strainer types with debris from 1.5-mil aluminum, 6.0-mil aluminum, and 2.5-mil stainless steel RMI. The stacked disk prototype #1 and #2 strainers, which are the only designs in this test series that resemble advanced strainers installed in BWRs, were not tested with RMI debris. The guidance document asserts that the available data can be extrapolated for the material of interest.

The procedure recommended in the BWROG guidance document gives the head loss across the RMI debris bed as a function of the approach velocity, the projected bed thickness, and empirical coefficients derived from the test data. The guidance document notes that this approach is valid only if the head loss across the bed is less than 10 ft of water (4.33 psi), which is the maximum height of the water column in the gravity head testing reported in C.D.I. Report No. 95-09 in NEDO-32686-A. The BWROG guidance document does not provide any recommendations for alternative approaches if this calculation produces a head loss greater than 10 ft of water.

Even for plants using only reflective metal insulation, the BWROG guidance document assumes that there will be some quantity of fibrous debris present, and there will always be sludge (corrosion products) in the suppression pool. Therefore, the recommended approach for determining the total strainer head loss is to calculate a value for the fiber and sludge alone (using the Appendix A methodology, as described in Section 4.1.1.1), and a value for RMI debris (using the Appendix B methodology), and take the higher of the two for the NPSH margin calculation. Similarly, if the plant also contains a significant quantity of miscellaneous debris, the total strainer head loss is taken as the higher of the value due to RMI debris and the value obtained for fiber, sludge, and miscellaneous debris (using the Appendix A methodology, as described in Section 4.1.1.2). (The SE issued by NRC on this document does not endorse this recommendation. See Section 4.1.3.)

4.1.1.4 Thin Bed Head Loss on Passive Strainers

The BWROG guidance document acknowledges that for flat plate strainers (typical of those installed at many BWRs prior to remediation in response to NRCB 95-02 and NRCB 96-03), the head loss can be high with only a small amount of fiber in the coolant. The BWROG guidance document defines this as an amount required to cover the strainer to a depth of about $^{1}/_{8}$ inch. (Subsequently, it has been found that filtering beds can occur at even lower fibrous debris loads, as noted in the SE for the BWROG guidance document. See Section 4.1.3.) The BWROG guidance document notes that this thin bed effect (TBE) "may not be applicable to strainers with low approach velocities, such as a strainer with large surface area," and that for alternate geometry strainers, such as the star and stacked disk strainers, the TBE does not occur.

The recommendation in the BWROG guidance document for dealing with the TBE is two-fold. For plant-specific evaluations where the strainer design corresponds to any of the alternate geometries tested to develop the methodology from Appendix A of C.D.I. Report No. 95-09 in NEDO-32686-A, the BWROG guidance document indicates that it is not necessary to consider the TBE. The guidance document asserts that these strainer designs do not develop thin debris beds, and therefore it is necessary to consider only the maximum quantity of fibrous debris available for deposition on the strainer. For flat plate designs, such as a truncated cone strainer, the evaluation of head loss should consider both the maximum fibrous debris source term and a source term that is sufficient to cover the strainer flow area to a depth of only $^{1}/_{8}$ inch. In such cases, the higher of the two values should be used to calculate the NPSH margin for the ECCS pumps.

4.1.1.5 Active Clearing of Debris from Suction Strainers

The BWROG evaluated two possible methods for actively mitigating the build-up of debris on the suction strainers; back-flushing during ECCS operation, and a "self-cleaning" strainer design in which a mechanical system would remove debris from the strainer. The guidance document specifically recommends against the use of strainer backflush as the primary means of verifying that debris clogging will not compromise NPSH margin. The main reason for this position is the time frame and frequency of backflushing required for it to be effective. However, the guidance document suggests that use of backflush for "defense in depth" might be a viable option to consider for plants with existing capability to perform such an operation.

The BWROG evaluation of the effectiveness of "self-cleaning" strainers included testing the performance of a single active strainer as part of the experimental program at the EPRI/NDE facility for alternative passive strainer designs. The "self-cleaning" strainer includes a rotating plow and brush assembly driven by a water-powered turbine. Water passing through the strainer provides the motive force so that the device removes debris from the flat front face of the strainer. The experimental results showed that the design is effective for the debris types and loadings tested.

The guidance document recommends installing a self-cleaning strainer design only if it proves impossible to achieve the required system performance with passive strainers. Although the BWROG considers self-cleaning strainers as a potentially effective option for mitigating the problems associated with debris in the suppression pool coolant, there are significant issues that must be addressed. These include qualifying the design as safety-grade equipment, performing adequate testing to qualify the design for the full range of operating conditions, and developing appropriate maintenance, surveillance, and instrumentation requirements for the active strainers. In addition, the evaluation must consider the effect of debris on downstream components.

4.1.2 Industry Guidance for Suction Strainer Head Loss Calculations in PWRs

The recommended "baseline methodology" for calculating the head loss from a debris bed that could form on the ECCS suction strainers[m] in a PWR is documented in Section 3.7 of NEI 04-07.[3] Sample problems for insulation debris are provided in the industry guidance document to illustrate the methodology, which consists of three basic steps:

1. Determine the clean suction strainer head loss.
2. Determine the head loss due to the debris bed on the suction strainer.
3. Add the results of the first two steps and compare to the plant-specific NPSH margin.

If the total head loss is below the NPSH limit for the "worst case" debris bed, no further analysis is needed to show that sufficient NPSH margin exists even when the strainers are fouled with debris. If the predicted total head loss across the suction strainer and debris bed is too high to maintain NPSH margin, further guidance is provided in Section 4 of NEI 04-07.[3] The following subsections describe the detailed guidance provided for each step in the analysis.

4.1.2.1 Clean Suction Strainer Head Loss

The clean screen head loss (CSHL) for an unfouled suction strainer is dependent on plant-specific screen design, sump geometry, and thermal-hydraulic conditions in the sump during the particular LOCA being evaluated. The CSHL depends mainly on the size of the openings in the strainer (mesh for wire-grids or hole diameter and pitch for perforated plates), the flow rate through the strainer, the water temperature and pressure, and the depth of water in the sump (which may not be sufficient to fully submerge the strainers during portions of some LOCA scenarios.)

(m) In the NEI document, the suction strainers are referred to as "sump screens," using the terminology for PWRs current at that time. The term "suction strainer" has since been adopted as applicable to both PWRs and BWRs, and is used throughout this section.

The guidance document does not provide detailed directions on how to calculate the clean strainer head loss, since this is simply an exercise in the standard methods of analysis in fluid mechanics. However, it is helpfully noted that some of this information is typically available from the manufacturer of the strainer material, and in some cases, the CSHL has been documented in other plant licensing calculations. The guidance document also notes that it may be necessary to include losses due to plant-specific features of the sump screen in the overall CSHL calculation, such as the support structures, bracing (for mechanical loads), and other sump structures, such as vortex suppressors.

4.1.2.2 Debris Bed Head Loss

The methodology recommended in the industry guidance document provides an approach for determining the debris bed head loss for a given total quantity and type of debris over a specified surface area at a given ECCS pump flow rate. The approach is based on the following scenario:

1. The suction strainer is initially clean, but the LOCA is filling the floor pool with coolant containing a homogenous mixture of debris (latent and LOCA-generated).
2. At switchover of ECCS pump suction from the water storage tank to the recirculation sump, debris-laden coolant begins to move through the suction strainer.
3. Debris smaller than the screen mesh (or hole size) passes through the strainer, but larger debris begins to form a debris bed on the surface of the strainer. It is assumed that the debris bed covers the strainer surface uniformly and continues to build until all available debris has been deposited on the strainer.
    a. For fibrous debris, or a mixture of fiber and particulate debris, the fibers form a fibrous mat that will also trap particulate once the mat has formed.
    b. For debris consisting only of RMI particles, the debris bed forms mainly because of particles larger than the strainer holes building up on the surface.
    c. For mixed debris beds consisting of fiber, particulate, and RMI particles, the debris bed is assumed to form in much the same way as with mixed fiber and particulate debris, except that the fiber bed traps RMI fragments as well as other particulate debris.
    d. For particulate debris (which could also include RMI particles, but not fiber) or a mixture of particulate and fibrous debris, the debris bed forms because of particles larger than the strainer holes building up on the screen surface.
4. The debris bed is assumed to cover the entire strainer and build up with a uniform thickness. As the debris bed builds, the head loss across the bed increases until a steady-state value is reached with the debris bed at its thickest condition.

The approach in the guidance document does not provide a method for directly analyzing the process described in the above scenario. Instead, it recommends specific head loss correlations for determining the final steady-state head loss across the fully formed debris bed, as described in step 4 of the basic scenario. However, the SE issued by NRC on this document does not accept the use of correlations, and recommends more comprehensive treatment of debris bed formation, including thin bed effect. This is discussed in Section 4.1.3.

4.1.2.2.1 Fiber and Particulate Debris Bed

For a debris bed consisting of fibers and particulate material, the industry guidance document recommends the head loss correlation presented in NUREG/CR-6224, *Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris*.[30] The correlation, which is generally referred to as "the NUREG/CR-6224 correlation," was developed from test data[(n)] modeling debris accumulation on suction strainers in a BWR suppression pool. The issues of debris blockage are similar for BWRs and PWRs, and it is the position of the guidance document from NEI that the validated range of the correlation makes it equally applicable to PWR systems.

The general form of the correlation reflects a semi-empirical simplification of the momentum equation for flow through a particle bed. It has two additive components, the first one linear with velocity (for laminar flow) and the second one with a second-order velocity term (for turbulent flow). This relationship gives pressure drop as a function of the bed porosity, the superficial velocity of the fluid (i.e., volumetric flow divided by the total cross-sectional area of the bed perpendicular to the flow direction), and various geometric and empirical coefficients.

From this basic model, the NUREG/CR-6224 correlation was developed to give head loss across a debris bed as a function of the following parameters:

1. the fluid approach velocity (i.e., the volumetric flow rate through the strainer, divided by the effective surface area)
2. the density and viscosity of the water
3. the mixed debris bed "solidity" (i.e., one minus the porosity of the bed)
4. the surface-to-volume ratio of the debris forming the bed
5. the actual debris bed thickness.

For conservatism, the industry guidance document recommends using the highest flow rate through the strainer, based on the maximum pump flows "as identified in current NPSH calculations" (see p. 3-55 of NEI 04-07).[3] The density and viscosity of the water are properties determined primarily by the water temperature, and as a conservative simplification, the guidance document suggests that the lowest expected temperature during ECCS operation may be used for the head loss analysis. If a more realistic estimate is needed, it may be necessary to examine thermal-hydraulic conditions in the sump calculated at multiple times during the LOCA transient, since it is not obvious which temperature and flow rate would be limiting.

The remaining three parameters that must be quantified to apply the NUREG/CR-6224 correlation depend on the physical properties of the debris, including density, geometric shape, and size distribution. Drawing on the work in NUREG/CR-6224 and NUREG/CR-6371,[31] the guidance document presents relationships for the solidity, the surface-to-volume ratio of the debris, and the bed thickness, and describes a computational procedure for applying this

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(n) The debris bed in this testing consisted of Nukon® fiber and iron oxide particulate, but in the NEI document, the correlation is assumed to apply to any debris bed consisting of only fiber and particulate. This approach was not accepted by the NRC. See Section 4.1.3.

empirical model. The procedure yields a converged estimate of the head loss and thickness for the debris bed.

The industry guidance document also contains repeated reminders within the discussion of individual components of the correlation that this is an empirical model. When applied in plant-specific analysis, it is necessary to determine that the validation data appropriately represent the debris type(s), mixture, and concentrations as well as the thermal-hydraulic conditions of the plant. If the plant-specific materials or combinations of materials are not included in the database, then head loss testing of the material(s) may be required to validate the NUREG/CR-6224 correlation for the plant-specific conditions.

4.1.2.2.2 RMI Debris Bed

For a debris bed consisting only of RMI fragments, the industry guidance document recommends essentially the same approach as described above for a fiber-and-particle bed, but with a different head loss correlation. For an RMI debris bed, the guidance document recommends the head loss correlation presented in NUREG/CR-6808,[32] *Knowledge Base for Effect of Debris on Pressurized Water Reactor Emergency Core Cooling Sump Performance* (2003). This correlation is based on testing with RMI debris and is an empirical function of the approach velocity (squared), geometry factors, the interfoil gap thickness, and an empirical coefficient. The interfoil gap thickness is an empirical parameter determined from testing documented in NUREG/CR-6808.[32]

The industry guidance document shows an example of a bounding formula for 2.5-mil stainless steel RMI debris. However, the document does not include guidance on how to determine suitably conservative empirical parameters for plant-specific conditions that are not bounded by the validation database of the correlation presented in NUREG/CR-6808.[32]

4.1.2.2.3 Mixed Debris Bed (fiber, particulates, and RMI)

For a mixed debris bed consisting of fiber, particulates, and RMI particles, the industry guidance document recommends developing a conservative estimate of head loss by superposition. The NUREG/CR-6224 [30] correlation, described in Section 4.1.2.2.1 above, is used to estimate the head loss, assuming that the bed is composed only of fiber and ordinary particulate. The correlation from NUREG/CR-6808 [32] is then used to estimate the head loss, assuming the debris bed is composed only of RMI fragments. The total head loss of the debris bed is then estimated as the sum of the two independent models.

The guidance document considers this approach automatically conservative, and notes that there is no need to consider the actual form of the mixed debris bed. The document further notes that this approach may give “overly conservative” results for conditions where there are only “trace amounts” of fibrous material in the total debris load. More realistic methods may be required for analysis of plants where there are only trace amounts of either RMI or fiber in the mixed debris load.

4.1.2.2.4 Particulate Debris and Mixed Particulate and Fiber Debris Bed

The industry guidance document recommends that particulate debris from calcium silicate (Cal-Sil)[(o)] alone or microporous insulation alone can be treated simply as particulate debris using the correlation from NUREG/CR-6808,[32] as described in Section 4.1.2.2.2 above for RMI-only debris beds. Only limited data are available for debris beds composed of these materials, and if plant-specific measurements are required, the testing parameters must include appropriate particle sizes, size distributions, and surface-to-volume ratios. For a mixed bed of microporous and Cal-Sil particulate, the limited available data show relatively high head loss, and NUREG/CR-6224 [30] does not appear to be applicable.

For beds composed of fibrous debris mixed with particulate material (Cal-Sil or microporous material), the head loss for the bed can be treated as purely fibrous debris using the NUREG/CR-6224 head loss correlation, if the particulate material is less than about 20% of the debris by mass. At concentrations above 20%, this correlation tends to be non-conservative. The industry guidance document notes that there is not sufficient data currently to develop a general correlation for this type of debris and recommends removing such insulation from the plant, if possible, or reducing it to less than 20% of potential debris. If that is not an option, it may be necessary to perform experiments for plant-specific conditions.

4.1.2.3 Thin Bed Head Loss

The industry guidance document for PWRs (NEI 04-07) recommends that as part of the sensitivity studies to determine the most limiting debris loading configuration, the analysis should include the case of sufficient fiber to form only a thin bed $^{1}/_{8}$-inch thick. In this case, the particulate material in the plant-specific mixture of debris will form a particulate layer of debris on top of the fiber bed, which may result in a higher head loss than would be obtained with a thicker bed with more uniformly distributed particles trapped within it. This is referred to as the thin bed effect (TBE).[(p)] The recommended approaches for the head loss calculations are as described above for fiber and particulate beds (see Section 4.1.2.2.1), using a formulation of the NUREG/CR-6224 correlation optimized for debris loading that could create a thin bed on the strainer.

4.1.2.4 Partially Submerged Strainer

The guidance document recommends that the same head loss computation methods described above assuming a fully submerged strainer are applicable to a partially submerged strainer. The only significant variation is in accounting for the reduced effective strainer area. It is also necessary to account for buoyant debris that would tend to congregate around the strainers because of the net flow toward the sump. If the debris transport analysis shows that only a negligible amount of buoyant debris can reach the suction strainers because of upstream trash racks and gates, this factor can be neglected in the head loss analysis.

(o) Cal-Sil is used in many PWRs and has a wide range of composition materials, including diatomaceous earths, perlite, and asbestos fibers. Plant-specific characterization (using scanning electron microscopy, at a minimum) is warranted to fully characterize the material.

(p) This approach was based on limited information related to the thin bed effect, and was not accepted in the SE of this document. See Section 4.1.3. The general definition of the 'thin bed effect' has been expanded to include a dense particulate layer that may form *in or on* a fiber bed.

However, rather than using total head loss in comparison to NPSH, the guidance document suggests that as an alternative, the bed thickness can be used as the sole criterion for evaluating suction strainer performance. The document states that numerical simulations[q] "confirm" that a debris bed height of approximately one-half of the pool height will prevent adequate water flow to the recirculation loop. Therefore, if the total calculated head loss (in feet of water) across the submerged portion of the strainer (i.e., debris bed head loss plus the "clean" head loss) is less than one-half the pool height, the partially submerged strainer can be expected to operate properly.

