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NUREG/CR-7172
ANL-10/38

Knowledge Base Report on Emergency Core Cooling Sump Performance in Operating Light Water Reactors

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Manuscript Completed: April 2013
Date Published: January 2014

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ABSTRACT

This report describes the current status of the knowledge base regarding the performance of long-term core and containment cooling in operating light water reactors. The report discusses the substantial knowledge that has been amassed as a result of the research on clogging issues related to the suction strainers in boiling water reactors (BWRs) and the sump strainers in pressurized water reactors (PWRs). These issues concern the potential insulation and other debris generated in the event of a postulated loss-of-coolant accident within the containment of a light water reactor and the subsequent transport to and accumulation on the recirculation strainers. This debris accumulation could potentially challenge the plant's capability to provide adequate long-term cooling water to the pumps in the emergency core cooling and in the containment spray systems.

The report briefly discusses the historical background on the sump performance issue and presents the NRC regulatory considerations, with emphasis on guidance provided by NRC to the licensees during recent years. The report presents the current state-of-the-art resolution methodology for understanding the strainer blockage phenomena and processes that have evolved over the years. In particular, the report discusses the details of plant-by-plant licensee responses to the NRC Bulletin 2003-01 and the NRC Generic Letter 2004-02. The licensee responses were collected in several areas such as strainer characteristics, physical and plant modifications, head loss testing procedures, head loss test information, net positive suction head data, debris generation, debris characteristics, coating debris, chemical effects, downstream effects, etc. as well as assessment of net positive suction head requirements and availability.

The report is designed to serve as a source of updated information from the previous reports (Rao et al. 2001, NUREG/CR-6808) on all aspects of issues concerning the emergency core cooling sump performance in both BWRs and PWRs.

FOREWORD

In the event of a loss-of-coolant accident (LOCA) within the containment of a light-water reactor (LWR), piping thermal insulation and other materials in the vicinity of the break will be dislodged by the pipe break and the ensuing steam/water-jet impingement. A portion of this fragmented and dislodged insulation and other materials, such paint chips, paint particulates, latent dirt and dust, suspression pool sludge, chemical corrosion products and concrete dust, will be transported to the containment floor by the steam/water flows induced by the break and by the containment sprays. Some of this debris will eventually be transported to and accumulate on the emergency core cooling system (ECCS) pump suction strainers. Debris accumulation on the strainers could challenge the plant's capability to provide adequate, long-term cooling water to the ECCS and to the containment spray system (CSS) pumps.
As a result of the research on the boiling water reactor (BWR) and pressurized water reactor (PWR) suction strainer clogging issues, a substantial base of knowledge has been amassed that covers all aspects of the issues, from the generation of debris to the head loss associated with a debris bed on a strainer or screen. This report describes the different analytical and experimental approaches that have been used to assess the various aspects of sump and strainer blockage and identifies the strengths, limitations, important parameters, and plant features and the appropriateness of the different approaches. The report also discusses significant U.S. Nuclear Regulatory Commission regulatory actions regarding resolution of the suction and sump strainer debris issue. In essence, the report is designed to serve as a reference for plant-specific analyses with regard to whether the sump or strainer would perform its function without preventing the operation of the ECCS pumps.

This report is an update of the previous ECCS debris clogging knowledge base document, NUREG/CR-6808, “Knowledge Base for the Effect of Debris on Pressurized Water Reactor Emergency Core Cooling Sump Performance,” published in Feburary 2003. The most notable additions to this report are related to the research performed for PWRs in response to Generic Letter 2004-02 in the technical areas of chemical effects, protective coatings, latent debris, downstream effects, and strainer head loss testing.

It is noted that this report does not address the risk-informed approach that is mentioned in SECY 12-0093 because it is still being evaluated. Nor does it address suction strainer debris clogging concerns for new reactor designs such as the AP 1000 or the Advanced Boiling Water Reactor (ABWR).

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The containment sump (also known as the emergency or recirculation sump) and emergency core cooling system (ECCS) strainers are parts of safety systems in both boiling water and pressurized water reactors (BWRs and PWRs). Every nuclear power plant in the United States is required by the Code of Federal Regulations (10 CFR 50.46) to have an ECCS that is capable of mitigating design basis accidents.

The containment emergency sump or suppression pool collects reactor coolant leakage and chemically inactive or reactive spray solutions after a loss-of-coolant accident (LOCA). The sump serves as the water source to support long-term recirculation for residual heat removal, emergency core cooling, and containment pressure control and atmosphere cleanup. This water source, the related pump inlets, and the piping between the source and inlets are important safety components. In the event of a LOCA within the containment of a light water reactor, piping thermal insulation and other materials in the vicinity of the break will be dislodged by the pipe break and steam/water-jet impingement. A fraction of this fragmented and dislodged insulation and other materials, such as paint chips, paint particulates, and concrete dust, will be transported to the containment floor by the steam/water flows induced by the break and by the containment sprays. Some of this debris eventually will be transported to and accumulate on the recirculation-sump suction strainers in PWR containments or on the pump-suction strainers in BWR containments. Debris accumulation on the suction strainers could challenge the plant's capability to provide adequate, long-term cooling water to the ECCS and the containment spray system (CSS) pumps and may compromise the containment cooling.

The Generic Safety Issue (GSI)-191 ("Assessment of Debris Accumulation on PWR Sump Performance") was established to determine if the transport and accumulation of debris in a containment following a LOCA would impede the operation of the ECCS in operating PWRs. Assessing the risk of the ECCS and CSS pumps at domestic PWRs experiencing a debris-induced loss of the net positive suction head (NPSH) margin during sump recirculation was the primary objective of the NRC's technical assessment of GSI-191.

This report describes the current status of the knowledge base on emergency core cooling sump performance in operating light water reactors. The compiled database information for various plants covers a period up to March 4, 2011. The compiled database also includes the Watts Bar-2 reactor, which is planned to be operational in the near future. The report discusses the substantial knowledge that has been developed as a result of the research on debris clogging issues for BWR suction strainers and PWR sump strainers. The report provides brief background information (Sections 1 through 4) regarding the clogging issues. This background information includes a historical overview of the resolution of the BWR issue with a lead-in to the PWR issue, a description of the safety concern relative to PWR reactors, the criteria for evaluating sump failure, descriptions of postulated accidents, descriptions of relevant plant features that influence accident progression, and a discussion of the regulatory considerations.

Section 5 of the report presents the current state-of-the-art resolution methodology for understanding the strainer blockage phenomena and processes that have evolved over the years. This section incorporates our current understanding of many of the actions/processes that can have an impact on the available NPSH margin in the ECCS. The section presents details on pipe break characterization, debris generation and zone of influence, debris transport evaluation, coatings and coating debris, latent debris, debris accumulation and head loss, debris head loss correlations, chemical effects on head loss, and downstream effects. The section also includes a description of the test programs conducted by several vendors in support of BWRs and PWRs.

Section 6 is a summary of the industry response of BWR licensees and the closure of NRC Bulletin 1996-03, based on the utility resolution guidance (URG) for ECCS suction strainer blockage and NRC audits of four plant sites. In 2001 Los Alamos National Laboratory published a report summarizing the efforts of the NRC, the NRC's contractors, and industry to resolve the BWR ECCS strainer clogging issue (LA-UR-01-1595).

Section 7 discusses in detail the plant-by-plant PWR licensee responses to the NRC Bulletin 2003-01 and the NRC Generic Letter 2004-02 (GL-04-02). The licensee responses to the initial generic letter and the responses to the requests for information were collected in several areas such as strainer characteristics, physical and plant modifications, head loss testing procedures, head loss test information for full debris-load beds and thin beds, net positive suction head data, debris generation, debris characteristics, coating debris, chemical effects, downstream effects, etc. as well as assessment of net positive suction head requirements and availability. The collected information has been incorporated in the Appendix A, in a user-friendly interface based on Microsoft Access, with a capability to select various criteria to filter the information, carry out search/sort of the data, and assess phenomenon-specific or plant-specific information.

ACKNOWLEDGMENTS

The U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) sponsored this work. Mr. John Burke is the Technical Monitor for this project. He provided technical direction and actively participated in all aspects of the project, including access to necessary proprietary and other documents to accomplish the goals of the project. The authors would also like to acknowledge S. J. Smith, R. E. Architzel, R. Torres and J. Lehning of the NRC for their assistance in providing up-to-date information on several nuclear power plants.

ACRONYMS

ABB	ABB Atom/Combustion Engineering
ACRS	Advisory Committee on Reactor Safeguards
AECL	Atomic Energy of Canada Limited
AES	Atomic Emission Spectroscopy
AJIT	Air-Jet Impact Testing
ANL	Argonne National Laboratory
ANS	American Nuclear Society
ANSI	American National Standards Institute
ARL	Alden Research Laboratory
ASTM	American Society for Testing and Materials
BS	Building Spray
BWR	Boiling Water Reactor
BWROG	Boiling Water Reactor Owners' Group
CCI	Control Components, Inc.
CDA	Containment Depressurization Actuation
CEQ	Containment Pressure Equalization
CHRS	Containment Heat Removal Systems
CNWRA	Center for Nuclear Waste Regulatory Analysis
COA	Candidate Operator Actions
CS	Containment Spray
CSNI	Committee on the Safety of Nuclear Installations
CSS	Containment Spray System
DBA	Design Basis Accident
DB-LOCA	Design-Basis Loss-of-Coolant Accident
DDTS	Drywell Debris Transport Study
DEGB	Double-Ended Guillotine Break
DGM	Debris Generation Model
ECCS	Emergency Core Cooling System
EPRI	Electric Power Research Institute
ESF	Engineered Safeguard Feature
FME	Foreign Material Exclusion
FSAR	Final Safety Analysis Report
GDC	General Design Criteria
GE	General Electric Nuclear Energy
GEH	General Electric-Hitachi
GGNS	Grand Gulf Nuclear Station
GL	Generic Letter
GSI	Generic Safety Issue
HELB	High Energy Line Break
HL	Head Loss
HPSI	High-Pressure Safety Injection
ICET	Integrated Chemical Effects Test
ICM	Interim Compensatory Measures
ICP	Inductively Coupled Plasma
LANL	Los Alamos National Laboratory

LBB	Leak-Before-Break
LBLOCA	Large-Break Loss-of-Coolant-Accident
L/D	Distance Divided by Pipe-Break Diameter
LER	Licensee Event Report
LDFG	Low-Density Fiberglass
LOCA	Loss-of-Coolant Accident
LLOCA	Large Loss-of-Coolant Accident
LPCI	Low-Pressure Coolant Injection
LPCS	Low-Pressure Core Spray
LPSI	Low-Pressure Safety Injection
LTR	Licensing Topical Report
LWR	Light Water Reactor
MLOCA	Medium Loss-of-Coolant Accident
MSL	Main Steam Line
MSLB	Main-Steam-Line Break
NDE	Non Destructive Evaluation
NEA	Nuclear Energy Agency
NEDO	New Energy and Industrial Technology Organization
NEI	Nuclear Energy Institute
NMR	Nuclear Magnetic Resonance
NPSH	Net Positive Suction Head
NPSHA	Available Net Positive Suction Head
NPSHR	Required Net Positive Suction Head
NRC	Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
OECD	Organization for Economic Cooperation and Development
OEM	Original Equipment Manufacturer
OPG	Ontario Power Generation
PCI	Performance Contracting Inc.
PIRT	Phenomena Identification and Ranking Table
PNNL	Pacific Northwest National Laboratory
PRT	Pressure Relief Tank
PVC	Polyvinyl Chloride
PWR	Pressurized Water Reactor
PWROG	Pressurized Water Reactor Owners Group
RB	Reactor Building
RBES	Reactor Building Emergency Sump
RCDT	Reactor Coolant Drain Tank
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RFI	Request for Information
RFO	Refueling Outage
RG	Regulatory Guide
RHR	Residual Heat Removal
RLB	Recirculation-Line Break
RMI	Reflective Metal Insulation
RMT	Recirculation Mode Transfer
RPV	Reactor Pressure Vessel

RSS	Reactor Spray System
RWST	Refueling Water Storage Tank
SAS	Sodium Aluminum Silicate
SBLOCA	Small-Break Loss-of-Coolant Accident
SE	Safety Evaluation
SAT	Spray Additive Tank
SEM	Scanning Electron Microscopy
SER	Safety Evaluation Report
SG	Steam Generator
SI	Safety Injection
SLOCA	Small Loss-of-Coolant Accident
SNL	Sandia National Laboratories
SONGS	San Onofre Nuclear Generation Station
SRP	Standard Review Plan
SRTC	Savannah River Technology Center
SRV	Safety Relief Valve
SS	Stainless Steel
SSC	System, Structure, and Component
STB	Sodium Tetraborate
STPP	Sodium Tripolyphosphate
TEM	Transmission Electron Microscopy
TLR	Technical Letter Report
TPI	Transco Products, Inc.
TSP	Trisodium Phosphate
UNM	University of New Mexico
URG	Utility Resolution Guidance
USI	Unreviewed Safety Issue
WSRC	Westinghouse Savannah River Company
XRD	X-ray Diffraction
ZOI	Zone of Influence

UNITS CONVERSION TABLE

Convert from	Convert to	Multiply by
Length		
in.	m	0.02540
mil*	m	2.540 x 10-5
ft	m	0.3048
Area		
in.2	m2	6.452 x 10-4
ft2	m2	0.09290
Volume		
ft3	m3	0.02832
gal	m3	0.003785
gpm	m3/s	6.308 x 10-5
Pressure		
psi	Pa	6895
Mass		
lbm**	kg	0.4536
Density		
lbm/ft3	kg/m3	16.02
Velocity		
ft/s	m/s	0.3048
Temperature		
°F***	°C	0.5556

* mil = one-thousandth of an inch
** lbm is often simply given as lb
*** Subtract 32 before multiplying

1 INTRODUCTION

This report describes the current status of the knowledge base regarding the performance of long-term core and containment cooling in operating light water reactors. The report discusses the substantial knowledge that has been amassed as a result of the research on clogging issues related to the suction strainers in boiling water reactors (BWRs) and the sump strainers in pressurized water reactors (PWRs). The containment sump (also known as the emergency or recirculation sump in PWRs and suppression pool in BWRs) and emergency core cooling system (ECCS) strainers are parts of a safety system in both reactor types. Every nuclear power plant in the United States is required by the Code of Federal Regulations (10 CFR 50.46) to have an ECCS that is capable of mitigating a design basis accident. The ECCS is one of several safety systems required by the Nuclear Regulatory Commission (NRC).

The containment sump collects reactor coolant and containment spray solutions after a loss-of-coolant accident (LOCA). The sump serves as the water source to support long-term recirculation for residual heat removal, emergency core cooling, and containment cooling and atmosphere cleanup. This water source, the related pump inlets, and the piping between the source and inlets are important safety components.

The performance of ECCS strainers in currently operating BWRs and PWRs was recognized decades ago as an important regulatory and safety issue. The primary concern is the potential for debris generated by a jet of high-pressure coolant during a LOCA to clog the strainer and obstruct core cooling. The issue was considered resolved for both reactor types a decade or more ago. But additional evaluation and testing indicated in the late 1990s that the issue should be re-evaluated for PWRs. The re-evaluation led the licensees to significantly increase the strainer sizes and to make other plant-specific modifications. A complex test and evaluation program was undertaken to verify that the larger strainers adequately meet the design requirements.

This report does not include new plants licensed to 10 CFR 52 which governs the issuance of early site permits, standard design certifications, combined licenses, etc. and may have different design considerations for the ECCS.

This report supplements the previous knowledge base report (NUREG/CR-6808). Research for PWRs to address Generic Letter 2004-02 (GL 04-02) has resulted in an enhanced knowledge base, which has led to additional questions regarding BWR strainer performance. Even though the BWR strainers are comparable in size to the replacement PWR strainers, the NRC staff and the BWR Owners Group are currently evaluating what, if any, additional changes are needed in BWRs to ensure adequate strainer performance.

2 DESCRIPTION OF THE SAFETY CONCERN

To function properly, the ECCS pumps require adequate available net positive suction head (NPSH). Inadequate NPSH could result in cavitation and subsequent failure to deliver the amount of water needed for cooling during a design basis accident. The available NPSH is a function of the static head of water above the pump inlet, the pressure of the atmosphere above the sump water surface, friction losses in the pump suction piping and strainer, and the temperature of the water at the pump inlet.

In the event of a LOCA or a high-energy pipe break within the containment of a BWR or a PWR, piping thermal insulation and other materials in the vicinity of the break can be dislodged because of the break and the ensuing steam/water-jet impingement. The area near the break where insulation debris is generated is called the zone of influence (ZOI). Some portion of the debris would likely be transported across the drywell, past and/or through structures such as gratings, and through the downcomer vents to the suppression pool in BWRs and may be transported to the containment floor by the steam/water flows induced by the break and by the containment sprays in PWRs. Some of this debris will eventually be transported to and accumulate on the recirculation-sump suction strainers in PWR containments or the pump suction strainer in BWR containments. Debris accumulation on the pump strainers could challenge the plant's capability to provide adequate, long-term cooling water to the ECCS and to the containment spray system (CSS) pumps.

The debris that accumulates on the sump strainer can form a bed that can increase the differential pressure across the sump. Head loss across the debris bed may reduce the NPSH available to the ECCS or containment spray pumps such that the pumps will not operate properly.

The purpose of the debris strainers installed on the pump suction lines is to minimize the amount of debris entering the ECCS and CSS suction lines. Debris can block openings or damage components in the systems served by these pumps. However, excessive head loss due to debris accumulation on containment sump strainers can prevent or impede the flow of water into the core or containment (via containment spray).

3 DISCOVERY OF SUMP PERFORMANCE ISSUE

The NRC first published regulatory guidance on the performance of PWR containment sumps and BWR suction strainers in 1974 with the issuance of revision 0 of Regulatory Guide (RG) 1.82, “Sumps for Emergency Core Cooling and Containment Spray Systems.” The BWR suction strainers perform the same function as PWR containment sump strainers.

Because of internal questions by the NRC staff, the NRC first sponsored research to study the accumulation of debris on PWR containment sump strainers and BWR suction strainers in the late 1970s (approximately 1979). With the information and engineering tools available in the late 1970s and early 1980s, the NRC concluded that its regulatory guidance needed to be revised and issued revision 1 of RG 1.82 (1985). As documented in Generic Letter-85-22, “Potential for Loss of Post-LOCA Recirculation Capability Due to Insulation Debris Blockage,” the NRC concluded that no additional regulatory action was warranted for operating nuclear power plants, but that new nuclear power plants would need to satisfy the guidance in the revised RG 1.82, and that operating nuclear power plants should consider the guidance in the revised RG 1.82 when making plant modifications, namely, to change thermal insulation to something like reflective metal insulation (RMI), which is less likely to cause blockage.

From a historical perspective, in January 1979 the NRC originally declared sump-strainer blockage to be an Unresolved Safety Issue (USI A-43, “Containment Emergency Sump Performance”) and subsequently published the concerns identified in the USI in the report NUREG-0510, “Identification of Unresolved Safety Issues Relating to Nuclear Power Plants.” USI A-43 dealt with concerns regarding the availability of adequate long-term recirculation cooling water following a LOCA. This cooling water should be sufficiently free of debris so that pump performance is not impaired and long-term recirculation flow capability is not degraded. However, the importance of particulate matter in debris beds was not recognized during USI A-43, and the issue was closed without realizing that particulate debris had a large effect on head loss.

3.1 Sump Performance Issues

The NRC has sponsored research to quantify sump performance and to look more deeply into the strainer blockage issue in general. Substantial experimental and analytical research was conducted to support the resolution of USI A-43, and USI A-43 was declared resolved in 1985. Subsequent to the closure of USI A-43, several discovery events regarding ECCS strainer and foreign material (e.g. corrosion products, dirt , etc.) prompted a review of the strainer blockage issue. The NRC-sponsored research had the objectives of estimating possible shortcomings of existing suction strainer designs in U.S. BWR plants and evaluating the actions taken by the nuclear power industry to ensure availability of long-term recirculation of cooling water in BWR plants. The historical overview of USI A-43 Resolution, including an overview of subsequent BWR strainer clogging and pump failure events, an overview of NRC research and regulatory actions, and the BWR issue resolution, was discussed in an earlier report (Rao et al., 2001). That report included the key technical findings of NRC research supporting the resolution of the BWR strainer blockage issue along with a summary of the actions taken by the nuclear power industry to ensure availability of long-term recirculation of cooling water in BWR plants. It has served as a source of information on the strainer blockage issue, summarizing the key aspects of the issue and identifying the most important documents. In particular, the report provided the following:

- An overview of the BWR strainer blockage issue and its resolution.

- A summary of the NRC-sponsored research performed to gain an understanding and insight into the BWR strainer blockage issue.

- A summary of the NRC review of applicable research sponsored by the U.S. industry and by international organizations.

- Details on the NRC review of the Boiling Water Reactor Owners Group (BWROG) issue resolution guidance to the industry.

- A summary of the implementation of industry resolutions of the strainer clogging issue and the NRC's review of individual plant strainer solutions.

The chronology of the BWR strainer blockage issue and its resolution is illustrated in the timeline presented in Table 3.1-1, and each of these events is discussed below.

Table 3.1-1. BWR Strainer Blockage Issue Timeline

Date	Event
January 1979	NRC declared "Containment Emergency Sump Performance" an Unresolved Safety Issue (USI A-43) and published the issue's concerns in NUREG-0510, "Identification of Unresolved Safety Issues Relating to Nuclear Power Plants."
October 1985	NRC published regulatory analysis results related to resolving USI A-43 in NUREG-0869, "USI A-43 Regulatory Analysis."
October 1985	NRC published technical findings of research related to resolving USI A-43 in NUREG-0897, "Containment Emergency Sump Performance."
October 1985	NRC declared USI A-43 resolved with resolution presented to Commission in SECY-85-349, "Resolution of Unresolved Safety Issue A-43, Containment Emergency Sump Performance."
November 1985	NRC Issued Regulatory Guide 1.82, Revision 1, "Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident."
December 1985	NRC issued GL-85-22, "Potential for Loss of Post-LOCA Recirculation Capability Due to Insulation Debris Blockage," outlining safety concerns and recommendations to all holders of operating licenses.
May 1992	First strainer clogging event occurred at Perry Nuclear Plant.
July 1992	Strainer blockage incident occurred at Barsebäck Unit 2 in Sweden.
March 1993	Second strainer clogging event occurred at Perry Nuclear Plant.
May 1993	NRC issued Bulletin 93-02, "Debris Plugging of Emergency Core Cooling Suction Strainers," to all holders of operating licenses for nuclear power plants. Licensees were requested to identify and remove sources of fibrous air filters and temporary fibrous material in primary containment not designed to withstand a LOCA.
September 1993	NRC initiated detailed study of a reference BWR4 Mark I plant.
January 1994	Organization for Economic Cooperation and Development (OECD) conference held in Stockholm, Sweden, to exchange information and experience and provide feedback of actions taken to the international community.

February 1994	NRC Issued Supplement 1 to Bulletin 93-02, “Debris Plugging of Emergency Core Cooling Suction Strainers,” requesting licensees to take further interim actions (e.g., implementing operating procedures and conducting training and briefings).
August 1994	NRC published results of reference plant study as draft for comment in NUREG/CR-6224, “Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris.”
September 1995	Strainer blockage event occurred at Limerick.
October 1995	NRC published final results of reference plant study (NUREG/CR-6224).
October 1995	NRC issued Bulletin 95-02, “Unexpected Clogging of a Residual Heat Removal (RHR) Pump Strainer While Operating in Suppression Pool Cooling Mode,” to all operating BWR licenses. This bulletin requested actions be taken by licensees to ensure that unacceptable buildup of debris that could clog strainers does not occur during normal operation.
February 1996	International Knowledge Base prepared by USNRC for OECD, CSNI PWG 1 was published in NEA/CSNI/R (95) 11, “Knowledge Base for Emergency Core Cooling System Recirculation Reliability.”
May 1996	NRC issued Revision 2 of RG 1.82, “Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident.” Revision 2 altered the debris blockage evaluation guidance for BWRs because operational events, analyses, and research work after the issuance of Revision 1 indicated that the previous 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 BWR operating licenses. Licensees were requested to implement appropriate measures to ensure the capability of the ECCS to perform its safety function following a LOCA.
September 1996	NRC initiated a drywell debris transport study (DDTS) to investigate debris transport in BWR drywells using a bounding analysis approach.
November 1996	The BWROG submitted their utility resolution guidance (URG) in NEDO-32686, Rev. 0, “Utility Resolution Guidance for ECCS Suction Strainer Blockage,” to NRC for review and approval.
December 1996	The NRC strainer blockage head loss analysis code, BLOCKAGE, was completed and the code manuals published as NUREG/CR-6370, "BLOCKAGE 2.5 User’s Manual," and NUREG/CR-6371, "BLOCKAGE 2.5 Reference Manual."
June 1997	The NRC reviewed submittals regarding Edwin I. Hatch Nuclear Plant, Units 1 and 2, response to NRC Bulletin 96-03. The findings were documented in a letter from N. B. Lee to H. L. Sumner, “Safety Evaluation Related to NRC Bulletin 96-03, ‘Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling Water Reactors,’ - Edwin I. Hatch Nuclear Plant, Units 1 and 2 (TAC Nos. M96148 and M96149).”
August 1997	NRC draft results of the DDTS in NUREG/CR-6369, “Drywell Debris Transport Study.”
October 1997	NRC issued GL-97-04, “Assurance of Sufficient Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal Pumps,” to all holders of operating licenses for nuclear power plants

	requesting current information regarding their net positive suction head (NPSH) analyses.
October 1997	The NRC technically reviewed submittals regarding Hope Creek Generating Station response to NRC Bulletin 96-03. These findings were documented in a letter from D. H. Jaffe to L. Eliason, “Safety Evaluation for Hope Creek Generating Station – NRC Bulletin 96-03 (TAC No. M96150).”
July 1998	NRC issued GL-98-04, “Potential for Degradation of the Emergency Core Cooling System and the Containment Spray System After Loss-of-Coolant Accident Because of Construction and Protective Coating Deficiencies and Foreign Material in Containment,” to all holders of operating licenses for nuclear power plants alerting addresses of continuing strainer blockage concerns and requested information under 10 CFR 50.54(f) to evaluate the addresses’ programs for ensuring that Service Level 1 protective coatings inside containment do not detach from their substrate during a design-basis LOCA and interfere with the operation of the ECCS and safety-related CSS.
August 1998	NRC issued Safety Evaluation Report (SER) regarding BWROG URG as Docket No. PROJ0691, “Safety Evaluation by the Office of Nuclear Reactor Regulation Related to NRC Bulletin 96-03 Boiling Water Reactor Owners Group Topical Report NEDO-32686, ‘Utility Resolution Guidance for ECCS Suction Strainer Blockage,” (NRC-SER-1988).
February 1999	NRC review of GE report NEDC-32721-P (ML081840175) for BWR stacked disc strainer.
September 1999	NRC published final results of DDTS (NUREG/CR-6369).
January 1999	NRC Audit of Limerick NRC Bulletin 96-03/95-02 Resolution.
March 1999	NRC Audit of Dresden NRC Bulletin 96-03/95-02 Resolution.
August 1999	NRC Audit of Grand Gulf NRC Bulletin 96-03/95-02 Resolution.
October 1999	NRC Audit of Duane Arnold NRC Bulletin 96-03/95-02 Resolution.
April 2000	NRC technically reviewed the licensee submittals regarding Brunswick Steam Electric Plant, Units 1 and 2, response to NRC Bulletin 96-03. The findings were documented in LA-UR-00-2574, “Technical Review of Licensee Submittals Regarding Brunswick Steam Electric Plant, Units 1 and 2 Response to US NRC Bulletin 96-03, ‘Potential Plugging of ECCS Strainers by Debris in Boiling Water Reactors’.”
October 2000	The NRC issued Amendment 185 to Facility Operating License No. DPR-35 for the Pilgrim Nuclear Power Station that changed the plant’s licensing basis involving the use of containment overpressure to ensure sufficient NPSH for ECCS pumps following a LOCA. This issuance was stated in a letter from A. B. Wang to M. Bellamy, “Pilgrim Nuclear Power Station – Issuance of Amendment Re: Use of Containment Overpressure (TAC No. MA7295).”
March 2001	A report entitled, “BWR ECCS Strainer Blockage Issue: Summary of Research and Resolution Actions” LA-UR-01-1595, prepared by Los Alamos National Laboratory for the USNRC (Rao et al., 2001).

After the closure of USI A-43, several discovery events regarding the ECCS strainer and foreign material prompted a review of the strainer blockage issue for BWRs. Operational events that have occurred at both BWR and PWR plants pertaining to the issue of sump-strainer or suction-strainer blockage are briefly reviewed below. These events are described in the general order of their relative severity, starting with operational events that have rendered systems inoperable with regard to their ability to complete their safety mission. Two of these events resulted from the generation of insulation debris by jet flow from a LOCA caused by the unintentional opening of safety relief valves (SRVs). Other events have resulted in accumulation of sufficient operational debris to effectively block a strainer or to plug a valve. Some event reports simply noted debris found in the containment, as well as inadequate maintenance that would likely cause potential sources of debris within the containment. Related event reports identified inadequacies in a sump strainer where debris potentially could bypass the strainer and enter the respective system.

Subsequent to the assessment of sump performance in BWRs, NRC concentrated on the sump-strainer clogging issues pertaining to PWRs. In the event of a LOCA within the containment of a PWR, piping thermal insulation and other materials in the vicinity of the break will be dislodged by break-jet impingement. A fraction of this fragmented and dislodged insulation and other materials such as paint chips, paint particulates, and concrete dust will be transported to the containment floor by the steam/water flows induced by the break and the containment sprays. Some of this debris eventually will be transported to and accumulate on the recirculation sump suction strainers. Debris accumulation on the sump strainer may challenge the sump's capability to provide adequate, long-term cooling water to the ECCS and the containment spray (CS) pumps.

Examination of plant drawings, preliminary analyses, and test results suggested that a prominent mechanism for recirculation sump failure involves pressure drop across the sump strainer induced by debris accumulation. However, sump-strainer failure through other mechanisms is also considered possible for some configurations. Three failure modes were considered as part of the study:

- Loss of the NPSH margin caused by excess pressure drop across the strainer resulting from debris buildup. This concern applies to all plant units having sump strainers that are completely submerged in the containment pool.