4.1.2.5 Alternative Methods for Head Loss Calculations

The Baseline Methodology recommended for suction strainer head loss calculations, summarized in the preceding sections, relies primarily on the NUREG/CR-6224 correlation, developed and validated with data from flat, horizontal screens. Section 4.2.5 of NEI 04-07 offers guidance for refinements that could make the analysis somewhat more realistic or better fitted to plant-specific conditions. The document specifically recommends that analysis should include a transient model that can investigate a range of the following features:

- amount and type(s) of debris reaching the strainers and the rate of transport at any given time during the LOCA and post-LOCA recirculation cooling
- size distribution and type of debris reaching the strainer
- filtration efficiency of the fibrous bed (i.e., how well it traps particulate material)
- ECCS flow rate (approach velocity)
- recirculation pool temperature
- plant-specific geometry for sump dimensions, strainer configuration, number and arrangement of strainers, and flood height.

The industry guidance document discusses a number of areas where the simplifications and conservatisms in the Baseline Methodology could be refined to yield a potentially more realistic estimate of head loss across the debris-laden strainer. These are discussed only as suggestions and in general invite the licensee to undertake a considerable body of work to develop and validate an alternative approach. The guidance document also notes that new advanced suction strainer designs, particularly self-cleaning or "active" strainers, will require developing new head loss correlations, since these strainers will not generally fall within the databases of existing correlations such as the NUREG/CR-6224 correlation. These correlations "should be developed by the designer and/or vendor of the new sump screen."

4.1.3 Regulatory Guidance on Head Loss across Suction Strainers

NRC issued SE reports on the BWROG guidance document (NEDO-32686) and the main guidance document for PWRs (NEI-04-07) in 1998 and 2004, respectively. In general, the NRC evaluations concluded that there is sufficient overall conservatism in the methodologies presented in the guidance documents, but certain portions of these documents were specifically not accepted. The unacceptable portions generally involved concerns related to the conservatism

(q) The guidance document does not provide a specific reference for these calculations, nor does it identify the code used.

or completeness of selected parameters, or insufficient technical justification of an approach. Additional work would be required in plant-specific submittals utilizing these aspects of the user group guidance document.

In addition to the SE reports on the guidance documents, NRC developed guidance for responses to GL 2004-02 and NRC Bulletins 96-03 and 95-02. Section 4.1.3.1 summarized the Regulatory guidance for BWRs. Section 4.1.3.2 summarizes the Regulatory guidance for PWRs.

4.1.3.1 Regulatory Guidance for BWRs

In the SE issued in 1998 for the BWROG guidance document, the methodology for determining strainer head loss with debris in the coolant was judged insufficient and potentially non-conservative for some debris configurations. NRC staff evaluations also recommended using head loss correlations developed by the vendors, based on performance testing with prototypic or conservative debris loading, rather than the correlations developed in the BWROG document. Furthermore, in other work related to the strainer clogging issue, including staff evaluations that led to the issuance of NRC Bulletins 95-02 and 96-03, NRC staff concluded that the then-existing BWR strainer designs required modification to ensure adequate functionality in post-LOCA conditions. Installation of alternative passive strainers with larger surface area was suggested as a possible resolution option.[r]

Closure of the multi-plant actions (MPAs) related to NRC Bulletins 95-02 and 96-03 is documented in NRC Memorandum[s] *Completion of Staff Reviews of NRC Bulletin 96-03 –* ***Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling Water Reactors****, and NRC Bulletin 95-02 –* ***Unexpected Clogging of a Residual Heat Removal (RHR) Pump Strainer while Operating in Suppression Pool Cooling Mode***, issued October 18, 2001. In evaluating responses to NRCB 95-02, NRC staff concluded that BWR licensees are cognizant of the need to minimize latent debris sources by regular cleaning of the suppression pool and by developing and maintaining pro-active housekeeping procedures and FME programs. In evaluating responses to NRCB 96-03, NRC staff concluded that the installation of large-capacity passive strainers provides conservative assurance that NPSH can be maintained when operating the ECCS in recirculation mode during a LOCA.

In essence, the regulatory guidance to BWR licensees on this issue consists of two main positions. First, licensees should minimize debris source terms through regular cleaning of the suppression pool, effective housekeeping practices, and a pro-active FME program. Second, the licensees should install alternative strainers with designs that have been adequately tested and validated by the manufacturer or vendor, including testing to determine the effect of debris loading on strainer head loss. The SE of the BWROG document does not, however, include detailed guidance on the type and extent of testing that must be performed to demonstrate the conservatism of a particular strainer design. Acceptability of a given methodology for validation

(r) Other resolution options presented in the BWROG document include installation of self-cleaning strainers, or developing operational procedures for a backflush system. In the SE for this document, NRC staff specifically discouraged the use of self-cleaning strainers, and recommended backflushing only as a “defense-in-depth” measure. All BWR licensees chose to implement the option of installing large capacity passive strainers.

(s) ADAMS accession number ML012970229.

of a strainer design is determined in evaluations of topical reports submitted by vendors or licensees.

4.1.3.2 Regulatory Guidance for PWRs

In the SE of the NEI guidance document for PWRs, issued in 2004, the basic approach of using the NUREG/CR-6224 correlation or variations of this correlation to determine head loss across a debris-laden suction strainer was rejected as unsupportable with the existing database of the correlation. PWR licensees using this correlation were required to provide appropriate experimental data demonstrating that this correlation could accurately predict head loss across their specific suction strainer design with the worst-case debris bed that could be generated in their particular plant. Alternatively, licensees could demonstrate the conservatism of their suction strainer design by obtaining appropriate experimental data showing that the head loss would remain low enough to maintain NPSH for the most adverse potential debris loading during a LOCA.

In effect, these two alternatives require essentially the same type of work, and PWR licensees opted to conduct prototypical head loss testing to qualify designs of plant-specific replacement suction strainers. NRC staff developed detailed review guidance to establish appropriate evaluation criteria for review of plant-specific submittals. This work included guidance for plant-specific chemical effect evaluations and coatings evaluations (which are discussed in Sections 2 and 3 of this report), as well as guidance for strainer head loss evaluations.

The documentation of regulatory positions regarding strainer head loss for PWRs is provided in *NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Strainer Head Loss and Vortexing*, issued[t] March 2008. This document contains detailed guidance in the areas of test scaling, debris near-field settlement simulation, surrogate debris similitude requirements, testing procedures, post-test data processing, and extrapolation to conditions beyond the tested database. Specific items covered in this document were taken directly from the *Content Guide for Generic Letter 2004-02 Supplemental Responses* (ML073110278), and are briefly summarized here.

1. Item #1: provide a summary of the methodology, assumptions, and results of prototypical head loss testing for the strainer (including chemical effects), including
    a. basis for scaling debris amounts and flow rates
    b. preparation of surrogate debris, and how it compares to actual debris
    c. paint chips or particulate paint debris should be shown to be conservative or prototypical with regard to head loss
    d. discussion of how near-field settlement was treated in testing
    e. discussion how debris is prepared and introduced into the fluid
    f. complete definition of basis for test termination, to assure that testing captured the maximum head loss
    g. discussion of method for modeling of representative geometries for sump pit and other hardware that could affect coolant flow path

(t) This document has ADAMS accession number ML080230038 and is available from the NRC web site.

h. discussion of thin bed and circumscribed beds, as appropriate

i. explanation of how chemical effects were accounted for during testing

j. addition of relevant vendor test reports, calculations, and specifications in the submittal

2. Item #2: show that the design can accommodate the maximum volume of debris that is predicted to arrive at the strainer;

   a. explain what the maximum debris load is expected to be and how the strainer design accommodates it

   b. for testing, the maximum debris load should include 100% (scaled) of the debris from the break being tested

   c. if significantly different debris mixtures can result from different postulated breaks, each should be tested or evaluated

3. Item #3: show that the strainer design prevents formation of a thin bed, or can accommodate partial thin bed formation;

   a. testing should include attempts to form a thin bed by incremental addition of fiber (in the form of easily suspended fines)

   b. Determine the most problematic debris loads and describe how they were implemented in the testing

4. Item #4: provide a summary of the methodology, assumptions, and results for the clean strainer head loss calculation (vendor reports are acceptable for this purpose)

5. Item #5: provide a summary of the methodology, assumptions, and results for the debris head loss analysis

6. Item #6: determine if the suction strainers are partially submerged or vented for any accident scenario. Describe any other failure criteria (in addition to loss of NPSH) that are used to address flow blockage at the strainer

   a. If not fully submerged, a strainer is assumed to fail if the head loss across the strainer exceeds half the height of the pool (unless the licensee can show otherwise)

7. Item #7: if near-field settling is credited in the head-loss testing, it must be justified as prototypic of plant conditions.

   a. near-field settling in the testing should not be allowed to occur, unless the licensee can show that it would actually occurs in the plant; even in such case, the flow and turbulence near the test strainer must be prototypic, or demonstrably conservative

   b. In plants with complex or widely varying flow parameters in the post-LOCA sump, the testing must include the full range of conditions; average flow rates are unlikely to be sufficient

8. Item #8: If temperature/viscosity relationships are used to scale test results to plant conditions, provide the basis for determining that in the testing, "boreholes or other differential-pressure induced effects did not affect the morphology of the test debris bed."

9. Item #9: describe the role of containment accident pressure in evaluating whether or not flashing would occur across the strainer surface

In addition to the detailed discussion of the items summarized in the above list, Appendix A of the regulatory guidance document contains more in-depth discussions on the approach to strainer head loss testing and the application of the test results to plant head loss evaluations. Specifically, NRC staff have observed testing for some PWR replacement strainer designs, and have noted problems with testing practices that could affect the prototypicality or conservatism of testing. These issues include (but may not be limited to)

1. Test strainer not scaled appropriately to the plant strainer design
2. Debris simulants not prototypic of plant materials
3. Debris transport in the test flume or test tank/sump not prototypic to the plant
4. Duration of testing not long enough to determine peak head losses
5. Post-test scaling of test data to plant conditions not technically correct
6. Thin bed testing is inadequate
7. Insufficient consideration of sequence of debris components in the testing.

The regulatory guidance document contains detailed discussions of each of these issues, and also includes NRC positions of the specifics of test facility design, testing procedures, and treatment of test data. Applicants are directed to consider conservative plant hydraulic conditions, and worst-case failure assumptions. Conservative assumptions for analytical modeling to determine "inputs" to the head loss testing must consider conservative plant hydraulic conditions, and conservative debris loading on the strainer. This includes

- All ECCS and CSS pumps are in operation for an extended period (up to the 30-day maximum mission time), resulting in maximum flow rate determined for "worst-case single failure assumption"
- Sump pool subcooling is assumed to be at minimum at the start of recirculation phase
- Sump pool is operating at minimum level
- Eroded fine fiber debris is assumed present at the strainer at the beginning of recirculation phase
- Agglomeration and/or settling out of debris in the sump pool is (usually) not taken into account
- Debris generation rate, amount, type, sequence of arrival in sump, etc., is determined from "worst-case single failure assumption"

If the inputs to the head loss testing are conservative, the test facility is scaled properly, and the testing procedures are conservative, the NRC staff considers that the measured head loss is also conservative.

4.1.4 Comparison of Regulatory Guidance for BWRs and PWRs

For both PWR and BWR analysis, the basis of the guidance provided by the respective industry representatives is experimental testing of various strainer designs under various conditions of debris loading. The industry guidance for PWRs relies on empirical correlations derived and validated for a range of strainer types and debris constituents. The BWROG guidance relies on empirical models developed from generic testing with seven alternative strainer designs, only two of which were similar in configuration to advanced strainer designs installed by licensees. For plant-specific conditions (i.e., strainer configurations, or debris characteristics) that are outside the ranges of the relevant experimental databases, both guidance documents warn licensees that they must justify extrapolation of the models, and this may require additional testing.

Although NRC approved both the BWROG guidance document (NEDO-32686-A) and the guidance document for PWRs (NEI-04-07), NRC staff did not accept the approach used in either document for determining debris laden strainer head loss. For PWRs and BWRs, NRC staff have recommended testing of suction strainer designs. The main difference is in the level of specificity of the guidance provided.

For BWR licensees, regulatory guidance is to install alternative strainers with designs that have been adequately tested and validated, including testing to determine the effect of debris loading on strainer head loss. The guidance does not, however, include details on the type and extent of testing that must be performed to demonstrate the conservatism of a strainer design. Documentation[33] of testing of large-area stacked disk strainer designs by the two main vendors (General Electric and Performance Contracting, Inc., which have provided approximately 80% of alternative strainers in BWR plants) shows that the majority of testing was generic (i.e., not plant-specific), and performed in the same facility and in the same manner as the testing documented in the BWROG guidance document. Some additional testing has been performed at specific plants and for specific strainer designs, but the documentation of this work is scattered through a number of different submittals, and has not been systematically compared for consistency and completeness.

For PWR licensees, regulatory guidance is to perform extensive testing of plant-specific strainer designs. As discussed in Section 4.1.3.2, guidance has been specified in exhaustive detail, defining the recommended approach to testing in the areas of test scaling, debris near field settlement simulation, surrogate debris similitude requirements, testing procedures, post-test data processing, and extrapolation to conditions beyond the tested database.

4.1.5 Recommendations for Guidance on Head Loss Calculations

The basic concept of relying on experimental evidence in developing a methodology for evaluating head loss due to debris bed formation is a valid engineering approach to the problem. However, the proper execution of the approach is vital to obtaining reliable results, and this is the basis for the additional guidance provided by NRC staff to both the PWR and BWR industries on this issue.

The detailed guidance developed by NRC staff for PWR licensees is based on first-hand experience with the manifold difficulties of obtaining appropriate experimental data to support an analysis methodology. The BWR licensees face the same difficulties and have the same requirement to show that their approach yields test data that is prototypic or conservative, compared to specific plant conditions. Therefore, the testing underlying the work presented by the BWR licensees should be held to the same standards as those required from PWR licensees. This suggests the following recommendations.

Recommendation 4.1	*Evaluate the specific strainer designs currently installed in BWR plants, on a plant-by-plant basis (if necessary), with regard to test scaling, debris near field settlement simulation, surrogate debris similitude requirements, range of independent variables tested, and testing procedures, to determine if the tests and evaluations can be considered prototypic or conservative with respect to these parameters.*
Recommendation 4.2	*Apply the same standards and guidance to evaluations of submittals from BWR licensees regarding suction strainer head loss calculations, including the potential for thin bed effects, as are applied to submittals from PWR licensees.*

4.2 Debris Carried Through Sump or Suppression Pool Suction Strainers

This subsection discusses guidance provided for determining the amount and type of debris that could be expected to pass through a suction strainer during a LOCA event and post-LOCA recirculation cooling. This subsection also discusses guidance provided for determining the amount and type of damage that such debris could cause in downstream components of the ECC, CS, and RHR systems.

Suction strainers are designed to severely limit the debris that can enter the ECCS, CSS, and RHR loops, but it is not possible to completely exclude all debris without incurring unacceptable head losses across the strainers. Regulatory Positions 1.1.1.12 (PWRs) and 2.1.2.2 (BWRs) from Regulatory Guidance 1.82, Revision 3, specify that the possibility of debris-clogging at flow restrictions downstream of the suction strainers should be assessed to ensure adequate long term cooling following a LOCA event.

For BWR systems, the original design criterion for determining the size of the openings in the suction strainers depended on the plant design. For BWR/2, /3, /4, and /5 designs, the strainer hole size was determined by the throat diameter for the containment spray nozzles or the core spray nozzles. For the BWR/6 design, the hole size was determined by the size of the cyclone separator orifices in the flushing subsystem for the ECCS pump seals. Suction strainer hole sizes prior to installation of new designs in response to strainer clogging issues, is reported in the BWROG guidance document as ranging from 0.06 inch to 0.6 inch, based on sampling from 16 plants (47% of all operating BWRs). Of the sampled plants, 50% reported hole sizes of 0.125 inch ($^{1}/_{8}$ inch) and approximately 38% reported hole sizes of 0.094 inch ($^{3}/_{32}$ inch). For PWR systems, the original design criterion for strainer openings was defined by the containment spray nozzle throat size. Typically, this dictated an upper limit of $^{1}/_{8}$ inch (0.125 inch) for the size of the openings. New replacement strainers installed in response to GSI-191 issues resolution typically have openings 0.094 inch ($^{3}/_{32}$ inch), and in some designs are only 0.0625 inch ($^{1}/_{16}$ inch) or smaller.

However, even the smallest strainer openings are large compared to the expected size ranges of fibrous and particulate debris, which have mean values on the order of 0.01 to 0.001 inch. Paint chips and some types of particulate debris have typical sizes in the micron and sub-micron range. It is therefore inevitable that some amount of debris would be carried through the strainers and subsequently reach the downstream components, including the reactor pressure vessel and core, and it is necessary to determine the quantity and characteristics of debris material that could get through.

The two main concerns with the presence of debris in the coolant being pumped through the ECCS and CSS systems and the reactor vessel are the possibility of plugging at flow restrictions, and excessive wear that could lead to failure of components within these systems. Both of these concerns could result in loss of recirculation cooling. The plant piping for these systems and the primary system are unlikely to be at risk since the pipes are relatively large in diameter and are thick-walled stainless steel with a high resistance to abrasive wear. The components of interest in evaluating the effect of debris in the coolant are pumps, valves, orifices, heat exchangers, areas within the reactor and core, and instrumentation tubing. Table 4.1 summarizes the types of these components that are found in PWR and BWR plants, and potential problems due to debris that could compromise ECCS, CSS, or RHR system performance.

The common causes of potential damage due to debris for all of the components listed in Table 4.1 are flow blockage or excessive wear due to abrasion. Flow blockage could shut down the recirculation loop for emergency cooling, and abrasion could lead to a secondary failure in the loop, which would also shut down emergency cooling. It is therefore advisable to determine where and how such problems could occur, and assess the severity of the consequences. Section 4.2.1 describes the approach that is recommended by the BWROG for BWR systems. Section 4.2.2 describes the industry guidance for PWR systems. Regulatory guidance on this issue is summarized in Section 4.2.3, and the treatment of BWR and PWR systems is compared in Section 4.2.4. Recommendations for appropriate development of consistent guidance for the two systems are provided in Section 4.2.5.

Table 4.1. Typical downstream components for ECCS and CSS in LWRs.

Component	Potential problems due to debris
Pumps:	
Centrifugal (single- and multi-stage)	Wear on bearing surfaces, seals, impeller, causing • increased pressure drop • decreased flow rate at given speed • increased vibration • leaking at shaft seals • loss of pressure boundary integrity
Valves:	
Needle valves Manual globe valves (with and without diaphragm seals) Check valves • lift type • piston type • swing type • tilting disc type diaphragm valves gate valves (manual, air-operated, motor-operated) globe valves (automated) butterfly valves	General hazards of debris in flow: • Wear on seals • Sticking open (when valve should be shut) • Sticking shut (when valve should be open) Plugging hazard for small valves: • needle valves with labyrinthine flow paths • globe valves with small-diameter holes in cage • sealed globe valves (limited clearance between seal and bonnet)
Orifices:	
Spray nozzles (typically $^{3}/_{8}$ in.)	Erosion due to abrasion Plugging due to accumulation of debris
Heat Exchangers:	
Primary side tubing	Debris accumulation in U-bend Scale build-up on tube inner wall Erosion of tube wall, potential for leakage of primary coolant
Instrumentation lines and tubing:	
In vessel, recirculation loop, sump or suppression pool	Plugging due to debris entering tubing; settled debris covering taps

4.2.1 Guidance from the BWROG for Debris Transport through Suction Strainers and Effects on Downstream Components

The BWROG guidance document does not provide recommendations for methods of determining the amount of debris that could be carried through the strainers. It is assumed that passive strainers will allow essentially no particulate to pass through because of the fibrous debris bed that very quickly develops on the strainer. Significant amounts of debris are assumed to pass through the strainers only if the fiber bed fails to develop, or if the plant has installed self-cleaning strainers. Even if that were the case in a specific plant, the BWROG guidance maintains the position that there is no need to consider effects on downstream components.

This guidance is based on a General Electric study of the effects of debris on components downstream of the strainers, GE-NE-T23-00700-15-21 (Rev. 1), *Evaluation of the Effects of Debris on ECCS Performance* (Reference 11 of NEDO-32686-A).[21] Based on the General Electric evaluation, the guidance document concludes that there is "no safety concern for the potential failure of the ECCS pumps, inadequate cooling capacity from the RHR heat exchangers, plugging of the core spray header nozzles, plugging of containment spray nozzles, corrosion or chemical reaction with other reactor materials, or fuel bundle flow blockage" due to debris in the recirculating coolant. The guidance document considers the issue essentially closed, based on the work reported in GE-NE-T23-00700-15-21 (Rev. 1), and does not include any suggestions, recommendations, or methodology for determining effects of debris on components downstream of the suction strainers. It also neglects any effects of suppression pool sludge, which may reach the suction strainers well before incoming material from the drywell can establish a debris bed.

4.2.2 Industry Guidance for PWRs on Debris Transport through Suction Strainers and Effects on Downstream Components

The industry guidance document containing recommendations related to this issue is WCAP-16406-P, Revision 1, *Evaluation of Downstream Sump Debris Effects in Support of GSI-191*. This document was developed to supplement NEI 04-07,[3] in response to the NRC staff's finding that the guidance in NEI 04-07 did not fully address the potential safety impact of LOCA-generated debris on downstream components. The guidance provided in WCAP-16406-P is comprehensive and detailed, and includes sample calculations illustrating applications to hypothetical plant conditions. Due to the complexity of this document, the PWROG stated the intention of providing training in proper application of the overall methodology for members, if it was accepted by NRC.

To address the specific question of how much debris can get through the strainers, WCAP-16406-P describes the development and application of a "Debris Ingestion Model" that licensees can apply to plant-specific conditions. The shape and size distributions of the debris are the main constraints on the amount of debris that can get through the strainers. The model ignores the effect of filtering due to the debris bed and assumes instead that any particulate material in the coolant that is small enough to pass through the strainer will do so. The guidance document also suggests that in plant-specific analysis, additional conservatism can be introduced by assuming that debris particulate considerably larger than the strainer hole size can still pass through and contribute to the debris load.

The Debris Ingestion Model assumes that there is no settling of debris within the floor pool of the sump. In addition, the guidance document suggests that in plant-specific analysis, the licensee could apply the extremely conservative assumption that the debris concentration remains constant in the ECCS throughout the post-LOCA recirculation period. Alternatively, the guidance document develops a methodology for calculating the reduction in debris concentration due to settling within the reactor vessel and elsewhere in the system. In general, this approach is based on simple one-dimensional modeling of the system, assuming velocity dependence for settling rates. Large heavy particles are expected to settle out in the lower plenum of the reactor vessel, but small light particles are assumed to carry through back to the sump and into the recirculation loop repeatedly without settling out.

The guidance document also contains a methodology for calculating the reduction in fibrous debris in the recirculating fluid due to capture on the strainers, using a model from LANL report[(u)] LA-UR-04-5416.[34] This model is recommended for plant-specific analysis where a "more realistic but still conservative" approach is required to appropriately characterize debris transport through the suction strainers.

In general, the perspective of the industry guidance document for PWRs is that debris effects on downstream components will not be a problem for long-term operation in post-LOCA conditions. However, this is not treated as a blanket assumption for all PWRs, and the document provides recommendations for specific analyses that should be done to evaluate this issue for plant-specific conditions.

The industry guidance document for PWRs describes the development of two empirical models to represent wear due to debris in the coolant; one based on abrasive wear, the other on erosive wear. Abrasive wear is defined as the removal of material due to the presence of hard or sharp particles between two moving surfaces in close proximity. Examples of affected surfaces in pumps are wear rings, impeller hubs, bushings, and diffuser rings. Erosive wear is defined as the removal of material due to particles in the flowing fluid impinging on a component surface or edge. Examples of surfaces that might be affected by erosive wear are valve internal flow paths, spray nozzle orifices, and heat exchanger tubing, particularly in the vicinity of sharp bends.

The industry guidance document presents detailed examples of evaluation methods applying the abrasive wear model to pumps used in the ECCS, CSS, and RHRS. Using plant-specific data, the licensee can obtain estimates of wear rates and evaluate the consequences of such wear for the specific components of the plant. Similarly, the guidance document presents examples for the erosive wear model, which applies to pumps, valves, orifices, and heat exchangers. The document specifically recommends evaluating both hot-leg and cold-leg break scenarios to determine the worst-case conditions of debris loading for potential wear damage to the system components. However, the document fails to note that these may not be the same conditions that lead to the worst case for head loss across the strainers due to the formation of the debris bed. The worse case break location for debris load on the strainer may not be the same worse case break location for debris downstream of the strainer. For suction strainer performance, the worst case probably would include a high percentage of fiber debris. For effects on downstream components, debris loading that is high in particulate, especially small sharp-edged particles that have high hardness values, is likely to be the most adverse.

To evaluate potential effects of debris on instruments that have sensing lines connected to the recirculation flow path and must function to support Emergency Operations Procedures (EOPs), the guidance document recommends specific methods to evaluate the potential for abrasive wear or erosion, or the possibility of plugging of such lines. The guidance document concludes that such analyses can show that instrumentation lines will not be subjected to abrasive wear or erosion and that debris blocking of instrument lines is not a viable failure mechanism.

(u) Subsequently issued by NRC as NUREG/CR-6885 in October 2005.

The guidance document considers flow blockage due to plugging of pumps, orifices, nozzles, valves, or heat exchanger tubing an unlikely mode of failure for the recirculation loop. This is based on analyses using conservatively bounding assumptions on the size of particles that can pass through the suction strainer openings. The design-basis for the size of these openings is the smallest flow path that the recirculating fluid is expected to encounter.

Based on these assumptions, the industry guidance document expects that licensees will be able to show in plant-specific analyses that debris particulate (both particles and fiber) will be too small to plug even the narrowest flow paths in the loop. The flow velocity in the narrow regions is expected to be high enough to preclude settling, and particulate debris will simply be swept through the system. However, the guidance document strongly reminds licensees that the recommendations provided were developed assuming passive strainers. For active strainers, the licensee must determine the size of particulate material that can pass through the holes, the debris concentration, and the resulting wear and plugging potential of this debris, which may be quite different from that of debris passed through passive strainers.

4.2.3 Regulatory Guidance on Debris Transport through Suction Strainers and Effects on Downstream Components

In the SE for the BWROG guidance document, there is no discussion of the BWROG position that there is "no safety concern" due to potential effects of debris on downstream components. This issue is not discussed in the memorandum on completion of NRC staff reviews of NRC Bulletin 96-03 and NRC Bulletin 95-02 in October, 2001 (ML0129702290). This suggests that as of 2001, NRC staff accepted the BWROG position on this issue.

In the SE for the industry guidance document for PWRs (NEI 04-07), issued in 2004, NRC staff found the guidance in NEI 04-07 insufficient in that it did not fully address the potential safety impact of LOCA-generated debris on components downstream of the containment sump. The SE offered specific guidance on what should be considered to address this issue. The major positions are summarized as follows:

1. evaluations for resolution of GSI-191should include the effects of debris on pumps and rotating equipment, piping and valves, and heat exchangers downstream of the containment sump related to ECCS and CSS. In particular, any throttling valves installed in the ECCS for flow balancing should be evaluated for blockage potential
2. evaluations should consider, on a plant-specific basis, equipment used for both long-term and short-term system operation lineups, conditions of operation, and mission times, at the maximum flow rates expected during operation
    a. for pumps and rotating equipment, consideration should be given to wear and abrasion of surfaces (e.g., running surfaces, bushings, wear rings); tight clearance components, or components where process water is used to either lubricate or cool should be identified and evaluated.
    b. component rotor dynamics changes and long term effects of vibrations caused by potential wear should be evaluated in the context of pump and rotating equipment operability and reliability, including potential impact on pump internal loads, to address such concerns as rotor and shaft cracking

c. for system piping, containment spray nozzles, and instrumentation tubing, consider how settling of debris and fines in low fluid velocity areas could impact system operating characteristics; evaluations should include tubing connections such as provided for differential pressure from flow orifices, elbow taps, venturi nozzles, and reactor vessel/RCS leg connections for reactor vessel level

d. for valves and heat exchangers, wetted materials should be evaluated for susceptibility to wear, surface abrasion, and plugging.

3. evaluations should consider the effect of possible decreased heat exchanger performance resulting from plugging, blocking, plating out of slurry materials, or tube degradation with respect to overall system required hydraulic and heat removal capability
4. an overall ECC or CS system evaluation integrating limiting or worst-case pump, valve, piping, and heat exchanger conditions should be performed and include the potential for reduced pump/system capacity resulting from internal bypass leakage or external leakage
5. the potential for leakage past seals and rings to areas outside containment caused by wear from debris fines should be evaluated with respect to fluid inventory, overall accident scenario design, and licensing bases environmental and dose consequences

In the SE for WCAP-16406-P, Revision 1,[35] which was developed by the PWROG in response to the guidance from the SE of NEI 04-07, NRC staff found the approach for performing assessments of the impact of debris on various equipment required by the ECCS, CSS and NSSS acceptable, subject to certain conditions and limitations. These conditions and limitations are specified in detail in Section 4 of the SE, but can be summarized as three main concepts:

1. licensees must use plant-specific information in performing the analyses
2. licensees must verify that models and/or data are applicable to plant-specific conditions
3. licensees must show that they have considered all equipment that could see debris-laden coolant, and analyzed the “worst case” conditions in all particulars.

4.2.4 Comparison of Regulatory Guidance for BWRs and PWRs

NRC staff appear to have accepted the BWROG position that there is no safety concern related to effects of debris on downstream components, and it is not necessary to perform plant-specific analyses to address this issue. No additional guidance is offered to BWR licensees on this issue. In direct contrast, NRC staff treats this issue as a significant concern in the SE for the industry guidance document for PWRs, and developed detailed and specific guidance on how the issue should be addressed.

The difference in the regulatory positions for BWRs and PWRs is due to the evolving nature of debris clogging concerns in nuclear power plants, and the earlier development of guidance for the BWRs, compared to PWRs. The actual nature of the technical issues involved is essentially the same for the two reactor types. There is nothing unique to PWRs that make them more susceptible to problems due to debris in downstream ECCS and CSS components, compared to BWRs, except possibly for the greater likelihood of chemical interaction problems in PWRs. Rather, the reverse might be considered more likely, at least in terms of potential damage due to material debris, as BWR systems have the suppression pool and its latent debris to deal with immediately upon activation of the ECCS, while PWRs would draw clean emergency cooling water from storage tanks for approximately the first 30 minutes of an event.

4.2.5 Recommendations for Guidance on Debris Transport through Suction Strainers and Effects on Downstream Components

The BWROG guidance is over-generalized from limited data and extremely liberal assumptions regarding the amount of debris that can be transported through the strainers. The industry guidance for PWRs, as expanded in WCAP-16406-P, Revision 1 and the additional regulatory guidance from NRC staff included in the SE for that document, defines a sound engineering approach to this issue. However, it requires appropriate experimental validation to verify overall conservatism in the methodology. Guidance on this issue should also be cognizant of the fact that for debris ingestion models, a "conservative" estimate of debris passing through the strainer is not the same as a "conservative" estimate of the amount of debris trapped on the strainer. In some plants, the bounding case for each analysis may not be the same postulated LOCA event. These observations suggest the following recommendations.

Recommendation 4.3 *Require validation of debris ingestion models with experimental data obtained for conditions where the maximum amount of debris is able to pass through the suction strainers. This should include the evaluation of conditions where an incomplete debris bed might form, and generally corresponds to conditions where the effect of debris on strainer head loss may be relatively low.*

Recommendation 4.4 *Require validation of abrasion and erosion wear models for specific particulate materials and ranges of particle sizes postulated for debris generated in BWR and PWR LOCA scenarios.*

Recommendation 4.5 *Apply the same standards and guidance to evaluations of submittals from BWR licensees regarding effect of debris in the recirculation coolant on downstream components as are applied to submittals from PWR licensees.*

4.3 Effects of Debris in Reactor Vessel and Core

This subsection discusses guidance provided for evaluating the effect on flow in the vessel and core as a result of debris that passes through the sump screen or suction strainer during a LOCA event and post-LOCA recirculation cooling. As noted in Sections 4.2, the issue of debris in the emergency cooling water is addressed by Regulatory Positions 1.1.1.12 (PWRs) and 2.1.2.2 (BWRs) from Regulatory Guidance 1.82, Revision 3. Both of these Regulatory Positions specifically require consideration of the build up of debris in the core fuel assemblies and fuel assembly inlet debris screens when assessing long-term cooling following a LOCA event.

The main concern with the presence of debris in the coolant being pumped into the reactor vessel is the possibility of flow blockage, resulting in loss of adequate cooling of the fuel rods, leading to high fuel cladding temperatures that could cause fuel damage. The time frame of greatest interest is long-term post-LOCA cooling. This is mainly because it will take time for sufficient debris to build up to cause problems, but also because during the initial stages of the LOCA event, coolant is leaving the core and vessel, generally at an extremely rapid rate, and debris blockage is essentially impossible. However, the main function of the ECCS is to get coolant to the core as quickly as possible in a LOCA. In a relatively short time, debris-laden water will enter the core.

For PWRs, there will be a delay of approximately 20-30 minutes duration, while the storage tank empties and before ECCS pumps start drawing from the sump. For BWRs, ECCS pumps drawing from the suppression pool are activated very early in the LOCA scenario. For both systems, a significant amount of debris will be present as soon as the ECCS pumps begin to draw cooling water from the sump or suppression pool. The amount of debris will tend to increase for some time interval, as debris is washed into the sump or suppression pool from containment.

The BWR ECCS components that can draw water from the suppression pool vary with plant design, as summarized in Table 4.2. All BWR designs have two or three ECCS components that can inject suppression pool water into the vessel. (The exception is the BWR/2 design, which has only the core spray system.) These components create two main paths for debris to reach the core. The core spray systems (both high- and low-pressure) spray water containing debris directly over the top of the core, or directly into the top of the core bypass region (BWR/5 and BWR/6). The coolant injection systems, when drawing from the suppression pool rather than the condensate storage tank, inject water containing debris into one of the vessel feedwater lines or recirculation lines. From the injection point, water containing debris can flow into the downcomer, through the jet pumps, into the lower plenum, and upward into the core.

The PWR ECCS components that draw water from the sump are essentially the same for all plants, although with significant variation in design details. The basic systems are summarized in Table 4.3. The location at which the ECCS water is injected can be the hot leg or the cold leg, depending on the LOCA scenario. In some Westinghouse plants, ECCS water can be injected directly into the vessel upper plenum or upper head. As with the BWR systems, this creates two main paths for debris to reach the core. Cold-leg injection sends sump water into the vessel downcomer where it can flow into the lower plenum and from the lower plenum up through the core. Hot-leg injection (and upper plenum or upper head injection) sends sump water into the vessel above the core, and debris-laden coolant enters the core from the top.