- Loss of the static head necessary to drive recirculation flow through a strainer because of excess pressure drop across the strainer resulting from debris buildup. This concern applies to all plant units having sump strainers that are not completely submerged or have vents that communicate with the containment atmosphere above the water level of the containment pool.

- Blockage of water-flow paths may (a) cause retention of water in some regions of the containment or (b) prevent adequate water flow through partially-blocked openings and result in lower water levels in the sump and thus a lower NPSH margin than estimated by the licensees.

3.2 Events Rendering a System Inoperable

In operating BWRs and PWRs, events have resulted in systems being declared inoperable; that is, the ability of that system to perform its safety-related mission was in considerable doubt. These events include the accumulation of debris on a strainer, excessive head loss caused by a strainer, and events in which debris entered a system and thereby adversely affected the operability of a component of that system. These events, which occurred at BWR and PWR plants within the U.S., are summarized in Table 3.2-1.

Table 3.2-1. Events Rendering a System Inoperable

Year	Plant (Type)	Event Initiator	Debris	Consequence	Reference
1988	Grand Gulf (BWR Mark III)	Inspection	Plastic wrap and other debris.	Clogged RHR strainers.	IN-93-34
1989	Grand Gulf (BWR Mark III)	Inspection	Plastic wrap and other debris.	Debris could potentially block ECCS strainers during LOCA.	IN-93-34
1989	Trojan (PWR Dry)	Inspection	Numerous debris items found in the sump. Sections of strainer missing, damaged, or did not agree with drawings. Welding rod jammed in RHR pump impeller.	Debris blocked one pump and could potentially have blocked other ECCS strainers during LOCA.	IN-89-77
1992	H. B. Robinson (PWR Dry)	Surveillance testing of safety injection pumps during Mode 4 hot shutdown operations	Small piece of plastic blocked in-line orifice. Plastic used in a modification of RHR system.	Pumps rendered inoperable and loss of recirculation flow.	IN-92-85
1992	Perry (BWR Mark III)	Inspection	Operational debris and a coating of fine dirt. Water samples showed fibrous material and corrosion products.	Clogged and deformed strainers.	IN-93-02 IN-93-34
1992	Point Beach Unit 2 (PWR Dry)	Quarterly test of containment spray pumps	Foam rubber plug.	Debris blocked pump impeller suction. One train of safety injection (SI) piping rendered inoperable in recirculation mode.	IN-92-85
1993	Perry	Several	Glass fibers	Clogged and deformed	IN-93-02

Year	Plant (Type)	Event Initiator	Debris	Consequence	Reference
	(BWR Mark III)	SRVs were manually lifted and RHR used for suppression pool cooling.	(from temporary cooling filters), corrosion products, dirt, and misc. debris.	strainers	IN-93-34
1994	Palisades (PWR Dry)	Inspection	Plastic material.	High-pressure safety injection (HPSI) and CS system pumps declared inoperable.	IN-95-06
1994	Quad Cities Unit 1 (BWR Mark I)	Post-maintenance test	Plastic bag and other miscellaneous operational debris.	Plugged valve on RHR torus cooling system. Pump fouled by metallic debris wrapped around a vane.	IN-94-57
1995	Limerick Unit 1 (BWR Mark II)	Unexpected opening of SRV at 100% power	Polymeric fibers and sludge.	RHR Loop A suction strainer (suppression pool cooling mode) covered by thin mat of fibers and sludge. Loop B to a lesser extent. Cavitation indicated on Loop A.	IN-95-47 NRC Bulletin-95-02

3.3 LOCA Debris Generation Events

The two LOCA events that generated insulation debris both involved the unintentional opening of SRVs; these occurred at:

- German reactor Gundremmingen-1 (KRB-1) in 1977, where the 14 SRVs of the primary circuit opened during a transient and
- Barsebäck-2 nuclear power plant on July 28, 1992, during a reactor restart procedure after the annual refueling outage.

Both of these reactors were BWRs with similarities to U.S. reactors. Details on these events are shown in Table 3.3-1.

Table 3.3-1. Events with LOCA-Generated Insulation Debris

Year	Plant (Type)	Event Initiator	Debris	Consequence	Reference
1977	Gundremmingen Unit 1 (BWR)	Unintentional opening of 14 SRVs	Fiberglass insulation debris.	Potential clogging of recirculation strainers.	NEA/CSNI/R (95) 11
1992	Barsebäck Unit 2 (BWR)	Unintentional opening of SRV	Metal-jacketed mineral wool insulation debris.	Clogged two of five spray-system suction strainers with loss of containment sprays at 1 hour.	NEA/CSNI/R (95) 11 IN-92-71 IN-93-02 (S1)

3.4 Events Involving Debris Found in Containment

In operating BWR and PWR plants, events have occurred in which debris was found inside the containment that had the potential to impair the operability of a safety system. Details on these events are listed in Table 3.4-1.

Table 3.4-1. Events with Debris Found Inside Containment

Year	Plant (Type)	Event Initiator	Debris	Consequence	Reference
1975	Haddam Neck (PWR Dry)	Inspection	Six 55-gal drums of sludge with varying amounts of other debris removed from ECCS sump.	Debris potentially could block ECCS strainers during a LOCA.	GL-98-04
1988	Surry Units 1 and 2 (PWR Sub)	Inspection	Construction materials and debris found in the sump, in cone strainer of recirculation spray system, and in recirculation pumps.	Materials could have rendered system inoperable.	GL-98-04 IN-89-77
1989	Diablo Canyon Units 1 and 2 (PWR Dry)	Inspection	Debris found in sumps.	Debris could potentially block ECCS strainers during LOCA.	GL-98-04 IN-89-77
1990	McGuire Unit 1 (PWR Ice)	Inspection	Loose material discovered in upper containment.	Material not likely to have made ECCS inoperable but debris could contribute to potential ECCS strainer blockage.	GL-98-04
1993	North Anna (PWR Sub)	Steam Generator	Most of the unqualified silicon	Paint fragments potentially could	IN-93-34

Year	Plant (Type)	Event Initiator	Debris	Consequence	Reference
		Replacement	aluminum paint had come loose from the steam generator (SG) and pressurizer and was supported only by insulation jacketing.	reach sump during a LOCA.	
1993	Spanish Plant (PWR)	Inspection	Unspecified debris (believed to have been there since commissioning), dirty sump water, and flow blockage.	ECCS lines taking suction from the sumps were partially blocked.	IN-96-10
1994	Browns Ferry Unit 2 (BWR Mark I)	Inspection	Cloth-like material.	Partial strainer blockage, potential for 25% blockage.	IN-95-06
1994	LaSalle Unit 1 (BWR Mark II)	Inspection	Assortment of operational debris and sludge.	Potentially contribute to strainer blockage.	IN-94-57
1994	River Bend (BWR Mark III)	Inspection	Miscellaneous operational debris and sediments. Plastic bag removed from RHR suction strainer.	Potentially contribute to strainer blockage.	IN-94-57
1996	Haddam Neck (PWR Dry)	Outage Maintenance	Five 55-gal drums of sludge with varying amounts of other debris removed from ECCS sump.	Debris could potentially block ECCS strainers during a LOCA.	GL-98-04
1996	LaSalle Unit 2 (BWR Mark II)	Outage suppression pool cleaning.	Miscellaneous operational debris and sludge.	Suppression pool debris could potentially block ECCS strainers during a LOCA.	IN-96-59
1996	Millstone Unit 3 (PWR Sub)	Inspection	Pieces of Arcor protective coating and mussel shell fragments. Construction debris found in recirculation spray system suction lines.	Potential failure of recirculation spray heat exchangers to perform specified safety function because of debris.	GL-98-04 IN-97-13
1996	Nine Mile Point Unit 2 (BWR Mark II)	Inspection	Miscellaneous operational debris, including foam rubber, plastic bags, Tygon	Suppression pool debris potentially could block ECCS strainers during a	IN-96-59

Year	Plant (Type)	Event Initiator	Debris	Consequence	Reference
			tubing, and hard hats.	LOCA.	
1996	Vogtle Unit 2 (PWR Dry)	Inspection	Loose debris identified inside containment.	Debris could potentially block ECCS strainers during LOCA.	GL-98-04
1996	Zion Unit 2 (PWR Dry)	Inspection	Extensive failure of protective coatings. Unqualified coatings identified. Miscellaneous debris found throughout containment.	Debris could potentially block ECCS strainers during LOCA.	IN-97-13
	Calvert Cliffs Units 1 and 2 (PWR Dry)	Inspection	Unit 2 sump contained 11.3 kg (25 lb) of dirt, weld slag, pebbles, etc. Unit 1 had less than 1 lb debris.	Debris could contribute to potential ECCS strainer blockage.	GL-98-04
	D. C. Cook Units 1 and 2 (PWR Ice)	Inspection	Fibrous material found in containment.	Debris potentially could block ECCS strainers during LOCA.	GL-98-04

3.5 Inadequate Maintenance Leading to Potential Sources of Debris

In operating BWR and PWR plants, events have occurred in which inadequate maintenance conditions within containments could potentially result in significant debris. Details on these events are listed in Table 3.5-1. In general, these events involved unqualified protective coatings and materials.

Table 3.5-1. Events of Inadequate Maintenance, Potentially Leading to Sources of Debris

Year	Plant (Type)	Event Initiator	Debris	Consequence	Reference
1984	North Anna Units 1 and 2 (PWR Sub)	Inspection	Unqualified coatings identified.	Debris could potentially block ECCS strainers during LOCA.	GL-98-04
1988	Susquehanna Unit 2 (BWR Mark II)	Inspection	Extensive delamination of aluminum-foil jacketing fiberglass insulation.	Debris could potentially block ECCS strainers during LOCA.	IN-88-28
1993	Sequoyah Units 1 and 2 (PWR Ice)	Inspection	Unqualified coatings identified.	Debris could potentially block ECCS strainers during LOCA.	GL-98-04 IN-97-13
1994	Browns Ferry Units 1, 2, & 3 (BWR Mark I)	Inspection	Unqualified coatings identified.	Debris could contribute to potential ECCS strainer blockage.	GL-98-04
1995	Indian Point Unit 2 (PWR Dry)	Inspection	Failure of protective coatings. Unqualified coatings identified.	Debris could potentially block ECCS strainers during LOCA.	IN-97-13 GL-98-04
1997	Clinton (BWR Mark III)	Inspection	Unqualified coatings identified.	Debris could potentially block ECCS strainers during LOCA.	GL-98-04
1997	Millstone Unit 1 (BWR Mark I)	Inspection	Unqualified coatings identified.	Debris could potentially block ECCS strainers during LOCA.	GL-98-04 IN-88-28
1997	Sequoyah Units 1 (PWR Ice)	Inspection	Oil cloth introduced into containment.	Potential to block one or both refueling drains.	GL-98-04

3.6 Sump Strainer Inadequacies

In operating BWR and PWR plants, events have occurred in which defects in the integrity of the strainers were found. These defects could have caused a potential failure to adequately filter the ECCS water source that could result in degradation and eventual loss of ECCS function as a result of damaged pumps or clogged flow pathways. Details on these events are given in Table 3.6-1.

Table 3.6-1. Events with Inadequacies Found in Suction Strainers

Year	Plant (Type)	Event Initiator	Strainer Condition	Consequence	Reference
1988	Millstone Unit 1 (BWR Mark I)	Safety Analysis	Existing suction strainers too small when criteria of RG 1.82, Rev. 1 applied.	Potential strainer blockage due to accumulation of debris.	GL-98-04
1990	Three Mile Island Unit 1 (PWR Dry)	Inspection	Modification of sump access hatches left holes in top of sump strainer cage.	Potential debris bypass of the sump strainers and subsequent potential damage to pumps or clogged spray nozzles.	GL-98-04
1993	Arkansas Nuclear One Unit 1 (PWR Dry)	Inspection	Several breaches found in sump strainers.	Potential debris bypass of sump strainers and subsequent potential degradation or even loss of ECCS function.	IN-89-77 Sup. 1
1993	Arkansas Nuclear One Unit 2 (PWR Dry)	Inspection	Seven holes found in masonry grout below strainer assembly of ECCS sump.	Potential debris bypass of sump strainers and subsequent potential degradation of both trains of HPSI and containment spray.	GL-98-04 IN-89-77 Sup. 1
1993	San Onofre Units 1 and 2	Inspection	Irregular annular gap surrounding low-temperature over-pressure discharge line penetrating horizontal steel cover plate.	Potential debris bypass of the sump strainers and subsequent potential degradation or even loss of ECCS function.	GL-98-04
1993	Vermont Yankee (BWR Mark I)	Safety Analysis	Low-pressure core spray (LPCS) suction strainers smaller than assumed in NPSH calculations.	Potential loss of NPSH margin on LPCS during accident conditions.	GL-98-04

Year	Plant (Type)	Event Initiator	Strainer Condition	Consequence	Reference
			Existing NPSH calculations invalid.		
1994	South Texas Units 1 and 2 (PWR Dry)	Inspection	Sump-strainer openings from initial construction discovered.	Potential debris bypass of sump strainers and potential degradation of ECCS function.	GL-98-04
1996	Watts Bar Unit 1 (PWR Ice)	Inspection	Containment sump trash-strainer door found open with plant in Mode 4 and ECCS required to be operable.	Potential impairment of sump strainer function.	GL-98-04
1996	Millstone Unit 2 (PWR Dry)	Inspection	Containment sump strainers incorrectly constructed.	Debris larger than analyzed could pass through strainers.	GL-98-04

The regulatory analysis results and the technical findings of research related to resolving USI A-43 were reported in NUREG-0869 and NUREG-0897, respectively.

The NRC findings documented in NUREG-0897 Revision 1 were:

- Formation of an air-core vortex that would result in unacceptable levels of air ingestion that potentially could severely degrade pump performance was a concern. This was more applicable to PWRs but was still relevant to BWRs. Hydraulic tests showed that the potential for air ingestion was less severe than previously hypothesized. In addition, under normal flow conditions and in the absence of cavitation effects, pump performance was only slightly degraded when air ingestion was less than 2%.

- Effects of LOCA-generated insulation debris on RHR recirculation requirements depend on:

    1. types and quantities of insulation,
    2. potential of a high-pressure break to severely damage large quantities of insulation,
    3. transport of debris to the sump strainer,
    4. blockage potential of the transported debris, and
    5. impact on available NPSH.

- The effects of debris blockage on the NPSH margin should be dealt with on a plant-specific basis. Insulation debris transport tests showed that severely damaged or fragmented insulation was readily transported at relatively low velocities (0.2 to 0.5 ft/s). Therefore, the level of damage near the postulated break location became a dominant consideration. The level of damage to insulation was correlated with distance between the insulation and the break, in terms of L/D (distance divided by the pipe-break diameter). Data showed that jet load pressures would inflict severe damage to insulation within 3 L/Ds, and substantial damage would occur in the 3- to 5-L/D range with damage occurring out to about 7 L/D.

- The types and quantities of debris small enough to pass through strainers or suction strainers and reach the pump impeller should not impair long-term hydraulic performance. However, in pumps with mechanical shaft seals, debris could cause clogging or excessive wear, leading to increased seal leakage. However, catastrophic failure of a shaft seal as a result of debris ingestion was considered unlikely. If the seal did fail, pump leakage would be restricted.

- Nineteen nuclear power plants were surveyed in 1982 to identify the insulation types used, the quantities and distribution of insulation, the methods of attachment, the components and piping insulated, the variability of plant layouts, and the sump designs and locations. The types of insulation found were categorized into two major groups: reflective metallic insulation (RMI) and fibrous insulations.

The regulatory analysis documented in NUREG-0869 did not support a generic backfit action because plant-specific design features and post-LOCA recirculation flow requirements govern debris blockage effects. As a result, the analysis conclusion was that the issue should be resolved on a plant-specific basis. The staff recommended that RG 1.82, Revision 1, be used as guidance for the evaluation (10 CFR 50.59) of plant modifications involving replacement and/or modification of thermal insulation installed on the piping and components of the primary coolant system.

3.7 Assessment of Plant Vulnerability

3.7.1 BWRs

On July 28, 1992, a spurious opening of a safety valve at Barsebick Unit 2, a Swedish BWR, resulted in clogging of two ECCS pump suction strainers leading to loss of both containment sprays within one hour after the accident. The release of steam dislodged mineral wool insulation, pieces of which were subsequently transported by steam and water into the suppression pool located at the bottom of the containment. Instances of clogging of ECCS pump suction strainers have also occurred at U.S. plants, including two instances that occurred at the Perry Nuclear plant, which is a BWR/6 with Mark III containment. The instances at Perry suggested that filtering of small particles, e.g., suppression pool sludge, by the fibrous debris bed will result in increased pressure drop across the strainers. Given these precursor events, NRC staff initiated analyses to estimate potential for loss of NPSH of the ECCS pumps in a BWR due to clogging of suction strainers by a combination of fibrous and particulate debris.

A BWR/4 with a Mark I containment was selected as the reference plant for the study. The analysis methodology ,as documented in NUREG/CR-6224, has two components: probabilistic and deterministic. Based on historical evidence and piping failure analyses, this study concluded that pipe breaks in reactor cooling systems would most likely occur at the weld locations, and that weld break frequency is strongly dependent on the type of weld and operating environment. As a result, the number, type and location of each weld in the drywell of the reference plant subjected to high pressure during normal operation were identified. For each weld type, a weld break frequency was obtained based on data extracted from a LLNL

BWR pipe break study described in NUREG/CR-4792 taking into consideration the effects of enhanced inspections.

A transient strainer blockage model was developed to estimate the impact of a break for each of the identified welds at the reference plant. Important components of this model included: 1. A reference plant specific LOCA debris generation model (DGM) developed to estimate the quantity of insulation debris generated by postulated DEGB at that weld and the size distribution of the debris. A three region spherical DGM was developed to account for the lower operating pressure of BWRs and the layout of BWR drywells. 2. A reference plant-specific transient drywell transport model was developed to estimate the fraction of the fibrous and particulate debris reaching the suppression pool as a result of transport by blowdown and washdown. 3. A suppression pool model was developed to estimate the type and volume of fibrous and particulate debris reaching the strainer as a function of time. The model accounts for (a) re-suspension of sludge contained at the bottom of the suppression pool, (b) gravitational sedimentation (or settling) of the particulate and fibrous debris, and (c) continued deposition on the strainer. 4. A head loss model was developed to estimate the pressure drop across the strainer due to debris bed buildup. The key components described above were integrated into a single strainer blockage model which was used to evaluate whether or not a pipe break at each of the welds located in the primary system piping of the reference plant resulted in a head loss larger than the available ECCS NPSH margin. Those welds that resulted in loss of NPSH margin were summed to obtain an estimate of the overall frequency for the loss of NPSH for the reference plant. The pipe break frequency estimates for a DEGB postulated to occur on piping systems analyzed ranged from 3.2 x 10-06 to 1. 2 x 10-04 and the overall pipe break frequency was estimated to be of 1.59 x 10-04. Almost all postulated DEGBs resulted in unacceptable strainer blockage leading to the loss of NPSH margin for the ECCS pumps. The estimates of the frequency for loss of NPSH margin attributable to the piping systems studied were essentially the same as the pipe break frequency estimates.

3.7.2 PWRs

To address plant vulnerability to debris accumulation on the sump strainer in PWRs, the NRC and industry groups compiled much of the information that is necessary to effectively judge the vulnerability of ECCSs during recirculation following specific accidents (large LOCA [LLOCA], medium LOCA [MLOCA], and small LOCA [SLOCA]) and to draw insights regarding the potential severity of the problem for classes of reactors with similar design features (subatmospheric containments, ice condenser containments, etc.). The study performed "representative" parametric analyses to address the following safety questions for each plant to the extent possible (NUREG/CR-6762):

> If a LOCA of a given break size occurs, would the amount and type of debris generated from containment insulation and other sources of debris cause significant buildup on the ECCS recirculation sump? If so, would such blockage be of sufficient magnitude to challenge the ECCS function either by reducing the available head, NPSHA, below the required head, NPSHR, or by reducing flow through the sump strainer below the ECCS pump flow demand?

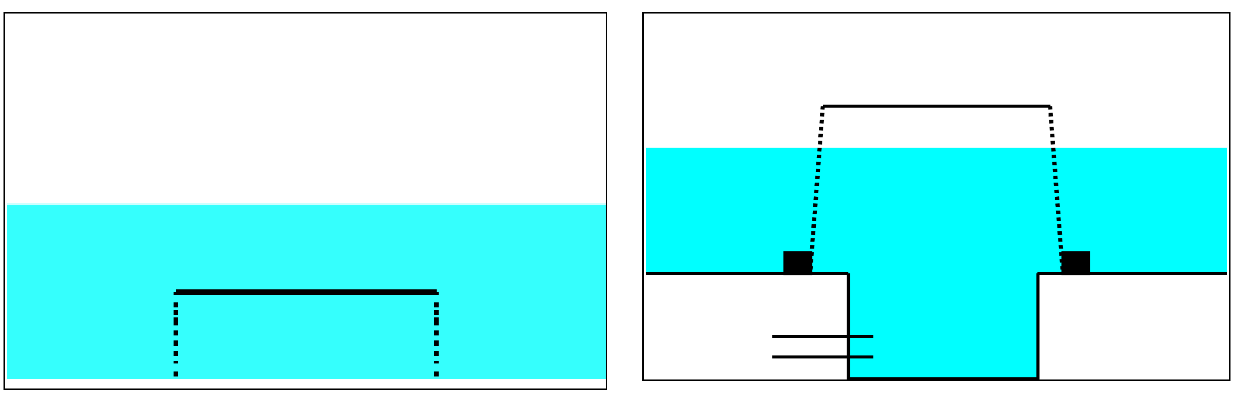
It was concluded that a firm determination of the vulnerability of any individual plant would require a plant-specific evaluation. It was reported that such an evaluation might have to incorporate plant features such as:

- physical layouts of primary and auxiliary piping in the containment,

- possible locations of the postulated breaks and the likely ECCS response to these breaks,
- locations, types, and quantities of insulation used on each piping system and equipment component,
- physical layouts of intervening structures that may inhibit debris transport,
- a physical description of the sump geometry and its location in containment,
- the time until switchover to recirculation, and
- and the required flow rates through the sump.

Because plant-specific analysis for the 69 operating PWRs is complex, a parametric study was used to examine the range of possible conditions present at these plants and to incorporate variations such as insulation type in proportion to its occurrence in the population so that the plausibility of sump blockage could be assessed. Approximations of individual plant features were used in the parametric analysis, and individual cases were developed to represent specific plants in the industry. Even though the best information available was used for each unit, it was recognized that these cases do not describe conditions at any single plant in great detail. Therefore, the individual entries for each unit were referred to as "cases" or as "parametric cases" rather than as "plant analysis" so that it would be understood that the individual cases do not provide a complete perspective of sump blockage risk at the corresponding plants.

The sump failure criterion applicable to each plant was determined primarily by sump submergence. Figure 3.7-1 illustrates the two basic sump configurations of fully and partially submerged strainers. Although only vertical sump configurations were considered, the same designations are applicable for inclined strainer designs. The key distinction between the fully and partially submerged configurations is that partially submerged strainers allow equal pressure above both the pit and the pool, which are potentially separated by a debris bed. Fully submerged strainers have a complete seal of water between the pump inlet and the containment atmosphere along all water paths through the sump strainer. The effect of this difference in evaluation of the sump failure criterion is described below.



(a) Fully submerged strainer configuration showing water from pump inlet to containment atmosphere.

(b) Partially submerged strainer configuration showing containment atmosphere over both the external pool and the internal sump pit with water on lower portion of strainer.

Figure 3.7-1. Sump-Strainer Schematics

For fully submerged sump strainers (see Figure 3.7-1a), failure is likely to occur because of cavitation within the pump housing when head loss caused by debris accumulation exceeds the NPSH margin (NPSHM). For this set of plants (in which sump strainers are fully submerged at the time of switchover), the onset of cavitation is determined by comparing the plant NPSHM, as reported by plants responding to GL-97-04 with the strainer head loss (∆HS) calculated in the parametric study. Therefore, for this case, the sump failure criterion is assumed to be reached when ∆HS ≥ NPSHM.

For the partially submerged sump strainers (see Figure 3.7-1b), failure can occur in one of two ways: pump cavitation as explained above or due to head loss caused by insufficient water entering the sump due to debris buildup. This flow imbalance occurs when water infiltration through a debris bed on the strainer can no longer satisfy the volumetric demands of the pump. Because the pit and the pool are at equal atmospheric overpressure, the only force available to move water through a debris bed is the static pressure head in the pool. Numeric simulations confirm that an effective head loss across a debris bed approximately equal to half of the submerged screen height is sufficient to prevent adequate water flow. For all partially submerged sump strainers, the sump failure criterion is assumed to be met when

$$\Delta H_S \geq NPSH_M \text{ or } \Delta H_S \geq 1/2 \text{ of submerged screen height.}$$

After switchover to ECCS recirculation, some plants can change their sump configuration from partially submerged to fully submerged. This can occur for a number of reasons, including accumulation of containment spray water, continued melting of ice-condenser reservoirs, and continued addition of refueling water storage tank (RWST) inventory to the containment pool. As the pool depth changes during recirculation, the "wetted area" (or submerged area) of the sump strainers can also change. The wetted area of the strainer determines the average approach velocity of water that may carry debris. It may be that the conditions for transport are enhanced due to the velocities present during washdown and early pool fill, but the most significant transport from the head loss perspective may be the fine debris that may transport over a longer period of time. Larger debris may stay at the base of the strainer while fine debris may collect over the entire strainer and result in high head losses. Because information about time-dependent pool depths was difficult to obtain, only the pool depth at the time of switchover to the ECCS was used in the parametric evaluations.

Calculations were made for the LLOCA events in large dry and ice condenser containments in PWRs. The simulations were used to develop a generic description of LLOCA accident progression in a PWR, both in terms of the system's response and its implications on debris generation and transport. Table 3.7-1 provides a general chronology of events for a PWR LLOCA sequence. Because plant designs vary, the descriptions are not accurate for every plant. Figure 3.7-2 summarizes key findings to supplement the tabulated results.

Table 3.7-1. PWR LLOCA Sequences
(from NUREG/CR-6762, Vol 1 Table 2-4)

Time after LOCA (s)	Accum. (SI Tanks)	HPSI	LPSI	CS	Comments
0-1	Reactor scram. Initially high containment pressure. Followed by low pressure in pressurizer. Debris generation begins due to initial pressure wave, followed by jet impingement. Blowdown flow rate is large; flow at the break is mostly saturated water. Quality <0.05. Saturated jet-models are appropriate. Sandia National Laboratories (SNL)/American National Standards Institute (ANSI) models suggest wider jets, but static pressures decay rapidly with distance.				
2		Initiation signal	Initiation signal	Initiation signal	Initiation signal from low pressurizer pressure or high containment pressure/temperature
5	Accumulator injection begins	Pumps start to inject into vessel	Pumps start (pressure of reactor coolant system greater than pump dead head)	Pumps start and sprays on	In a cold-leg break, ECCS bypass is caused by counter-current injection in the downcomer. Hot-leg break does not have this problem.
10	Blowdown flow rate decreases steadily from ≈20,000 lb/s to 5000 lb/s. Cold-leg pressure falls considerably to about 1000 psia. At the same time, effluent quality increases from 0.1 to 0.5 (especially that from steam generator side of the break). Flow at the break is vapor continuum with water droplets suspended in it. Saturated water or steam jet models are appropriate. At these conditions, SNL/ANSI models show that jet expansion induces high pressures far from break location.				
25		End of bypass; high-pressure safety injection (HPSI)			
25-30	Break velocity reaches a maximum > 1000 ft/s. Quality in excess of 0.6. Steam flow at less than 500 lb/s. Highly energetic blowdown is probably complete. However, blowdown continues as residual steam continues to be vented.				
35	Accumulators empty		LPSI ramps to design flow.		
40	Blowdown is terminated, and therefore debris generation is mostly complete. Blowdown pressure at nozzle <150 psi. Debris would be distributed throughout the containment. Pool is somewhat turbulent.				
55-200	Reflood and quenching of fuel rods (Tmax about 1036oF). In the cold-leg break, quenching occurs between 125 and 150 s. In hot-leg break, quenching occurs between 45 and 60 s (Tmax about 950oF).				

200-1200	Debris added to lower containment pool by spray washdown drainage and break washdown. Containment pool keeps filling. Heavy debris may settle down.				
1200	Low-level indication in RWST received by operator. Operator prepares to turn on ECCS in sump recirculation mode.				
1500		Switch suction to sump	Switch suction to sump	Terminate or to sump	Many plants have containment fan coolers for long-term cooling.
1500-18000	Debris may be brought to the sump strainer. Buildup of debris on sump strainer may cause excessive head loss. In general, containment sprays may be terminated in large dry containments at the 2-h mark.				
>36000		Switch to hot-leg recirculation.	Switch to hot-leg recirculation		

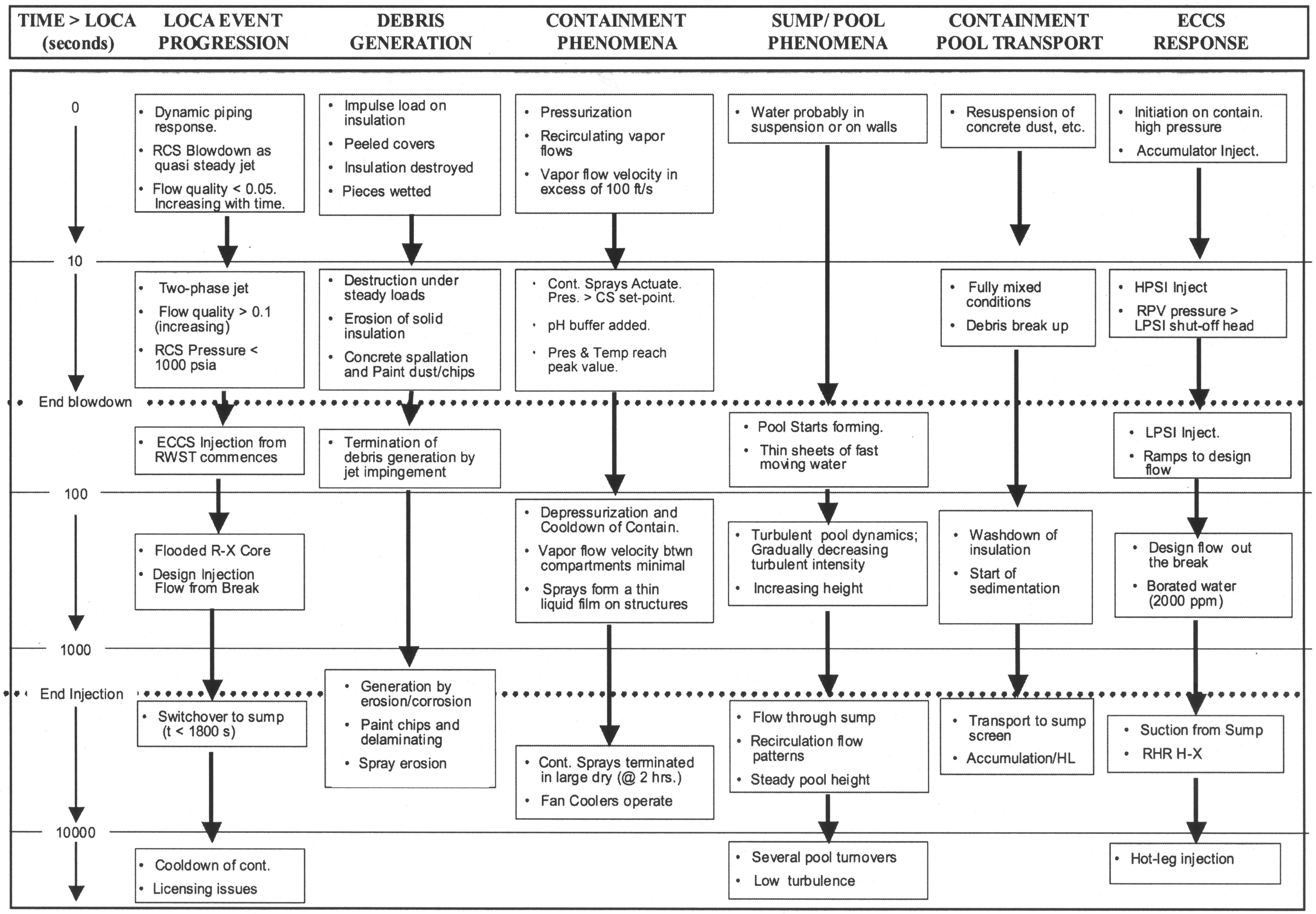


Figure 3.7-2. PWR LLOCA Accident Progression in Large Dry Containment (Figure 2-2 NUREG/CR-6762)

3.8 Other PWR Plant Design Features That Influence Accident Progression

Other plant design features (beyond those previously discussed) may influence the debris-related accident progression. For example, many plants have heat exchangers installed directly in the core-cooling recirculation flow paths to ensure that the water is cooled before it is returned to the core. However, in some plants, the core cooling recirculation systems do not have dedicated heat exchangers and instead make indirect use of heat exchangers from other systems (e.g., CSS) to ensure that heat is removed from the reactor coolant. Examples of plants where core cooling makes indirect use of heat exchangers from CSS include those with subatmospheric containments and some Combustion Engineering (CE) plants. For these types of plants, successful core cooling during recirculation may require (a) direct sump flow from the core cooling system and (b) sump recirculation cooling from the CSS.

3.8.1 Plant Features

Some general conclusions regarding important plant features that influence accident outcome are listed below. The primary source for this information is the PWR plant survey published in 2002 (NUREG/CR-6762) and is presented from an historical perspective of the issues addressed by the NRC and the industry and may not represent the current status of operating PWRs(i.e, post-GSI-191). See Appendix A for data on PWR suction strainers installed in response to GL 04-02.

Sump Design and Configurations

- The ECCS and/or CSS pumps in nearly one-third of the PWR plants surveyed have an NPSH margin of less than 2 ft of water, and another one-third have an NPSH margin between 2 and 4 ft of water. In general, PWR sumps have low NPSH margins compared with the potential head loss effects of debris accumulation on the sump strainer. This assessment was based on the information available prior to the modification made in response to NRC Generic Letter 2004-02 (GL-04-02).

- PWR sump designs vary significantly, ranging from horizontal strainers located below the floor elevation to vertical strainers located on pedestals. The sump-strainer surface areas vary significantly from unit to unit and some plants employ curb-like features to prevent heavier debris from accumulating on the sump strainer, while others do not have noticeable curbs.

In some PWR units, the sump strainer would not be completely submerged when ECCS recirculation starts. However, these strainers are fully submerged relatively quickly. The mode of failure is strongly influenced by sump submergence.
Sources and Locations of Debris

- U.S. PWRs employ a variety of types of insulation and modes of encapsulation, ranging from non-encapsulated fiberglass to fully encapsulated stainless steel RMI. A significant majority of PWRs have fiberglass and calcium-silicate insulation in the containment, either on primary piping or on supporting systems.[1] The types of fibrous insulation varied

[1] About 40 PWR units have in excess of 10% of the plant insulation in the form of fiberglass and another 5–10% in the form of calcium-silicate. A typical plant has approximately 7500 ft^3 of insulation on the primary pipes and supporting systems pipes that are in close proximity to the primary pipes.

significantly, but most are in the form of generic low-density fiberglass (LDFG) and mineral wool.

- Given that (a) very small quantities of fibrous insulation would be necessary to induce large pressure drops across the sump strainers and (b) many plants have comparatively large inventories of fibrous insulation, plant-specific analyses are necessary before the recirculation sumps of any particular plant can be declared safe with respect to strainer blockage.

- Additional sources of debris in the PWR containments include cement dust and dirt (either present in the containment a priori or generated by a LOCA), particulate insulations used on the fire barriers (e.g., marinite), failed containment coatings, and precipitates (of zinc and aluminum precipitation by-products).[2] Estimates for this type of debris range from 100 to several thousand pounds; either of these quantities of particulate debris could result in very large head losses when combined with fibrous material.

Containment Features Affecting Debris Transport

- Set points for the CSS typically are defined based on LLOCA and equipment qualification considerations. Consequently, sprays may not (automatically) actuate during SLOCAs[3] because of their lower peak containment pressures. Actuation of the CS plays an important role in the transport of debris to the sump, and at the same time, it affects the timing of potential sump failure.[4]

- A number of features in nuclear power plant containments would significantly affect the transport of insulation debris. These features include the containment's engineered safety features and associated plant operating procedures. Perhaps the most significant containment feature is the containment pressure-suppression system.

- In a PWR plant, the relatively large free volume functions to keep pressure from becoming excessive thus, the large free volume is essentially a pressure-suppression system. The containment sprays also help keep pressure from becoming excessive. Containment size was reduced in ice-condenser plants because of their banks of ice, which would condense steam effectively,.

- The most significant difference between PWR and BWR containments with respect to debris transport is the pressure-suppression system, and its location relative to the postulated break. In BWR containments, the break effluences would flow down and through the suppression pool via downcomer vents (i.e., toward the ECCS suction strainers). In PWR containments, the break effluences would tend to flow generally up

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[2] PWR design basis accidents evaluate the potential for precipitation of aluminum and zinc when they are subjected to high-pH, hot, borated water because these chemical reactions generate H_2.

[3] Fan cooler response to LOCAs also plays a vital role in determining spray actuation following SLOCA. These concerns are not applicable to LLOCAs or MLOCAs, where automatic actuation of sprays is expected in every plant. Some plants such as Fort Calhoun uses water management and do not have sprays automatic actuate for any size LOCA.

[4] The drainage of the spray water from the upper reaches of the containment down to the containment sump could transport substantial quantities of debris to the sump that otherwise would likely remain where deposited following the RCS depressurization (i.e., the containment sprays would substantially increase the fraction of debris transported to the sump strainers over the fraction that would be transported without spray operation).

toward the large free volume of the containment dome (i.e., away from the ECCS sump strainers). For example, in ice-condenser containments, the containment is designed to direct the break flows through the ice banks, which exit into the dome. These flows also would carry debris into these regions. This means that for PWR plants, substantial quantities of debris would be propelled away from the lower regions of the containment and toward the higher regions of the containment. If it were not for the containment sprays washing the debris down toward the recirculation sump, some portion of the debris carried aloft likely would remain in the higher reaches of the containment.

- The flow propelling debris upward in the containment could be channeled through relatively narrow passageways in some containment designs, such as an ice condenser bank, where substantial portions of the debris entrained within the flow likely would be deposited initially within the channel. Such an effect could potentially be analyzed to determining the debris quantity that would not likely be subsequently transported downward to the sump if there are no sprays to wash off the debris.

- After the airborne debris is dispersed throughout the containment, the washdown of that debris to the recirculation sump would be determined primarily by the design of the CSS, including the drainage of the sprayed water. First, the spray droplets would tend to sweep any remaining airborne debris out of the containment atmosphere, and then the falling droplets would wash debris off surfaces (structures, equipment, walls, floors, etc.). As the drainage water works its way downward, the entrained debris would move along with the flow. However, not all debris would be washed off the surfaces and the containment sprays may not flow over substantial areas within the containment.

- Containments are generally designed to readily drain the spray water to the sump in order to minimize water holdup and maximize sump water levels. However, the refueling pools could hold up substantial quantities of water if the pool drains are not open or are blocked by debris. Thus, the design of the refueling pools, including the pool drainage system, can be an important containment feature with regard to debris inventory in the sump.

3.8.2 Debris Accumulation

Debris generated by a LOCA will have an adverse effect on recirculation sump performance if this matter either (a) covers the sump strainer in sufficient quantity and over a sufficient surface area to impede flow or, (b) accumulates at critical locations for the flow of recirculation water such that the debris diverts water away from the sump.[5] After debris is transported to a location of concern, it must accumulate in sufficient quantity and in a configuration that impedes flow. The principal location of concern for debris accumulation is the surface of a recirculation sump strainer. The physical configuration of the sump strainer, as well as its position and orientation in the pool of water that it services, varies among U.S. PWRs. Additional locations of concern are those in which the flow path for recirculating water passes through a narrow passageway or restriction in cross-sectional area. If debris were to accumulate at these locations (because of the presence of a trash rack or a similar feature), water might be diverted away from the sump, thereby reducing the sump water level and associated hydraulic head.

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[5]The knowledge associated with debris accumulation also applies to strainers in the upper containment levels (e.g., refueling pool drain strainers), but the potential blockage of such strainers usually is treated as part of debris transport from the upper levels down to the sump pool.

Historically, the sump strainer has been the principal location of concern for debris accumulation. For fully submerged strainers, excessive accumulation of debris can cause the head loss across the debris bed to reduce the available NPSH to ECCS or containment spray pumps. For partially submerged strainers, excessive debris accumulation can reduce the static head necessary to drive recirculation flow through the strainer. Details on parameters such as local flow field, local geometry, degree of submergence, and debris characteristics are discussed in NUREG/CR-6808, Section 6.

Several experiments have been performed to evaluate the hydrodynamic conditions required to move debris of various types from their position of arrival on the containment floor to the recirculation sump. The BWROG and various ECCS recirculation suction strainer vendors performed experiments to characterize the accumulation and head loss associated with LOCA-generated debris for replacement strainer designs. Based on several experiments, the flow conditions required for debris to deposit on the upper portions of a vertical strainer were inferred from measurements made of the velocity required to “lift” debris over a 2- or 6-in. curb. The so-called “lifting” velocities for fiber fragments, moderate-size pieces of fiber matting, and RMI foils are listed in Table 3.8-1. These values were reported to be generally consistent with earlier measurements of the flip-up velocity. That is, debris can be lifted over a 6-in. curb (or up onto a vertical strainer) at relatively low velocities (i.e., less than 0.3 ft/s), if the flow field in the pool of water is turbulent. In laminar flow fields, the “lift” velocity increases only slightly for fiber fragments. Stainless steel RMI debris was observed to remain near the base of the strainer at velocities greater than 1 ft/s when the flow stream was laminar.

Table 3.8-1. Minimum Strainer Approach Velocity for Debris to “Flip Up” or be Hydraulically “Lifted” onto a Sump Strainer (Source: Table 6-1 in NUREG/CR-6808)

	Velocity (ft/s)				
DATA SOURCE	Intact Fiber Pillows *	Fiber Fragments * #	Shredded Fiber *	Intact RMI Cassettes	SS RMI foils
NRC (1983)=NUREG 2982	1.1–2.4	0.5–0.7 (turbulent)	0.2 (turbulent)	—	—
NRC (1984) =NUREG 3616	—	—	—	> 1.0	1.8–2.0 **
Bremen Polytech. (1995)	0.9–1.3	0.7–1.1 (laminar)	0.9–1.2 (laminar)	Tested by flipping on strainer not observed	1.9 **
NRC (2001) = NUREG 6772	—	0.30–0.47 (laminar) 0.25–0.39 (turbulent)	0.28–0.34 (laminar) 0.25–0.30 (turbulent)	—	No lift (laminar) 0.30 (turbulent)

*Fibrous material varied among tests, but included fiberglass and mineral wool.
**Although stainless steel (SS) foil fragments were observed to “lift” and flip onto the vertical strainer at these velocities, the debris mass remained primarily near the bottom of the strainer. Brocard reports maximum flow blockage in such cases was 60-70% of the strainer area (NUREG/CR-3616).
#Fragment size typically 4 x 4-in.pieces of fiber matting.

A limitation of the studies listed in Table 3.8-1 is that none of them involved a sufficiently large quantity of debris fragments to allow an accumulation pattern that would result at water velocities above the "lifting" threshold. Experiments conducted at the University of New Mexico examined debris bed patterns on a vertical strainer for moderate- and small-size debris fragments of fiber, RMI foils, and calcium-silicate. Three specific observations were made from these tests:

- Shredded fiber and disintegrated calcium silicate developed a near-uniform debris bed at velocities exceeding approximately 0.5 ft/s, when the strainer was fully submerged.
- Crumpled stainless-steel RMI foils (~2 in. in size) accumulated in a bottom-skewed pattern at velocities less than 1 ft/s. Individual foils that arrived at the base of the strainer "climbed" on top of foils that arrived earlier and gradually formed a debris bed that was triangular in cross-section.
- Very small particles of calcium silicate and suspended fibers collected on the strainer in a uniform pattern at velocities as low as 0.2 ft/s. A significant fraction of larger calcium silicate debris (e.g., clumps of particulate and binding fiber) either settled to the floor of the flume before reaching the strainer or collected as a mass near the base of the strainer at velocities as high as 0.9 ft/s.

3.8.3 Debris Head Loss

Information related to estimating the pressure drop (or head loss) across the ECCS strainer or sump strainer as a result of debris buildup was addressed in a knowledge base report published in 1996 by the Committee on the Safety of Nuclear Installations (CSNI), specifically Section 4 of that report, entitled "Strainer Pressure Drop." NUREG/CR-6808 discussed the head loss data and technical developments achieved subsequent to the CSNI report. Two major uncertainties identified in the CSNI document are:

A proven, accurate, and repeatable methodology for predicting the head loss caused by mixed beds is not yet fully developed. Although the NRC methodology performs well for flat strainers, its application to specialty strainers has not been established.

Various test methodologies, setup designs, and test debris preparations may contribute significantly to pressure drop. No systematic evaluation has been performed to analyze the desirability of each test methodology relative to that of other methods.

Head loss across the debris bed depends to a great extent on the debris bed constituents and their morphology. Debris beds of importance can be divided broadly into the following groups: (a) fibrous debris beds, (b) mixed fibrous and particulate debris beds, (c) beds formed by fragments of RMI, and (d) mixed RMI and fibrous/particulate debris beds. We discuss the first two groups below.

Fibrous Beds

In the case of fibrous beds, the flow to a strainer would deposit the fibrous shreds on the strainer surfaces such that the fibers generally lay across the strainer penetrations and the subsequent drag caused by the fibers would create a pressure differential across the bed of debris. As the pressure drop across the fibrous beds increases, such beds have been observed to compress, leading to progressively higher head losses. Furthermore, it has been observed that compressed beds do not completely regain their original state when the water flow is terminated. Head loss across a debris bed increases linearly with velocity in the viscous region and increases with the square of the velocity in the turbulent region.

The head loss across the strainer depends on the quantity of the fibrous debris trapped on the strainer surface. A convenient measure for this quantity is the debris bed thickness based on the as-fabricated density of the insulation, i.e., defined as the mass of fibrous debris per unit of strainer area divided by the as-fabricated density. This thickness has been generally referred to as the "theoretical" thickness. Typically, head loss varies linearly with bed thickness for beds that are uniform or nearly uniform. Deviation from this linear behavior has been seen where debris has accumulated in a non-uniform manner on the strainer surface; specifically, such behavior has been observed at lower bed thicknesses, where clumps of fibrous debris have deposited non-uniformly on the strainer surface. The non-uniformity also may lead to lower filtration efficiencies for entrapment of non-fibrous debris passing through the strainer. As a result, pressure drop for non-uniform beds would be lower than that predicted by extrapolating the data obtained for uniform beds. This is mentioned as an important issue in the evaluation of specialized strainers designed to collect debris in a non-uniform manner (e.g., a star strainer).

Size distribution of the fibrous debris is another factor that significantly influences head loss. Fibrous debris reaching the strainer may range in size from individual fibers to shreds or clumps to large pieces of torn blankets. Considerable attention was given to studying the head loss characteristics of finer debris, which is much more likely to be transported to the strainer surface and form more uniform and compact beds, thereby offering more resistance to flow than non-uniform or loose beds. Additional factors that influence head loss include fibrous material type (e.g., mineral wool vs. fiberglass) and water temperature. Typically, higher water temperatures result in lower pressure drops that are caused primarily by corresponding decreases in viscosity of the water. Analyses have successfully handled this effect by simply accounting for the temperature dependency of viscosity in the respective head loss correlations. Similarly, the differences in materials can typically be handled by accounting for differences in the material properties of the insulation and the individual fibers.

Mixed Particulate and Fiber Beds

A mixture of fibrous material and particulates such as corrosion products, paint chips, organic sludge, concrete dust, and fragments of non-fibrous insulation (such as calcium silicate) are generally termed "mixed bed" or "debris bed." Attempts have been made to characterize the characteristics of the debris (e.g., size distributions) and to use appropriate material to simulate LOCA-generated debris in experiments and the appropriate characteristics in analyses. Experiments have shown that the addition of particulate debris would increase the pressure drop substantially. The data demonstrated that the head loss could increase by a factor of 100 as the particle-to-fiber mass ratio increases from zero to about 20.

The experiments also established that for a fixed amount of particulate debris, pressure differentials across the bed are significantly higher for smaller, rather than larger, quantities of fibrous material if amount of particulate debris in the bed is maintained at a constant value. This effect, which often is referred to as the "thin-bed effect," has been studied extensively. Closer examination of the bed morphology reveals that thin beds closely resemble granular beds (rather than fibrous beds) and that higher head loss is a direct result of bed morphology. This effect is illustrated in Figure 3.8-1, which shows head losses vs. fiber volume for fixed quantities of particulate, as predicted using the head loss correlation in NUREG/CR-6224. In Figure 3.8-1, the thin-bed peaks reflect the higher head losses associated with the thin layer fiber supporting a granular bed of particulates. Even if a plant has large quantities of fibers that could lead to potentially thick mixed beds of debris, the initial bed formation would begin with a thin layer of fibers that could cause a thin bed head loss relatively early into the accident.

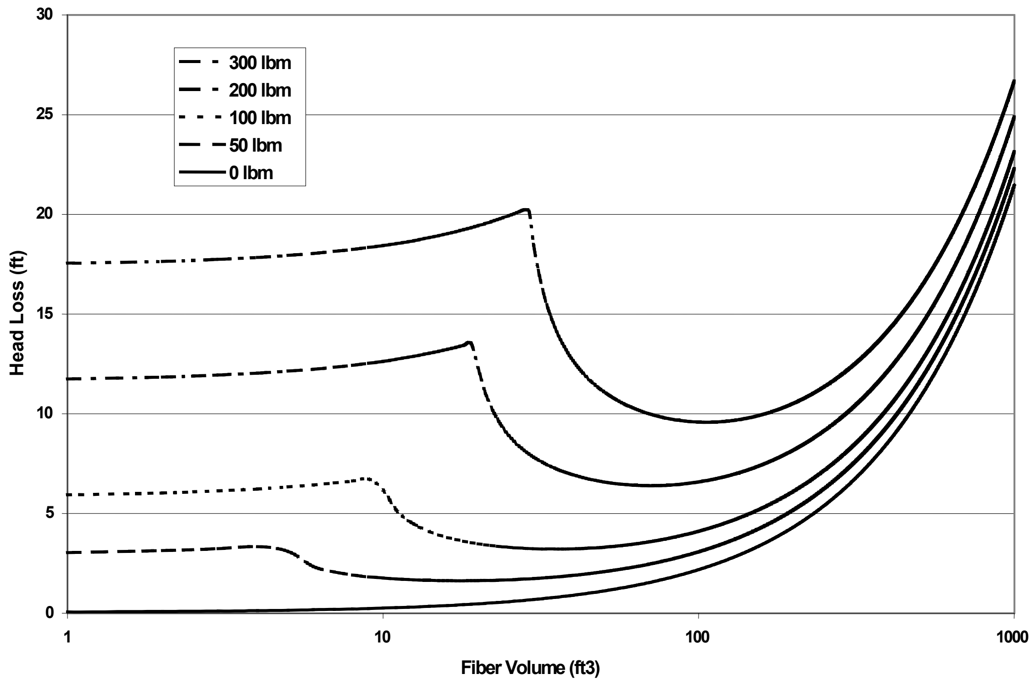

Figure 3.8-1. Head Losses vs. Fiber Volume for Fixed Quantities of Particulate (predictions assumed LDFG insulation debris, dirt particulate, 200°F, 100 ft2 of strainer area, and 5000 GPM flow)

In the prior PWR knowledge-base report (NUREG/CR-6808), details are presented on various analytical and experimental approaches used to assess the various aspects of sump blockage and to identify the strengths, limitations, important parameters, plant features, and the propriety of the different approaches. That report also discussed significant NRC regulatory actions regarding resolution of the issue. In essence, the report was designed to serve as a reference for plant-specific analyses with regard to whether the sump would perform its function without preventing the operation of the ECCS pumps. In particular, the report provided the following:

- A description of the safety concerns pertaining to PWRs
- A description of the major phenomena associated with the potential for strainer failure and a summary of research and experiment s conducted to date
- An evaluation of the research conducted for the various phenomena associated with strainer blockage
- Criteria for evaluating sump failure
- Descriptions of postulated PWR accidents
- Relevant plant features that influence accident progression, and

- Regulatory considerations.

Due to lessons learned in the 1990s during the assessment of BWR suction strainers and oversight of BWR plant-specific evaluations and modifications, NRC sponsored a new research effort to study the accumulation of debris on PWR containment sump strainers. The 2001 parametric study, "GSI-191 Technical Assessment: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance" (NUREG-6762, Volume 1), concluded that recirculation sump clogging is a credible concern for the population of domestic PWRs. However, as a result of limitations with respect to plant-specific data and other modeling uncertainties, the parametric study did not definitively identify whether or not particular PWR plants are vulnerable to sump clogging when phenomena associated with debris blockage are modeled mechanistically.

The NRC implemented a plan to have all PWR licensees (i) perform a plant-specific evaluation for the potential for head loss across the containment sump strainer because of the accumulation of debris on the containment sump strainer and (ii) evaluate effects of the debris that might pass through the sump strainers. To provide additional assurance regarding the continued operation of PWRs, the NRC asked the licensees of PWRs to implement compensatory measures at least until plant specific evaluations were completed. This was done through the issuance of NRC Bulletin 2003-01, "Potential Impact of Debris Blockage on Emergency Sump Recirculation at Pressurized-Water Reactors."

In November 2003, the NRC issued Revision 3 of RG 1.82, "Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident," to include guidance on the effects of debris on PWR sump screens. Revision 3 also incorporated guidance on the net positive suction head of the ECCS and containment heat removal pumps.

In September 2004, NRC issued a Generic Letter 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized Water Reactors." This Generic Letter requested all holders of operating licenses for PWRs to perform an evaluation of the ECCS and CSS recirculation functions in light of the information provided in the Generic Letter and, if appropriate, take additional actions to ensure system function. Additionally, the addressees were requested to submit the information specified in the letter to the NRC. This request was based on the potential susceptibility of PWR recirculation sump strainers to debris blockage during design basis accidents and on the potential for additional adverse effects due to debris blockage of flowpaths necessary for ECCS and CSS recirculation and containment drainage.

4 REGULATORY CONSIDERATIONS

Federal regulations are established to govern design and operational aspects of nuclear power reactors that affect the safety of those plants. These regulations are codified in the U.S. Code of Federal Regulations (CFR). Title 10 of the CFR deals with energy, and Part 50 of Title 10 consists of regulations promulgated by the NRC to provide for the licensing of production and utilization facilities. The NRC publishes Regulatory Guidance (RG) documents for the nuclear power industry on compliance with the regulations.

4.1 Code of Federal Regulations

This section describes the regulations that apply to the strainer blockage issue. Title 10 of the CFR provides the authority to the NRC to regulate nuclear power plants. Section 50.46, "Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors," of 10 CFR requires that licensees of a boiling or pressurized water reactor design their ECCS systems to meet five criteria. Specifically the rule provides acceptance criteria for peak cladding temperature, maximum cladding oxidation, maximum hydrogen generation, coolable core geometry, and long-term cooling.

The long-term cooling criteria states "After any calculated successful initial operation of the ECCS, the calculated core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core." Licensees are required to demonstrate this capability while assuming the most conservative (worst) single failure. The capability of the ECCS pumps to fulfill the criteria of limiting the peak cladding temperature and to provide long-term cooling over the duration of the postulated accident could be seriously compromised by a loss of adequate NPSH and the resulting cavitation. Because excessive buildup of debris on ECCS pump strainers may result in a common-cause failure of the ECCS, thereby preventing the ECCS from providing long-term cooling after a LOCA, Section 50.46 clearly applies to the strainer blockage issue. Licensees must demonstrate that their respective plants are in compliance with the regulations.

General Design Criteria (GDC) 35, 36, and 37 (Appendix A to 10 CFR Part 50) require appropriate design, inspectability, and testability of the ECCS. Note that the GDC establish minimum requirements for the principal design criteria for water-cooled nuclear power plants similar in design to plants for which the NRC has issued construction permits. The GDC are also considered to be generally applicable to other types of nuclear power units and are intended to provide guidance in establishing the principal design criteria for such other units. Specifically, these criteria state the following:

Criterion 35 -- Emergency core cooling. A system to provide abundant emergency core cooling shall be provided. The system safety function shall be to transfer heat from the reactor core following any loss of reactor coolant at a rate such that (1) fuel and clad damage that could interfere with continued effective core cooling is prevented, and (2) clad metal-water reaction is limited to negligible amounts. Suitable redundancy in components and features, and suitable interconnections, leak detection, isolation, and containment capabilities shall be provided to assure that for onsite electric power system operation (assuming offsite power is not available) and for offsite electric power system operation (assuming onsite power is not available) the system safety function can be accomplished, assuming a single failure.

Criterion 36 -- Inspection of emergency core cooling system. The emergency core cooling system shall be designed to permit appropriate periodic inspection of important components, such as spray rings in the reactor pressure vessel, water injection nozzles, and piping, to assure the integrity and capability of the system.

Criterion 37 -- Testing of emergency core cooling system. The emergency core cooling system shall be designed to permit appropriate periodic pressure and functional testing to assure (1) the structural and leak-tight integrity of its components, (2) the operability and performance of the active components of the system, and (3) the operability of the system as a whole and, under conditions as close to design as practical, the performance of the full operational sequence that brings the system into operation, including operation of applicable portions of the protection system, the transfer between normal and emergency power sources, and the operation of the associated cooling water system.

Section 50.65 of 10 CFR Part 50, "Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants," (referred to hereinafter as the maintenance rule) provides the requirements for monitoring and maintenance of plant structures, systems, and components (SSCs). The maintenance rule requires the licensee of a nuclear power plant to monitor the performance or condition of SSCs in a manner sufficient to provide reasonable assurance that the SSCs are capable of fulfilling their intended functions. When the performance or condition of an SSC does not meet its established goals, appropriate actions are required to be taken. Based on the criteria in the rule, the maintenance rule includes in its scope PWR and BWR ECCS suction strainers, all safety-related SSCs, and those non-safety-related SSCs that fall into the following categories:

(1) Those that are relied upon to mitigate accidents or transients or are used in plant emergency operating procedures,
(2) Those whose failure could prevent safety-related SSCs from fulfilling their safety-related function, and
(3) Those whose failure could cause a reactor scram or an actuation of a safety-related system.

Protective coatings are also covered by the maintenance rule to the extent that coating activities can affect operability of safety-related equipment, e.g., suction strainers or safety-related components subject to corrosion. On the basis of the guidelines in the rule, the maintenance rule requires that licensees monitor the effectiveness of maintenance for these protective coatings. The staff also considers the requirements of 10 CFR Part 50, Appendix B, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants," to be applicable to safety-related containment coatings. Criterion IX of Appendix B, "Control of Special Processes," is especially relevant requiring that "Measures shall be established to assure that special processes are controlled and accomplished by qualified personnel using qualified procedures in accordance with applicable codes, standards, specifications, criteria, and other special requirements."

Appendix K of 10 CFR Part 50, "ECCS Evaluation Models," establishes requirements for analytical determinations that impact aspects of the strainer blockage issue. These analytical requirements include the following: (1) fission-product decay heat generation rate (impacts the calculated containment pool temperature), (2) break flow characteristics and discharge model (impacts the estimated amounts of debris), (3) post-blowdown phenomena and heat removal by the ECCS, and (4) required ECCS model documentation. Appendix K also specifies that single failures be considered and that containment pressure be used for evaluating cooling effectiveness.

4.2 Regulatory Guidance

This section provides a description of regulatory guidance that applies to the strainer blockage issue. The NRC provides regulatory guidance on ensuring adequate long-term recirculation cooling following a LOCA in RG 1.82, “Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident.” The guide describes acceptable methods for implementing applicable GDC requirements with respect to the sumps and suppression pools functioning as water sources for emergency core cooling, containment heat removal, and containment atmosphere cleanup. Guidelines for evaluating availability of the sump and suppression pool for long-term recirculation cooling following a LOCA are included in the RG.