Table 4.3. Summary of BWR ECCS components that draw from suppression pool.

ECCS component	Action	Plant Type(s)
Core Spray System	• sprays water on top of core through nozzles on 2 independent sparger rings within core shroud above the fuel assemblies • 2 low-pressure loops (activated at <285 psig) • draws water from suppression pool	BWR/2 BWR/3 BWR/4
High Pressure Core Spray System	• provides high-pressure core cooling for small, intermediate, and large line breaks • single-loop system, with motor-driven pump • draws water from the condensate storage tank • alternatively, draws water from suppression pool • pumps water to sparger on upper core shroud	BWR/5 BWR/6
Low Pressure Core Spray System	• single loop system with motor-driven pump • draws water from suppression pool • discharges water through core spray sparger directly into core bypass region inside the core shroud	BWR/5 BWR/6
Low Pressure Coolant Injection System	• can be part of Residual Heat Removal System, or a separate system • 2 recirculation loops • injects water into reactor recirculation system discharge lines • draws water from suppression pool	BWR/3 BWR/4 BWR/5 BWR/6
High Pressure Coolant Injection System	• turbine-driven; needs no external power • pumps water into vessel feedwater piping • draws water from condensate storage tank • alternatively, draws water from suppression pool • for core cooling during small and intermediate break LOCAs	BWR/3 BWR/4

Table 4.3. Summary of PWR ECCS components that draw from water storage tank or sump.

ECCS component	Action	Plant Type(s)
Cold Leg Accumulators (Core Flood Tank System) (Safety Injection Tanks)	• passive system consisting of a pressurized tank filled with borated water on each cold leg of the reactor vessel • activated by drop in reactor coolant system pressure below 600 psig • injects coolant directly into reactor vessel to rapidly reflood core following a LOCA	Westinghouse Combustion Engineering Babcock & Wilcox
High Head (Pressure) Injection System	• provides high-pressure core cooling for small to intermediate size LOCAs • two-loop system, with centrifugal charging pumps • draws water from the borated water storage tank during injection phase • draws water from boron injection tank to maintain shutdown margin following steamline break accident • (optionally) can be used during recirculation phase following a LOCA	Westinghouse Combustion Engineering Babcock & Wilcox
Intermediate Head (Pressure) Injection System	• provides intermediate-pressure core cooling for small- or intermediate-size break loss of coolant accidents • 2-loop system with 2 multi-stage centrifugal pumps • draws water from the borated water storage tank during injection phase • draws water from the containment sump during recirculation phase • normal alignment injects directly into cold leg; can be manually aligned to inject into hot leg	Westinghouse
Low Head (Pressure) Injection System	• injection portion of Residual Heat Removal System; provides low-pressure core cooling for large break loss of coolant accidents • two-loop system, with single-stage centrifugal pumps • draws water from the borated water storage tank during injection phase • draws water from the containment recirculation sump during recirculation phase • normal alignment injects directly into cold leg; can be manually aligned to inject into hot leg • (optionally) can supply coolant to the intermediate and high pressure injection systems	Westinghouse Combustion Engineering Babcock & Wilcox

Table 4.3. Summary of PWR ECCS components that draw from water storage tank or sump.

ECCS component	Action	Plant Type(s)
Containment Spray System	• reduces reactor building pressure following a loss of coolant accident or steam line break • redundant 2-loop system, each consisting of spray pump, shutdown cooling heat exchanger, and spray nozzles • spray nozzles are mounted in concentric circles on headers near top of containment dome • initially draws water from the borated water storage tank, then switches to containment sump at beginning of recirculation phase • sodium hydroxide added to spray to capture radioactive iodine • provides cooling of hot sump water during recirculation phase of LOCA	Westinghouse Combustion Engineering Babcock & Wilcox
Residual (Decay) Heat Removal System	• aligned with High Head Injection System during the injection phase following a LOCA when coolant is drawn from the storage tank • aligned with Low Head Injection System during recirculation phase following a LOCA, when coolant is drawn from the containment sump	Westinghouse Combustion Engineering Babcock & Wilcox
Upper Head Injection System	• passive subsystem of ECCS to provide additional core cooling during system blowdown during a LOCA • activates at 1250 psig; shuts down when pressure drops below 1185 psig • injects borated water from accumulator tank into vessel upper head	Westinghouse

For both PWR and BWR primary systems, the design basis for long-term core cooling in post-LOCA conditions postulates a stable two-phase flow configuration in the core for some break locations. The inlet flow rate is just sufficient to match a boil-off rate in the partially submerged core, and this has been shown analytically to maintain fuel rod temperatures within acceptable limits. Because the coolant leaves the core as steam, any debris in the recirculating flow will be left behind in the core. This is another source of potential blockage in the fuel assemblies, in addition to the potential plugging of inlet orifices and other flow paths for cooling water entering at the bottom or top of the core.

The approach for evaluating the effect of debris in the vessel and core recommended by the BWROG for BWR systems is described in Section 4.3.1. Section 4.3.2 describes the industry-recommended approach for PWR systems. Regulatory guidance for BWRs and PWRs on this issue is summarized and compared in Section 4.3.3. Recommendations for appropriate development of consistent guidance for the two systems are provided in Section 4.3.4.

4.3.1 Guidance from BWROG for Debris Effects in Reactor Vessel and Core

The BWROG guidance on evaluating debris effects in the reactor vessel and core is based on the same General Electric[21] study in which the effects of debris on ECCS components are evaluated (see Section 4.2.1). It is assumed that debris will be transported to the reactor vessel only if the plant is equipped with self-cleaning strainers. The guidance document asserts that the General Electric study demonstrates that debris in the coolant will not adversely affect core cooling. This is based on the assumption that because flow velocities in the lower plenum will be quite low, "much of the debris" suspended in the coolant from the suppression pool will settle out in the lower plenum and will never reach the core inlet. Because most of the debris will not remain suspended in the flowing fluid, very little will be available to be caught on the lower tie plate, inlet debris screen, or other narrow flow paths at the core inlet.

If some local blockage occurs, the guidance document assumes it will be innocuous since very little material will remain in suspension after the coolant passes through the lower plenum. (The possibility of creating a flow blockage due to the build up of debris in the lower plenum is dismissed as "not credible" in the General Electric study.) In addition, the guidance document asserts that because the core flow rate is relatively low in the latter stages of the transient, even if some local blockage might occur due to debris, it is unlikely to cause problems, as the flow rate has only to remain high enough to balance the core boil-off rate. The guidance document does not present any recommendations for considering the potential effect of debris left behind in the fuel assemblies as a result of the boil-off, due to local blockages or degraded heat transfer from the fuel rods.

The guidance document dismisses the potential for fuel bundle flow blockage and fuel damage on the strength of "General Electric's judgment that, on a best-estimate basis," it would not adversely affect core cooling, "even in the highly unlikely situation of a blocked bundle inlet." This argument is based on a SE of the GE11 and GE13 fuel (General Electric Report).[v] This report shows that adequate core cooling would be maintained, even with complete flow blockage

(v) See Section 4.5, page 10 of General Electric Report, *10 CFR 50.59 Safety Evaluation of the GE11 and GE13 Fuel Bundle Debris Filter*, prepared by J.L. Embley, dated September 7, 1995. (GE Class III Proprietary Information.) This document is Reference 12 of Reference 11 of NEDO-32686-A.

of the lower tie plate debris filter for a single bundle. Core spray cooling would deposit enough water from the top to keep the core below the 2200ºF (~1200ºC) peak cladding temperature limit. The guidance document does not consider the potential effect of debris in the coolant sprayed into the core from the top, which would be left behind in the fuel assemblies as a result of the boil-off.

The guidance provided consists only of the suggestion that "licensees should review their plant-specific conditions to assure they are bounded by the GE evaluation and address any unresolved issues."

4.3.2 Industry Guidance for PWRs on Debris Effects in Reactor Vessel and Core

The industry guidance document for PWRs (WCAP-16406-P) was evaluated by the NRC staff as incomplete in the treatment of debris effects in the reactor vessel and core (SE WCAP-16406-P). A second document was submitted for review (WCAP-16793-NP, Revision 0),[36] as a supplement to WCAP-16406-P, providing more specific and detailed guidance on assessing

- the impact on long-term core cooling of debris in the ECCS
- the effects of debris that could form blockages in the fuel bundles or adhere to the cladding surface
- the effects of chemical precipitates that could plate out on fuel cladding surfaces.

Revision 1 of WCAP-16793-NP was accepted for review by NRC in April 2009, and the SE on this document is expected to be completed by early summer 2010. Because of this extended time frame, the industry guidance described in this section is based only on WCAP-16406-P, Revision 1 and its corresponding SE.

In general, the industry guidance document for PWRs (WCAP-16406-P) expects that debris effects on core flow will not be a problem for long-term operation in post-LOCA conditions. However, this is not treated as a blanket assumption for all PWRs in all accident conditions. The guidance document provides recommendations for specific analyses that should be done to evaluate this for plant-specific conditions.

As in the case of the BWROG guidance, the industry guidance for PWRs asserts that collection of a large volume of fibrous debris in the lower plenum (or upper plenum) sufficient to completely block flow to the core is "not considered credible." However, the effect of debris carried to the core should be evaluated based on plant-specific debris loading (as determined in responses to GL 2004-02 provided in NEI 04-07).[3]

Because fibrous debris has the capability of collecting on any structure in the reactor vessel, the guidance document recommends that plant-specific analyses should be performed to determine the effect of fibrous, mixed fibrous-particulate, and particulate debris on flow through the fuel assemblies. In cold-leg recirculation mode (which can be used for both hot-leg and cold-leg postulated breaks), ECCS water is injected into the cold leg and follows the normal flow path through the reactor; i.e., through the downcomer, the lower plenum, and on up through the core.

For a cold-leg break, long-term core cooling is achieved by relatively low velocity flow (typically about 0.2 ft/sec) from the lower plenum driven by a matching boil-off of liquid inventory in the core. For a hot-leg break, core flow is driven directly by the recirculation loop and can be up to an order of magnitude higher (i.e., up to about 2 ft/sec). Boiling may occur in the core, depending on the specific break scenario. The guidance document offers recommendations for determining the rate of accumulation of debris in the lower plenum, due mainly to settling of particulate, but generally assumes that fiber will not settle out even at low flow velocities because of its low density. The tight clearances in the lower core plate support structure and between the rods and spacer grids is expected to be very effective at trapping debris, and the guidance document outlines general steps for determining the flow reduction due to local blockages, based on geometry and hydraulics modeling.

In hot-leg recirculation mode, the flow path through the vessel is the reverse of normal. ECCS water is injected into the hot leg, flows into the upper plenum and then down through the core. In some break scenarios, the ECCS flow rate is balanced with the core boil-off rate to achieve adequate core cooling. In such cases, the flow regime in the two-phase region of the core will be counter-current, with steam flowing upward (carrying some entrained liquid droplets) and saturated liquid water flowing downward. As a result, the velocities are even lower in the lower plenum, compared to cold-leg injection. The guidance document offers general recommendations for determining the rate of accumulation of debris in the lower plenum, due mainly to settling of particulate, and models for determining fibrous debris build up on fuel rods and spacer grids.

The guidance document suggests options for remedial actions that might be taken if the plant-specific analysis shows problems with reduced core flow and elevated core temperatures due to the capture of debris within the fuel assemblies or core inlet structures. These suggestions include

- remove all fibrous insulation from containment
- install “pre-conditioned” suction strainers or intermediate debris interceptors to trap a larger amount of debris before it enters the ECCS loop(s)
- switch to hot-leg recirculation to back-flush the core (as per current EOPs for hot-leg switchover, but with additional justification), if the problem occurs in cold-leg recirculation.

The guidance document notes that this list is not exhaustive. Plant-specific features should be evaluated to determine additional strategies to mitigate debris collection in the core during ECCS recirculation.

4.3.3 Regulatory Guidance for Debris Effects in Reactor Vessel and Core

As noted in the introduction to this section, Regulatory Positions 1.1.1.12 (PWRs) and 2.1.2.2 (BWRs) from Regulatory Guidance 1.82, Revision 3 specifically require consideration of the build up of debris in the core fuel assemblies and fuel assembly inlet debris screens when assessing long-term cooling following a LOCA event. In the SE for the BWROG guidance document (NEDO-32686-A), issued in 1998, NRC staff did not reject the BWROG position that there is no safety concern related to effects of debris on downstream components, including the reactor vessel and core, nor did the SE offer any guidance on plant-specific analyses to address this issue.

In direct contrast, NRC staff treated this issue as a significant concern in the SE for the industry guidance documents for PWRs, and developed detailed and specific guidance on how the issue should be addressed. In the SE for WCAP-16406-P, Revision 1, NRC staff found the treatment of debris effects in the reactor vessel and core incomplete. The SE states that "NRC staff has reached no conclusions regarding the information presented in TR WCAP-16406-P, Section 9 [which addresses reactor internal and fuel blockage evaluations.]" The SE further states that "Licensees should refer to TR WCAP-16793-NP and the NRC staff's SE of the TR WCAP-16793-NP in performing their reactor internal and fuel blockage evaluations."

In the SE of WCAP-16406-P, NRC staff identified seven specific issues regarding the evaluation of reactor internal components and fuel. These are summarized below.

1. evaluation methodology should account for differences in PWR RCS and ECCS designs that could affect core conditions such as boiling time
2. evaluation methodology should consider that hot spots could be produced from debris trapped by swelled and/or ruptured cladding
3. long-term core boiling effects on debris and chemical concentrations in the core should be accounted for
4. evaluation methodology should consider debris and chemicals that might be trapped behind spacer grids and could potentially affect heat transfer from the fuel rods
5. consideration should be included for plating out of debris and/or chemicals on the fuel rods during long-term boiling
6. evaluations should address effect of high concentrations of debris and chemicals in the (core due to long-term boiling) on the natural circulation elevation head that brings coolant into the core
7. if hot spots are found to occur, evaluations should address cladding embrittlement and demonstrate that a coolable geometry is maintained

The methodology presented in WCAP-16793-NP addresses these seven issues. The SE for WCAP-16793-NP will present the NRC staff's assessment of the methodology.

4.3.4 Recommendations on Determining Debris Effects in Reactor Vessel and Core

The BWROG guidance is inadequate in that it over-generalizes from limited data and does not consider the wide variation of plant-specific conditions. The industry guidance for PWRs uses a sound approach, but any approach must be validated with appropriate experimental data and its applicability verified for specific plant conditions. Given the current state of knowledge about debris blockage in fuel assemblies and core inlet structures, it is very difficult to define "conservative" assumptions with confidence. Testing in prototypic geometries is needed to explore effects of such factors as the amount and type of debris and the debris mixture. The effects of debris left behind by core boil-off should also be investigated. The limited studies that have been performed have dealt only with debris deposited by forced flow through such structures as the bundle inlet plate, debris screen, and spacer grids.

Recommendation 4.6	*Require prototypic testing of debris mixtures in core flow at pressures and temperatures corresponding to post-LOCA conditions to determine the effect of local blockages on local fuel rod cladding temperatures for postulated for BWR and PWR LOCA scenarios. Include testing to show the effects of debris left behind by core boil-off.*
Recommendation 4.7	*For PWRs, require testing to determine the effects on local fuel rod cladding temperatures of chemical plate-out (with and without trapped debris) for forced flow and core boil-off conditions in postulated for LOCA scenarios.*
Recommendation 4.8	*Apply similar standards and guidance to evaluations of submittals from BWR licensees regarding effects of debris in the reactor vessel and core as are applied to submittals from PWR licensees.*

5. DEBRIS TRANSPORT IN SUPPRESSION POOL AND CONTAINMENT SUMP

In addition to the quantity of LOCA generated or pre-existing debris, the quantity of debris that physically reaches the suction strainers in the BWR suppression pool or PWR containment sump can significantly impact the head loss and downstream debris effects. This section considers the BWR and PWR industry guidance and NRC staff position on reducing potential debris quantity because of settling in the suppression pool or containment sump.

The NRC regulatory positions for debris transport in the suppression pool and containment sump are provided in Regulatory Guide 1.82, Rev. 3,[18] Sections 1.3.3.1 through 1.3.3.6 for PWRs, and in Sections 2.3.2.4 and 2.3.2.5 for BWRs. The position specified for the PWRs (see Section 1.3.3.4), suggests that credit may be taken for settling of debris, provided the approach used is shown to be appropriately validated and conservative. For BWRs, Section 2.3.2.4 specifically prohibits considering debris settling “until LOCA-induced turbulence in the suppression pool has ceased.” The analogous time frame in a PWR (i.e. the injection phase of the LOCA) has flow from the break and spray drainage; no recirculation flow is occurring. (The full text of this regulatory guidance, with a summary of the differences in requirements, is included in Appendix A.)

The BWR industry guidance on debris transport in the suppression pool during a LOCA event is summarized in Section 5.1. The PWR industry guidance on debris transport in the containment sump(s) during a LOCA event is summarized in Section 5.2. Both sections include a discussion of the NRC staff evaluations of the respective industry guidance. The BWR and PWR guidance and NRC staff evaluations are compared and evaluated in Section 5.3. Section 5.4 summarizes recommendations for consistent treatment of debris transport in both BWRs and PWRs.

5.1 BWR Guidance for Debris Transport in Suppression Pool

This section summarizes the BWR industry guidance and correspondingNRC staff evaluation. No interpretation of the guidance or the evaluation has been made here. Industry guidance and NRC staff evaluations for this issue are discussed in Section 5.3.

The BWR guidance (NEDO-32686-A)[1] for debris transport in the suppression pool conforms to Regulatory Position 2.3.2.4, specifying the “conservative assumption” that “No credit should be taken for the settling of fibrous debris, sludge, and other light material during the high energy phase...” of a LOCA. Further, the “conservative and simplifying assumption” is recommended that all modes of recirculation within the suppression pool will preclude the settling of fibrous debris, and it will always be available for transport to the strainers. Equivalent conservative and simplifying assumptions are made for all modes of recirculation within the suppression pool, precluding the settling of sludge and any “relatively light debris.”

An alternative approach suggested in the BWR guidance allows for settling of fibrous debris, sludge, and “relatively light debris.” For each debris type, this approach requires establishing the expected flow velocities in the pool during and subsequent to the high energy phase of the postulated LOCA. The settling behavior of the specific debris species must also be determined, as well as the effect of the specific LOCA failure condition on flow velocities and system alignments/modes during the event. Appendices B and E of NUREG/CR-6224 [30] and NUREG/CR-6368 [37] are identified as sources of relevant information on the settling velocity of specific debris.

The NRC staff accepted the BWR industry guidance in their SE of the guidance document (NEDO-32686-A),[1] summarizing the approach as follows:

- High energy phase: no settling in the pool (all suppression pool debris will be suspended or re-suspended)
- Low energy phase:
  - Option 1: no settling (all suppression pool debris remain suspended)
  - Option 2: settling accounted for using appropriate models.

The NRC staff notes that Appendix B to NUREG/CR-6224 [30] provides the suppression pool settling data only for specific debris types. Licensees using the NUREG/CR-6224 suppression pool transport methods are cautioned about extrapolating the experimental data and models to untested debris species. Such extrapolation should be justifiable and validated.

5.2 PWR Guidance for Debris Transport in Containment Sump

This section summarizes the PWR industry guidance and corresponding NRC staff evaluation. No interpretation of the guidance of the evaluation has been made here. Industry guidance and NRC staff evaluations for this issue are discussed in Section 5.3.

The baseline PWR guidance for debris transport assumes the transportation of 100% of the small fines in the active volumes of the pool during recirculation, but no transport of the large pieces (NEI 04-07).[3] Thus, any small fines debris in the active pool volumes is assumed to reach the suction strainers. However, analytical refinement options are suggested for reducing the conservatism in assumptions underpinning the baseline model. For debris transport in general, the PWR guidance suggests using approaches such as developing models of flow in the active sump, such as nodal network models or three-dimensional CFD models. No specific guidance is provided for using the nodal network approach to determine rates of debris transport within the sump, but the CFD approach is noted as specifically applicable to determining appropriate settling rates in the sump. The guidance document notes that if the settling velocities of debris species are known, in the area of the sump where fluid velocities are higher than the settling velocity of a given species, "it may be conservatively assumed that debris in this area (of the given type and size being analyzed) will be transported to the sump screen." The logical converse of this is that in regions where the fluid velocity is lower than the settling velocity of a given species, credit may be taken for debris in the sump that would settle out before reaching the screen.

The NRC staff does not comment on the baseline PWR guidance with respect to debris settling in the sump (SE NEI 04-07).[4] The NRC staff accepted the nodal network method as an alternative method for determining debris transport to the sump screens, but only if licensees use experimental data to ensure that their use of the approach is conservative with respect to debris type and quantity. The staff accepted the CFD method, but provided specific comments and guidance on how it should be implemented (Appendices III and IV, SE NEI 04-07).

5.3 Evaluation of Guidance for Debris Transport in Suppression Pool and Containment Sump

This section provides a comparison of the PWR and BWR industry guidance for suppression pool and containment sump debris transport summarized in Sections 5.1 and 5.2. The approaches for determining the flow field and debris material settling characteristics are compared.

The "baseline" guidance from industry for both BWRs and PWRs with respect to debris settling within the suppression pool or sump is that no credit should be taken for settling. Each industry, however, provides alternative debris transport methods wherein credit may be taken for settling of debris before reaching the strainer. Although the BWR guidance states that it will be necessary to establish the expected flow velocities in the pool during and subsequent to the high energy phase of the postulated LOCA, no guidance for determining the flow field is provided. Thus, BWR licensees could employ different methodologies to analysis of similar containment environments.

The PWR guidance is more specific with regard to the methodology for determining the flow field, but a specific modeling approach is not identified. As with the BWR guidance, different PWR licensees may thus employ different methodologies.

The relevant Regulatory Positions provide specific guidance defining conditions when debris settling cannot be considered, and NRC staff provides additional detail and requirements for the approach. However, the SEs by NRC staff allow individual licensees to develop alternative methods for predicting debris transport, which could include settling.

5.4 Recommendations on Guidance for Debris Transport in Suppression Pool and Containment Sump

Although the geometry can differ significantly between the suppression pool for BWRs and the containment sumps for PWRs, the basic characteristics of their respective flow fields can be expected to be quite similar during a postulated LOCA event. For both systems, water is flowing into the pool or sump from containment and at the same time, water is being rapidly drawn out to meet the performance requirements of the ECCS and CSS. To ensure that debris transport through these coolant reservoirs is treated with comparable conservatism in the analysis for each type of reactor, similar analytical approaches should be required for both systems. The analytical approach to determining the flow field should not be a function of reactor type.

Recommendation 5.1 *Unless an assumption of 100% transport is employed, the approach used for flow field modeling in the sump and suppression pool should be validated and consistent in the basic approach and the degree of conservatism of assumptions.*

In guidance provided by the Owners Groups and NRC, licensees are advised to determine debris material settling characteristics on a plant-specific basis or via NUREG/CR-6224 or

NUREG/CR-6772,[38] consistent with PWR Regulatory Position 1.3.3.4 of Regulatory Guide 1.82, Rev. 3 [18]). Settling velocities from the NUREG references for NUKON™ insulation may differ by up to three orders of magnitude, depending on the assumed size of the fiber particles. Differences in the settling characteristics of the same debris material are thus possible for BWR and PWR licensees. Debris settling characteristics of the material are physical properties of the material, not functions of reactor type.

Recommendation 5.2	*Settling behavior of debris in the sump and suppression pool, if credited, should be based on the properties of the specific debris material, considering particle density, geometry, and size distribution.*

6. RECOMMENDATIONS

This section summarizes and prioritizes the recommendations developed in the preceding sections for developing Regulatory guidance on appropriate treatment of the technical issues related to effects of debris on system performance during postulated design basis LOCA events. The recommendations are intended to provide a basis for conservative treatment of these issues in analyses for both reactor types, and for consistent treatment of the same phenomena for both reactor types. Table 6.1 lists the specific recommendations from Sections 2 through 5, following the organization of Table 1.1, which summarizes the differences in guidance for PWR and BWR analysis of post-LOCA cooling of the reactor core.

Table 6.1. Summary of recommendations for developing conservative and consistent guidance for analysis of LOCA and post-LOCA recirculation cooling in PWRs and BWRs.

Index number	**Recommendation**
Debris characteristics (see Section 2)	
2.1	*Plant-specific determination of the types, quantities, and distributions of physical debris, similar to the individual plant walkdowns for PWRs, is recommended for all commercial light water reactors, including BWRs. A sampling methodology, such as the guidelines offered through the SE to NEI 04-07, should be implemented across all plants to determine the relative quantity of fibrous debris. Methods to estimate the quantities and types of insulation debris, the largest contributor to the post-LOCA debris inventory, should be unified across BWRs and PWRs.*
2.2	*A determination of the effects of coolant, solutes, and insulation on the creation of chemical debris and the influence of the debris on head loss and downstream effect, along the lines of the ICET program and Westinghouse studies conducted for PWRs, is recommended for BWRs.*
Debris generation (see Section 3)	
3.1	*The zone of influence (ZOI) of the high-energy jet of steam or saturated liquid water released in a LOCA should be determined using an experimentally validated free-jet expansion model that is applicable to both BWR and PWR conditions.*
3.2	*A validated basis that is consistent as applicable between reactor types for insulation material failure pressures should be developed for the range of thermodynamic conditions encountered in LOCA scenarios.*

Table 6.1 (contd)

Index number	Recommendation
3.3	*A validated basis consistent as applicable between reactor types for qualified and unqualified coatings thickness should be developed.*
3.4	*Reducing potential debris quantity by means of the definition of a specific ZOI extent, debris location, and contribution to subsequent head loss should only be considered after validated and consistent approaches for free-jet expansion, debris material failure pressure, and debris quantity are established.*
3.5	*A validated approach consistent as applicable between reactor types for the failure of insulation and coating systems outside of the ZOI is recommended.*
Debris bed formation on screens or strainers (see Section 4)	
4.1	*Evaluate the specific strainer designs currently installed in BWR plants, on a plant-by-plant basis (if necessary), with regard to test scaling, debris near field settlement simulation, surrogate debris similitude requirements, range of independent variables tested, and testing procedures, to determine if the tests and evaluations can be considered prototypic or conservative with respect to these parameters.*
4.2	*Apply the same standards and guidance to evaluations of submittals from BWR licensees regarding suction strainer head loss calculations, including the potential for thin bed effects, as are applied to submittals from PWR licensees.*
Downstream effects of debris in recirculating coolant (see Section 4)	
4.3	*Require validation of debris ingestion models with experimental data obtained for conditions where the maximum amount of debris is able to pass through the suction strainers. This should include the evaluation of conditions where an incomplete debris bed might form, and generally corresponds to conditions where the effect of debris on strainer head loss may be relatively low.*
4.4	*Require validation of abrasion and erosion wear models for specific particulate materials and ranges of particle sizes postulated for debris generated in BWR and PWR LOCA scenarios.*
4.5	*Apply the same standards and guidance to evaluations of submittals from BWR licensees regarding effect of debris in the recirculation coolant on downstream components as are applied to submittals from PWR licensees.*
4.6	*Require prototypic testing of debris mixtures in core flow at pressures and temperatures corresponding to post-LOCA conditions to determine the effect of local blockages on local fuel rod cladding temperatures for postulated for BWR and PWR LOCA scenarios. Include testing to show the effects of debris left behind by core boil-off.*
4.7	*For PWRs, require testing to determine the effects on local fuel rod cladding temperatures of chemical plate-out (with and without trapped debris) for forced flow and core boil-off conditions in postulated for LOCA scenarios.*
4.8	*Apply similar standards and guidance to evaluations of submittals from BWR licensees regarding effects of debris in the reactor vessel and core as are applied to submittals from PWR licensees.*
Debris transport in sump or suppression pool (see Section 5)	

Table 6.1 (contd)

Index number	Recommendation
5.1	*Unless an assumption of 100% transport is employed, the approach used for flow field modeling in the sump and suppression pool should be validated and consistent in the basic approach and the degree of conservatism of assumptions.*
5.2	*Settling behavior of debris in the sump and suppression pool, if credited, should be based on the properties of the specific debris material, considering particle density, geometry, and size distribution.*

The overall methodology must be an integrated approach, even when it is conducted in segments. It must also have consistent modeling between segments of the analysis. Assumptions must be conservative for all parts of the analysis to produce an overall conservative result. This means that assumptions may need to shift when performing one part of the analysis, compared to those used for another part. The merit of a multi-conservatism approach is the relatively high level of confidence that may be ascribed to the result. The guidance to licensees from the NRC SEs of the BWROG guidance, the PWROG guidance, Regulatory Guide 1.82, and other Regulatory guidance on specific issues should provide a consistent overall methodology that captures the appropriate conservatisms in all elements of the model.

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APPENDIX A

REGULATORY GUIDE 1.82, REV. 3, NOVEMBER 2003, PWR-BWR COMPARISON

Regulatory Guide 1.82, Rev. 3, November 2003, PWR-BWR Comparison

PWR	BWR	Difference(s)
1.1 Features Needed To Minimize the Potential for Loss of NPSH The ECC sumps, which are the source of water for such functions as ECC and containment heat removal following a LOCA, should contain an appropriate combination of the following features and capabilities to ensure the availability of the ECC sumps for long-term cooling. The adequacy of the combinations of the features and capabilities should be evaluated using the criteria and assumptions in Regulatory Position 1.3.	2.1 Features Needed To Minimize the Potential for Loss of NPSH The suppression pool is the source of water for such functions as ECC and containment heat removal following a LOCA in conjunction with the vents and downcomers between the drywell and the wetwell. It should combine the following features and capabilities to ensure the availability of the suppression pool for long-term cooling. The adequacy of the combinations of the features and capabilities should be evaluated using the criteria and assumptions in Regulatory Position 2.3.	Guidance essentially the same for PWR and BWR.
1.1.1 ECC Sumps, Debris Interceptors, and Debris Screens		
1.1.1.1 A minimum of two sumps should be provided, each with sufficient capacity to service one of the redundant trains of the ECCS and CSS. The distribution of water sources and containment spray between the sumps should be considered in the calculation of boron concentration in the sumps for evaluating post-LOCA subcriticality and shutdown margins. Typically, these calculations are performed assuming minimum boron concentration and minimum dilution sources. Similar considerations should also be given in the calculation of time for Hot Leg Switchover, which is calculated assuming maximum boron concentration and a minimum of dilution sources.		PWR provided with specific guidance on details of sump system design in Regulatory Positions 1.1.1.1 through 1.1.1.5, 1.1.1.7, 1.1.1.10, and 1.1.1.15. BWR provided no guidance beyond the general statement of Regulatory Position 2.1.
1.1.1.2 To the extent practical, the redundant sumps should be physically separated by structural barriers from each other and from high-energy piping systems to preclude damage from LOCA, and, if within the design basis, main steam or main feedwater break consequences to the components of both sumps (e.g., trash racks, sump screens, and sump outlets) by whipping pipes or high-velocity jets of water or steam.		

Regulatory Guide 1.82 (contd)

PWR	BWR	Difference(s)
1.1.1.3 The sumps should be located on the lowest floor elevation in the containment exclusive of the reactor vessel cavity to maximize the pool depth relative to the sump screens. The sump outlets should be protected by appropriately oriented (e.g., at least two vertical or nearly vertical) debris interceptors: (1) a fine inner debris screen and (2) a coarse outer trash rack to prevent large debris from reaching the debris screen. A curb should be provided upstream of the trash racks to prevent high-density debris from being swept along the floor into the sump. To be effective, the height of the curb should be appropriate for the pool flow velocities, as the debris can jump over a curb if the velocities are sufficiently high. Experiments documented in NUREG/CR-6772 and NUREG/CR-6773 have demonstrated that substantial quantities of settled debris could transport across the sump pool floor to the sump screen by sliding or tumbling.		
1.1.1.4 The floor in the vicinity of the ECC sump should slope gradually downward away from the sump to further retard floor debris transport and reduce the fraction of debris that might reach the sump screen.		
1.1.1.5 All drains from the upper regions of the containment should terminate in such a manner that direct streams of water, which may contain entrained debris, will not directly impinge on the debris interceptors or discharge in close proximity to the sump. The drains and other narrow pathways that connect compartments with potential break locations to the ECC sump should be designed to ensure that they would not become blocked by the debris; this is to ensure that water needed for an adequate NPSH margin could not be held up or diverted from the sump.		

PWR	BWR	Difference(s)
1.1.1.7 Where consistent with overall sump design and functionality, the top of the debris interceptor structures should be a solid cover plate that is designed to be fully submerged after a LOCA and completion of the ECC injection. The cover plate is intended to provide additional protection to debris interceptor structures from LOCA-generated loads. However, the design should also provide means for venting of any air trapped underneath the cover.		
1.1.1.10 The debris interceptor structures should include access openings to facilitate inspection of these structures, any vortex suppressors, and the sump outlets.		
1.1.1.15 Advanced strainer designs (e.g., stacked disc strainers) have demonstrated capabilities that are not provided by simple flat plate or cone-shaped strainers or screens. For example, these capabilities include built-in debris traps where debris can collect on surfaces while keeping a portion of the screen relatively free of debris. The convoluted structure of such strainer designs increases the total screen area, and these structures tend to prevent the condition referred to as the thin bed effect. It may be desirable to include these capabilities in any new sump strainer/screen designs. The performance characteristics and effectiveness of such designs should be supported by appropriate test data for any particular intended application.		