Revisions 1 and 2 of RG 1.82 were issued in November 1985 and May 1996, respectively. Revision 1 reflected the staff’s technical findings, related to USI A-43, that were reported in NUREG-0897. A key aspect of the revision was the staff’s recognition that the 50% strainer blockage criteria of Revision 0 did not adequately address the potential for strainer blockage and was inconsistent with the technical findings developed for the resolution of USI A-43. It was assumed in Revision 0 that the minimum NPSH margin could be computed by assuming that 50% of the strainer area was blocked by debris. GL-85-22 recommended use of Revision 1 of RG 1.82 for changeout and/or modifications of thermal insulation installed on primary coolant system piping and components. Revision 2 altered the strainer blockage guidance for BWRs because operational events, analyses, and research following Revision 1 indicated that the previous guidance was not comprehensive enough to adequately evaluate a BWR plant’s susceptibility to the detrimental effects caused by debris blockage of the suction strainers.

Revision 2 of RG 1.82 addressed operational debris, as well as debris generated by a postulated LOCA. Specifically, this revision stated that all potential debris sources should be evaluated, including, but not limited to, insulation materials (e.g., fibrous, ceramic, and metallic), filters, corrosion material, foreign materials, and paints/coatings. Operational debris included corrosion products, (such as BWR suppression pool sludge), and foreign materials (although foreign material exclusion [FME] procedures were not specifically introduced into Revision 2). This revision also noted that debris could be generated and transported by the washdown process, as well as by the blowdown process. Other important aspects of Revision 2 included: the use of debris interceptors (i.e., suction strainers) in BWR designs to protect pump inlets and NPSH margins; the design of passive and/or active strainers; instrumentation, in-service inspections; suppression pool cleanliness; the evaluation of alternate water sources, analytical methods for debris generation, transport, and strainer blockage head loss, and the need for appropriate supporting test data. Revision 2 references provide further detailed technical guidance for the evaluation of potential strainer clogging.

Revision 2 of RG 1.82 cited RG 1.1, “Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal System Pumps,” for specific conditions to be used in determining the available NPSH for ECCS pumps in a BWR plant’s licensing basis RG 1.1 considered the potential for degraded pump performance for ECCS and containment heat removal, which could be caused by a number of factors, including inadequate NPSH. If the available NPSH to a pump is insufficient, cavitation of the pumped fluid can occur, thereby significantly reducing the capability of the system to accomplish its safety functions. The proper performance of ECCS and containment heat removal systems should be independent of calculated increases in containment pressure caused by postulated LOCAs in order to ensure reliable operation under a variety of postulated accident conditions. The NRC's regulatory position is that the ECCS and containment heat removal systems should be designed with an adequate NPSH margin, assuming the maximum expected temperatures of the pumped fluids and no increase in containment pressure from that present before postulated LOCAs.

Revision 1 of RG 1.54, "Quality Assurance Requirements for Protective Coatings Applied to Water-Cooled Nuclear Power Plants," in July 2000 provided guidance regarding compliance with quality assurance requirements related to protective coating systems applied to ferritic steel, aluminum, stainless steel, zinc-coated (galvanized) steel, and masonry surfaces. The revision endorsed industry developed codes, standards, and guides. The American Society for Testing Materials (ASTM) standards cited in the regulatory position of Revision 1 for the selection, qualification, application, and maintenance of protective coatings in nuclear power plants were reviewed by the NRC staff and found acceptable. NRC issued Revision 2 of RG 1.54 in October 2010 to update the guidance to the latest ASTM documents..

4.3 Generic Safety Issue-191

The Generic Safety Issue (GSI)-191 study, "PWR Sump Blockage," was established to determine if the transport and accumulation of debris in a containment following a LOCA would impede the operation of the ECCS in operating PWRs. The primary objective of the GSI-191 study was to assess the likelihood of debris induced failures of ECCS and CSS pumps at domestic PWRs. The technical assessment culminated in a parametric study that mechanistically treated phenomena associated with debris blockage. The study used analytical models of domestic PWRs generated with a combination of generic and plant-specific data.

As documented in Volume 1 of NUREG/CR-6762, "GSI-191 Technical Assessment: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance," the GSI-191 parametric study concludes that recirculation sump clogging is a credible concern for the population of domestic PWRs. However, as a result of limitations with respect to plant-specific data and other modeling uncertainties, the parametric study does not definitively identify whether particular PWR plants are vulnerable to sump clogging.

The methodology employed by the GSI-191 parametric study is based on the substantial body of test data and analysis documented in technical reports generated during the GSI-191 research program and earlier technical reports generated by the NRC and industry during the resolution of the BWR strainer clogging issue and USI A-43. The following pertinent technical reports, which cover debris generation, transport, accumulation, and head loss, are incorporated by reference into the GSI-191 parametric study:

NUREG/CR-6770, "GSI-191: Thermal-Hydraulic Response of PWR Reactor Coolant System and Containments to Selected Accident Sequences," dated August 2002.

NUREG/CR-6762, Vol. 3, "GSI-191 Technical Assessment: Development of Debris Generation Quantities in Support of the Parametric Evaluation," dated August 2002.

NUREG/CR-6762, Vol. 4, "GSI-191 Technical Assessment: Development of Debris Transport Fractions in Support of the Parametric Evaluation," dated August 2002.

NUREG/CR-6224, "Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris," dated October 1995.

In addition to demonstrating the potential for debris to clog containment recirculation sumps, operational experience and the NRC's technical assessment of GSI-191 have identified three integrally related modes by which post-accident debris blockage could adversely affect the sump strainer's design function of intercepting debris that could impede or prevent the operation of the ECCS and CSS in the recirculation mode.

First, as a result of the 50% blockage assumption (in RG Revision 0), PWR sump strainers were typically designed with the assumption that relatively small structural loadings would result from the differential pressure associated with debris blockage. Consequently, PWR sump strainers may not be capable of accommodating the substantial structural loadings that would occur due to debris beds that may cover essentially the entire strainer surface. Inadequate structural reinforcement of a sump strainer may result in its deformation, damage, or failure, which could allow large quantities of debris to be ingested into the ECCS and CSS piping, pumps, and other components, potentially leading to their clogging and failure. The ECCS strainer plugging and deformation events that occurred at Perry Unit 1 are further described in

- Information Notice (IN) 93-34, "Potential for Loss of Emergency Cooling Function Due to a Combination of Operational and Post-LOCA Debris in Containment," dated April 26, 1993 and
- Licensee Event Report (LER) 50-440/93-011, "Excessive Strainer Differential Pressure Across the RHR [Residual Heat Removal] Suction Strainer Could Have Compromised Long Term Cooling During Post-LOCA Operation," submitted May 19, 1993.

These documents were cited for the credibility of this concern for strainers that have not been designed with adequate reinforcement.

Second, in some PWR containments, the flowpaths by which containment spray or break flows return to the recirculation sump may include "chokepoints" at which the flow path becomes so constricted that it could become blocked with debris following a high-energy line break (HELB). For example, chokepoints may include drains for pools, cavities, or isolated containment compartments, and other constricted drainage paths between physically separated containment elevations. As a result of debris blockage at certain chokepoints, substantial amounts of water required for adequate recirculation could be held up or diverted into containment volumes that do not drain to the recirculation sump. The holdup or diversion of water assumed to be available to support sump recirculation could result in an available NPSH for ECCS and CSS pumps that is lower than the analyzed value, thereby reducing assurance that recirculation would function successfully. A reduction in available NPSH directly affects sump strainer design because the NPSH margin of the ECCS and CSS pumps should be conservatively calculated in order to determine the required surface area of sump strainers when debris loadings are considered. Significant holdup of inventory could also result in the lack of full submergence for some strainers. The NRC's GSI-191 research identified the holdup or diversion of recirculation sump inventory as an important and potentially credible concern, and a number of LERs associated with this concern have further confirmed both its credibility and potential significance. These LERs include:

> LER 50-369/90-012, "Loose Material Was Located in Upper Containment During Unit Operation Because of an Inappropriate Action," McGuire Unit 1, submitted August 30, 1990.
>
> LER 50-266/97-006, "Potential Refueling Cavity Drain Failure Could Affect Accident Mitigation," Point Beach Unit 1, submitted February 19, 1997.

LER 50-455/97-001, “Unit 2 Containment Drain System Clogged Due to Debris,” Byron Unit 2, submitted April 17, 1997.

LER 50-269/97-010, “Inadequate Analysis of ECCS Sump Inventory Due to Inadequate Design Analysis,” Oconee Unit 1, submitted January 8, 1998.

LER 50-315/98-017, “Debris Recovered from Ice Condenser Represents Unanalyzed Condition,” D.C. Cook Unit 1, submitted July 1, 1998.

Third, debris blockage at flow restrictions within the ECCS recirculation flowpaths downstream of the sump strainer is of potential concern for PWRs. For this mode of debris blockage to occur, pieces of debris would need to have dimensions that would allow them to pass through the sump strainer’s intended openings, or through strainer defects such as gaps or breaches. This debris could then become lodged at downstream flow restrictions such as pump internals, HPSI throttle valves, fuel assemblies, or containment spray nozzles. In particular, conditions conducive to downstream debris blockage may be present at PWRs with strainer defects, and at PWRs where the dimension of the sump strainer’s openings is not the most restrictive point in the ECCS and CSS recirculation flowpaths. Downstream debris blockage at restrictions in the ECCS flow path could impede or prevent the recirculation of coolant to the reactor core, thereby leading to inadequate core cooling. Similarly, downstream debris blockage at restrictions in the CSS flow path could impede or prevent CSS recirculation, thereby leading to inadequate containment heat removal.

Three additional items increased the urgency of the NRC staff’s efforts to ensure that PWR licensees were aware of and had appropriately responded to the above concerns about the potential for debris blockage. These were:

1 LER submitted by the licensee for Davis-Besse Unit 1 that declared the recirculation sump inoperable (LER 50-346/02-005-01)
2 subsequent LER submitted by the Davis-Besse licensee that declared the high-pressure injection (HPI) pumps inoperable (LER 50-346/02-002-00)
3 NRC-sponsored risk study concerning operator actions to mitigate sump clogging (Kern and Thomas, 2003).

In February 2003, Los Alamos National Laboratory published the NRC-sponsored technical report LA-UR-02-7562 entitled, “The Impact of Recovery From Debris-Induced Loss of ECCS Recirculation on PWR Core Damage Frequency” (Kern and Thomas, 2003). The report analyzes the potential risk benefit of operator actions to recover from sump clogging events using a generic probabilistic model to demonstrate that the potential increase in risk due to sump clogging could be reduced by approximately one order of magnitude if PWR licensees have appropriate mitigation measures in place.

In response to these items associated with the potential post-accident debris blockage concerns identified in NRC Bulletin 03-01, the NRC requested that individual PWR licensees submit information on an expedited basis to document that they have either (1) analyzed the ECCS and CSS recirculation functions with respect to the identified post-accident debris blockage effects, taking into account the recent research findings and determined that compliance exists with all applicable regulatory requirements, or (2) implemented appropriate interim compensatory measures to reduce the risk which may be associated with potentially degraded or non-conforming ECCS and CSS recirculation functions while evaluations to determine compliance proceeded.

To assist in determining whether the ECCS and CSS recirculation functions are in compliance with existing applicable regulatory requirements, addressees were directed to use the guidance in Draft Regulatory Guide 1107 (DG-1107), "Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident," dated February 2003. The NRC also published a technical report entitled NUREG/CR-6808, "Knowledge Base for the Effect of Debris on Pressurized Water Reactor Emergency Core Cooling Sump Performance," dated February 2003, which is designed to serve as a reference for plant-specific analyses with regard to whether a sump would perform its function without preventing the operation of the ECCS and CSS pumps.

Conditions at various PWRs were expected to vary with respect to susceptibility to post-accident debris blockage, and various options may have been available to addressees for preventing or mitigating the effects of debris blockage. For these reasons, addressees that were unable to confirm compliance with all existing regulatory requirements within 60 days were asked to consider a range of possible interim compensatory measures and to implement those that they deemed appropriate, based upon the specific conditions associated with their plants. As stated above, the risk benefit of certain interim compensatory measures was demonstrated by the NRC-sponsored technical report LA-UR-02-7562 (Kern and Thomas, 2003). Addressees electing to implement interim compensatory measures in response to this bulletin were asked to ensure that the interim measures are implemented as soon as practical.

A parametric evaluation was performed as part of the GSI-191 study to demonstrate the potential for recirculation-sump clogging for operating PWRs. Each of the 69 domestic PWRs was modeled in the evaluation using a mixture of generic and plant-specific data. The minimum amount of debris accumulation on the sump strainer that was needed to exceed the required NPSH margin for the ECCS and CSS pumps was determined for each of the 69 representative models. GSI-191 PWR research activities, as well as existing BWR research results, were used to support the development of these models and the input to these models. The evaluation considered small, medium, and large LOCAs and used both favorable and unfavorable assumptions, relative to the plant, for a number of parameters. The results of the parametric evaluation formed the technical basis for making the determination that sump blockage was a credible concern.

However, the parametric evaluation had a number of limitations. The most notable were attributed to the extremely limited plant-specific data available to the study. The need for more accurate plant-specific assessments of the adequacy of the recirculation function of the ECCS and CSS for each operating PWR was indicated clearly. The Nuclear Energy Institute (NEI) also recognized this need and conducted a program to develop evaluation guidance for the industry. NEI issued a report (NEI, 2004) to provide licensees with guidance for evaluating the post-accident performance of the containment sump screen for a PWR. The report presented an approach called, "Baseline Evaluation Method," for evaluating the generation and transport of debris to the sump screen, and the resulting head loss across the sump screen. Section 1 of the report contains an introduction to the PWR strainer debris issue, including a historical review describing the steps that led to the current understanding. Section 2 is a high-level summary of the overall process considerations that need to be addressed during the evaluation process, while Section 3 describes a Baseline Evaluation Method that may be applied to all PWR's and provides sample calculation using the Baseline Evaluation Method. In Section 5, refinements in administrative control and design are discussed. Section 6 provides a guidance on a risk-informed evaluation. Section 7 provides guidance for additional design considerations.The document did not address the implementation and/or licensing of any design or operational changes resulting from the use of the evaluation methodology.

The NRC staff has performed a safety evaluation of the NEI guidance report (SE NEI-04-07, ML043280007, 2004) and found portions of the proposed guidance to be acceptable. For the areas that were found to be inadequate, the staff stipulated conditions and limitations for use of the NEI report, including alternative guidance which supplemented the guidance in the NEI submission. It was concluded that the resultant combination of the NEI submission and staff safety evaluation provided an acceptable overall guidance methodology for the plant-specific evaluation of ECCS or CSS sump performance with specific attention given to the potential for debris accumulation that could impede or prevent the ECCS or CSS from performing its intended safety functions. Methods for calculating strainer head loss due to debris accumulation on the strainer or on downstream components was not within the scope of this guidance.

4.4 NRC Bulletin 2003-01

The NRC issued Bulletin 2003-01 to:

(1) Inform addressees of the results of NRC-sponsored research identifying the potential susceptibility of PWR recirculation sump strainers to debris blockage in the event of a HELB requiring recirculation operation of the ECCS or CSS.

(2) Inform addressees of the potential for additional adverse effects due to debris blockage of flowpaths necessary for ECCS and CSS recirculation and containment drainage.

(3) Request that, in light of these potentially adverse effects, addressees confirm their compliance with 10 CFR 50.46(b)(5) and other existing applicable regulatory requirements, or describe any compensatory measures implemented to reduce the potential risk due to post-accident debris blockage as evaluations to determine compliance proceed.

(4) Require addressees to provide the NRC a written response in accordance with 10 CFR 50.54(f).

All addressees were requested to provide a response within 60 days that contains the information in either Option 1 or Option 2:

Option 1: State that the ECCS and CSS recirculation functions have been analyzed with respect to the potentially adverse post-accident debris blockage effects identified in this bulletin, taking into account the recent research findings described in the Discussion Section, and that they are in compliance with all existing applicable regulatory requirements.

Option 2: Describe any interim compensatory measures that have been implemented or that will be implemented to reduce the risk that may be associated with potentially degraded or nonconforming ECCS and CSS recirculation functions, until an evaluation to determine compliance is complete. If any of the interim compensatory measures listed in the Discussion Section will not be implemented, provide a justification. Additionally, for any planned interim measures that will not be in place before the response to this bulletin, submit an implementation schedule and provide the basis for concluding that their implementation is not practical until a later date.

The NRC justified the information request on the basis of research and analysis suggesting that (1) most PWR licensees' current safety analyses do not adequately address the potential for the failure of the ECCS and CSS recirculation functions as a result of debris blockage, and (2) the ECCS and CSS recirculation functions at a significant number of operating PWRs could become degraded as a result of the potential effects of debris blockage identified in this bulletin. An ECCS that is incapable of providing long-term reactor core cooling through recirculation operation would be in violation of 10 CFR 50.46. A CSS that is incapable of functioning in the recirculation mode may not comply with GDC 38 and 41 or with other plant-specific licensing requirements or safety analyses. Furthermore, to address the risk that may be associated with potentially degraded or nonconforming ECCS and CSS recirculation functions, NRC required addressees that are unable to confirm regulatory compliance to implement compensatory measures until a determination can be made.

4.5 NRC Generic Letter (GL) 2004-02

The NRC issued GL-2004-02 to:

(1) Request that addressees perform an evaluation of the ECCS and CSS recirculation functions in light of the information provided in the letter and, if appropriate, take additional actions to ensure system function. Additionally, addressees were requested to submit the information specified in this letter to the NRC. This request was based on the potential susceptibility of PWR recirculation sump strainers to debris blockage and on the potential for additional adverse effects due to debris blockage of flowpaths necessary for ECCS and CSS recirculation and containment drainage.

(2) Require addressees to provide the NRC a written response in accordance with 10 CFR 50.54(f).

To assist in determining, on a plant-specific basis, the impact on sump strainer performance and other related effects of extended post-accident operation with debris-laden fluids, addressees were permitted to use the guidance in RG 1.82, Revision 3, "Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident," dated November 2003.

The timeframes for addressee responses in this generic letter were selected to allow (1) adequate time to perform an analysis, (2) proper design and installation of any identified modifications, (3) adequate time to obtain NRC approval, as necessary, for any licensing basis changes, (4) adequate time to obtain NRC approval, as necessary, for any exemption requests, and (5) closure of the generic issue in accordance with the published schedule.

The NRC requested all addressees to take the following actions: Using an NRC-approved methodology, perform an evaluation of the potential for adverse effects of post-accident debris blockage on ECCS and CSS recirculation. All postulated accidents should be considered for which the recirculation of these systems is required. Alternative methodologies were also allowed, but were subject to additional NRC review.

Further, NRC requested all addressees to provide the following information within 90 days:

(a) A description of the methodology that is or will be used to analyze the ECCS and CSS recirculation functions considering the potential for post-accident debris blockage. Also, specify the completion date for the analysis that will be performed.

(b) A statement of whether a containment walkdown will be performed in support of the analysis. Also, justification if no containment walkdown will be performed. If a containment walkdown is planned, provide the methodology to be used and the planned completion date.

In addition, NRC requested the licensees to provide the following information no later than September 1, 2005:

(a) Confirmation that the ECCS and CSS recirculation functions are or will be in compliance with the applicable regulatory requirements. Also, the configuration of the plant that will exist once all required modifications have been made and the licensing basis has been updated to reflect the results of the analysis.

(b) A general description of and implementation schedule for corrective actions, including any plant modification that the licensee identified while responding to this generic letter.

(c) A description of the methodology that was used to perform the analysis.

(d) The following information was requested:

(i) The minimum available NPSH margin for the ECCS and CSS pumps with an unblocked sump strainer.

(ii) The submerged area of the sump strainer under the current design and a statement as to whether the strainer is fully or partially submerged at the time of the switchover to sump recirculation.

(iii) The maximum head loss postulated from debris accumulation on the sump strainer, and a description of the primary types of debris that result in this head loss. Debris created by the post-LOCA containment environment (thermal and chemical) and CSS washdown were to be considered in the analyses. Examples of this type of debris are disbonded coatings in the form of chips and particulates and chemical precipitants caused by chemical reactions in the pool.

(iv) The basis for concluding that the inventory required to ensure adequate recirculation would not be held up or diverted by debris blockage at chokepoints in the containment.

(v) The basis for concluding that adequate core or containment cooling would result considering debris blockage at flow restrictions in the ECCS and CSS flow paths downstream of the sump strainer. Also, an evaluation of the adequacy of the sump strainer's design openings and the basis for concluding that adverse gaps or breaches are not present in the strainer.

(vi) Verification that close-tolerance subcomponents in pumps, valves, and other ECCS and CSS components are not susceptible to plugging or excessive wear due to extended post-accident operation with debris-laden fluids.

(vii) Verification that the strength of any trash rack is adequate to protect the strainers from missiles and other large debris. Also, verification that the trash racks and sump strainers are capable of withstanding the loads imposed by expanding jets, missiles, the accumulation of debris, and pressure differentials caused by post-LOCA blockage under predicted flow conditions.

(viii) A description of any active approach selected (e.g., backflushing, powered strainers) in lieu of or in addition to a passive approach.

(e) A description and schedule for any changes to the plant licensing bases resulting from actions taken in response to the generic letter. Also, any licensing actions or exemption requests needed to support changes to the plant-licensing basis.

(f) A description of existing or planned programmatic controls that ensure that potential sources of debris in the containment (e.g., insulation, signs, coatings, and foreign materials) will be assessed for potential adverse effects recirculation.

4.6 NRC Guidance on Strainer Head Loss and Vortexing

The Guidance Report, Pressurized Water Reactor Sump Performance Evaluation Methodology (NEI-04-07), was developed by Westinghouse and Alion Science and Technology under the sponsorship of the Westinghouse and Babcock & Wilcox Owners Groups and under the technical guidance of the NEI PWR Sump Performance Task Force. The methodology in the document provided basic guidance on approaches and various methods for evaluating sump performance but recognized that the best strategy for each plant could involve a combination of methods since PWRs vary greatly in containment size, floor layout, sump configuration, insulation types and location, and post-LOCA operational requirements. The Baseline Evaluation Method, and the guidance to perform the Baseline Evaluation Method, provided a conservative approach for evaluating the generation and transport of debris to the sump screen, and the resulting head loss across the sump screen.

The NRC staff evaluated each area of the Guidance Report, concluded that the guidance proposed by NEI, as approved in accordance with the NRC Safety Evaluation of NEI-04-07 (ML04328007), provided an acceptable evaluation methodology and established the necessary basis and provided the realistic conservatism for an acceptable PWR guidance document. However, the staff questioned aspects of the baseline that are clearly not conservative, while other aspects are conservative. The subject aspects were identified at the appropriate locations in the SE Report (ML04328007). NRC further stipulated that acceptance of the baseline evaluation requires that the approach results in an evaluation that, overall, is realistically conservative.

At the time that the NEI guidance report and staff SE were issued, methodologies for performing strainer head loss tests had not been developed to the point that consistent results could be attained. Strainer test vendors used different test methods and made different assumptions when developing test procedures. To establish appropriate staff review criteria for head loss testing, the NRC staff developed review guidance and documented the staff's positions for the areas important to the topic in "NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Strainer Head Loss and Vortexing" (ML080230038) in March 2008. The important aspects of strainer evaluations discussed in this guidance are presented in some detail in Section 5 of this document.

The staff recognized that because the procedures for integrated prototypical head loss testing were still being developed by the industry the document could be revised to reflect new information. While the NRC staff intended to use this guidance in its review, licensees were allowed to use this guidance in their strainer evaluations. Licensees were also allowed to use alternative approaches to resolve sump performance issues as long as the approach was adequately justified and complied with the NRC's regulations.

4.7 NRC Guidance on Coatings Evaluation

In March 2008, NRC staff provided guidance on the information needed for a supplemental response to GL-04-02 in the review area of protective coatings. In April 2010, NRC provided a supplement to this guidance document (ML080230462). The document described acceptable technical assumptions based on research conducted by the NRC and industry. Both the NRC and the industry conducted numerous testing efforts to address technical uncertainties in areas such as zone of influence (ZOI), coating debris characteristics, unqualified coating performance, and assessment of qualified coatings. Licensees were given an option to provide an interpretation of the test data from the industry test reports that differed from the NRC staff perspective and to supply adequate technical justification in the supplemental response to support the licensee's interpretation.

The NRC requested information in the following areas to support closure of GL-04-02 in the area of protective coatings:

1. A summary of type(s) of coating systems used in containment, (e.g., Carboline CZ 11 Inorganic zinc primer and Ameron 90 epoxy finish coat). If licensees are taking credit for a reduction of unqualified coating debris based on the Original Equipment Manufacturers (OEM) coatings testing program of the Electric Power Research Institute, an accurate estimate of the quantities of each coating type and its substrate may be necessary.

2. Description of the assessment program for the containment coating condition. This description should include the frequency, extent, and method of coating assessment. It should also discuss qualification of personnel. A description of how degraded coatings are reported, tracked, remediated, and/or scheduled for future remediation is also needed. Licensees were allowed to reference the EPRI coatings adhesion-testing program as confirmation of the validity of their coatings assessment program (EPRI, 2007a).

3. Description and bases for assumptions about coatings debris generation. Based on the NRC generic safety evaluation (SE, ML043280007), the licensees were to use a coatings ZOI spherical-equivalent as determined by plant-specific analysis based on experimental data that correlate to plant materials over the range of temperatures and pressures of concern, or 10D (10 pipe diameters). In addition, the NRC generic SE recommended that licensees assume 100% failure of unqualified coatings.

4. Description of which debris characteristics were assumed, i.e., chips, particulate, size distribution, and bases for the assumptions. The NRC generic SE addresses two scenarios for formation of a fiber bed on the sump strainer surface. For a thin-bed case, the SE states that all coating debris should be treated as particulate and assumes 100% transport to the sump strainer. For the case in which no thin bed is formed, the SE states that the coating debris should be sized on the basis of plant-specific analyses for debris generated from within the ZOI and from outside the ZOI, or that a default chip size equivalent to the area of the sump strainer openings should be used.

5. Description and bases for assumptions made in analysis of post-LOCA paint debris transport. If less than 100% of the coating debris generated is analyzed to arrive at the

strainer surface, the basis for settlement of the debris should be assessed. That basis may be computational fluid dynamics (CFD) analysis, plant-specific transport testing, NRC-sponsored coating chip transport testing (NUREG/CR-6916), or some combination of these. If coatings debris is assumed to settle, a detailed description of the debris characteristics is needed and should include the assumed chip or particle size and the basis for that assumption.

6. Discussion of testing regarding suction strainer head loss testing performed as it relates to both qualified and unqualified coatings and type and basis for the surrogate material used to simulate coatings debris. Licensees were asked to address the type of surrogate material used, the size range of surrogate coatings debris, and the density of the surrogate debris, compare the surrogate debris characteristics to the actual coatings debris characteristics, and establish that the choice of surrogates conservatively represents the coating debris that is expected in a LOCA and the characteristics of the coatings debris assumed in the mechanistic analysis.

4.8 NRC Guidance on Evaluations of Plant-Specific Chemical Effects For PWRs

In March 2008, the NRC provided guidance on the important technical issues to be considered when reviewing plant-specific chemical effect evaluations of individual licensees in response to GSI-191, “Assessment of Debris Accumulation on PWR Sump Performance.” The NRC also provided guidance to licensees on the content of the chemical effects portion of their final supplemental responses to GL-04-02. The fundamental issue requiring assessment was whether the plant-specific evaluations appropriately address the chemical effects that can occur following a postulated LOCA (NRC, 2008c, ML080380214).

In the PWR post-LOCA environment, several challenges are created to material integrity based on temperature, chemical reactions, and effects from sprayed and pooled water. During a LOCA, materials in the ZOI of the break can become debris that may be transported to the sump area, where spray solution, spilled reactor coolant, and borated water from other safety injection sources are accumulating. The combination of spray chemicals, insulation, corroding metals, and submerged materials can create a potential condition for the formation of chemical substances that may impede the flow of water through the sump strainers or that may affect downstream components in the emergency core cooling or reactor coolant systems.

Evaluations of plant-specific chemical effects should use a conservative analytical approach. In general, areas considered include:

- Break selection and location
- Debris generation
- Latent debris
- Debris transport
- Chemical interactions ahead of the sump strainer
- Prolonged interaction (chemical) with recirculating liquid while materials are impinged on the sump strainer
- Potential of debris to decompose and generate suspended particulates in the liquid flowing over the debris
- Head loss
- Potential chemical effects on components downstream of the sump strainer

The flow diagram in Figure 4.8-1 provides a logical sequence that outlines the paths of various plant-specific approaches to chemical effect evaluations. The diamonds represent decision points for testing that needs to be performed. These decision points lead to options used in vendor testing. The description for the diamond identifies the options that may be selected. The evaluation process flow path chosen by the licensee can affect the relevant technical issues to be addressed as part of the plant-specific evaluation. These topics are further described in the sections that follow.