PWR	BWR	Difference(s)
1.3.1 Net Positive Suction Head of ECCS and Containment Heat Removal Pumps	2.1.1 Net Positive Suction Head of ECCS and Containment Heat Removal Pumps	
1.3.1.1 ECC and containment heat removal systems should be designed so that sufficient available NPSH is provided to the system pumps, assuming the maximum expected temperature of pumped fluid and no increase in containment pressure from that present prior to the postulated LOCA. (See Regulatory Position 1.3.1.2.) For sump pools with temperatures less than 212°F, it is conservative to assume that the containment pressure equals the vapor pressure of the sump water. This ensures that credit is not taken for the containment pressurization during the transient. For subatmospheric containments, this guidance should apply after the injection phase has terminated. For subatmospheric containments, prior to termination of the injection phase, NPSH analyses should include conservative predictions of the containment atmospheric pressure and sump water temperature as a function of time.	2.1.1.1 ECC and containment heat removal systems should be designed so that adequate available NPSH is provided to the system pumps, assuming the maximum expected temperature of the pumped fluid and no increase in containment pressure from that present prior to the postulated LOCAs. (See Regulatory Position 2.1.1.2.)	Guidance essentially the same for PWR and BWR, but PWR guidance has more details on specific conservatisms for the analysis.
1.3.1.2 For certain operating PWRs for which the design cannot be practicably altered, conformance with Regulatory Position 1.3.1.1 may not be possible. In these cases, no additional containment pressure should be included in the determination of available NPSH than is necessary to preclude pump cavitation. Calculation of available containment pressure and sump water temperature as a function of time should underestimate the expected containment pressure and overestimate the sump water temperature when determining available NPSH for this situation.	2.1.1.2 For certain operating BWRs for which the design cannot be practicably altered, conformance with Regulatory Position 2.1.1.1 may not be possible. In these cases, no additional containment pressure should be included in the determination of available NPSH than is necessary to preclude pump cavitation. Calculation of available containment pressure should underestimate the expected containment pressure when determining available NPSH for this situation. Calculation of suppression pool water temperature should overestimate the expected temperature when determining available NPSH.	Guidance the same for PWR and BWR.

PWR	BWR	Difference(s)
1.3.1.3 For certain operating reactors for which the design cannot be practicably altered, if credit is taken for operation of an ECCS or containment heat removal pump in cavitation, prototypical pump tests should be performed along with post-test examination of the pump to demonstrate that pump performance will not be degraded and that the pump continues to meet all the performance criteria assumed in the safety analyses. The time period in the safety analyses during which the pump may be assumed to operate while cavitating should not be longer than the time for which the performance tests demonstrate that the pump meets performance criteria.	2.1.1.3 For certain operating BWRs for which the design cannot be practicably altered, if credit is taken for operation of an ECCS or containment heat removal pump in cavitation, prototypical pump tests should be performed along with post-test examination of the pump to demonstrate that pump performance will not be degraded and that the pump continues to meet all the performance criteria assumed in the safety analyses. The time period in the safety analyses during which the pump may be assumed to operate while cavitating should not be longer than the time for which the performance tests demonstrate the pump meets performance criteria.	Guidance the same for PWR and BWR.
1.3.1.4 The decay and residual heat produced following accident initiation should be included in the determination of the water temperature. The uncertainty in the determination of the decay heat should be included in this calculation. The residual heat should be calculated with margin.	2.1.1.4 The decay and residual heat produced following accident initiation should be included in the determination of the water temperature. The uncertainty in the determination of the decay heat should be included in this calculation. The residual heat should be calculated with margin.	Guidance the same for PWR and BWR.
1.3.1.5 The hot channel correction factor specified in ANSI/HI 1.1-1.5-1994 should not be used in determining the margin between the available and required NPSH for ECCS and containment heat removal system pumps.	2.1.1.5 The hot channel correction factor specified in ANSI/HI 1.1-1.5-1994 should not be used in determining the margin between the available and required NPSH for ECCS and containment heat removal system pumps.	Guidance the same for PWR and BWR.
1.3.1.6 The calculation of available NPSH should minimize the height of water above the pump suction (i.e., the level of water on the containment floor). The calculated height of water on the containment floor should not consider quantities of water that do not contribute to the sump pool (e.g., atmospheric steam, pooled water on floors and in refueling canals, spray droplets and other falling water, etc.). The amount of water in enclosed areas that cannot be readily returned to the sump should not be included in the calculated height of water on the containment floor.	2.1.1.6 The level of water in suppression pools should be the minimum value given in the technical specifications reduced by the drawdown due to suppression pool water in the drywell and the sprays.	Differences due to differences between BWR and PWR systems; intent of guidance the same (i.e., obtain a conservative [low] estimate of gravity head seen by strainers).
1.3.1.7 The calculation of pipe and fitting resistance and the calculation of the nominal screen resistance without blockage by debris should be done in a recognized, defensible method or determined from applicable experimental data.	2.1.1.7 Pipe and fitting resistance and the nominal screen resistance without blockage by debris should be calculated in a recognized, defensible method or determined from applicable experimental data.	Guidance the same for PWR and BWR.

PWR	BWR	Difference(s)
1.3.1.8 Sump screen flow resistance that is due to blockage by LOCA-generated debris or foreign material in the containment, which is transported to the suction intake screens, should be determined using Regulatory Position 1.3.4.	2.1.1.8 Suction strainer screen flow resistance caused by blockage by LOCA-generated debris or foreign material in the containment that is transported to the suction intake screens should be determined using the methods in Regulatory Position 2.3.3.	Guidance essentially the same for PWR and BWR.
1.3.1.9 Calculation of available NPSH should be performed as a function of time until it is clear that the available NPSH will not decrease further.	2.1.1.9 Calculation of available NPSH should be performed as a function of time until it is clear that the available NPSH will not decrease further.	Guidance the same for PWR and BWR.
1.1.1 ECC Sumps, Debris Interceptors, and Debris Screens (Guidance for PWRs in Section 1.1.1 addresses issues covered in Section 2.1.2 for BWRs.)	2.1.2 Passive Strainer The inlet of pumps performing the above functions should be protected by a suction strainer placed upstream of the pumps; this is to prevent the ingestion of debris that may damage components or block restrictions in the systems served by the ECC pumps. The following items should be considered in the design and implementation of a passive strainer.	Difference in organization of BWR and PWR sections of the Regulatory Guide; overall intent of guidance essentially the same
1.1.1.6 The strength of the trash racks should be adequate to protect the debris screens from missiles and other large debris. Trash racks and sump screens should be capable of withstanding the loads imposed by expanding jets, missiles, the accumulation of debris, and pressure differentials caused by post-LOCA blockage under design-basis flow conditions. When evaluating impact from potential expanding jets and missiles, credit for any protection to trash racks and sump screens offered by surrounding structures or credit for remoteness of trash racks and sump screens from potential high energy sources should be justified.	2.1.2.5 The strength of the suction strainers should be adequate to protect the debris screen from missiles and other large debris. The strainers and the associated structural supports should be adequate to withstand loads imposed by missiles, debris accumulation, and hydrodynamic loads induced by suppression pool dynamics. To the extent practical, the strainers should be located outside the zone of influence of the vents, downcomers, or spargers to minimize hydrodynamic loads. The strainer design, vis-a-vis the hydrodynamic loads, should be validated analytically or experimentally.	Differences due mainly to differences between BWR and PWR systems; BWR systems are expected to experience more severe dynamic loads in postulated LOCA events; intent of guidance the same.
1.1.1.8 The debris interceptors should be designed to withstand the inertial and hydrodynamic effects that are due to vibratory motion of a safe shutdown earthquake (SSE) following a LOCA without loss of structural integrity.	2.1.2.6 The suction strainers should be designed to withstand the inertial and hydrodynamic effects that are due to vibratory motion of a safe shutdown earthquake (SSE) without loss of structural integrity.	PWR postulates a LOCA before the earthquake, or there would not be water in the sump; BWR has water in suppression pool at all times. Intent of the guidance is the same.

Regulatory Guide 1.82 (contd)

PWR	BWR	Difference(s)
1.1.1.9 Materials for debris interceptors and sump screens should be selected to avoid degradation during periods of both inactivity and operation and should have a low sensitivity to such adverse effects as stress-assisted corrosion that may be induced by chemically reactive spray during LOCA conditions.	2.1.2.7 Material for suction strainers should be selected to avoid degradation during periods of inactivity and operation and should have a low sensitivity to such adverse effects as stress-assisted corrosion that may be induced by coolant during LOCA conditions.	Differences due to differences between BWR and PWR systems; intent of guidance the same.
1.1.1.11 A sump screen design (i.e., size and shape) should be chosen that will avoid the loss of NPSH from debris blockage during the period that the ECCS is required to operate in order to maintain long-term cooling or maximize the time before loss of NPSH caused by debris blockage when used with an active mitigation system (see Regulatory Position 1.1.4).	2.1.2.1 The suction strainer design (i.e., size and shape) should be chosen to avoid the loss of NPSH from debris blockage during the period that the ECCS is required to operate in order to maintain long-term cooling or maximize the time before loss of NPSH caused by debris blockage when used with an active mitigation system (see Regulatory Position 2.1.5).	Guidance essentially the same for PWR and BWR.
1.1.1.12 The possibility of debris-clogging flow restrictions downstream of the sump screen should be assessed to ensure adequate long term recirculation cooling, containment cooling, and containment pressure control capabilities. The size of the openings in the sump debris screen should be determined considering the flow restrictions of systems served by the ECCS sump. The potential for long thin slivers passing axially through the sump screen and then reorienting and clogging at any flow restriction downstream should be considered. Consideration should be given to the buildup of debris at downstream locations such as the following: containment spray nozzle openings, HPSI throttle valves, coolant channel openings in the core fuel assemblies, fuel assembly inlet debris screens, ECCS pump seals, bearings, and impeller running clearances. If it is determined that a sump screen with openings small enough to filter out particles of debris that are fine enough to cause damage to ECCS pump seals or bearings would be impractical, it is expected that modifications would be made to ECCS pumps or ECCS pumps would be procured that can operate long term under the probable conditions.	2.1.2.2 The possibility of debris clogging flow restrictions downstream of the strainers should be assessed to ensure adequate long-term ECCS performance. The size of openings in the suppression pool suction strainers should be based on the minimum restrictions found in systems served by the suppression pool. The potential for long thin slivers passing axially through the strainer and then reorienting and clogging at any flow restriction downstream should be considered. Consideration should be given to the buildup of debris at the following downstream locations: spray nozzle openings, throttle valves, coolant channel openings in the core fuel assemblies, fuel assembly inlet debris screens, ECCS pump seals, bearings, and impeller running clearances. If it is determined that a strainer with openings small enough to filter out particles of debris that are fine enough to cause damage to ECCS pump seals or bearings would be impractical, it is expected that modifications would be made to ECCS pumps or ECCS pumps would be procured that can operate long term under the probable conditions.	Guidance essentially the same for PWR and BWR. PWR specifies adequate long term recirculation cooling, containment cooling, and containment pressure control capabilities. BWR mentions only adequate long-term ECCS performance.

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PWR	BWR	Difference(s)
1.1.1.13 ECC and containment spray pump suction inlets should be designed to prevent degradation of pump performance through air ingestion and other adverse hydraulic effects (e.g., circulatory flow patterns, high intake head losses).	2.1.2.3 ECC pump suction inlets should be designed to prevent degradation of pump performance through air ingestion and other adverse hydraulic effects (e.g., circulatory flow patterns, high intake head losses).	Guidance essentially the same for PWR and BWR.
1.1.1.14 All drains from the upper regions of the containment building, as well as floor drains, should terminate in such a manner that direct streams of water, which may contain entrained debris, will not discharge downstream of the sump screen, thereby bypassing the sump screen.	2.1.2.4 All drains from the upper regions of the containment should terminate in such a manner that direct streams of water, which may contain entrained debris, will not impinge on the suppression pool suction strainers.	Differences due to differences between BWR and PWR systems.
1.1.2 Minimizing Debris The debris (see Regulatory Position 1.3.2) that could accumulate on the sump screen should be minimized.	2.1.3 Minimizing Debris The amount of potential debris (see Regulatory Position 2.3.1) that could clog the ECC suction strainers should be minimized.	Guidance essentially the same for PWR and BWR.
1.1.2.1 Cleanliness programs should be established to clean the containment on a regular basis, and plant procedures should be established for control and removal of foreign materials from the containment.	2.1.3.1 Containment cleanliness programs should be instituted to clean the suppression pool on a regular basis, and plant procedures should be established for control and removal of foreign materials from the containment.	Differences due to differences between BWR and PWR systems; intent of guidance is essentially the same
1.1.2.2 Insulation types (e.g., fibrous and calcium silicate) that can be sources of debris that is known to more readily transport to the sump screen and cause higher head losses may be replaced with insulations (e.g., reflective metallic insulation) that transport less readily and cause less severe head losses once deposited onto the sump screen. If insulation is replaced or otherwise removed during maintenance, abatement procedures should be established to avoid generating latent debris in the containment.	2.1.3.3 Insulation types (e.g., fibrous and calcium silicate) that can be sources of debris that is known to more readily transport to the strainer and cause higher head losses should be avoided. Insulations (e.g., reflective metallic insulation) that transport less readily and cause less severe head losses once deposited onto the strainers should be used. If insulation is replaced or otherwise removed during maintenance, abatement procedures should be established to avoid generating latent debris in the containment.	Guidance essentially the same for PWR and BWR.
1.1.2.3 To minimize potential debris caused by chemical reaction of the pool water with metals in the containment, exposure of bare metal surfaces (e.g., scaffolding) to containment cooling water through spray impingement or immersion should be minimized either by removal or by chemical-resistant protection (e.g., coatings or jackets).	2.1.3.4 To minimize potential debris caused by chemical reaction of coolant with metals in the containment, exposure of bare metal surfaces (e.g., scaffolding) to spray impingement or immersion should be minimized either by removal or by using chemical-resistant protection (e.g., coatings or jackets).	Guidance essentially the same for PWR and BWR.

PWR	BWR	Difference(s)
1.1.3 Instrumentation If relying on operator actions to mitigate the consequences of the accumulation of debris on the ECC sump screens, safety-related instrumentation that provides operators with an indication and audible warning of impending loss of NPSH for ECCS pumps should be available in the control room.	2.1.4 Instrumentation If relying on operator actions to mitigate the consequences of the accumulation of debris on the suction strainers, safety-related instrumentation that provides operators with an indication and audible warning of impending loss of NPSH for ECCS pumps should be available in the control room.	Guidance essentially the same for PWR and BWR.
1.1.4 Active Sump Screen System An active device or system (see examples in Appendix B) may be provided to prevent the accumulation of debris on a sump screen or to mitigate the consequences of accumulation of debris on a sump screen. An active system should be able to prevent debris that may block restrictions found in the systems served by the ECC pumps from entering the system. The operation of the active component or system should not adversely affect the operation of other ECC components or systems. Performance characteristics of an active sump screen system should be supported by appropriate test data that address head loss performance.	2.1.5 Active Strainers An active component or system (see Appendix B) may be provided to prevent the accumulation of debris on a suction strainer or to mitigate the consequences of accumulation of debris on a suction strainer. An active system should be able to prevent debris that may block restrictions found in the systems served by the ECC pumps from entering the system. The operation of the active component or system should not adversely affect the operation of other ECC components or systems. The use of active strainers should be validated by adequate testing. 2.3.3.6 The performance characteristics of a passive or an active strainer should be supported by appropriate test data that addresses, at a minimum, (1) suppression pool hydrodynamic loads and (2) head loss performance.	Guidance essentially the same for PWR and BWR.
1.1.5 Inservice Inspection To ensure the operability and structural integrity of the trash racks and screens, access openings are necessary to permit inspection of the ECC sump structures and outlets. Inservice inspection of racks, screens, vortex suppressors, and sump outlets, including visual examination for evidence of structural degradation or corrosion, should be performed on a regular basis at every refueling period downtime. Inspection of the ECC sump components late in the refueling period will ensure the absence of construction trash in the ECC sump area.	2.1.6 Inservice Inspection Inservice inspection requirements should be established that include (1) inspection of the cleanliness of the suppression pool, (2) a visual examination for evidence of structural degradation or corrosion of the suction strainers and strainer system, and (3) an inspection of the wetwell and the drywell, including the vents, downcomers, and deflectors, for the identification and removal of debris or trash that could contribute to the blockage of suppression pool suction strainers. These inservice inspections should be performed on a regular basis at every refueling period downtime.	Differences due to differences between BWR and PWR systems; intent of guidance is essentially the same

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PWR	BWR	Difference(s)
1.2 Evaluation of Alternative Water Sources To demonstrate that a combination of the features and actions listed above are adequate to ensure long-term cooling and that the five criteria of 10 CFR 50.46(b) will be met following a LOCA, an evaluation using the guidance and assumptions in Regulatory Position 1.3 should be conducted. If a licensee is relying on operator actions to prevent the accumulation of debris on ECC sump screens or to mitigate the consequences of the accumulation of debris on the ECC sump screens, an evaluation should be performed to ensure that the operator has adequate indications, training, time, and system capabilities to perform the necessary actions. If not covered by plant-specific emergency operating procedures, procedures should be established to use alternative water sources that will be activated when unacceptable head loss renders the sump inoperable. The valves needed to align the ECCS and containment spray systems (taking suction from the recirculation sumps) with an alternative water source should be periodically inspected and maintained.	2.2 Evaluation of Alternative Water Sources To demonstrate that a combination of the features and actions listed above are adequate to ensure long-term cooling and that the five criteria of 10 CFR 50.46(b) will be met following a LOCA, an evaluation using the guidance and assumptions in Regulatory Position 2.3 should be conducted. If a licensee is relying on operator actions to prevent the accumulation of debris on suction strainers or to mitigate the consequences of the accumulation of debris on the suction strainers, an evaluation should be performed to ensure that the operator has adequate indications, training, time, and system capabilities to perform the necessary actions. If not covered by plant-specific emergency operating procedure, procedures should be established to use alternative water sources. The valves needed to align the ECCS with an alternative water source should be periodically inspected and maintained.	Differences due to differences between BWR and PWR systems; intent of guidance is essentially the same