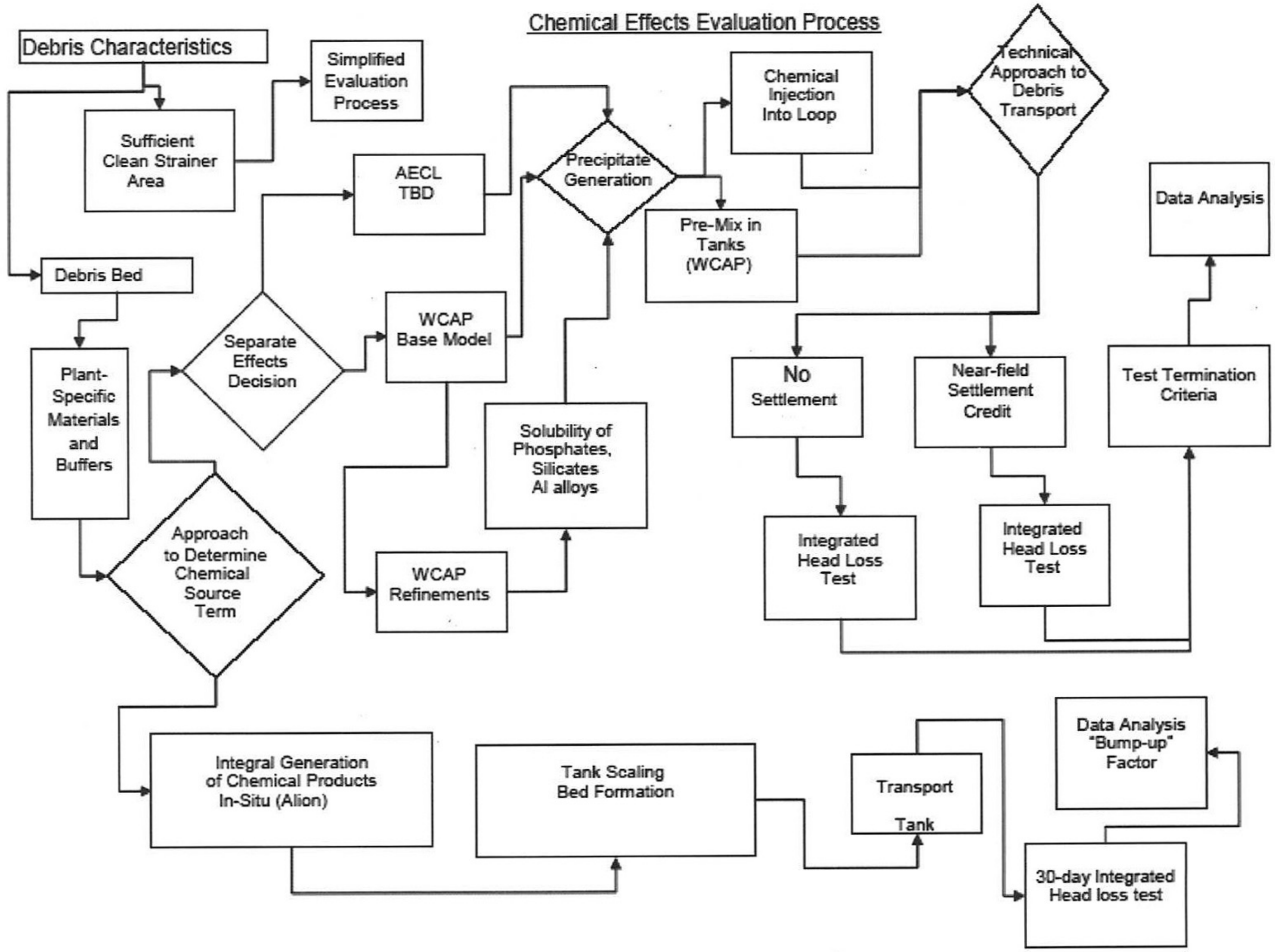

Figure 4.8-1. Chemical Effect Evaluation Process Flow Diagram

Debris Characteristics

Plants should follow the NEI guidance report (NEI, 2007) supplemented by the NRC safety evaluation (NRC-SER-2004), to determine plant-specific debris characteristics. An alternative approach may be used with justification and NRC concurrence. Consistent with the safety evaluation, the licensee testing should simulate the debris from the break location that produces the maximum head loss.

Plants that are able to demonstrate sufficient bare strainer area may use a more simplified chemical effect evaluation because chemical precipitates are expected to pass through a bare strainer. The methodology used to determine sufficient clean strainer area should demonstrate that sufficient bare strainer area will remain available to support the design basis flow rate to the reactor core, considering all break locations within the uncertainties of debris generation and transport.

Debris Bed Formation

Licensees should follow the NEI guidance report (NEI, 2004) supplemented by the NRC safety evaluation (NRC-SER-2004), to determine the bed characteristics of plant-specific debris. Alternative approaches are acceptable if justified. Licensees should discuss why the debris from the break location selected for plant-specific head loss testing with chemical precipitate yields the realistic head loss for the plant condition.

Plant-Specific Materials and Buffers

To assess potential chemical effects, licensees should identify the specific materials in their containment building that may react with the post-accident containment environment. Plant materials should identify metallic and non-metallic items in the containment building, including insulation types, concrete, and coatings. Other considerations should include plant systems in containment that may contain chemicals (e.g., reactor coolant pump oil, corrosion prevention chemicals in thermal barrier system, air handling system, drying materials such as molecular sieves, etc.). The materials inventory evaluation includes overall mass, location in the containment, and potential for being sprayed or immersed following a LOCA.

Approach to Determine Chemical Source Term

This is the first decision point in determining the method to be selected for plant-specific testing. The strainer vendor selected by the licensee decides upon the basic approach to determine the chemical source term. These require single chemical-effect tests that are later combined via a specific algorithm or integrated chemical effect tests (ICETs) in which a plant-specific mixture of materials is tested in a representative post-LOCA environment to identify the specific chemical effects that will be observed in the plant. The evaluation should consider the chemical form of each of these materials and the potential for interaction with the environment during the LOCA and the subsequent ECCS mission time.

Separate Effects Decision

The methods to assess the plant-specific chemical effects are based on single-variable test measurements in WCAP-16530 (Lane et al., 2006) or on single-effects bench testing developed by the strainer vendors (e.g., Atomic Energy of Canada Ltd.). Input of plant parameters (e.g., sump temperature, pH, and containment spray durations) into the WCAP-16530 spreadsheet should be in a manner that results in a conservative amount of precipitate formation. In other words, plant parameter input selection will not be biased so as to lower the predicted amount of precipitate beyond that justified.

Precipitate Generation

Two basic methods of precipitate generation have been used in strainer head loss tests. Each of these methods has advantages and drawbacks. In the first method, chemicals are injected into the flowing stream of the test flume. Both solutions initially contain no precipitates, and the combination of the two causes a reaction leading to precipitation from a homogeneous solution. The second method creates a surrogate precipitate in a separate mixing tank, and the precipitate is then injected into the flowing system to simulate the transport of precipitated material to the sump strainer area. This leads to precipitation from a heterogeneous solution. The time-dependency effect of injection of the precipitate into the loop should be understood in terms of the amount of chemical that transforms into precipitate and the timing of precipitation relative to test termination.

Debris Transport

Debris transport represents another decision point in the flow chart. Plant-specific analysis determines the amount of debris that is generated and transported to the sump strainer. Test vendors have selected two basic debris transport approaches. These include the attempt to credit settlement of debris away from the strainer surface, i.e., “near-field” settlement, and the use of agitation or other means to keep debris suspended so that essentially all debris analyzed as reaching the strainer in the plant reaches the strainer in head loss testing.

Integrated Head-Loss Testing

For tests with near-field settlement credit in which settling of chemical precipitates occur, it is critical that the precipitate used in these tests settle no more rapidly than would be expected in the projected plant environment. For tests without near-field settlement credit, the surrogate chemical debris should be kept suspended in solution until it is able to deposit on the test strainer’s surface. Low-flow areas of test tanks and flumes should be agitated mechanically or hydraulically so that the debris does not settle out before reaching the strainer surface.

Test Termination Criteria

All measurement objectives that determine test termination should be stated before commencement of the test. Factors that should be considered in these measurement objectives are:

1 Has all the material that will yield an effect had the opportunity to get into solution?

2 Do the test termination criteria represent a point in time where formation of further significant impediments to flow will not occur?

3 For precipitates formed by chemical injection into the test loop, measurement of the test solutions at various times in the event sequence is needed to show that the precipitation is completed before test termination.

4 Have the overall chemical effects stopped or slowed to the point that any further changes will be insignificant?

Data Analysis

When evaluating head loss test results, licensees should consider items such as settlement of debris and precipitates, presence of debris bed boreholes, test repeatability, and pressure drop across the bed as a function of time.

5 STATE-OF-THE-ART RESOLUTION METHODOLOGY

An evaluation of recirculation strainer issues began with the declaration of USI A-43 in 1979. Issuance of USI A-43 was based on the safety concerns associated with potential ingestion of air and debris into either PWR sump screens or BWR pump suction intake strainers, and the potential blockage of these strainers. The overall blockage issue has continued beyond the closure of USI A-43, through resolution of the BWR blockage issue and the GSI-191 PWR blockage issue, and finally with the ongoing BWR reassessment based on recent PWR-related research. Disparities between PWRs and BWRs were identified in NUREG/CR-7011. The techniques and guidance associated with evaluation of the issue have evolved over a considerable period, with research efforts being based on the state of the methodology of the time. An understanding of this evolutionary process is needed to fully understand and apply the accumulated base of knowledge.

Revision 0 of RG 1.82 included a 50% strainer blockage criterion that was recognized as technically inconsistent with the findings related to the resolution of USI A-43, as documented in NUREGs-0869 and 0897. The general idea of the 50% blockage criterion is that debris would cover no more than 50% of the screen surface area, leaving the remaining area unobstructed. We now know that the flow velocities approaching the large passive replacement strainers now installed in PWR containments are generally too slow to entrain larger debris that has a higher probability of settling. As such, the more likely debris accumulation would consist of small groups of fibers and particles that tend to remain suspended in water with moderate flow turbulence. Such fine debris is not significantly influenced by gravitational pull and, therefore, tends to accumulate more or less equally on surfaces of any orientation. Further, this type of debris accumulates on all screen surfaces, leaving no strainer screen area free and clear of debris. The NRC staff has repeatedly observed this accumulation behavior during visits to vendor test sites (e.g., a trip report to the Alden Research Laboratory by S. Smith dated 4/30/2008 in document ML 080920398 discussed this behavior with distinctive photos included). These debris accumulation realities are very different from the accumulation process assumed before initiation of the debris blockage concerns. Similarly, debris accumulation on BWR suppression pool recirculation strainers would result in debris accumulation on all strainer surfaces, leaving no area completely uncovered. However, unique to BWRs, the initial vigorous downcomer discharge into the suppression pool immediately following a LOCA causes substantial pool turbulence capable of maintaining larger debris in suspension until the pool turbulence dissipates.

Investigation of the strainer blockage phenomena and processes has continued to evolve over a period of approximately 30 years. Early head loss testing, as presented in NUREG/CR-2982, published in 1983, was based on fiberglass insulation debris prepared as either as-fabricated pieces or hand-torn shreds. Neither preparation technique resulted in a significant contribution from suspendable fines. In addition to a non-prototypical preparation of the test debris, early head loss testing failed to recognize the importance of particulates so that head loss testing was based on fibrous debris alone resulting in an underassessment of potential head losses. The preparation of fibrous debris in head loss testing has evolved from using pieces of as-fabricated insulation and hand-torn shreds during the resolution of USI A-43, to machine-shredded insulation used during the BWR resolution, to the special attention paid to preparing adequate suspendable fines during the GSI-191 resolution. In addition, flow velocities through the strainer surfaces slowed considerably from the 0.1 to 3 ft/s associated with the early PWR strainers to the typical velocity of about 0.005 ft/s for the large replacement PWR strainers (velocities based on total screen area). Velocities also slowed through the replacement BWR strainers with respect to the initial strainer installations. State-of-the-art head loss testing requires the prototypical or conservative representation of suspended fibrous and particulate fines that can accumulate as a relatively thin layer with a much lower porosity than that of fibrous debris alone. A thin layer of debris with a relatively high particulate to fiber ratio resulting in a significant head loss has been referred to as a thin-bed debris bed.

The potential sources for particulate debris were not fully recognized in the early evaluations of strainer blockage; for example, coating particulates generated by the impact of the depressurizing jet were not realistically considered until the GSI-191 PWR resolution. The BWR resolution considered coating debris only as paint chips (NUREG/CR-6224). Calcium silicate insulation debris was treated in the early assessments (NUREG/CR-2982) as insoluble and buoyant (NUREG-0897). We now know that LOCA-generated calcium silicate insulation debris can include a substantial quantity of relatively fine particulates and that a relatively small quantity of such calcium silicate fines can cause significant strainer head losses when combined with fibrous debris. The potential effects of calcium silicate were not recognized during the original BWR resolution. Further, it was found that calcium silicate debris from calcium silicate insulation manufactured by different processes (e.g., press shaping or molding shaping) could have different characteristics. For BWRs, iron-oxide corrosion products in the suppression pool can be a dominant type of particulate debris in terms of quantity.

Implementation of large passive replacement strainers in PWRs and BWRs changed the focus of the debris transport analyses due to the resulting lower strainer approach velocities. With PWR strainer perimeter approach velocities of less than about 0.1 ft/s (based on the perimeter area of the overall strainer rather than the total surface area), even the fibrous shreds that have settled onto the sump pool floor are not likely to become sufficiently re-entrained to leave the floor and accumulate on the strainer. The RMI debris will typically have settled to the PWR pool floor and will remain there with the possible exception of a few floating pieces of crumpled debris having retained trapped pockets of air. Similarly, the bulk of the coating paint chips will reside on the pool floor. Again, it is the suspendable fines that are most important in strainer head loss testing. With BWR recirculation strainers, vent downcomer discharge due to RCS depressurization could churn the suppression pool so that larger debris can accumulate on the strainer screen areas before the turbulence dissipates.

The significance of the impact of particulate penetration of the recirculation strainer screens was underestimated in the early debris evaluations. The report NUREG-0897, published in 1985, found that ingestion of small particulates did not appear to pose a pumping problem for the post-LOCA circulating pumps, and that catastrophic failure of shaft seals was unlikely. This issue was reconsidered in the resolution of GSI-191 under the important subject of downstream effects, which was not evaluated during the BWR resolution. Prior to GSI-191 the effects of chemical interactions and chemical precipitates on strainer blockage had not been evaluated realistically.

The evolution of debris generation modeling began with the assumption of conical jets from the two completely separated restrained ends of broken piping striking containment structures and other piping (NUREG/CR-2791). A USI A-43 plant-specific probabilistic study (NUREG/CR-3394) which evaluated a large number of potential weld breaks, needed a more efficient method of calculating debris generation than considering all the potential orientations of the cone model for each of the weld breaks. A three-region hemispherical model was adopted to simulate projected zones-of-destruction (ZOI), i.e., regions of space where insulation is postulated to become damaged into debris. A hemisphere was projected from the end of each broken pipe extending first to a radius of 3 times the diameter of the broken pipe (Region 1), then onto 5 times the diameter (Region 2), and then onto 7 times the diameter (Region 3). Within each radial region (to 3, then 3 to 5, and then 5 to 7 diameters), a specified fraction of insulation contained therein was assumed destroyed into debris that could reach the strainer and affect head loss, leaving the remainder of the insulation intact. The degree of destruction was generally assumed to lessen with distance from the break. The fractions of insulation assumed destroyed have been referred to as the destruction fractions. Beyond a radius of 7 diameters, the insulation was assumed to remain undamaged. The NRC BWR reference plant study (NUREG/CR-6224) that supported the BWR resolution adopted this probabilistic model but extended it to a full sphere to consider both ends of a double-ended guillotine break (DEGB) simultaneously. The spherical model was adapted for the GSI-191 evaluation as well, except for the specifically selected destruction regions. Here, the outer radius of the ZOI sphere was specified as an outer threshold for destruction, and the overall debris size distribution was based on experimental data. In addition to practical convenience, the rationale for the use of the spherical ZOI model is that it accounts for jet reflections, jet interference, and pipe whip assuming the insulation is located relatively uniformly throughout containment. Because the spherical approach is the primary model in use, it is considered state-of-the-art; however users should remain aware of the possibilities of a directed jet striking either an unusually dense source of insulation or a significant source of problematic insulation that the spherical model does not include within its boundary.

5.1 System Pumps

The ECCS and containment heat removal system (CHS) are to be designed so that sufficient available NPSH is provided to the system pumps, with no increases in containment pressure from that present before the postulated LOCA. The ECCS and CSS pumps are normally centrifugal pumps. For a centrifugal pump to operate properly, there should be adequate margin between the available and the required NPSH. Failure to provide and maintain adequate NPSH for the ECCS and CSS pumps could cause cavitation and subsequent failure to deliver the amount of water assumed in design-basis LOCA safety analyses. Because the safety of a nuclear power plant depends on the performance of the pumps in the ECCS and the containment heat removal system, it is important to maintain an adequate margin between the available and required NPSH under all potential conditions. The NRC guidance on this issue appears in RG 1.82, GL-97-04, NEI 04-07 (NEI, 2004), and NRC-SER-2004.

The definition of NPSHM from RG 1.82 is the difference between the NPSHA and NPSHR. The NPSHA is the total suction head of liquid absolute, determined at the first-stage impeller datum, less the absolute vapor pressure of the liquid. The NPSHR, as defined in Hydraulic Institute standards, is the amount of suction head, over vapor pressure, required to prevent more than a 3% loss in total head of the first stage of the pump (due to factors such as cavitation and the release of dissolved gas) at a specific capacity.

In general, the NPSHA is computed as the difference between the containment atmosphere pressure and the vapor pressure of the sump water at its assumed temperature, plus the height of water from the surface of the containment pool to the pump inlet centerline, minus the hydraulic losses for the suction piping (not including the head loss contribution from the sump strainer and debris bed, which are accounted for separately).

- A conservative assumption that the containment pressure equals the vapor pressure of the sump water ensures that credit is not taken for the containment pressurization above the vapor pressure during the transient. For PWR subatmospheric containments, after 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.

- Because high water temperatures reduce available NPSH, the decay and residual heat produced after accident initiation should be included in the determination of water temperature. This calculation should include the uncertainty in the determination of the decay heat (the uncertainty in decay heat is typically included at the 2 sigma level). The residual heat should be calculated with margin.

- Calculation of available NPSH should minimize the height of water above the pump suction and strainer surfaces. The calculated height of water 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, and the volume of empty system piping).

- Calculating pipe and fitting resistance and nominal strainer resistance without blockage by debris should be done in a recognized, defensible method or determined from applicable experimental data. The clean strainer head loss (i.e., the friction head loss caused by the passage of flow through the strainer and any associated connecting pipes and plenums) should be calculated with consideration of the potential worst-case distribution of flow through the strainer under debris loading conditions. In general, the staff considers equal flow through all strainer surfaces to be a realistic condition. For strainers that are not uniform flow design the majority of the flow enters the clean strainer close to the pump suction thus reducing the clean strainer head loss. As debris is deposited on the strainer it is likely that a relatively uniform flow distribution will occur.

- Available NPSH should be calculated as a function of time until it is clear that the available NPSH will not further decrease.

5.2 Pipe Break Characterization

The objective of the break selection process is to identify the most challenging break location and size that results in debris generation that produces a conservative head loss across the sump strainer considering plant specific conditions. All aspects of the accident scenario are to be considered for each postulated break location, including debris generation, debris transport, latent debris, coating debris, chemical effects, upstream and downstream effects of debris accumulation, and sump strainer head loss.

5.3 Debris Generation/Zone of Influence

The debris potentially capable of being transported to the recirculation strainers includes: latent debris already in containment at the time of the LOCA break; debris directly generated by the impact of the break effluent onto piping and structures; and debris created by post-LOCA environmental effects. This section addresses the generation of debris as a result of the impact of break effluent onto insulation and fire barrier materials.

The generation of coating debris has been treated separately from that of other potential debris sources. Qualified coatings that are not directly affected by the break effluents are assumed to remain intact in the post-LOCA environment and therefore not form debris.

Alternately, unqualified coatings are conservatively assumed to fail, thereby forming some type of debris. All coatings located within the break's ZOI are assumed to fail, resulting in debris.

The aspects of debris generation discussed herein include (1) the applicable blast and jet erosion phenomena associated with debris generation, (2) the analytical modeling of blast wave dispersion and the dispersion of an established jet, (3) the scaling considerations important to the realistic or conservative performance of debris generation testing, (4) the analytical models that have been used to assess the ZOI and the bounding quantities of debris and the application of those models, and (5) the assessment of debris size distributions and associated characteristics.

5.3.1 Applicable Phenomena

The rupture of a PWR or BWR high-energy high-pressure pipe in a PWR or BWR would result in compression waves and jets of coolant that project from the piping due to the high system pressure, until that pressure dissipates. Debris is generated as the compression waves and jets impact surrounding insulation, coatings, surfaces, and other materials within the ZOI. The spherical volume of space affected by this impact (the ZOI) are modeled to define and characterize the debris generated (ML043090005, 2004). The proper development of such a model requires a reasonable understanding of the applicable phenomena involved. The discussion of these phenomena leads off and focuses on PWR breaks followed by BWR specific considerations. The PWR systems operate at higher pressure than the BWR systems, but the BWR main steam lines (MSL) breaks would create essentially single-phase steam jets whereas all PWR breaks of significance would release a two-phase jet. The typical hydraulic conditions of each reactor type are briefly discussed.

The hydraulic conditions of a postulated depressurization jet would depend on the hydraulic conditions upstream of the break and the size of the break. To put the initial RCS conditions into perspective, selected RCS hydraulic temperatures taken from NUREG/CR-5640 are shown in Table 5.3-1 for seven PWR plants and Table 5.3-2 for five BWR plants. The typical PWR operating pressure is 2250 psia with the corresponding saturation temperature of 652.7°F. Table 5.3-1 shows the approximate degrees of subcooling associated with the cold and hot sides of the RCS. The points to note are (1) the degree of subcooling depends on the location of the postulated break, (2) there is substantially less subcooling associated with the larger hot legs than with the smaller and colder cold legs, and (3) the degree of subcooling depends on the specific plant, as well as the specific RCS design. Further, the least subcooling would presumably be associated with piping lines connected to the pressurizer. Debris generation analysis and testing should be based either on a conservative position or on the plant-specific and break-specific initial hydraulic conditions and break sizes. For a specific pipe, the temperature of the fluid flowing within it indicates the energy transported within it. Engineering intuition would seem to indicate that the higher the energy density, the greater the destruction potential following a break, whereas some steady-state fully-established jet models indicate that more subcooling, to a point, results in higher stagnation jet pressures due to the increased mass flux out of a critically choked break. When considering the high energy density consideration, the potential non-plant-specific conservative position would be to analyze and test while assuming saturated water at 2250 psia. The NRC staff has adopted the position that the cold leg break conditions will produce the controlling destruction pressures.

The typical BWR operating pressure is 1015 to 1040 psia, and the corresponding saturation temperature is 546 to 549°F. Table 5.3-2 shows the typical BWR RCS temperatures for the reactor vessel steam dome, the core inlet, and the feedwater. A single-phase break in a MSL pipe would be more destructive than a break in a two-phase break in either a recirculation pipe or a feedwater pipe of the same diameter. The BWR resolutions focused on MSL breaks but considers breaks in all locations required by the approved guidcance.

Table 5.3-1. Selected PWR RCS Hydraulic Conditions*

Plant	RCS Design	Saturation Temperature at Operating Pressure (°F)	Vessel Temperatures		RCS Subcooling	
			Inlet (°F)	Outlet (°F)	Cold Leg (°F)	Hot Leg (°F)
Ginna	W 2-Loop	653	552	634	101	19
H. B. Robinson	W 3-Loop		546	642	107	11
South Texas 1&2	W 4-Loop		560	629	93	24
San Onofre 2&3	CE 2-Loop		553	611	100	42
Palo Verde 1,2&3	CE 2-Loop		564	621	88	32
TMI-1	B&W	649	555	602	94	47
Davis-Besse	B&W		555	608	94	41

*Note that the temperatures and pressures are subject to change due to plant modifications and power uprates.

Table 5.3-2. Selected BWR RCS Hydraulic Conditions*

Plant	Reactor Type	Nominal Dome Pressure (psia)	Saturation Temperature (°F)	Approximate Core Inlet Temperature (°F)	Feedwater Temperature (°F)
Oyster Creek	BWR/2	1035	549	525	312
Monticello	BWR/3	1015	546	529	376
Peach Bottom	BWR/4	1020	547	533	376
La Salle	BWR/5	1020	547	533	420
Grand Gulf	BWR/6	1040	549	533	420

*Note that the temperatures and pressures are subject to change due to plant modifications and power uprates.

A large break in a PWR RCS pipe at 2250 psia or a BWR RCS pipe at 1015 psia would be a rather violent event within the immediate proximity of the break. The generation of debris following a LOCA is caused by the effects of an initial compression wave emerging from the pipe rupture and subsequently by erosion associated with the jet impingement. Since the relative destructiveness of the initial compression wave to that of erosion of an established jet flow has not been experimentally determined, both should be properly accounted for in debris generation testing.

The RCS pressure boundary separates high-pressure, high-temperature water from the surrounding environment that is essentially quiescent at atmospheric pressure. If a section of the pressure boundary in a PWR were instantaneously removed, the high-pressure high-temperature water nearest the break would flash to a high-quality wet steam very quickly and a large amount of energy would be deposited into a small localized volume. For BWR MSL breaks, the effluent would be single-phase steam. A powerful compressive wave would propagate outwards from the break as the energy of this flashed steam performed work against a quiescent atmosphere. The power or amplitude of the compression wave would depend on the area of the break and the temperature of the water.

The PWR RCS coolant is subcooled prior to a break due to the 2250 psia system pressurization. When this subcooled RCS coolant is released through the break, it becomes a superheated fluid. This superheated fluid will then evaporate vigorously as the fluid rapidly depressurizes The vapor pressure of the superheated liquid at the point of release drives the gas dynamics of the vapor release.

A Battelle-Columbus report (Scott et al., 1996) discussed the role of sonic velocities in the formation of a shock wave. The report described the shock wave as a more damaging type of a compression wave, due to increased rate of pressure change as the wave interacts with the target. The sonic velocities of interest are, first, that of the surrounding air and, second, that of the two-phase mixture. The sonic velocity of the air limits the speed of the expanding two-phase mixture. The sonic velocities in a two-phase mixture can be much slower than either of the associated single-phase velocities, but two-phase sonic data (e.g., Städtke, 2006) show that sonic velocity for two-phase high-void fraction wet steam exceeds that of the surrounding air. If water initially at 620°F and 2250 psia, for example, were adiabatically expanded to atmospheric pressure, the void fraction would be 99.93%, where the mixture sonic velocity would certainly exceed that of air. An additional uncertainty is the effect of the two-phase slip factor, which could result in the liquid component slipping behind the vapor component.

The NRC staff position is that a significant blast wave is not likely to form during a hypothetical LOCA where the fluid upstream of the break location is sub-cooled, and if a blast wave did occur, the forces exhibited by the subsequent jet blowdown would probably cause most of the damage. Further, the staff determined that the two-phase debris generation testing performed is representative of conditions expected during LOCAs and that the staff accepts damage predictions based on established-jet destruction pressures as an adequate metric rather than predictions due to shock wave metrics. That is, the two-phase jet testing included the effects of any shock wave that would occur during a LOCA.

After the initial propagation of a shock or compression wave, an expanding jet develops as the RCS depressurizes. The shape of an expanding jet depends on what the geometry of the break is (e.g., circumferential vs. longitudinal), and whether or not pipe separation occurs. Immediately downstream of a subcooled water break, the choked-flow liquid jet core extends from the pipe under the same stagnation conditions as the RCS. A cone shaped jet would be assumed for a break at one end of a DEGB. Outside the jet's core the fluid undergoes a continued free isentropic expansion to a condition referred to as an asymptotic condition with the fluid reaching supersonic velocities. Additional expansion occurs as the jet interacts with the surrounding environment. Whenever the supersonic flows encounter a structure such as piping insulation, a stationary shock wave is established immediately upstream of the structure because the flow velocity at the front stagnation point should be subsonic. This standing shock wave should not be confused with the potential shock wave propagating outward from the break immediately following the breach. Whereas the propogating shock wave would impact a structure at sonic speeds with a singular impact, the developed jet would continue to flow around the structure with the potential of eroding that structure.

During the NRC-sponsored air jet debris generation/transport testing conducted for the DDTS (NUREG/CR-6369), the air-jet-impacted targets were videotaped and those tapes clearly showed essentially instantaneous target destruction. The initial wave striking the target in the single-phase air-jet testing could have been a shock wave, however regarding the initial wave following a two-phase break, the staff deems it likely that that wave would be a simple compression wave rather than a shock wave. In the single-phase air-jet testing, the initial shock wave was decidedly more destructive than the subsequent erosion of the expanded jet. Definitive controlled experiments have not been conducted that would conclusively determine the presence or lack of a shock wave or whether the initial wave or the subsequent jet erosion would be the more destructive following a two-phase break. The Battelle-Columbus report (Scott et al., 1996) discussed building damage that followed a weld failure test that was an illustration of blast damage. Here, a pressure wave in the building caused the end of the building roof to separate from the roof trusses. The damage was attributed to a pressure wave being focused in a corner, which was approximately 65 ft from the crack location. In addition, a ¼-inch thick blast plate located 10 ft from the crack was significantly bent. In addition, the Heisdampfreaktor tests (NEA/CSNI/R(95)11) demonstrated high dynamic loadings within the vicinity of the break.

In addition, CFD analytical results from a Sandia study that used the CSQ code (NUREG/CR-2913) to examine the steady-state expansion of a two-phase jet (based on saturation conditions for stagnation pressures varying between 30 and 100 bars) demonstrated that: (1) the steady-state jet centerline target pressure was reduced to about 2% of the test initial pressure within about 5 L/Ds from the nozzle and (2) the extension of the water core from the break is limited to about 2 L/D from the nozzle for a PWR hot leg break and about 3 L/D for cold leg breaks. The steady state jet centerline pressure reduction mentioned above, is an asymptotic curve. Even at 20L/D it is still near 2%. It is also noted that 2% of 2250 psi is 45 psi which is large enough pressure to damage some insulation types. While this analytical information suggests that the destructiveness of a relatively steady-state expanding test jet is limited to within about 5 L/D from the nozzle, the Ontario Power Generation tests (OPG, 2001) performed with 1450 psia saturated water showed that destruction occurred at significantly greater distances than 5 L/D. For OPG Test 15, where the target was placed 20 L/D from the nozzle, considerable damage was done to the target (22% of the calcium silicate became debris).

It is evident that steady-state jet expansion does not explain the BWROG results. However, it should be noted that these are single-phase air-jet test results and not two-phase test results. The BWROG argued against a blast wave in Volume 4 of the URG based on the time required for piping components to separate. This volume included an embedded technical evaluation report on this subject, which was prepared by General Electric (GE) Nuclear Energy (Moody and Green, 1996). Two independent technical reviews were performed on the BWROG-sponsored GE technical evaluation that argued against the potential to form blast waves following a DEGB. Battelle-Columbus (Scott et al., 1996) conducted the first technical review and Wilfred Baker Engineering, Inc. (non-public) performed the second review. The technical review findings stated that the GE report did not substantiate the BWROG's position that a blast wave capable of damaging insulation will not be generated following a DEGB, and that the model used in the GE study was overly simplistic and nonconservative. The review determined that the GE criteria for production of a blast wave based on the ratio of the rupture opening time to the acoustic propagation time lacked foundation, so that the validity of the approach was questionable. The Battelle-Columbus review also pointed out that a compression wave can form even if the pipe halves only partially separate. Therefore, the debris generation analysis has treated a DEGB as an instantaneous rupture, and debris generation testing resorted to testing the break flow from a scaled-down section of piping associated with one side of the DEGB.