PWR	BWR	Difference(s)
1.3 Evaluation of Long-Term Recirculation Capability The following techniques, assumptions, and guidance should be used in a deterministic, plant-specific evaluation to ensure that any implementation of a combination of the features and capabilities listed in Regulatory Position 1.1 are adequate to ensure the availability of a reliable water source for long-term recirculation following a LOCA. The assumptions and guidance listed below can also be used to develop test conditions for sump screens. Evaluation and confirmation of (1) sump hydraulic performance (e.g., geometric effects, air ingestion), (2) debris effects (e.g., debris transport, interceptor blockage, head loss), and (3) the combined impact on NPSH available at the pump inlet should be performed to ensure that long-term recirculation cooling can be accomplished following a LOCA. Such an evaluation should arrive at a determination of NPSH margin calculated at the pump inlet. An assessment should also be made of the susceptibility to debris blockage of the containment drainage flow paths to the recirculation sump; this is to protect against reduction in available NPSH if substantial amounts of water are held up or diverted away from the sump. An assessment should be made of the susceptibility of the flow restrictions in the ECCS and CSS recirculation flow paths downstream of the sump screens and of the recirculation pump seal and bearing assembly design to failure from particulate ingestion and abrasive effects to protect against degradation of long-term recirculation pumping capacity.	2.3 Evaluation of Long-Term Recirculation Capability During any evaluation of the susceptibility of a BWR to debris blockage, the considerations and events shown in Figures 4 and 5 should be addressed. The following techniques, assumptions, and guidance should be used in a deterministic evaluation to ensure that any implementation of a combination of the features and capabilities listed in Regulatory Position 2.1 are adequate to ensure the availability of a reliable water source for long-term recirculation after a LOCA. An assessment should be made of the susceptibility to debris blockage of the containment drainage flowpaths to the suppression pool, flow restrictions in the ECCS, and containment spray recirculation flowpaths downstream of the suction strainer to protect against degradation of long-term recirculation pumping capacity. Unless otherwise noted, the techniques, assumptions, and guidance listed below are applicable to an evaluation of passive and active strainers. The assumptions and guidance listed below can also be used to develop test conditions for suction strainers or strainer systems.	Differences due to differences between BWR and PWR systems; intent of guidance is essentially the same

PWR	BWR	Difference(s)
1.3.2 Debris Sources and Generation	2.3.1 Debris Sources and Generation	
1.3.2.1 Consistent with the requirements of 10 CFR 50.46, debris generation should be calculated for a number of postulated LOCAs of different sizes, locations, and other properties sufficient to provide assurance that the most severe postulated LOCAs are calculated. The level of severity corresponding to each postulated break should be based on the potential head loss incurred across the sump screen. Some PWRs may need recirculation from the sump for licensing basis events other than LOCAs. Therefore, licensees should evaluate the licensing basis and include potential break locations in the main steam and main feedwater lines as well in determining the most limiting conditions for sump operation.	2.3.1.1 Consistent with the requirements of 10 CFR 50.46, debris generation should be calculated for a number of postulated LOCAs of different sizes, locations, and other properties sufficient to provide assurance that the most severe postulated LOCAs are calculated.	Differences due to differences between BWR and PWR systems; intent of guidance is essentially the same

PWR	BWR	Difference(s)
1.3.2.2 An acceptable method for estimating the amount of debris generated by a postulated LOCA is to use the zone of influence (ZOI). Examples of this approach are provided in NUREG/CR-6224 and Boiling Water Reactor Owners' Group (BWROG) Utility Resolution Guidance (NEDO-32686 and the staff's Safety Evaluation on the BWROG's response to NRC Bulletin 96-03). A representation of the ZOI for commonly used insulation materials is shown in Figure 3. • The size and shape of the ZOI should be supported by analysis or experiments for the break and potential debris. The size and shape of the ZOI should be consistent with the debris source (e.g., insulation, fire barrier materials, etc.) damage pressures, i.e., the ZOI should extend until the jet pressures decrease below the experimentally determined damage pressures appropriate for the debris source. • The volume of debris contained within the ZOI should be used to estimate the amount of debris generated by a postulated break. • The size distribution of debris created in the ZOI should be determined by analysis or experiments. • The shock wave generated during the postulated pipe break and the subsequent jet should be the basis for estimating the amount of debris generated and the size or size distribution of the debris generated within the ZOI. Certain types of material used in a small quantity inside the containment can, with adequate justification, be demonstrated to make a marginal contribution to the debris loading for the ECC sump. If debris generation and debris transport data have not been determined experimentally for such material, it may be grouped with another like material existing in large quantities. For example, a small quantity of fibrous filtering material may be grouped with a substantially large quantity of fibrous insulation debris, and the debris generation and transport data for the filter material need not be determined experimentally. However, such analyses are valid only if the small quantity of material treated in this manner does not have a significant effect when combined with other materials (e.g., a small quantity of calcium silicate combined with fibrous debris).	2.3.1.2 An acceptable method for determining the shape of the zone of influence (ZOI) of a break is described in NUREG/CR-6224 and NEDO-32686. The volume contained within the ZOI should be used to estimate the amount of debris generated by a postulated break. The distance of the ZOI from the break should be supported by analysis or experiments for the break and potential debris. The shock wave generated during postulated pipe break and the subsequent jet should be the basis for estimating the amount of debris generated and the size or size distribution of the debris generated within the ZOI. Certain types of material used in a small quantity inside the containment can, with adequate justification, be demonstrated to make a marginal contribution to the debris loading for the ECC sump. If debris generation and debris transport data have not been determined experimentally for such material, it may be grouped with another like material existing in large quantities. For example, a small quantity of fibrous filtering material may be grouped with a substantially larger quantity of fibrous insulation debris, and the debris generation and transport data for the filter material need not be determined experimentally. However, such analyses are valid only if the small quantity of material treated in this manner does not have a significant effect when combined with other materials (e.g., a small quantity of calcium silicate combined with fibrous debris).	Guidance essentially the same for PWR and BWR. Note that the text of 1.3.2.2 is a severe condensation of a complex topic, and can be confusing if read out of context. Expanded discussion of the ZOI (describing how it is defined and how it is used) can be found in the two cited sources, NUREG/CR-6224 and NEDO-32686, which are common to the guidelines for both BWRs and PWRs.
	2.3.1.3 All sources of fibrous materials in the containment such as fire protection materials, thermal insulation, or filters that are present during operation should be identified.	No specific guidance on this topic for PWR; however, it appears to be covered in Regulatory Position 1.3.2.2 above.

PWR	BWR	Difference(s)
1.3.2.3 A sufficient number of breaks in each high-pressure system that relies on recirculation should be considered, to reasonably bound variations in debris generation by the size, quantity, and type of debris. As a minimum, the following postulated break locations should be considered. • Breaks in the reactor coolant system (e.g., hot leg, cold leg, pressurizer surge line) and, depending on the plant licensing basis, main steam and main feedwater lines with the largest amount of potential debris within the postulated ZOI, • Large breaks with two or more different types of debris, including the breaks with the most variety of debris, within the expected ZOI, • Breaks in areas with the most direct path to the sump, • Medium and large breaks with the largest potential particulate debris to insulation ratio by weight, and • Breaks that generate an amount of fibrous debris that, after its transport to the sump screen, could form a uniform thin bed that could subsequently filter sufficient particulate debris to create a relatively high head loss referred to as the "thin-bed effect." The minimum thickness of fibrous debris needed to form a thin bed has typically been estimated at 1/8 inch thick based on the nominal insulation density (NUREG/CR-6224).	2.3.1.5 A sufficient number of breaks in each high-pressure system that relies on recirculation should be considered to reasonably bound variations in debris generation by the size, quantity, and type of debris. As a minimum, the following postulated break locations should be considered. • Breaks in the main steam, feedwater, and recirculation lines with the largest amount of potential debris within the postulated ZOI, • Large breaks with two or more different types of debris, including the breaks with the most variety of debris, within the expected ZOI, • Breaks in areas with the most direct path between the drywell and wetwell, • Medium and large breaks with the largest potential particulate debris to insulation ratio by weight, and • Breaks that generate an amount of fibrous debris that, after its transport to the suction strainer, could form a uniform thin bed that could subsequently filter sufficient particulate debris to create a relatively high head loss referred to as the "thin-bed effect." The minimum thickness of fibrous debris needed to form a thin bed has typically been estimated at 1/8 inch thick based on the nominal insulation density (NUREG/CR-6224).	Differences due to differences between BWR and PWR systems; specific guidance on types of breaks to be considered is essentially identical, and the intent of guidance is clearly the same.
1.3.2.4 All insulation (e.g., fibrous, calcium silicate, reflective metallic), painted surfaces, fire barrier materials, and fibrous, cloth, plastic, or particulate materials within the ZOI should be considered a debris source. Analytical models or experiments should be used to predict the size of the postulated debris. For breaks postulated in the vicinity of the pressure vessel, the potential for debris generation from the packing materials commonly used in the penetrations and the insulation installed on the pressure vessel should be considered. Particulate debris generated by pipe rupture jets stripping off paint or coatings and eroding concrete at the point of impact should also be considered.	2.3.1.4 All insulation, painted surfaces, and fibrous, cloth, plastic, or particulate materials within the ZOI should be considered debris sources. Analytical models or experiments should be used to predict the size of the postulated debris.	Differences due to differences between BWR and PWR systems; specific guidance on postulated debris is identical and the intent of guidance is clearly the same.

PWR	BWR	Difference(s)
1.3.2.5 The cleanliness of the containment during plant operation should be considered when estimating the amount and type of debris available to block the ECC sump screens. The potential for such material (e.g., thermal insulation other than piping insulation, ropes, fire hoses, wire ties, tape, ventilation system filters, permanent tags or stickers on plant equipment, rust flakes from unpainted steel surfaces, corrosion products, dust and dirt, latent individual fibers) to impact head loss across the ECC sump screens should also be considered.	2.3.1.6 The cleanliness of the suppression pool and containment during plant operation should be considered when estimating the amount and type of debris available to block the suction strainers. The potential for such material (e.g., thermal insulation other than piping insulation, ropes, fire hoses, wire ties, tape, ventilation system filters, permanent tags or stickers on plant equipment, rust flakes from unpainted steel surfaces, corrosion products, dust and dirt, latent individual fibers) to impact head loss across the suction strainer should also be considered.	Guidance essentially the same for PWR and BWR. Differences due to differences between BWR and PWR systems.
	2.3.1.7 The amount of particulates estimated to be in the pool prior to a LOCA should be considered to be the maximum amount of corrosion products (i.e., sludge) expected to be generated since the last time the pool was cleaned. The size distribution and amount of particulates should be based on plant samples.	Guidance for BWR only; PWR sump is normally dry. This issue covered in 1.3.2.5 for PWR, and intent of guidance is clearly the same for the two types of LWR.
1.3.2.6 In addition to debris generated by jet forces from the pipe rupture, debris created by the resulting containment environment (thermal and chemical) should be considered in the analyses. Examples of this type of debris would be disbondment of coatings in the form of chips and particulates or formation of chemical debris (precipitants) caused by chemical reactions in the pool.	2.3.1.8 In addition to debris generated by jet forces from the pipe rupture, debris created by the resulting containment environment (thermal and chemical) should be considered in the analyses. Examples of this type of debris would be disbondment of coatings in the form of chips and particulates or formation of chemical debris (precipitants) caused by chemical reactions in the pool.	Guidance the same for PWR and BWR.
1.3.2.7 Debris generation that is due to continued degradation of insulation and other debris when subjected to turbulence caused by cascading water flows from upper regions of the containments or near the break overflow region should be considered in the analyses.		Guidance for PWR only; BWR containment is not as tall or compartmentalized. This issue adequately covered in 2.3.1.8 for BWR, and intent of guidance is clearly the same for the two types of LWR.

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PWR	BWR	Difference(s)
1.3.3 Debris Transport	2.3.2 Debris Transport	
1.3.3.1 The calculation of debris quantities transported from debris sources to the sump screen should consider all modes of debris transport, including airborne debris transport, containment spray washdown debris transport, and containment sump pool debris transport. Consideration of the containment pool debris transport should include (1) debris transport during the fill-up phase, as well as during the recirculation phase, (2) the turbulence in the pool caused by the flow of water, water entering the pool from break overflow, and containment spray drainage, and (3) the buoyancy of the debris. Transport analyses of debris should consider: (1) debris that would float along the pool surface, (2) debris that would remain suspended due to pool turbulence (e.g., individual fibers and fine particulates), and (3) debris that readily settles to the pool floor.	2.3.2.1 It should be assumed that all debris fragments smaller than the clearances in the gratings will be transported to the suppression pool during blowdown. Credit may be taken for filtration of larger pieces of debris by floor gratings and other interdicting structures present in a drywell (NEDO-32686 and NUREG/CR-6369). However, it should be assumed that a fraction of large fragments captured by the gratings would be eroded by the combined effects of cascading break overflow and the drywell spray flow. The fraction of the smaller debris generated and thus transported to the suppression pool during the blowdown, as well as the fraction of the larger debris that may be eroded during the washdown phase, should be determined analytically or experimentally.	PWR guidance outlines specific requirements of analytical models developed to calculate the amount of debris transported to the sump screens. BWR guidance requires the potentially more conservative assumption that *all* debris below a certain size is transported to the suppression pool. Analytical or empirical models must then be developed to determine the amount and size distribution of debris generated, including accounting for the various processes that could erode larger debris fragments into smaller fragments. Differences reflect slightly different approaches to the problem, but the intent of the guidance is clearly the same; developing a conservative estimate of the amount of debris that reaches the sump screens or suction strainers.
1.3.3.2 The debris transport analyses should consider each type of insulation (e.g., fibrous, calcium silicate, reflective metallic) and debris size (e.g., particulates, fibrous fine, large pieces of fibrous insulation). The analyses should also consider the potential for further decomposition of the debris as it is transported to the sump screen.	2.3.1.4 All insulation, painted surfaces, and fibrous, cloth, plastic, or particulate materials within the ZOI should be considered debris sources. Analytical models or experiments should be used to predict the size of the postulated debris.	Organization of guidance is different, but requirements to consider all types of debris source materials and full range of possible debris size are essentially the same for both types of systems.

PWR	BWR	Difference(s)
1.3.3.3 Bulk flow velocity from recirculation operations, LOCA-related hydrodynamic phenomena, and other hydrodynamic forces (e.g., local turbulence effects or pool mixing) should be considered for both debris transport and ECC sump screen velocity computations.	2.3.2.5 Bulk suppression pool velocity from recirculation operations, LOCA-related hydrodynamic phenomena, and other hydrodynamic forces (e.g., local turbulence effects or pool mixing) should be considered for both debris transport and suction strainer velocity computations.	Guidance essentially the same for PWR and BWR.
1.3.3.4 An acceptable analytical approach to predict debris transport within the sump pool is to use computational fluid dynamics (CFD) simulations in combination with the experimental debris transport data. Examples of this approach are provided in NUREG/CR-6772 and NUREG/CR-6773. Alternative methods for debris transport analyses are also acceptable, provided they are supported by adequate validation of analytical techniques using experimental data to ensure that the debris transport estimates are conservative with respect to the quantities and types of debris transported to the sump screen.	2.3.2.2 It should be assumed that LOCA-induced phenomena (i.e., pool swell, chugging, condensation oscillations) will suspend all the debris assumed to be in the suppression pool at the onset of the LOCA. 2.3.2.3 The concentration of debris in the suppression pool should be calculated based on the amount of debris estimated to reach the suppression pool from the drywell and the amount of debris and foreign materials estimated to be in the suppression pool prior to a postulated break. 2.3.2.5 Bulk suppression pool velocity from recirculation operations, LOCA-related hydrodynamic phenomena, and other hydrodynamic forces (e.g., local turbulence effects or pool mixing) should be considered for both debris transport and suction strainer velocity computations.	PWR guidance explicitly states that analysis based on CFD modeling or other “alternative methods” could be acceptable approaches to predicting debris transport within the sump pool. BWR guidance provides specific assumptions regarding the amount and location of debris, but does not give specific guidance on the types of analyses that would be acceptable to determine debris transport.
1.3.3.5 Curbs can be credited for removing heavier debris that has been shown analytically or experimentally to travel by sliding along the containment floor and that cannot be lifted off the floor within the calculated water velocity range.	2.3.2.1 It should be assumed that all debris fragments smaller than the clearances in the gratings will be transported to the suppression pool during blowdown. Credit may be taken for filtration of larger pieces of debris by floor gratings and other interdicting structures present in a drywell (NEDO-32686 and NUREG/CR-6369). However, it should be assumed that a fraction of large fragments captured by the gratings would be eroded by the combined effects of cascading break overflow and the drywell spray flow. The fraction of the smaller debris generated and thus transported to the suppression pool during the blowdown, as well as the fraction of the larger debris that may be eroded during the washdown phase, should be determined analytically or experimentally.	Differences due mainly to differences between BWR and PWR systems; intent of guidance appears to be essentially the same.