The debris generation testing for the BWR resolution was performed using single-phase air jets to simulate a single-phase steam jet emanating from a MSL break. The air jets were produced using a 1000 psig rupture disk attached to a large source of compressed air. The primary differences between the test air jet and the postulated MSL line break are the thermodynamic behaviors of differing gases and the diameters of the pipes. A CFD analysis performed for the BWROG indicated that the air and steam would generate similar jets from the standpoint of steady-state jet expansion. Analysis was not performed to verify the air/steam similarities for the initial compression or blast wave emanating from the break. The NRC current staff position is that the steady state stagnation pressures measured during destruction testing provided an adequate metric to determine destruction thresholds for different debris, when tested under conditions similar to those in the plant.

5.3.2 Break Jet Dispersion Analytical Models

5.3.2.1 Blast Wave Dispersion Models

When a blast wave is generated at a point source, if unobstructed, that wave would propagate spherically outward. The original wave would likely become fragmented due to reflection and diffractions by the structures and some of those fragments could merge once again. Blast wave analysis is done using complex numerical computer codes.

No method was developed for scaling the potential blast wave destructiveness from the debris generation test data based on the relatively small size of the test nozzle up to a postulated LBLOCA. Rather, scaling has been based on a steady-state jet expansion model in which the volume within a conical jet isobar was used to calculate the zones of destruction. If the primary cause of insulation destruction is the result of a shockwave or pressure wave rather than the sustained erosion of an expanded jet, then there is the concern that the steady-state expanded jet method of scaling is neither physically representative nor realistic.

5.3.2.2 Established Jet Dispersion Models

The typical jet dispersion model for a postulated high-energy line break accident is based on the idealized case of a DEGB, in which high-temperature, high-pressure reactor coolant is ejected (from both sides of the broken pipe) and may impinge on structures, equipment, piping, insulation, and coatings in the vicinity of the break. The degree of damage induced by the break jets is specific to the materials and structures involved, but the size and shape of the expanding jets and the forces imparted to surrounding objects depend on the thermodynamic conditions of the reactor coolant. Destruction models based on jet dispersion maximize the volume of the damage zone (ZOI) by conservatively considering free expansion of the break jet to ambient conditions with no perturbation, reflection, or truncation by adjacent structures. Jet volumes within an isobar at which damage to a given material may occur are defined by empirical correlations of local jet pressure. The material damage pressure is based on material behavior during testing. The volume within the isobar can then be integrated over the free-jet conditions and remapped into convenient geometries, such as spheres, disks, or cones. These shapes can approximate the shape of the damage zone by assuming the effects of reflection in a congested space without crediting the associated shadowing, jet disruption, and energy dissipation.

The analytical methods used to evaluate the expansion of a LOCA jet have included CFD codes, the ANSI/ANS-58-2-1988 standard (ANSI, 1988), and a few other smaller-scale efforts. The CFD analyses included a two-phase jet load study conducted at SNL (NUREG/CR-2913) and the BWROG steam jet analysis with the NPARC code reported in the URG, Vol. 3. The ANSI/ANS-58-2-1988 standard, applicable to a steady state or perhaps a quasi-steady-state jet, has been accepted for determining the volumes within a specific pressure isobar and calculating an equivalently sized sphere to be used as the ZOI.

The jet model in the ANSI/ANS-58-2-1988 standard subdivides the expanding jet into three regions. Region 1 contains the core region, where it is assumed that liquid extrudes from the pipe under the same stagnation conditions as the upstream reservoir. Region 2 represents a region of continued isentropic expansion. Region 3 represents a region of significant mixing with the environment, where the jet boundary is assumed to expand at a fixed 10-degree half angle. Despite the apparent complexity of the equation set needed to evaluate the ANSI jet model, it is based on relatively few thermodynamic assumptions and limited comparisons with experimental observation. Key geometry features that are determined by the thermodynamic conditions of the break include the length of the core region, the distance to the asymptotic plane between Regions 2 and 3, and the radii of the jet envelope at the transition planes between regions. At the asymptotic plane, the centerline static pressure is assumed to approach the absolute ambient pressure outside the jet. Due to the standard's built-in assumptions and decision steps in its application, the calculational results can differ among analysts. The NRC evaluation and accepted application of the standard is found in Appendix I of the safety evaluation (NRC-SER-2004).

The Advisory Committee on Reactor Safeguards (ACRS) reviewed the ANSI model and noted several inconsistencies and errors in the models described in the standard, which were provided to the NRC in a letter dated October 18, 2004 (Bonaca, 2004; Wallis, 2004). The ACRS review concluded that there were several problematic areas with the methods in the standard regarding the model's ability to simulate supersonic jet flow, the unrealistic representation of the physics, the inappropriate use of one-dimensional assumptions for an asymptotic plane, the assumption of a non-physical asymptotic plane, the evaluation of the density at this fictional asymptotic plane as if the fluid were at rest (whereas in reality it is flowing at a high Mach number), and the user manipulation of the model assumptions. In the SE, the staff agreed with the ACRS comments on the ANSI/ANS model and observed that additional model inaccuracies, such as unrealistically large isobars calculated for lower stagnation pressures, are noted in Appendix I of NRC-SER-2004. Notwithstanding these technical points, the staff considers the standard acceptable for use in determining the ZOI to be used for modeling debris generation during DBAs. This determination is based in large part on the method that is used to approximate the debris generation resulting from postulated breaks. To account for jet reflections, shadowing effects, directionally changing discharge from a whipping pipe, and the difficulty of assessing all potential orientations of breaks, the GR proposes using a spherical volume equivalent to a volume determined using the ANSI/ANS model using the demonstrated destruction pressure of debris sources. This volume translation conservatively ignores the energy that would be lost in multiple reflections and in the generation of debris. The SE stated that the precision that could be gained by the development of a more accurate method to determine the characteristics of a freely expanding jet is more than offset by conservatism in using an equivalent-volume approach for determining ZOIs.

The NRC staff accepted that the ANSI/ANS 58.2-1988 standard provides a suitable basis for computing spatial volumes inside a damage zone defined by a jet impingement pressure isobar. Specific application recommendations accepted by the staff for generic implementation of the model and calculation of isobar volumes for conversion to alternate models included:

1 The mass flux from the postulated break was determined using the Henry Fauske model, as recommended in the standard, for subcooled water blowdown through nozzles, based on a homogeneous, non-equilibrium flow process without considering

irreversible losses (irreversible losses refer to internal pipe and pipe component friction losses between the upstream reservoir and the location of the break). However, licensees using this technique should refer to confirmatory Appendix I to NRC-SER-2004 for guidance.

2 The initial and steady-state thrust forces were calculated on the basis of guidance in Appendix B to the standard, with reservoir conditions postulated. However, only the steady-state thrust coefficient should be used in this calculation as a conservative bound.

3 The jet outer boundary and regions were mapped using the guidance in Section 1.1 of Appendix C for a circumferential break with full separation.

4 A spectrum of isobars was mapped using the guidance in Appendix D to the standard.

5 The volume encompassed by the various isobars was calculated using a trapezoidal approximation to the integral with results doubled to represent a DEGB.

6 The radius of an equivalent sphere was calculated to encompass the same volume as twice the volume of a single freely expanding jet.

7 Insulation damage pressures can only be interpreted with a full understanding of the test conditions under which they were experimentally measured. The computed jet conditions will not match the experimental test conditions; therefore, care should be taken to ensure that equivalent damage effects are considered.

5.3.3 Debris Generation Testing Considerations

Small-scale debris generation testing is conducted to determine the jet centerline stagnation pressures needed to cause threshold damage to various kinds of insulation blankets and cassettes and to determine the debris size characteristics corresponding to degrees of destruction. It is important that these debris generation test results should be conservative for both bounding quantities and debris size with respect to the postulated breaks for the full-sized plant. The validity of the small-scale debris generation testing depends on establishment of test conditions prototypical of the plant RCS and on a conservative scaling of (1) the test jet with respect to a full-sized jet, and (2) the test target with respect to the full-sized plant blanket or cassettes. It also depends on the positioning of the target within the test jet to allow the entire test target to be prototypically impacted by the test jet. The tests need to be properly instrumented to gain the data needed to accomplish the scaling. The test debris should be processed to obtain debris size characteristics.

5.3.3.1 Established Prototypical RCS Conditions

Small-scale debris generation testing should be conducted at test conditions either prototypical or conservative with respect to the plant RCS conditions. Prototypical conditions are established by the plant-specific RCS pressures and temperatures. Regarding jet pressures on target for an established two-phase jet, analyses using, for example, the HEM choked flow model and the ANSI/ANS 58.2-1988 standard (both steady-state models) demonstrated higher stagnation pressures on target to be associated with colder breaks, primarily due to the higher choked break flow associated with the higher density water of colder water. Regarding the destructive capability of the initial compression wave impacting a target, the conservative position is less clear, the affect of the higher energy density associated with the hot leg relative to a cold leg on the destructive capability of a compression wave can only be reliably assessed experimentally (steady-state models do not apply to a very dynamic compression wave). After considerable review, the staff has concluded that the established jet would be more destructive that the initial compression wave; therefore resolution analyses focused on the established jet, as conservatively analyzed using the ANSI/ANS 58.2-1988 standard.

During an experiment, the water temperature directly upstream of the rupture disk should be properly maintained, as must the bulk tank temperature. Rupture disks have typically been used to initiate debris generation testing in an attempt to simulate instantaneousness because the alternative of using fast-opening valves has been perceived as much too slow to properly simulate a LOCA break. It is crucial that the test procedures ensure that the water temperature directly upstream of the rupture disk be maintained within a few degrees of the test specification, as should the bulk tank temperature.

Regarding debris generation testing practices, such matters as the piping resistance associated with the piping components between the tank of water and the nozzle exit could affect the jet or compression wave properties. It is important that resistance to flow upstream of the rupture disk does not restrict the flow so that choked flow will not occur at any upstream location. Any piping downstream of the disk should be minimized, so that the break flow is not significantly altered by the downstream piping. Note that for a postulated LOCA, there is no piping flow resistance immediately downstream of the break. Because the piping and fittings between the test tank and the nozzle will affect the nozzle discharge flow with respect to that of a LOCA, the actual break flow conditions can differ substantially from the conditions predicted by the application of a choked flow model without evaluating the effect of the piping. Therefore, jet dispersion analysis of the test jet using ANSI/ANS-58.2-1988 (ANSI, 1998) should determine the actual test nozzle exit conditions and test rate of flow using a computer code like RELAP, which models the choked flow at the limiting flow location and the subsonic flow elsewhere in the piping. The jet blowdown is transient, rather than steady state, and the flow in the piping will transition from an initial single phase flow to two-phase flow further transitioning through the various two-phase flow regimes. Test measurements designed to determine rates of flow must consider the two-phase aspects of the flow.

5.3.3.2 Test Jet Scaling Considerations

The size of a DEGB on the RCS piping of a typical PWR ranges from about 27 in. for some cold leg pipes to 42 in. for some hot leg piping, depending on the plant design. Conducting full-scale debris generation testing is expensive and impractical. However, it is not clear how large a test nozzle should be for the test results to be considered sufficiently prototypical of the full-sized postulated break. The typical test nozzle diameter for currently accepted scaled destruction testing has ranged from about 2.8 to 4 in. Test nozzle diameter has also been related to test duration (i.e., a smaller diameter allows the jet to continue longer for a given volume of water reservoir), albeit in a more limited spatial range. The use of a relatively small nozzle may provide realistic results (for locations on the target where the stagnation pressure is fully realized) if the primary mechanism for debris generation was erosion (where duration would be important), but the validity of using a relatively small jet size is less clear when considering the instantaneous destruction caused by a forces that would be applied over the full area of the insulation system. These forces could include pressure from the jet impingement or potentially from a compression wave. Generally speaking, a larger test nozzle would provide more realistic the test results than a smaller test nozzle.

Whether the diameter of a test jet can be considered large enough depends on the destruction mechanics of the target. If, for example, the target is a coating of paint where the destruction mechanics are localized, then prototypical results can be obtained with a relatively small nozzle and target coupon because the jet centerline conditions are the most important variables. But when destruction of a target depends on the failure of more than one jacketing latch or bands on a piece of pipe insulation, then an entire prototypical section of the jacketing may have to be subjected to near-prototypical pressures associated with destruction; otherwise, the test insulation jacketing might remain intact due to latches located outside the main jet flow. The stagnation pressure associated with a test jet peaks near the jet centerline and generally decreases with the radial distance from that centerline.

For a given test nozzle diameter, it is likely that there is a minimum nozzle-to-target distance that can be accepted as prototypical, although the minimum distance may be difficult to define for some conditions. The closer a target is placed to the test nozzle, the larger the test nozzle needs to be for the test data to be considered prototypical. The staff's position, agreed to with the PWROG, for jacketed banded targets, is that the jet profile will be measured at the distance from the nozzle that the target will be placed. The profile is to be relatively flat over the full diameter of the pipe and also over two times the band spacing. If a banding strap fails or moves significantly during the test the area of flat profile would have to be larger to ensure that the components are stressed adequately to determine if a failure would occur. Between jacketed targets and coatings targets are unjacketed blankets. These should be subjected to a jet profile adequate to stress the blanket material, seams, and straps such that the potential failure modes are explored.

The quality of the debris generation test data depends on the diameter of the test nozzle with respect to the target characteristic dimensions, as well as the jet centerline stagnation pressures (and the impact of the initial pressure wave) and perhaps the prototypicality of the target installation on the piping. For example, if the target insulation is held onto the pipe more aggressively than it would be in the plant it may have more damage than if it is allowed to blow off the pipe and out of the jet influence. Also some types of insulation may be damaged to a greater degree if they are blown off and strike a solid object. This is illustrated by Figure 5.3-1 (Figure II-2 of NRC-SER-2004 with a reduced set of data), which shows the destruction of unjacketed LDFG relative to the jet centerline stagnation pressure and which compares BWROG air jet test data for a 3-in.-diameter nozzle.

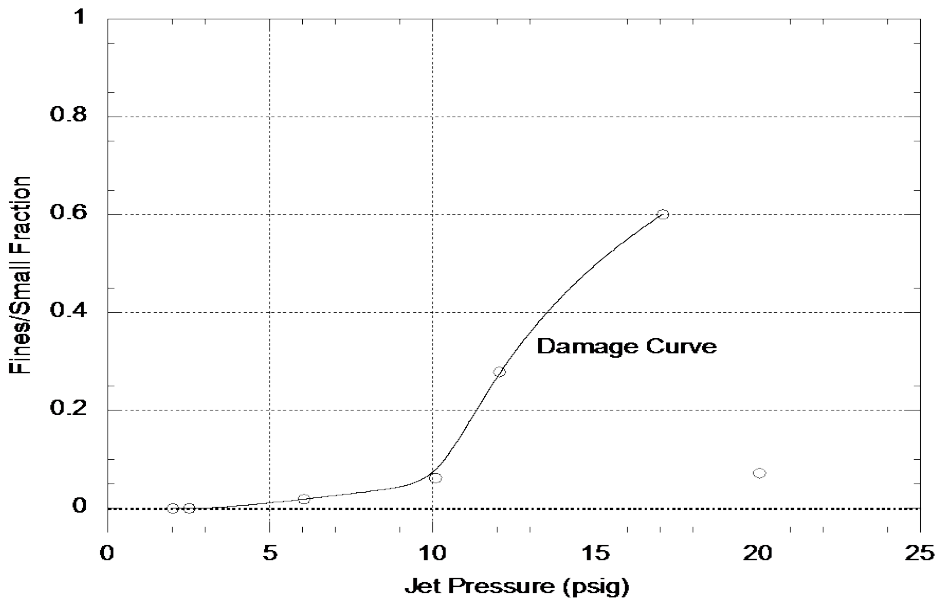

Figure 5.3-1. Air-Jet Testing Destruction Data (BWROG 3-in. Nozzle)

The data point shown in Figure 5.3-1 that shows 7% destruction for the 3-in. nozzle at about 20 psig and another data point not shown in the figure where 25% destruction occurred at a pressure of 190 psig demonstrate that targets mounted too closely to the jet nozzle were probably too close to generate valid test data. The jet likely completely pulverized the center of the test blanket but left the ends relatively intact. That is, the ends of the target extended beyond the effective reach of the jet. The data for these two test data points should have been interpreted as complete destruction, but the BWROG interpreted the data to mean that as the target was placed ever closer to the jet nozzle, the level of destruction actually decreased (refer to Figures G.1 and G.3 in NRC-SER-1998).

The SE-accepted 2D ZOI for Transco RMI was based on BWROG 3-in. nozzle testing in which the cassettes were placed too close to the nozzle for the test data to be prototypical. Because RMI debris is relatively benign with respect to causing significant strainer head losses, this testing issue had not been a concern to the staff. However, several licensees that use Transco-encapsulated non-RMI insulation have assumed a 2D ZOI for these insulation materials (e.g., Microtherm) based on the SE-approved 2D ZOI for similarly jacketed RMI. Some of the BWROG-tested Transco RMI cassettes were disassembled at relatively low pressures (e.g., Test 21-1), thereby exposing the RMI foils without generating significant quantities of small RMI debris. However, if problematic insulation materials were exposed to the sump pool, the 2D ZOI could become an issue. The BWROG tested a Transco SS-encapsulated cassette containing lead and Min-K insulation. Following Test 27-3, the atmosphere was noticeably thick with a fine particulate attributed to the Min-K insulation. This Min-K particulate was generated even though the dented and deformed steel cassette was still mounted on the pipe (as shown in an NRC-SER-1998 post-test photo). The test jet centerline pressure was approximately 42 psig (approximately 4D). The same discussion may also apply to the SE-approved 2.4D ZOI for NUKON® secured with Sure-Hold® bands, although few, if any PWRs have this NUKON® system installed. In addition, the OPG testing did not actually determine the threshold pressure for a jet to cause damage to calcium silicate insulation, although this difference appears to be due to how OPG intended to apply their data. The technical basis for nozzle size should ensure that the test jet is large enough to prototypically engulf the target with respect to the target's characteristic damage dimension.

5.3.3.3 Target Scaling, Construction, and Positioning Considerations

The scaling, construction, and positioning of a test insulation target should be considered with respect to the size of the test jet compared to a full-sized LOCA. The important test target characteristics depend on the target's failure mechanism. That failure mechanism suggests a dimension associated with the primary failure mechanism, as well as the target's physical dimension, referred to herein as the target's "characteristic damage dimension." This dimension probably depends more on the effective failure mechanism than on the physical dimension. There may be more than one potential failure mechanism for any insulation system. For coatings, the failure mechanism is the localized strength of the coating; therefore the test coupon would not need to be overly large, nor would the test jet need to be. Conversely, for a 36-in.-long stainless steel jacket held in place by three mechanical latches evenly spaced along the target, where the failure mechanism for this jacket involves the failure of all three latches, the characteristic damage dimension could be the target length. A jet that effectively impacted the center latch but not the other two latches would be less likely to cause jacket failure than a more prototypical jet that would effectively impact all three latches. Under some conditions, the center latch could fail but the jacketing would remain held in place by the outer latches so that the jacketing continues to protect the enclosed insulation material. In the prototypical RCS LOCA, the jet would have been much larger so that all three latches would be stressed to a similar degree, causing insulation failure under that condition. In addition, the mode of jacket failure varies with jacket design. Failure of the latches or banding may be the primary mode of jacket failure. In other situations where the bands could remain relatively intact, the failure mechanism could be tearing of the sheet metal between the bands, thereby exposing the underlying insulation material. This failure mechanism was seen, for instance, by OPG in the testing of aluminum-jacketed calcium silicate with stainless steel bands (OPG, 2001).

As the target is placed ever closer to the jet nozzle, the pressure becomes more focused toward the center. Conversely, further away from the nozzle, the distribution would tend to flatten out. Four radial pressure profiles calculated with the ANSI/ANS-58-2-1988 standard are compared in Figure 5.3-2. These profiles illustrate how jet pressures become more focused toward the target center as the target is mounted closer to the jet nozzle. If the test jet radial profile is too skewed relative to the target characteristic failure dimension, then the jet nozzle is too small for that axial positioning down range from the nozzle.

The linearity of these distributions is likely related to the standard assumption in ANSI/ANS-58-2-1988 that the jet was assumed to expand at the half angle of 10° after the jet became fully expanded asymptotically. Physically, the distribution could be non-linear. The calculated pressures in the ANSI/ANS-58-2-1988 standard have uncertainties that would only increase with the distance from the break plane.

Another potential jet size concern is how the jet flows around the test target and thus affects the stresses at jacketing seams. If a full-sized LOCA jet were to impact a prototypically sized insulated pipe, the flow at the jet center would be essentially two-dimensional, with half the flow passing above the pipe and half the flow passing below the pipe. When a jet impacts a solid plate (or a solid wall) perpendicularly, the jet is redirected in a full 360° circle. The flow direction associated with a small jet impacting a full-sized piping target would be somewhere between these two considerations, with part of the deflected flow re-orienting more along the target axis; this situation, for example, could reduce the stresses on a jacket seam oriented 45° off center.

Because target diameter can strongly affect the jet flow patterns, diameter is a characteristic dimension associated with insulation damage and could, for jet size scaling purposes, become the limiting characteristic damage dimension relative to the corresponding axially oriented dimensions, such as the spacing between the bands.

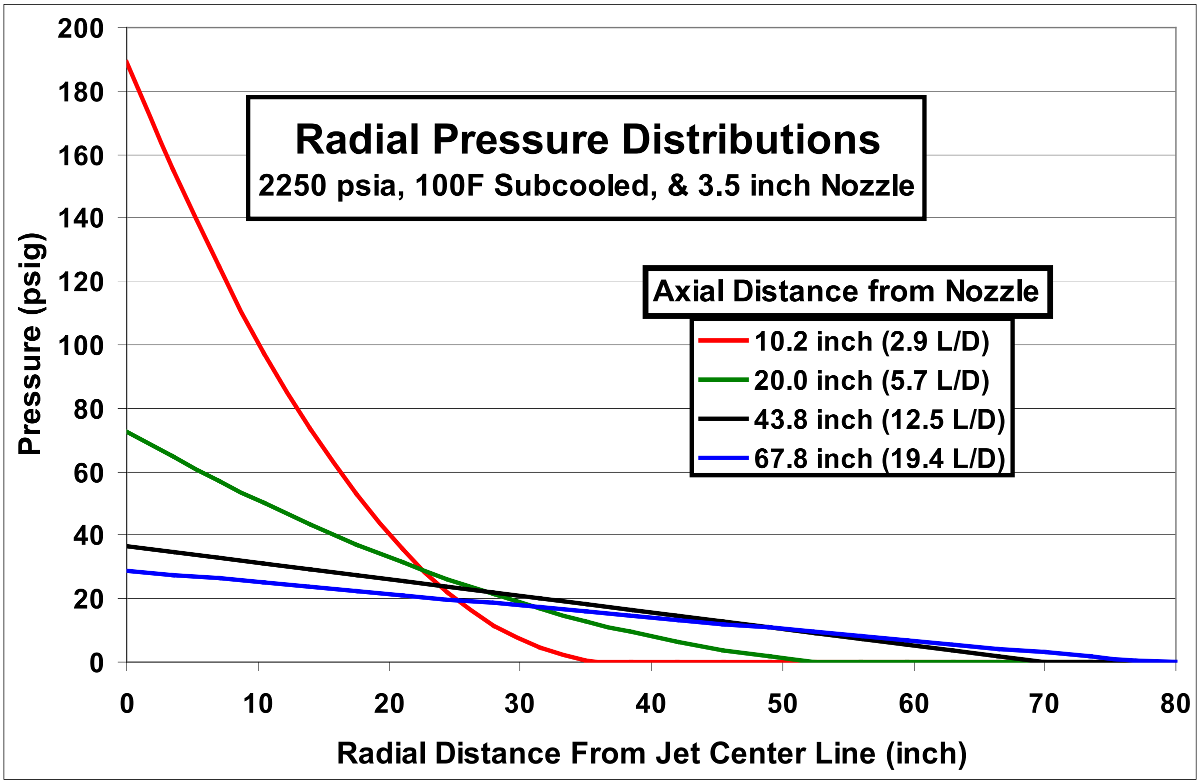

Figure 5.3-2. Radial Pressure Profiles at Selected Axial Distances

Determining the threshold pressure for destruction has involved selective placement of the target further and further from the jet nozzle until a certain distance is reached whereby the target does not sustain significant damage. The pressure at that distance then becomes the threshold destruction pressure for the target.

When adapting data from debris generation tests to plant-specific conditions other than the conditions of the test, users should take into account both the test conditions and the relative strengths of the test targets. The jacketing and banding systems of the insulation system being evaluated should be at least as structurally strong as the tested jacketing and banding systems to ensure that the test data are applicable to the plant installation. Differences in designs of jacketing and banding systems for piping and other components such as steam generators, pressurizers, and reactor coolant pumps should be considered. The jet size should be adequately scaled to the plant condition, and the limiting orientation of the break jet impacting the insulation should be considered. Additionally, the base insulation materials used in the adopting plant should be as strong as the materials used in testing. For example, two very different manufacturing processes have been used to produce calcium silicate. One of the processes results in a product that readily dissolves in water, while the other type dissolves relatively slowly. It stands to reason that these two types of calcium silicate insulation may also behave differently in debris generation testing.

5.3.3.4 Instrumentation

Test instrumentation is needed to control the test environment and to characterize the resultant jet, making it possible to correlate insulation destruction with test conditions and to scale test results to plant conditions. The staff has not established guidance regarding test instrumentation. Test instrumentation should be included to measure the water temperature and pressure in the bulk reservoir, the piping between the reservoir and the nozzle, and/or immediately upstream of the rupture disk. In addition, the mass flow rate should be measured during the blowdown. Test instrumentation could be included to measure jet parameters downstream of the nozzle. Measurements should include jet stagnation pressures, static pressures, temperatures, and the dynamic pressures associated with any compression wave. Data recorders should be used to measure test results from before the test initiation to test completion. Rapid response instrumentation is required to accurately measure the jet during blowdown. Destruction tests cannot be instrumented to the same degree as tests that do not include targets. It is unlikely that parameters of the jet can be measured during target tests. However, the parameters upstream of the nozzle can be measured and compared to instrumented tests conducted under similar conditions to verify that the mass flow rates, system pressures, and fluid temperatures are similar between the tests.

5.3.3.5 Debris Characterization

Analysis of debris transport and behavior in a debris bed requires specification of the debris size distribution for each type of insulation affected by the LOCA jet. The size distributions should be realistic or conservatively biased toward finer debris since finer debris transport more easily and result in greater strainer head loss. For these reasons, a debris generation test program should include a procedure for collecting post-test insulation debris and characterizing that debris.

5.3.3.6 Comparison of Debris Generation Testing

Test protocols for the debris generation test programs have varied considerably, and insights can be gained by comparing these test protocols and their test results. A general pattern of test results based on the test conditions and protocols might be expected. The test programs include: (1) air jet testing conducted at the Colorado Engineering Experiment Station, Inc. (CEESI) by the BWROG (NRC-SER-1998); (2) NRC-sponsored air jet testing for the DDTS (NUREG/CR-6369); (3) OPG two-phase testing (OPG, 2001); (4) prototypically sized HDR (Heisdampfreaktor) experiments in Germany (NUREG-0897, NEA/CSNI/R(95)11); and (5) high-pressure water jet fibrous insulation pillow testing conducted by SNL (NUREG/CR-3170).

BWROG Air Jet Testing

The BWROG debris generation testing was conducted at the CEESI, where a high-pressure jet of air was focused on an insulation target (NRC-SER-1998). Air pressurized to 1110 psig in a large tank was piped to a nominal 3-inch-diameter test nozzle through a control valve assembly. When the control valves were opened, air pressure built up behind a single rupture disk designed to burst at a pressure of 1000 psig. Targets of various insulation types and jacketing were placed at various distances from the jet with the objective of determining the minimum threshold pressures for generating insulation debris. The BWROG placed a differential pressure transducer in a target-mounting pipe to measure the actual jet pressure at specific distances from the jet nozzle to benchmark a CFD model used to define jet stagnation pressures at any targeted distance so that target damage could be correlated to the jet stagnation pressure. A 20 L/D pressure measurement confirmed the results of the CFD predictions inside 20 L/D and other more distance measurements were used to interpolate pressures between 20 and 117 L/D.

NRC-Sponsored Air Jet Testing

The NRC-sponsored air jet testing for the DDTS was conducted at CEESI using the same basic equipment as in the BWROG testing (NUREG/CR-6369). Initial testing used a nominal 3-in. jet nozzle, but after an initial exploratory testing phase, the 3-in nozzle was replaced with a 4-in. nozzle to enhance the destruction of the insulation blankets. The objective of these tests was to study the transport behavior of LDFG debris as the debris passed through or impacted a prototypical representation of BWR drywell congestion of structural obstacles such as gratings. An array of pitot tubes was used to measure the downstream flow velocities in an axial and radial configuration for comparison with a CFD flow simulation used to estimate stagnation pressures. The targets were LDFG blankets mounted on a test pipe and generally placed to maximize blanket destruction, thereby generating the greatest potential density of debris transiting the chamber test obstructions. At 30 L/D (distance from jet nozzle divided by nozzle diameter), the fraction of the debris small enough to pass through the test gratings was typically greater than 90% of the original insulation material. At 10 L/D and 20 L/D, the target was too close to the jet to be completely engulfed by it so that substantial insulation at the target ends became debris too large to pass through the first grating. A video camera focused directly on the test target showed that destruction was essentially instantaneous and did not appear to be due to erosion.

OPG Debris Generation Testing

Ontario Power Generation conducted debris generation testing to support its programs. The NRC staff reached an agreement in which a test report for aluminum-clad calcium silicate insulation (OPG, 2001) was made available for staff review. A dual rupture disk assembly attached to a 2.87-in. diameter test nozzle was used to release water pressurized to 10 MPa (1450 psia) and heated to saturation. Piping heaters were installed to maintain the initial test conditions within the piping before initiating the test. Because the OPG did not measure test pressures downstream of the jet nozzle, the NRC staff calculated the pressures associated with insulation destruction by using the jet model in the ANSI/ANS-58.2-1988 standard. Target placement at the greatest test distance from the nozzle (20 L/D) was used to estimate the threshold damage pressure for calcium silicate insulation; however, the target at this position still sustained substantial damage. In addition, for at least some of the trials, the target may have been too close to the jet for the jet to impact the entire target with a prototypical pressure.

HDR Debris Generation Testing

The HDR experiments were conducted in Germany and used an out-of-production prototype BWR reactor vessel that had been refitted as a testing facility for blowdown testing (NEA/CSNI/R(11)). The initial conditions were typically water at 11 MPa (1595 psig) and saturation temperature. Significant damage was noted in the vicinity of the break which seemed to be caused by the dynamic pressure wave that occurred at rupture, as well as by the forces of the outflowing jet. The HDR deflection plate was placed in front of the nozzle at a distance of about 3.3 L/D, such that the jet first struck this plate before reflecting and hitting the insulation materials. Test observations that illustrate the destructive capability of the jet include: (1) conventional fibrous insulation (mineral wool reinforced with wire mesh and jacketed with galvanized carbon steel sheet) was blown away as soon as the cover was damaged, and material located within a radius of 3 to 5 m from the break nozzle (about 6.7 to 11.1 L/D) was dislodged; (2) unjacketed NUKON® or NUKON® covered with metal mesh located within 9 L/D was totally destroyed, and more than 90% of the insulation was reduced to fine fibers; (3) metal-jacketed wool insulation within 7 L/D was damaged, with up to 50% of the wool reduced to fine fibers; and (4) inspection revealed that concrete spallation had occurred, which was attributed to thermal shock.

SNL Water Jet Debris Generation Testing

In 1983, the NRC sponsored testing conducted by SNL designed to assess the susceptibility of fibrous insulation pillows to debris formation under impingement by break-flow jets (NUREG/CR-3170). Three types of fibrous insulation pillows were tested by using liquid jets with an objective to determine the stagnation pressure required for damage to the cover fabrics and for failure of the insulation pillows through insulation material release. A 300-ft-head (130 psi) centrifugal pump supplied low-temperature water to a 2-inch nozzle that directed the flow vertically downward toward an insulation pillow. The procedure was to expose the pillow to the jet flow for 5 min at a set pressure, which was incrementally increased in 5-psi steps until insulation material was released from the pillow. Because the pressure loadings on the insulation pillows were at steady state, the pressures needed to fail the pillow protective covers were substantially higher than those typical of dynamic loadings such as in the air jet testing.

The above four test programs are compared in Table 5.3-3. Because each test program had relatively independent test objectives, none of the tests involved the same insulation and jacketing systems and the same specified test conditions so that the test results could be directly compared to ascertain, for example, the effects of air jet testing vs. two-phase jet testing. This comparison leaves unanswered the question of whether an air jet is more destructive than a two-phase jet. The video from the air jet testing showed that in many cases the blanket destruction was virtually instantaneous. This supports the concept that the primary mode of blanket destruction is the initial dynamic effect from the jet. Further, LDFG blankets were damaged at a distance corresponding to a stagnation pressure of 6 psig in the dynamic air jet testing; substantially lower pressure than the minimum steady-state pressure of about 35 psig was required to rip the canvas covers in the SNL water jet tests, i.e. dynamic vs. static pressure loadings.

Table 5.3-3. Test Program Comparison

Test Program	Nozzle (in.)	Initial Conditions	Target Position / Stagnation Pressure	Damage Description
Air Jet	3	Air at 1110 psig	20 L/D 20 psig	SS jacket removed, and NUKON® destroyed with 46.3% small fines and 53.7% large pieces
			50 L/D 12 psig	SS jacket removed, and NUKON® damaged with 11.9% small fines and 29% large pieces
	4	Air at 1110 psig	30 L/D 19 psig	Unjacketed LDFG totally destroyed
OPG	2.87	Saturated water at 1435 psig	20 L/D 24 psig	Substantial damage to Al clad calcium silicate
HDR	17.72	Saturated water at 1595 psig	9D (deflected once), unknown pressure	Unjacketed LDFG totally destroyed
SNL Water Jet	2	130 psi pump head	Damage occurred at > 35 psig	Covers ripped with onset of debris generation

Experimental data is lacking to definitively determine the relative destructiveness of the initial pressure wave impacting a target (whether the wave is a simple compression wave or a shock wave) to the subsequent pressures associated with a fully expanded jet. While the steady-state HEM choked flow model combined with the steady-state ANSI/ANS-58-2-1988 standard jet expansion model predicts greater stagnation pressures for the cold leg break over that of a hot leg break, primarily due a greater mass flow rate associated with the higher density cold leg break, the relative destructiveness of the initial pressure wave is not determined by these models, nor is the relative destructiveness of the wave to that of the established jet. At break initiation, the system pressure at the break water/atmospheric interface dropped off rapidly to the saturation pressure where the water flashes to steam. The saturation pressures for the HDR and OPG debris generation tests are compared in Figure 5.3-3 (solid circles) to prototypical saturation pressures for PWR hot and cold leg piping (dashed boxes). The typical PWR operating pressure of 2250 psia is also noted. The saturation pressures for the hot leg generally range from about 1500 to 1800 psia, and those for the cold leg range from about 980 to 1120 psia. The HDR saturation pressure of 1595 psia was within the general PWR hot leg range but the OPG saturation pressure of 1435 psia was significantly lower than that of the typical PWR hot leg saturation pressures. Flashing following a 620°F hot leg break would be associated with a saturation pressure of about 1800 psia. Additional study would be required to understand the magnitude of difference between pressure waves that would occur at saturation pressures corresponding to cold and hot leg breaks.

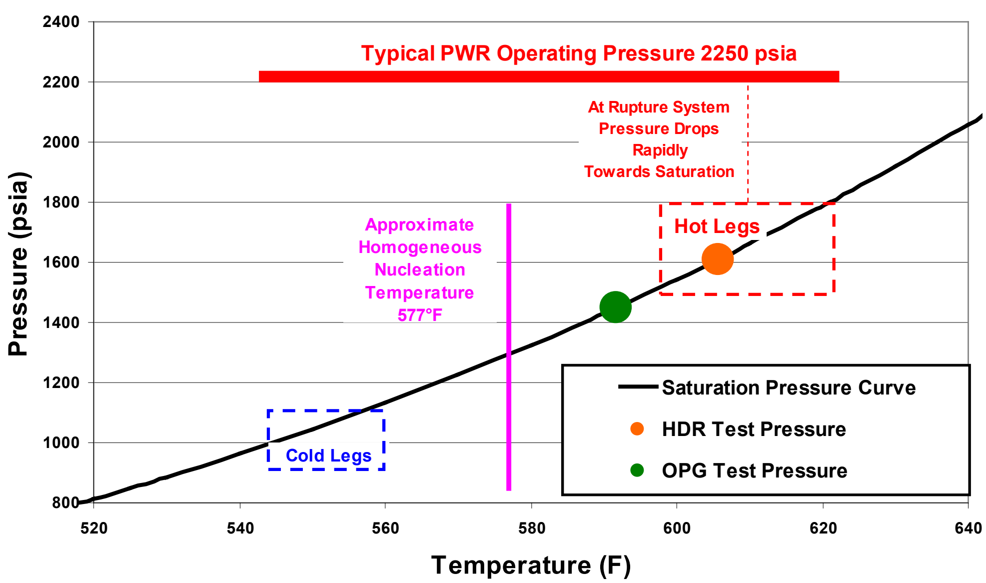

Figure 5.3-3. Saturation Pressures for Debris Generation Testing

5.3.4 Zone-of-Influence Debris Generation Models

The shape of the jet formation immediately after a break would be transient and complex. The flow from the two broken pipe ends would interact, and the broken ends would move (i.e., pipe whip) within the limits of the pipe restraints, with those limits depending on the number and location of restraints and structures near the break. Simulation of pipe motions would require modeling of the structures and the jet thrusts. The jets would be affected by containment obstructions including other piping, vessels, pumps, walls, and gratings. Further, the number of potential pipe break locations for evaluation is large even if the break locations were limited to welds. A detailed evaluation of even one break scenario could be resource-intensive.

A simplified evaluation model was clearly needed to evaluate potential debris quantities so that limited resources could be used to achieve the goals of conservatively calculating a bounding quantity for each type of insulation debris in each break scenario.

5.3.4.1 USI A-43 Conical ZOI Modeling

A conical jet model, illustrated in Figure 5.3-4, was used in 1982 during the USI A-43 evaluation (NUREG/CR-2791). The conical model assumed a DEGB with complete pipe separation but essentially located at a point source. The conical model was not implemented during the GSI-191 resolution but was not disallowed by the NRC staff. If a licensee chose the conical model, that licensee would have had to justify the conservative use of the model, which likely would have proven difficult for a large number of potential breaks, and required evaluation of the pipe whip effects. Implementation of this model did not account for jet reflections from a structure.

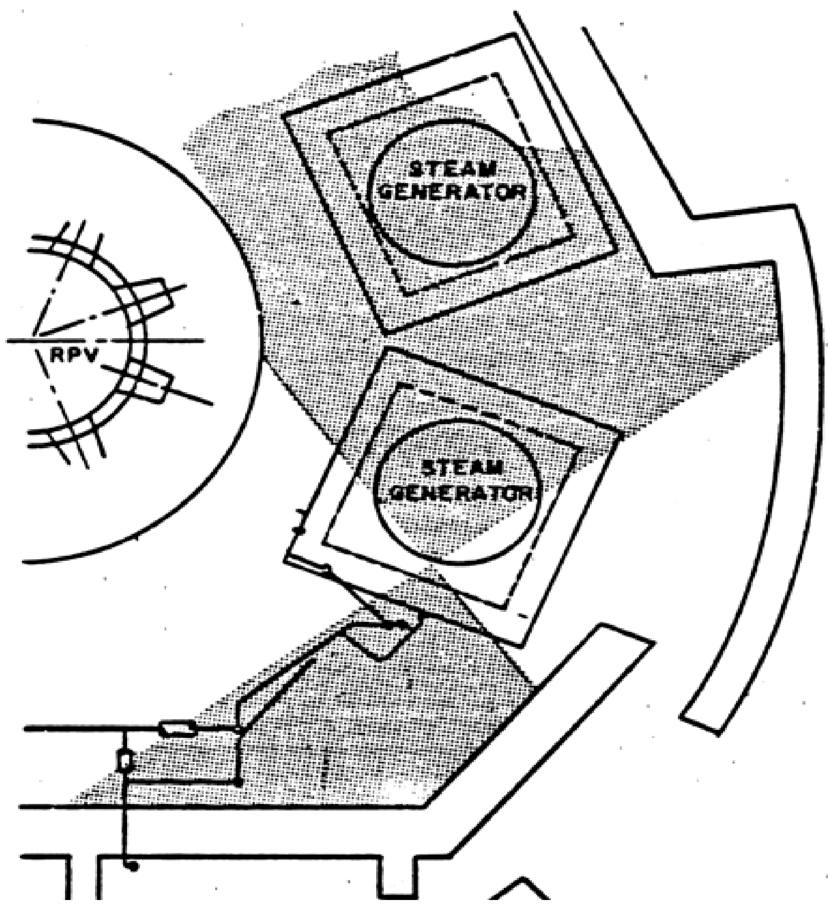

Figure 5.3-4. Schematic of Conical Jet Model

5.3.4.2 Spherical ZOI Plant Analysis Model

A simple volume-equivalent model was initiated for a probabilistic study in 1983 in which a large number of breaks needed to be readily evaluated (NUREG/CR-3394). The model is illustrated as a hemisphere in Figure 5.3-5 for one end of a fully separated DEGB. Subsequently, a full sphere was used to simulate both the ends of DEGB. The concept of the sphere is that the volume within the sphere is equivalent to the conical jet volumes associated with both pipe-end jets. The figure shows three hemispherical zones of destruction (L/Ds of 3, 5, and 7) where the probabilistic study postulated the damage percentages for the insulation located within each of these zones; those damage percentages were used to calculate quantities of debris generated for the break. The report NUREG/CR-3394 did not provide validation of the spherical model. Rather, the justification was apparently the need of the probabilistic study to quantify a large number of breaks and the spherical ZOI model met that need. In retrospect, the probabilistic study would have provided somewhat relative debris generation probabilities with the general idea that perhaps once a grouping worst case breaks were identified, and then refined analyses could be performed for this subset of breaks to determine bounding debris estimates.

The spherical concept was again used in a BWR strainer blockage volunteer plant analysis study (NUREG/CR-6224) where the concept was extended from a hemisphere to a full sphere to evaluate the discharge from both ends of a double ended pipe break simultaneously. In this study, the sphere was systematically applied to all RCS pipe locations where a weld existed. The use of the spherical model was subsequently adopted for the BWR strainer blockage resolution methodology.

The spherical model was again adopted for the GSI-191 resolution. The diameter defined the ZOI within which insulation damage was assumed to occur. The ZOI was based on a damage pressure defined as the threshold for the insulation material. The damage threshold and the severity of damage within the ZOI was either based on experimental data or conservatively specified.

RG 1.82, Revision 4 does not specifically recommend the shape of ZOI used in the debris generation analyses. Rather, RG 1.82, Revision 4 states that the size and shape of the ZOI should be consistent with experiments performed for specific debris sources and should extend until the pressure wave impulse and jet pressures decrease below the experimentally determined damage pressures appropriate for the debris source. Further, Rather, RG 1.82, Revision 4 states that if the evaluation uses simplified ZOI models, such as the spherical ZOI models, licensees should apply sufficient conservatism to account for simplifications and uncertainties in the model. The NRC staff's acceptance of the spherical ZOI model is based on the URG's adoption of the use of the spherical model as the best means to account for the impact of drywell congestion, drywell structural interactions, and the dynamic effects of pipe separation. The staff acceptance of the spherical model for the GSI-191 resolution appears in the staff safety evaluation report, "Safety Evaluation by the Office of Nuclear Reactor Regulation Related to NRC Generic Letter 2004-02, Nuclear Energy Institute Guidance Report, NEI 04-07, Pressurized Water Reactor Sump Performance Evaluation Methodology," on the industry 2004 resolution guidance document, NEI 04-07. The staff agreed that 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 the pipe whip, and that the staff concurs with the use of a spherical ZOI as a practical approximation for jet impingement damage zones.

The spherical model is applied by determining the volume of the isobar within a freely expanding jet that corresponds to the destruction pressure for a specific material.

The destruction pressure for the material of interest is determined on the basis of experimental data. If the jet stagnation pressure exceeds this pressure, damage to the insulation can be expected. The volume of a pressure isobar within the freely expanding jet which corresponds to the destruction pressure for the material is then calculated, typically using the ANSI/ANS-58-2-1988 standard (ANSI, 1988). This volume is then doubled to simultaneously account for jets from both ends of a DEGB and then converted to an equivalent spherical volume for each specific insulation-system type.

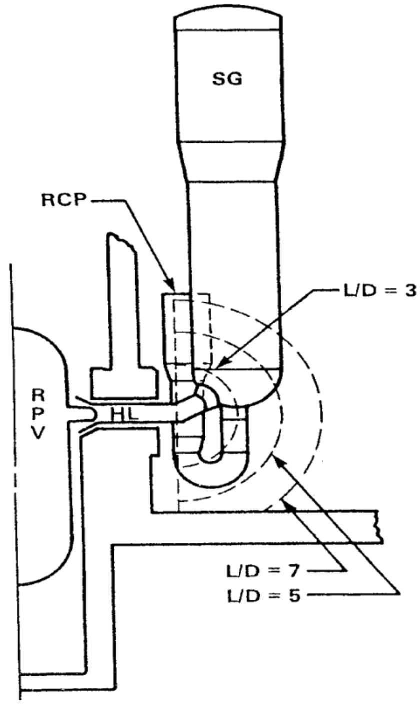

Figure 5.3-5. Schematic Diagram of Spherical-Equivalent Jet Model (SG = steam generator, RCP = reactor coolant pump, RPV = reactor pressure vessel, HL = hot leg)

The dynamics of an expanding jet have been correlated to the diameter of the pipe break to facilitate the analysis of post-LOCA debris generation in reactor containments. Using this relationship destruction pressure test data for various target materials taken with small-diameter nozzles have been correlated with the larger-diameter plant piping breaks. The jet expansion model in the ANSI/ANS-58-2-1988 standard (ANSI, 1988) is also correlated to the break diameter. Since the equivalent spherical ZOI model is based on the ANSI standard, it also correlated to the break pipe diameter. The terminology associated with the dispersing jet and with the corresponding spherical model is similar and can be confusing. In relation to an actual jet, the jet centerline pressures and associated destruction are typically correlated to the number of L/Ds, where L represents the axial distance from the jet nozzle to the point in question and D represents the nozzle diameter. For example, if the test target was physically placed 20 in. in front of a 4-in. diameter test nozzle, then that target was placed 5 L/D downstream of the nozzle. With respect to the spherical ZOI model, the radius of the sphere is specified in a number of pipe diameters. For example, a 5D specification refers to a spherical ZOI radius that is five times that of the pipe diameter, whereas a 5 L/D specification refers to an axial position inside a prototypical jet that is five times the test nozzle diameter downstream from the test nozzle. These two very different specifications are related only when the volumes within isobar pressures of a test jet are related to the equivalent spherical volumes. These two specifications have sometimes been misreported and perhaps misunderstood. Herein, “L/D” refers to a test jet and “D” refers to a spherical ZOI.

Basis for Model

For unobstructed flow, the equivalent spherical model preserves the pressure isobar volumes associated with jet dispersion as predicted by the ANSI/ANS-58-2-1988 standard or an alternate model. 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 concurs with the use of a spherical ZOI as a practical approximation for jet impingement damage zones. Extensive damage due to a redirected jet was demonstrated in the HDR tests, although destructive energies would decrease with each deflection. The spherical ZOI has not been validated with respect to pressure wave effects, where unobstructed wave propagation likely differs from that of an expanding jet, and wave dispersions, reflections, diffractions, merging, and focusing were not evaluated.

The spherical ZOI model has the inherent assumption of a uniform distribution of insulation within the break compartment, that is, the piping and insulation around the break reasonably well represents that of the break compartment. The model might give non-conservative results in a situation where the conical jet could impact the substantial quantities of insulation on a steam generator, for example, but the spherical model does not reach from the break to the steam generator. Nonetheless, insulation quantities tend to collocate with the concentration of probabilistic break locations. This issue is a greater concern for the insulation types that require higher destruction pressures, and hence smaller ZOIs. Many of the lower destruction pressures result in ZOIs so large that the ZOI nearly encompasses the entire break compartment and all such insulation within the compartment is predicted to become debris. In other words, the uncertainty associated with this inherent assumption is greater for a smaller ZOI. In certain cases, an important insulation type, such as calcium silicate (known to cause high strainer head losses), is located rather sporadically at locations where bulkier insulations do not fit well. As noted in RG 1.82, Revision 4, the spherical model may or may not conservatively encompass such insulation. It is up to the analyst to ensure that these conditions are conservatively treated. The staff allowed the truncation of the spherical ZOI whenever the ZOI intersects a robust barrier, such as a wall structure or large piece of equipment. The spherical ZOI should be centered at the location of the break, and where the sphere extends beyond robust barriers, such as walls, or encompasses large components, such as tanks and steam generators, the extended volume can be truncatedThe shadowed surfaces of components should be included in this analysis and not truncated, because debris generation tests clearly demonstrate damage to shadowed surfaces of components. Licensees electing the conical jet model (direct impingement model refinement) should retain the volume for conservatism.

In some cases it may be necessary to resize a truncated ZOI. If a truncated ZOI is resized to retain the original jet isobar volume, the resized ZOI radius would increase from that of the un-truncated ZOI. Although jet reflections off of the robust barrier would dissipate energy, the reflection would not remove all of the reflected jet’s energy. The impact of the truncation process depends on the extent of the truncation. The truncation could shave off a small sector of the sphere or could reduce a sphere to a near hemisphere (a break next to a wall), and even more severe truncations are possible. For example, for a nozzle break inside the annular gap between the reactor vessel and the shield wall, truncation of the ZOI would reduce the original ZOI to a small fraction of the original volume, but this is clearly unreasonable. In this situation, the annulus would channel the break flow, extending the region of destruction well beyond the original ZOI radius from the break location. Sound judgment should be used when determining whether to resize the ZOI after truncation.

A different ZOI size can be used for each material based on its specific destruction pressure, or alternatively, the largest ZOI based on the least robust material, could be applied to all containment materials.

Accepted ZOIs for Insulations, Fire Barriers, etc.

Table 5.3-4 presents the material-specific destruction pressures for both BWRs and PWRs that were accepted by the NRC staff as documented in the respective utility guidance staff evaluation reports [NRC-SER-1998 for BWRs and NRC-SER-2004 for PWRs]. Destruction pressures were obtained from small-scale debris generation tests and volumes were obtained by using the ANSI/ANS-58.2-1988 standard; these data were used to determine the pressure isobars corresponding to each destruction pressure. The isobar volume calculated for one pipe end is doubled to account for both pipe ends. A different ZOI size can be used for each material-specific destruction pressure for each potential debris source in the vicinity of a break.

With one exception, all the destruction pressures in Table 5.3-4 were obtained from the air jet debris generation testing conducted during the course of the BWR resolution. Some pressures were adjusted downwards from the original utility recommendations by the staff to account for uncertainties, such as interpretation of the data and the conservative application of air jet test data to a two-phase depressurization flow. During the BWR resolution, it was recognized that a main steam line break would generate substantially greater volumes of debris than would a recirculation pipe break because the steam line break was not only live steam, it was at a higher temperature than a low-quality two-phase recirculation pipe break. A CFD evaluation demonstrated that compressed air at 1000 psig would be considered a reasonable approximation of a live steam at a BWR operating pressure of about 1015 to 1040 psig. The CEESI test facility had the capability of compressing air to 1110 psig and could deliver air to a test nozzle at 1000 psig. Hence, it was decided that the CEESI test facility could generate data compatible with a BWR steam line break. Targets of various insulation types and jacketing were placed at various distances from the jet with the objective of determining the minimum threshold pressures for generating insulation debris. These thresholds became the evaluation's destruction pressures.

A PWR hot leg break would result in a two-phase steam/water jet at a higher pressure than a BWR steam line break. The saturation pressures in the PWR hot leg can reach about 1800 psia. Lacking debris generation test data specific to PWR two-phase break, the staff conservatively reduced some destruction pressures from those accepted for BWRs due to the associated uncertainties. For example, the destruction pressure for K-wool, shown in Table 5.3-4, was reduced 40% from 40 psig down to 24 psig. The staff's evaluation of the ANSI standard isobars [NRC-SER-2004] associated with the PWR destruction pressures resulted in the ZOI radii are also shown in Table 5.3-4 to provide visualization of the impact of the destruction pressures on ZOI size.

The reduction of the Cal-Sil destruction pressure from 150 psig down to 24 psig was based on the OPG two-phase test data (OPG, 2001) where calcium silicate with aluminum cladding and stainless steel bands was tested. The destruction pressure of 24 psig was based on the OPG test that was located farthest from the nozzle, i.e., 20 L/D. There were two non-conservative factors associated with this 20 L/D test. First, substantial damage occurred to the target (22% of the target was reduced to debris); therefore the actual threshold for the onset of destruction was not experimentally achieved. Second, the OPG test pressure of 1450 psia was less than the typical PWR operating pressure. Regardless the staff, after careful review, chooses to accept the 24 psig as the calcium silicate destruction pressure and considers it conservative for the application.

Table 5.3-4. Damage Pressures and Corresponding Volume-Equivalent Spherical ZOI Radii

Insulation Type	Destruction Pressures for BWRs (psig)a	Destruction Pressures for PWRs (psig)	PWR ZOI Radius/ Break Diameter
Transco RMI Darchem DARMET	190	114	2.0
Jacketed NUKON® with Sure-Hold® bands Mirror® with Sure-Hold® bands	150	90	2.4
K-wool	40	24	5.4
Cal-Sil (Al cladding, SS bands)	150	24	5.45
Temp-Mat with stainless steel wire retainer	17	10.2	11.7
Unjacketed NUKON®, Jacketed NUKON® with standard bands Knaupf	10	6	17.0
Koolphen-K	6	3.6	22.9
Min-K/Mirror® with standard bands	4	2.4	28.6

[a]The destruction pressures for Cal-Sil and Min-K for BWRs are from NUREG/CR-6762, Vol. 3.

Debris generation tests and studies have confirmed that insulation products having outer casings, jackets, or other similar mechanical barriers resistant to jet impingement yield smaller quantities of debris than do less robust systems. Various studies have also demonstrated dependence between the orientation of the jacketing seam relative to the jet and the amount of debris generation. This finding suggests that the integrity of the jacket during impingement is an important feature for minimizing debris generation. Russell reports (OPG, 2001), for example, that double-jacketing of an insulation product with a second overcladding of stainless steel having a rotated opposing seam was effective in minimizing the distance between the jet and target before the onset of damage occurred.

Estimating Size Distributions

The debris transport analysis requires the realistic or conservative specification of a size distribution for each type of debris. Finer debris is transported much more readily than coarser debris. The first step in specifying debris size distribution is characterizing debris categories with respect to the transport properties of the various debris sizes. The following discussion (taken from SE Appendix II of NRC-SER-2004) pertains to debris formed from fibrous insulation blankets and serves as a good example of debris size categorization.

The debris generation analysis assumed some damage to all insulation within the break-region ZOI such that all of the insulation within the ZOI is assumed to be debris. The damage could range from slight (e.g., insulation erosion occurring through a rip in the blanket cover), which leaves the blanket attached to its piping, to the total destruction of a blanket with its insulation reduced to small or very fine debris. Fibrous debris was categorized into one of four categories based on transport properties so that the transport of each type of debris could be analyzed independently. Table 5.3-5 shows these categories and their properties. The two smaller and two larger categories differed primarily with regard to whether the debris was likely to pass through a grating typical of those found in nuclear power plants. Thus, fines and small pieces pass through gratings but large and intact pieces do not. The fines and small pieces are much more transportable than the large debris. The fines were then distinguished from the small pieces because the fines would tend to remain in suspension in a sump or suppression pool, even under relatively quiescent conditions, whereas the small pieces would tend to sink. Furthermore, the fines tended to transport more like an aerosol in the containment-air/steam flows and were slower to settle than the small pieces when airflow turbulence decreased. The CEESI tests (NUREG/CR-6369) illustrated that when an LDFG blanket was completely destroyed, 15 to 25% of the insulation was in the form of very fine debris (i.e., debris too fine to collect readily by hand). The distinguishing difference between the large and intact debris was whether the blanket covering still protected the fibrous insulation. Fibrous insulation without a cover may erode further due to containment sprays, spray drainage, or exposure within a sump or suppression pool, whereas a covered blanket is not likely to undergo further erosion.

Debris-transport analysis has used volumes of fibrous debris interchangeably with mass on the basis that the density is that of the undamaged (as-fabricated) insulation. Certainly, the density would be altered by the destruction of the insulation and by water saturation of the debris. Estimation of debris-size distribution should be based on experimental data, but when such data are not available, it is conservative to assume that all of the ZOI debris would be reduced to highly transportable suspendable fines.

The volume of debris generated within a ZOI depends on (1) the size of the ZOI defined by the spherical ZOI radius, (2) the concentration of a particular insulation within the ZOI. Plant-specific information (i.e., the volume of a particular insulation within the ZOI divided by the volume of the ZOI) determines the insulation average concentration within a ZOI. Integration of experimental data on debris generation is required in order to determine the fraction of the ZOI insulation that is damaged into a particular debris-size classification. The integration is represented by the following equation:

$$F_{ZOI} = \frac{3}{r_{ZOI}^3} \int_0^{r_{ZOI}} f_d\left(P_{jet}(r)\right) r^2 \, dr$$

where,

F_{ZOI} = fraction of the ZOI insulation type i that is damaged into a particular debris size classification

f_d = fraction of debris damaged into a particular debris size as a function of the jet pressure P_{jet}, which is a function of the spherical radius, r, within the ZOI, and

r_{ZOI} = outer radius of the ZOI.

Implicit in this integration is the assumption that the insulation is uniformly distributed within the ZOI, which may not be realistic. Because the functional information needed for this integration is not available in an equation form simple enough for a formal integration to proceed, the following simplification is used.

$$F_{ZOI} = \frac{1}{r_{ZOI}^3} \sum_j \left[\frac{f_{fines}\left(P_{jet}\left(r_j\right)\right) + f_{fines}\left(P_{jet}\left(r_{j-1}\right)\right)}{2} \left(r_j^3 - r_{j-1}^3\right) \right]$$

where

f_{fines} = fraction of debris damaged into a particular debris size as a function of the jet pressure P_{jet} at a radius of rj

The spherical ZOI is first subdivided into numerous spherical shells (j), which could, but not necessarily, correspond to specific pressure isobars. The same integration would be performed for each debris size classification, e.g., fines, small, large, and intact debris size categories. The precision of the integration increases with the number of subdivisions. In a spreadsheet, jet pressures are listed in increasing values, and then the spherical radii are determined, followed by the damage fractions evaluated at each rj. For the intervals, the average damage across the interval and the volume of the interval are determined. Multiplying the average interval damage by the interval volume, then summing, and dividing by the total ZOI volume, yields the debris fraction for the ZOI.

A review of the air jet testing debris generation data, both the BWROG air-jet impact testing (AJIT) data (NRC-SER-1998) and the DDTS data (NUREG/CR-6369) indicated that NUKON®, Transco Products Inc., and Knauf fiberglass insulation underwent similar damage. These types of insulation have approximately the same as-manufactured density (approximately 2.4 lb/ft3), and their recommended minimum pressures for destruction are usually taken to be the same pressure. Therefore, these and similar insulations have been grouped together as LDFG insulation. The fractions for the small fines (small and fine categories together) from the AJIT debris generation test data as a function of the jet centerline pressure for these three types of LDFG insulation are plotted in Figure II-2 of Appendix II in NRC-SER-2004 (from which Figure 5.3-1 was generated). The data represented by a curve drawn though the data correlate the damage as a function of jet pressure, which subsequently can be used to integrate the damage over the ZOI. The DDTS test data in Figure 5.3-1 used a 4-in. nozzle, whereas the BWROG test data used a 3-in. nozzle. For LDFG, any jet pressures greater than 17 psi have been observed to destroy a significant portion the blanket into small fine debris.