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PWR	BWR	Difference(s)
1.3.3.6 If transported to the sump pool, all debris (e.g., fine fibrous, particulates) that would remain suspended due to pool turbulence should be considered to reach the sump screen.	2.3.2.2 It should be assumed that LOCA-induced phenomena (i.e., pool swell, chugging, condensation oscillations) will suspend all the debris assumed to be in the suppression pool at the onset of the LOCA. 2.3.2.4 Credit should not be taken for debris settling until LOCA-induced turbulence in the suppression pool has ceased. The debris settling rate for the postulated debris should be validated analytically or experimentally.	Guidance for PWR for BWR essentially the same.
1.3.3.7 The time to switch over to sump recirculation and the operation of containment spray should be considered in the evaluation of debris transport to the sump screen.		Guidance applies to PWR only.
1.3.3.8 In lieu of performing airborne and containment spray washdown debris transport analyses, it could be assumed that all debris will be transported to the sump pool. In lieu of performing sump pool debris transport analyses (Regulatory Position 1.3.3.4), it could be assumed that all debris entering the sump pool or originating in the sump will be considered transported to the sump screen when estimating screen debris bed head loss. If it is credible in a plant that all drains leading to the containment sump could become completely blocked, or an inventory holdup in containment could happen together with debris loading on the sump screen, these situations could pose a worse impact on the recirculation sump performance than the assumed situations mentioned above. In this case, these situations should also be assessed.	2.3.2.1 It should be assumed that all debris fragments smaller than the clearances in the gratings will be transported to the suppression pool during blowdown. Credit may be taken for filtration of larger pieces of debris by floor gratings and other interdicting structures present in a drywell (NEDO-32686 and NUREG/CR-6369). However, it should be assumed that a fraction of large fragments captured by the gratings would be eroded by the combined effects of cascading break overflow and the drywell spray flow. The fraction of the smaller debris generated and thus transported to the suppression pool during the blowdown, as well as the fraction of the larger debris that may be eroded during the washdown phase, should be determined analytically or experimentally.	Guidance for PWR and BWR is essentially the same. For PWR it is an alternative option, but for BWR, it is the main assumption for all debris transport analysis.
1.3.3.9 The effects of floating or buoyant debris on the integrity of the sump screen and on subsequent head loss should be considered. For screens that are not fully submerged or are only shallowly submerged, floating debris could contribute to the debris bed head loss. The head loss due to floating or buoyant debris could be minimized by a design feature to keep buoyant debris from reaching the sump screen.		BWR guidelines do not address the possible effects of floating debris, or partially uncovered suction strainers. The suppression pool is expected to remain deep enough to preclude such issues.

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PWR	BWR	Difference(s)
1.3.4 Debris Accumulation and Head Loss	2.3.3 Strainer Blockage and Head Loss	
1.3.4.1 ECC sump screen blockage should be evaluated based on the amount of debris estimated using the assumptions and criteria described in Regulatory Position 1.3.2 and on the debris transported to the ECC sump per Regulatory Position 1.3.3. This volume of debris should be used to estimate the rate of accumulation of debris on the ECC sump screen.	2.3.3.1 Strainer blockage should be based on the amount of debris estimated using the assumptions and guidance described in Regulatory Position 2.3.1 and on the debris transported to the wetwell per Regulatory Position 2.3.2. This volume of debris, as well as other materials that could be present in the suppression pool prior to a LOCA, should be used to estimate the rate of accumulation of debris on the strainer surface. 2.3.3.2 The flow rate through the strainer should be used to estimate the rate of accumulation of debris on the strainer surface.	Guidance for PWR and BWR appears to be essentially the same for estimating the rate of accumulation of debris. The explicit guidance for BWR, specifying use of the flow rate to estimate rate of accumulation of debris, may be redundant, and could potentially be inconsistent with Regulatory Position 2.3.3.1.
1.3.4.2 Consideration of ECC sump screen submergence (full or partial) at the time of switchover to ECCS should be given in calculating the available (wetted) screen area. For plants in which containment heat removal pumps take suction from the ECC sump before switchover to the ECCS, the available NPSH for these pumps should consider the submergence of the sump screens at the time these pumps initiate suction from the ECC sump. Unless otherwise shown analytically or experimentally, debris should be assumed to be uniformly distributed over the available sump screen surface. Debris mass should be calculated based on the amount of debris estimated to reach the ECC sump screen. (See Revision 1 of NUREG-0897, NUREG/CR-3616, and NUREG/CR-6224.)	2.3.3.3 The suppression pool suction strainer area used in determining the approach velocity should conservatively account for blockage that may result. Unless otherwise shown analytically or experimentally, debris should be assumed to be uniformly distributed over the available suction strainer surface. Debris mass should be calculated based on the amount of debris estimated to reach or to be in the suppression pool. (See Revision 1 of NUREG-0897, NUREG/CR-3616, and NUREG/CR-6224.)	Differences are due to differences between PWR and BWR systems; intent of guidance is the same for both designs.
1.3.4.3 For fully submerged sump screens, the NPSH available to the ECC pumps should be determined using the conditions specified in the plant's licensing basis.	2.3.3.4 The NPSH available to the ECC pumps should be determined using the conditions specified in the plant's licensing basis.	Guidance for PWR and BWR appears to be essentially the same.

Regulatory Guide 1.82 (contd)

PWR	BWR	Difference(s)
1.3.4.4 For partially submerged sump [screen]s, NPSH margin may not be the only failure criterion, as discussed in Appendix A. For partially submerged sumps, credit should only be given to the portion of the sump screen that is expected to be submerged, as a function of time. Pump failure should be assumed to occur when the head loss across the sump screen (including only the clean screen head loss and the debris bed head loss) is greater than one-half of the submerged screen height or NPSH margin.		Guidance for PWR only; assumes BWR suction strainers are always fully submerged.
1.3.4.5 Estimates of head loss caused by debris blockage should be developed from empirical data based on the sump screen design (e.g., surface area and geometry), postulated combinations of debris (i.e., amount, size distribution, type), and approach velocity. Because debris beds that form on sump screens can trap debris that would pass through an unobstructed sump screen opening, any head loss correlation should conservatively account for filtration of particulates by the debris bed, including particulates that would pass through an unobstructed sump screen.	2.3.3.5 Estimates of head loss caused by debris blockage should be developed from empirical data based on the strainer design (e.g., surface area and geometry), postulated debris (i.e., amount, size distribution, type), and velocity. Any head loss correlation should conservatively account for filtration of particulates by the debris bed.	Guidance for PWR and BWR is essentially the same.
1.3.4.6 Consistent with the requirements of 10 CFR 50.46, head loss should be calculated for the debris beds formed of different combinations of fibers and particulate mixtures (e.g., minimum uniform thin bed of fibers supporting a layer of particulate debris) based on assumptions and criteria described in Regulatory Positions 1.3.2 and 1.3.3.	2.3.3.5 Estimates of head loss caused by debris blockage should be developed from empirical data based on the strainer design (e.g., surface area and geometry), postulated debris (i.e., amount, size distribution, type), and velocity. Any head loss correlation should conservatively account for filtration of particulates by the debris bed.	Organization of guidance is different, but intent is same for both PWR and BWR.

APPENDIX B

TIME-LINE OF EVOLUTION OF POST-LOCA ECCS SAFETY ISSUES IN COMMERCIAL LWRS

Appendix B: Time-Line of Evolution of Post-LOCA ECCS Safety Issues in Commercial LWRs

Date	Event
January 1979	**Unresolved Safety Issue A-43**, *Containment Emergency Sump Performance* (included in NUREG-0510, ***Identification of Unresolved Safety Issues Relating to Nuclear Power Plants***); initiated to address concerns about adequate recirculation water following a LOCA for long-term cooling; initially raised for PWRs, technically also applied to BWRs, but scope later included BWRs as well.
October 1985	**USI A-43** considered resolved with publication of NUREG-0896 ***USI A-43 Regulatory Analysis*** and NUREG-0897 ***Containment Emergency Sump Performance***, revision of the **Standard Review Plan** (Section 6.2.2).
November 1985	NRC issued **Regulatory Guide 1.82, Revision 1**, addressing *Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident.*
December 1985	NRC issued **Generic Letter 85-22**, *Potential for Loss of Post-LOCA Recirculation Capability Due to Insulation Debris Blockage* to inform licensees of BWRs and PWRs of the closure of USI A-43, the updates made to regulatory guidance for strainer performance, and the regulatory analysis which determined that backfitting the revised regulatory guidance on operating plants was not justified
1988,1989	Strainer blocking events at Grand Gulf Nuclear station (a BWR/6, Mark III plant) in Mississippi during testing of RHR pump suction strainers.
May 1992	Strainer clogging event at Perry Nuclear Station (a BWR/6, Mark III plant) in Ohio.
July 1992	Strainer blockage incident at Barsebäck Unit 2 BWR plant in Sweden (similar to BWR/4, Mark II containment).
May 1993	NRC issued **Bulletin 93-02**, *Debris Plugging of Emergency Core Cooling Suction Strainers* to all nuclear power plant licensees.
September 1993	Second strainer clogging event at Perry Nuclear Station in Ohio; strainers deformed due to excessive head loss in one incident at Perry.
January 1994	Divers discover cloth-like material partially blocking ECCS strainers at Browns Ferry Unit 2 (a BWR/4, Mark I plant).
February 1994	NRC issued **Supplement 1** to **Bulletin 93-02**, requesting further interim actions by licensees.
August 1994	NRC published draft-for-comment version of NUREG/CR-6224, **Parametric Study of Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris**, documenting results of detailed study of BWR/4 Mark I "reference plant," initiated in September 1993.
September 1995	Strainer blockage incident at Limerick Unit 1 (a BWR/4, Mark II plant); pump cavitation in ECCS loop indicated at Limerick.
October 1995	NRC published final report NUREG/CR-6224, **Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris.**

Date	Event
	NRC issued **Bulletin 95-02**, *Unexpected Clogging of a Residual Heat Removal Pump Strainer While Operating in Suppression Pool Cooling Mode* to all operating BWR licensees, requesting licensees to take action to ensure that unacceptable build-up of debris in suppression pool would not occur during normal operation.

Time-Line of Post-LOCA ECCS Safety Issues (contd)

Date	Event
March 1996	Strainer blockage event at LaSalle plant (BWR/4; Mark II)
May 1996	NRC issued **Revision 2** of **Regulatory Guide 1.82**, altering the debris blocking evaluation guidance for BWRs; operational events, analyses, and research work indicated that Revision 1 guidance was not comprehensive enough.
May 1996	NRC issued **Bulletin 96-03**, *Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling Water Reactors* to all holders of operating licenses, requiring that they implement “appropriate measures” to ensure ECCS performance following a LOCA.
November 1996	BWROG submitted **Utility Resolution Guidance** in NEDO-32686, Rev. 0, ***Utility Resolution Guidance for ECCS Suction Strainer Blockage,*** for NRC review and approval.
October 1997	NRC issued **Generic Letter 97-04**, *Assurance of Sufficient Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal Pumps* to all nuclear power plant licensees, requesting current information on net positive suction head (NPSH) analyses.
July 1998	NRC issued **Generic Letter 98-04**, *Potential for Degradation of the Emergency Core Cooling System and Containment Spray System after Loss-of-Coolant Accident Because of Construction and Protective Coatings Deficiencies and Foreign Material in Containment*, to all licensees of operating nuclear power plants requesting information on licensees’ programs for ensuring that protective coatings do not detach from substrate during DBLOCA.
August 1998	NRC issued Safety Evaluation on BWROG Utility Resolution Guidance, granting approval of the document, but with specific limitations.[w]
October 1998	BWROG published NEDO-32686-A, **Utility Resolution Guidance for ECCS Suction Strainer Blockage**, consisting of the original NEDO-32686, Revision 0, plus the SE from NRC and a summary of the elements NRC did not accept or approve.

(w) BWROG did not directly address the NRC limitations. NEDO-32686-A (October 1998) summarizes the guidelines that NRC did not accept and suggests that the individual utilities can address the relevant issues that pertain to their plant-specific remediation proposals when they submit them for NRC approval.

Time-Line of Post-LOCA ECCS Safety Issues (contd)

Date	Event
1998	NRC defined **Generic Safety Issue 191** (**GSI-191**), *Assessment of Debris Accumulation on PWR Sump Performance* in footnotes 1691 and 1692 of NUREG-0933, in response to NRR request for re-examination of USI A-43, made in 1996; initiated studies to determine if debris in containment after LOCA would impede ECCS operation in PWRs.
September 1999	NRC published NUREG/CR-6368, Vol. 1, ***Drywell Debris Transport Study***, documenting efforts to determine transport rates for debris generated in BWR containment.
March 2001	NRC issued LA-UR-01-1595, ***BWR ECCS Strainer Blockage Issue: Summary of Research and Resolution Actions***, a report summarizing technical basis for resolution of the BWR strainer blockage issue.
September 2001	NRC issued review draft of NUREG/CR-6762, Vol. 1, **GSI-191 Technical Assessment: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance**, documenting technical basis showing that sump blockage is a credible concern for PWR operation.
October 2001	NRC Memorandum *Completion of Staff Reviews of NRC Bulletin 96-03 –* ***Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling Water Reactors****, and NRC Bulletin 95-02 –* ***Unexpected Clogging of a Residual Heat Removal (RHR) Pump Strainer while Operating in Suppression Pool Cooling Mode***, documenting closure of multi-plant actions (MPAs) related to NRC Bulletins 95-02 and 96-03
May 2002	PWR owners group submitted NEI 02-01, ***Condition Assessment Guidelines: Debris Sources Inside PWR Containments***, to NRC for review and approval
August 2002	NRC published NUREG/CR-6762, **GSI-191 Technical Assessment:** Vol. 1, **GSI-191 Technical Assessment: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance**, Vol. 2 **Summary and Analysis of US Pressurized Water Reactor Industry Survey Responses and Responses to GL 97-04,** Vol. 3 **Development of Debris Generation Quantities in Support of the Parametric Evaluation,** Vol. 4 **Development of Debris Transport Fractions in Support of the Parametric Evaluation.**
February 2003	NRC published NUREG/CR-6808, **Knowledge Base for Effect of Debris on Pressurized Water Reactor Emergency Core Cooling Sump Performance.**
November 2003	NRC issued **Revision 3** of **Regulatory Guide 1.82**, clarifying and reconciling the requirements for ensuring ECCS water supply in BWRs and PWRs.
May 2004	PWR owners group submitted NEI 04-07, **Pressurized Water Reactor Sump Performance Evaluation Methodology**, to NRC for review and approval.
September 2004	NRC issued **Generic Letter 2004-02**, *Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized Water Reactors*, to all licensees.

Time-Line of Post-LOCA ECCS Safety Issues (contd)

Date	Event
November 2004	NRC issued SE on NEI 04-07, approving the general Baseline Methodology for sump performance issues, with certain reservations and requirements for additional work.
December 2004	NRC issued **Volume 2 – Safety Evaluation by the Office of Nuclear Reactor Regulation Related to NRC Generic Letter 2004-02**, Revision 0, December 6, 2004
July 2005	NRC published NUREG/CR-6877, **Characterization and Head Loss Testing of Latent Debris from Pressurized Water Reactor Containment Buildings.** Study to quantify parameters critical to application of NUREG/CR-6224 head loss correlation for sump screens.
August 22, 2006	NRC agreed to review PWROG technical report WCAP-16406-P, Rev. 1, **Evaluation of Downstream Sump Debris Effects in Support of GSI-191.**
December 2006	NRC published NUREG/CR-6917, **Experimental Measurements of Pressure Drop Across Sump Screen Debris Beds in Support of Generic Safety Issue 191.**
June 2007	WCAP-16793-NP, *Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid*, submitted by the PWR Owners Group in response to NRC staff determination in the review of WCAP-16306-P that additional information is needed on downstream effects of debris on primary system components
September 12, 2007	NRC agreed to review PWROG technical report WCAP-16530-NP, **Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191**, February 2006.
September 2007	NRC issued draft guidance for review of licensee responses to **GL 2004-02.**
November 2007	NRC issued revised content guide for **GL 2004-02** supplemental responses.
December 2007	NRC approved PWROG guidance reports WCAP-16406-P, Rev. 1, **Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191**, and WCAP-16530-NP, **Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191**, both with supporting supplemental information (see Section 4 of SEs).

Time-Line of Post-LOCA ECCS Safety Issues (contd)

Date	Event
March 2008	NRC issued revised guidance for review of final licensee responses to **GL 2004-02**, via letter dated March 28, 2008 to A.R. Pietrangelo of Nuclear Energy Institute from W.H. Ruland, NRC; subject: *Revised Guidance for Review of Final Licensee Response to Generic Letter 2004-02*, ***Potential Impact of Debris Blockage on Emercency Recirculation During Desing Basis Accidents at Pressurized-Water Reactors***: - Enclosure I: *NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Strainer Head Loss and Vortexing* - Enclosure II: *NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Coatings Evaluation* - Enclosure III: *NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Plant-Specific Chemical Effect Evaluations*
May 2008	NRC developed draft white paper on differences in treatment of containment sump screen and suppression pool suction strainer clogging issues for PWRs and BWRs.
June 2008	NRC contracted with PNNL for study of disparate treatment of debris issues in BWRs and BWRs.
July 24, 2008	NRC issued a recision of the draft SE for WCAP-16793-NP, having determined that additional information was needed on certain subject areas in the report, which the PWROG agreed to address by submitting Revision 1of WCAP-16793-NP.
April 2009	WCAP-16793-NP, Revision 1, *Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid*, submitted by the PWR Owners Group in response to NRC staff determination that additional information was needed to supplement Revision 0 of the report.