At the NRC-SER-2004 damage pressure of 6 psi for NUKON insulation, the integration of the curve in Figure 5.3.1 resulted in 22% of the ZOI debris being either small pieces or suspendable fines. The baseline methodology assumes that all of this debris transports to the strainer. Plants that perform evaluations that are more realistic than the baseline method may need to subdivide the baseline small-fine-debris class into fines and small-piece debris. In the refined analysis the fines (e.g., individual fibers) remain suspended in the pool, and the small-piece debris sinks to the pool floor and may or may not transport to the sump screen. In the debris generation tests conducted during the DDTS, 15 to 25% of the debris from a completely disintegrated fiberglass blanket was classified as non-recoverable because the debris either exited the test chamber through a fine-mesh catch screen or was otherwise too small for hand collection. Therefore, it would be reasonable to assume that 25% of the small fine debris is in the form of individual fibers, and that the other 75% is in the form of small-piece debris.

The focus of the debris size categorization should be on conservatively estimating the suspendable fines. The rather large PWR replacement strainers typically resulted in sump pools that flowed so slowly that only the suspendable debris would tend to be transported to the strainers. However, debris accumulation on BWRS strainers may differ somewhat from the PWRs strainer in that the BWRs located in a suppression pool would be subjected to a period of higher turbulence associated with RCS depressurization and some BWR have relatively smaller strainers.

5.3.5 Characteristics of Generated Debris

The debris generation evaluation must characterize the debris and estimate the bounding quantities of the debris. The most important characteristic is size distribution, which has been discussed above with respect to both debris generation testing and analytical determination of debris size distribution within the spherical ZOI model. Debris size can affect buoyancy and the tendency for the debris to be affected by turbulence in the pool. Some debris would readily sink in a pool of water, very fine debris would remain suspended in solution, and some debris could even float on the surface. Debris size strongly affects the transport of debris, its accumulation on a strainer, and how it affects head loss when deposited in a debris bed. Whether or not a piece of settled debris would move with the flow of water across the floor of the pool depends on the size of the debris. The uniformity of accumulation on a strainer also depends upon the size of the debris.

In addition to debris size, density is important. Specifically, both the bulk density of the piece of debris and the density of the material itself. For example, the bulk density of fibrous debris includes the free space between the fibers that is filled with air. The material density is the density of the fiberglass forming the fibers. The densities, the fiber diameters, and the spacing between the fibers affect how readily water can replace the air once a piece of fibrous debris becomes submerged in water, thus affecting its buoyancy. Staff evaluation of the debris density values and their concerns on the use of the density data are discussed in SE of NEI 04-07 (ML043280007).

The rate at which individual fibers can erode or break away from a bulk piece of debris is important. The erosion process is typically treated in the transport analysis. Erosion or disintegration of larger debris into smaller pieces increases debris transport; especially important is the generation of individual fibers or fine particulates, which would effectively remain suspended.

Table 5.3-5. Fibrous Debris-Size Categories and Their Capture and Retention Properties

Size	Description	Airborne Behavior	Waterborne Behavior	Debris-Capture Mechanisms	Requirements for Crediting Retention
Fines	Individual fibers or small groups of fibers.	Readily moves with airflows and slow to settle out of air, even after completion of blowdown.	Easily remains suspended in water, even relatively quiescent water.	Inertial impaction Diffusiophoresis Diffusion Gravitational settling Spray washout	Should be deposited onto surface that is not subsequently subjected to CSs or to spray drainage. Natural-circulation airflow likely will transport residual airborne debris into a sprayed region. Retention in quiescent pools without significant flow through the pool may be possible.
Small Pieces	Pieces of debris that easily pass through gratings.	Readily moves with depressurization airflows and tends to settle out when airflows slow.	Readily sinks in hot water, then transports along the floor when flow velocities and pool turbulence are sufficient. Subject to subsequent erosion by flow water and by turbulent pool agitation.	Inertial impaction Gravitational settling Spray washout	Should be deposited onto surface that is not subsequently subjected to high rates of CSs or to substantial drainage of spray water. Retention in quiescent pools (e.g., reactor cavity). Subject to subsequent erosion.
Large Pieces	Pieces of debris that do not easily pass through gratings.	Transports with dynamic depressurization flows but generally is stopped by gratings.	Readily sinks in hot water and can transport along the floor at faster flow velocities. Subject to subsequent erosion by flow water and by turbulent pool agitation.	Trapped by structures (e.g., gratings) Gravitational settling	Should be either firmly captured by structure or on a floor where spray drainage and/or pool flow velocities are not sufficient to move the object. Subject to subsequent erosion.
Intact	Damaged but relatively intact pillows.	Transports with dynamic depressurization flows, stopped by a grating, or may even remain attached to its piping.	Readily sinks in hot water and can transport along the floor at faster flow velocities. Assumed to remain encased in its cover, thus, it is not subject to significant subsequent erosion by water and by turbulent pool agitation.	Trapped by structures (e.g., gratings) Gravitational settling Not detached from piping	Should be either firmly captured by structure or on a floor where spray drainage and/or pool flow velocities are not sufficient to move the object. Intact debris subsequently would not erode because of its encasement.

5.4 Debris Transport Evaluation

5.4.1 Overview

The debris generation methodology is used for estimating bounding quantities of debris that could result from dislodged piping thermal insulation, fire barrier materials, coatings, and other materials in the vicinity of the break. Subsequently, the debris would be chaotically propelled by the jet effects as the primary system coolant is blown down and pressurizes the containment. RCS depressurization flow would dynamically propel debris, which could, due to inertial forces, impact structures causing the debris to stick onto those structures. Larger debris could be captured by structures, such as gratings, and wherever depressurization flow slowed, the debris could settle due to gravity. Because the containment pressurization results in air and vapor flow into all containment free space, fine debris would be propelled toward the space. At the end of the primary system depressurization, debris would be dispersed into both the upper and lower containments, where debris would be both inertially captured onto surfaces of all orientations and gravitationally settled onto compartment floors and equipment. These transport processes are referred to as the "blowdown transport." For PWRs, some debris would reside on the sump pool floor before the sump pool is established. For BWRs, some debris would reside on the drywell floor and within the suppression pool.

This LOCA-generated debris, along with the preexisting containment latent debris, would then be subject to subsequent transport by the drainage of the break overflow, the containment sprays, and any condensate flow. These transport processes are referred to as the "washdown transport." For PWRs, debris that is either initially deposited onto the sump pool floor or washed down from the upper containment to the sump pool would subsequently undergo transport within the sump pool, first as the sump pool fills before the recirculation pumps start, and then within the established sump pool. For BWRs, the debris is either deposited within the suppression pool by the depressurization flows through vent downcomers or subsequently by the break, spray, and condensate drainage flows. For BWRs, the blowdown and chugging associated with RCS depressurization has a large influence on transport (and erosion) within the suppression pool. Additionally the ECCS recirculation starts immediately in BWRs, while in PWRs there is a significant delay. This delay may allow significant debris to settle and prevent its transport. Within the BWR suppression pool or PWR sump pool, debris transport would be governed by various physical processes, including the settling of debris in pools in which turbulence levels may vary significantly, tumbling/sliding of settled debris along the pool floor, re-entrainment of settled debris, lifting of debris over structural impediments, retention of debris on strainers of various orientations, and further destruction of debris as a result of pool flow dynamics, thermal effects, and chemical effects. Some types of debris residing within a pool can be further degraded by pool flow dynamics (e.g., individual fibers can detach from fibrous shreds). Some portion of the debris within the pool would subsequently be transported to and accumulated on the recirculation suction strainers.

The blowdown/washdown processes also have the potential to generate additional debris due to the interactions of flows, elevated temperatures, and moisture with various otherwise undamaged materials within the containment. These include, but are not limited to, such materials as unjacketed insulations, unqualified coatings, and labels. For example, a deluge of spray drainage over unjacketed/uncovered fibrous insulation could erode transportable fibers from that insulation. The primary concern has been the generation of coating debris from unqualified coatings, but all potential sources should be considered.

Long-term recirculation cooling must operate according to the range of possible accident scenarios. A comprehensive debris transport study should consider an appropriate selection of these scenarios, as well as all engineered safety features and plant-operating procedures. The maximum debris transport to the strainer likely will be determined by a small subset of accident scenarios, but this scenario subset should be determined systematically. Many important debris transport parameters will be dependent on the accident scenarios. These parameters include the timing of specific phases of the accident (i.e., blowdown, injection, and recirculation phases) and pumping flow rates. The blowdown phase refers to primary-system depressurization. The injection phase corresponds to ECCS injection into the primary system from an external source, a process that subsequently establishes the PWR sump pool. The recirculation phase refers to long-term ECCS recirculation.

The physical processes of all these transport phases are so varied and complex that detailed analysis is difficult at best and is typically considered to be too complex to pursue, except in areas where debris characteristics ans conditions affecting transport can be predicted with more confidence. Because the primary analytical objective is the realistic or conservative estimation of the maximum quantity of debris that can reach the strainer by type and size category, the more difficult-to-analyze processes can be conservatively bounded, while processes more amenable to analysis can be more realistically yet conservatively estimated. An analytical approach was developed during the BWR Drywall Debris Transport Study (DDTS) referred to as the "logic chart" approach (NUREG/CR-6369). It uses event-tree models to decompose the complex overall process into many smaller steps; some of which may be solved analytically or estimated based on data obtained from small-scale experiments. In quantifying such a chart, conservatively estimated fractions are used for steps where data or analysis is not available and more realistic fractions are used for the steps where data or analysis is available. The multiplication of step fractions throughout the logic chart results in a final distribution of the debris that is conservative with respect to debris accumulation on the strainer. An example logic chart is shown in Figure 5.4-1.

The transport of each debris type and size category should be considered separately because each has unique transport characteristics. The important transport characteristics are whether the debris is buoyant, prone to settling, or likely to be transported as relatively uniformly dispersed suspended debris. A four-category size classification for fibrous debris, shown in Table 5.3-5, was developed during a reference plant study (Appendix VI in NRC-SER-2004), which addressed the associated key aspects of fibrous debris transport. The four-category system was recommended (NRC-SER-2004) for licensee use in the GSI-191 resolutions. The size categories are (1) fines that remain suspended, (2) small-piece debris that is transported along the pool floor, (3) large-piece debris with the insulation exposed to potential erosion, and (4) large debris with the insulation still protected by a covering, thereby preventing further erosion.

The level of detail employed in a transport evaluation depends on resources and resolution tolerance to conservatism. The simplest analysis uses the conservative assumption of complete transport and accumulation onto the strainer, but this oversimplification is typically unacceptable. A more detailed evaluation could involve analysis such as CFD simulations to predict flow metrics of a PWR sump pool, combined with debris (type and size specific) empirical transport data, to determine whether transport would occur.

Alternately small-scale plant-specific experiments could be conducted to gain understanding of the transport processes. The remaining subsections discuss (1) blowdown/washdown debris transport, (2) sump or suppression pool transport, and (3) erosion of containment materials and further degradation of debris. The final subsection discusses the importance of characterizing the size distribution of the debris estimated to arrive at the recirculation strainers (i.e., characteristics that affect debris accumulation).

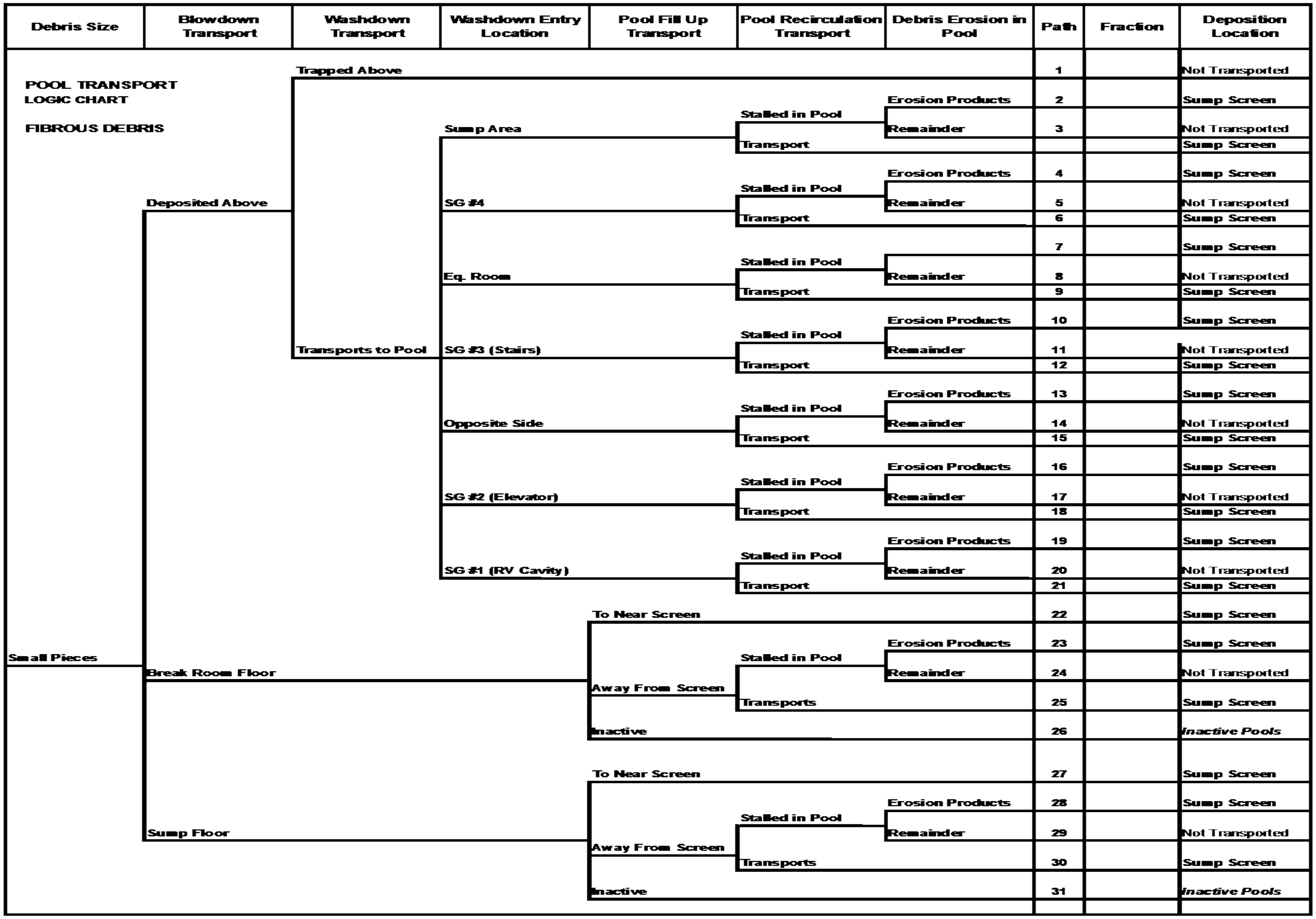

Figure 5.4-1. Chart for Sump Pool Debris Transport

5.4.2 Blowdown/Washdown Debris Transport

This section discusses the blowdown and washdown transport methodology that provides an estimate for the transport of debris from its points of origin to the sump or suppression pool. The transport analysis consists of two components: blowdown debris transport, where the effluences from a high-energy pipe break would destroy insulation near the break and then transport that debris throughout the containment, and washdown debris transport due primarily to operation of the containment sprays. Along the debris-transport pathways, substantial quantities of debris would come into contact with containment structures and equipment, where that debris could be retained, thereby preventing or delaying further transport. The blowdown/washdown debris-transport analysis provides the source term for the subsequent recirculation transport (i.e., within PWR sump pool or a BWR suppression pool. Different types of insulation would havd different capture mechanisms. For example, RMI and fibrous debris would be captured by significantly different mechanisms during blowdown. The methodology would also consider particulate types of insulation (e.g., calcium silicate) where the primary difference might be in the erosion process. Further detailed guidance includes (1) a detailed blowdown/washdown transport analysis performed for a PWR reference plant that had a Westinghouse reactor and large-dry containment (Appendix VI in NRC-SER-2004) and (2) the DDTS (NUREG/CR-6369).

5.4.2.1 Blowdown/Washdown Debris-Transport Phenomenology

A spectrum of physical processes and thermal-hydraulic phenomena govern the transport of debris within containment. The physical processes range from the transport/deposition physics of aerosols to the dynamic impaction of larger pieces of debris onto containment surfaces. The design of a particular containment would influence the flow dispersions and thereby affect debris transport and deposition. Because of the energetic blowdown flows following a LOCA, insulation destruction and subsequent debris transport are rather chaotic. For example, a piece of debris could be deposited directly near the sump strainer or it could take a much more tortuous path, first going to the dome and then being washed back down to the sump by the sprays. Alternately, a piece of debris could be trapped in any number of locations. Aspects of the blowdown/washdown portion of the debris transport analysis include characterization of the break, design and configuration of the plant, generation of debris by the break flows, and both air- and water-borne debris dynamics.

Many features in nuclear plant containments significantly affect the transport of insulation debris. As the RCS depressurizes, the break effluents will flow towards the suppression pool in BWRs and towards the containment dome in PWRs. Structures such as gratings located in the paths of the dominant flows likely would capture substantial quantities of debris. For PWRs, the lower compartment geometry - such as the open floor areas, ledges, structures, and other obstacles - defines the shape and depth of the sump pool area and is important in determining the potential for airborne debris to deposit directly onto the sump floor. Furthermore, the relative locations of the sump, LOCA break, and drainage paths from the upper regions to the sump pool are important in determining the distribution of debris deposition onto the sump floor during blowdown and washdown. For BWRs, the geometry of drywell floor and entrances into the vent downcomers influence the transport of debris into the suppression pool.

Transport of debris is strongly dependent on the characteristics of the debris that has formed. These characteristics include the types of debris (insulation type, coatings, dust, etc.) and the size distribution and form of the debris. Each type of debris has its own set of physical properties, such as density, specific surface area, buoyancy (including dry, wet, or partially wet), and settling velocity in water. Pooled water can form within the upper containment regions, e.g., the drywell floor in a BWR or a refueling pool in a PWR. These pools can affect the transport of debris during the washdown phase. The size and form of the debris, in turn, depends on the method of debris formation (e.g., jet impingement, erosion, aging, and latent). The size and form of the debris affect transport of the debris to the sump or suppression pool. For example, fibrous debris may consist of individual fibers or large sections of an insulation blanket and all sizes between these two extremes.

Debris transport is affected by a full spectrum of physical processes, including particle deposition and re-suspension for airborne transport and both settling and re-suspension within calm and turbulent water pools for both buoyant and non-buoyant debris. The dominant debris-capture mechanism in a rapidly moving flow likely would be inertial capture; however, in slower flows, the dominant process likely would be gravitational settling. Much of the debris deposited onto structures likely would be washed off by the containment sprays or possibly even by condensate drainage. Other debris on structures could be subject to erosion. Relatively complete discussion of the range of transport phenomena is found in the BWR and PWR PIRT panel reports (BWR-PIRT, PWR-PIRT). The BWR DDTS and the PWR SE on NEI 04-07, Appendix VI, provide analysis processes that focus on the phenomena determined to most govern the transport processes.

5.4.2.2 PWR Blowdown/Washdown Transport

PWR Blowdown Containment Dispersion

Following a break, primary system depressurization effluents flow toward the upper containment dome in a PWR. For large dry and subatmospheric containments, the steam generator compartments are designed to direct the flows directly into the upper containment. For ice condenser containments, the flows are directed into the ice condenser banks, which exit into the upper containment. Debris generated by a LOCA would be carried by these flows until either the debris was captured by or deposited onto a structure, or the debris gravitationally settled onto equipment and floors. The dominant deposition mechanism for larger airborne debris ejected from a steam generator compartment into the upper containment dome would be gravitational settling. For very fine particulate, containment spray fallout may become the dominant mechanism. The reference plant blowdown transport analysis presented in Appendix VI of staff SE on the NEI guidance document, NEI 04-07 (SE NEI-04-07, 2004) provides further guidance for conducting a detailed debris dispersion analysis.

The source of insulation debris is the region immediately surrounding the LOCA break, which is typically contained within a steam generator compartment. This region would be subject to the most violent of the containment flows where the primary debris capture mechanism would be inertial capture.1 For these reasons, the transport of debris within the region of the pipe break should be solved separately from that of the rest of the containment.

The first step in determining the dispersal of debris from near the break is to determine the distribution of the break flow from the region, specifically, the fractions of the flow directed to the dome vs. other locations.

In the Appendix VI analysis of NRC-SER-2004, the containment thermal-hydraulics code, MELCOR, was used to determine the flow distribution within and out of the steam generator compartment in which the break occurs for a large dry PWR containment.[6]

The LOCA-generated debris not captured within the region of the break would be carried away from the break region by the break flows. The primary capture mechanism near the break would be inertial capture or entrapment by a structure such as a grating. The break-region flow that occurred immediately after the initiation of the break would be much too energitic to allow debris simply to settle to the floor of the region.

The inertial capture of fine and small debris occurs when a flowpath changes directions, such as flowpaths through doorways from a steam generator compartment into the sump-level annular space. These flowpaths often have at least one 90° bend, and because the structural surfaces are wetted by steam condensation and the liquid blowdown from the break, a portion of this debris could stick to the impacted surfaces. Debris-transport experiments conducted at CEESI (NUREG/CR-6369) demonstrated an average capture fraction of 17% for fine debris and small debris that make a 90° bend at a wetted surface. The flow in any of the flowpaths could encounter bends as the break effluents interacted with various equipment and walls.

The platform gratings within the break region steam generator compartment would capture substantial debris, even if the gratings do not extend across the entire compartment.[7] The CEESI debris-transport tests demonstrated that an average of 28% of the fine and small debris was captured when the airflow passed through the first wetted grating that it encountered, and that an average of 24% was captured at the second grating. The large and intact debris would, by definition, be trapped completely by a grating. In addition, equipment such as beams and pipes were shown to capture fine and small debris. In the CEESI tests, the structural congestion of a typical BWR drywell was simulated using gratings, beams, and piping. Air jet generated fibrous debris was driven through this structural simulation to determine realistic capture fractions that could be applied to containment analysis. An average of 9% of the debris passing through the entire test section was captured.

To evaluate the transport and capture within the break region, the evaluation should be separated into many smaller problems that are amenable to resolution. The Appendix VI NRC-SER-2004 analysis accomplished this separation using a logic-chart approach similar to that in Figure 5.4-1, but based on the structural details of the break region compartment. The headers across the top of the chart alternated among volume capture, flow split, and junction capture as the debris transport process progressed through the nodalization scheme. The nodalization scheme was constructed to place the gratings at junction boundaries. Chart header questions

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[6]Most of the break effluent would be directed upward toward the large upper containment volume. Effluents venting into lower-level compartments by way of open access doorways would flow at much lower mass flow rates than those flowing to the upper containment. The MELCOR calculations predicted reference plant characteristic flow velocities within the break region steam generator compartment that ranged from approximately 25 to 200 m/s (80 to 660 ft/s) for a large break LOCA. Such large break flow velocities are capable of propelling even intact insulation blankets upwards into the upper containment. Inertial debris deposition is dependent on the flow velocities transporting the debris, debris properties, surface properties, and flow direction changes.

[7]If a steam generator compartment grating at a level above the break is continuous across the entire compartment, then large piece debris may be effectively prevented from being ejected into the upper containment. If there is no grating or only partial gratings, large piece debris can be propelled into the upper containment and fall into the refueling pool, which is a concern for the upstream effects evaluation.

asked (1) how much debris would be captured in a specific volume, (2) what is the debris transport distribution at a flow split, and (3) how much debris would be captured at a flow junction between two volumes? This analytical approach is rather detailed; therefore the interested reader is directed to the detailed example presented in Appendix VI of staff SE on the NEI guidance report, NEI 04-07 (SE NEI-04-07, 2004) for a more detailed discussion. The results were based on estimates of inertial capture on structures within a sub-volume region and at grating at specific junctions, and the airflow distributions at junction flow splits. For fine and small-piece debris, it is reasonable to assume that the debris split is approximated by the flow split. For large and intact-piece debris, the debris split may differ substantially from the flow split, depending on the geometry. The break region chart is used to track the progress of small debris from the pipe break until the debris is assumed to be captured or is transported beyond the compartment. Each application of this methodology should develop a plant specific chart.

Outside the break region compartment, debris dispersion and capture throughout the containment could also be handled by such detailed modeling, but the effort would be highly resource-intensive. Figure 5.4-2 shows an example of a small section of a potentially very large logic chart. This figure is an illustration of the number of decisions possible in a detailed transport analysis. In this chart, the regions are designated as Region j and Region j+1 indicating that total number of regions for which the containment is subdivided is determined by the depth of the analysis and could be a substantial number. A simpler method was used in the reference plant study. The method was based first on dispersion of the debris by free volume and then by surface orientation within specific free-volume regions. First the free volume of each specific volume region was divided by total containment free volume, then these fractions were multiplied with the debris quantity of each debris type and size category to arrive at distributions for dispersing the debris among the volume regions. Then, in a similar manner, areas fractions were used to distribute the debris among the surfaces within each volume region. Dispersion distributions were based on actual volumes and areas and then adjusted with weighting factors based on engineering judgment. Obviously, the debris would preferentially settle to the floor surfaces, hence the weighting factors were adjusted to make most of the debris deposit onto the floors; however some of the fines would stick to vertical surfaces.

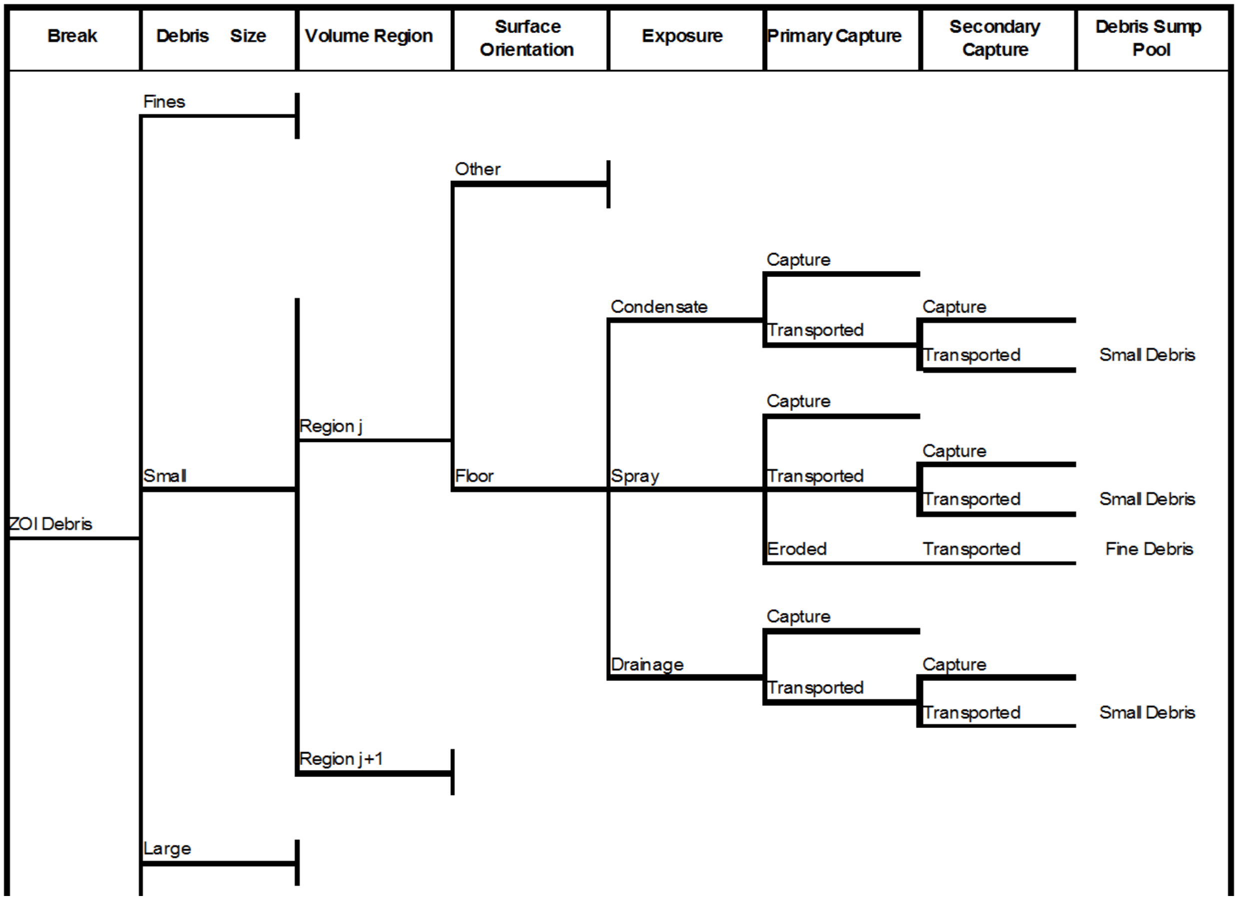

Figure 5.4-2. Example of a Section of a Debris Transport Chart

PWR Containment Spray and Condensate Drainage Washdown

Debris that is deposited throughout the containment subsequently would be subject to potential washdown by the containment sprays and by drainage of the spray water to the sump pool and (to a lesser extent) by drainage of condensate. Debris on surfaces that would be hit directly by the sprays would be much more likely to be transported with the flow of water than would debris on a surface that is merely wetted by condensation. The transport of debris entrained in spray water drainage is not as easy to characterize. If the drainage flows were substantial and rapidly flowing, the debris likely would be transported with the water. However, at some locations, the drainage flow could slow enough for the debris to remain in place. That is, the force that the water exerts on a piece of debris depends on both the localized velocity of the water flow and on the projected contact surface area. When the water depth is shallow, then only a portion of the piece of debris (depending on the size of the debris) may be in contact with the water and the water would simply flow around the piece. With smaller amount of water, a sheeting effect can be effective at moving the debris. As drainage water drops from one level to another, as it would through the floor drains, strairwells, or by falling over floor edges, the impact of the water on the next lower level could cause splashing sufficiently to transport debris beyond the main flow of the drainage, thereby essentially capturing the debris a second time. In addition, the flow of water could erode the debris further, generating more fine debris. These considerations should be factored into the analysis. The washdown processes are illustrated schematically in Figure 5.4-3.

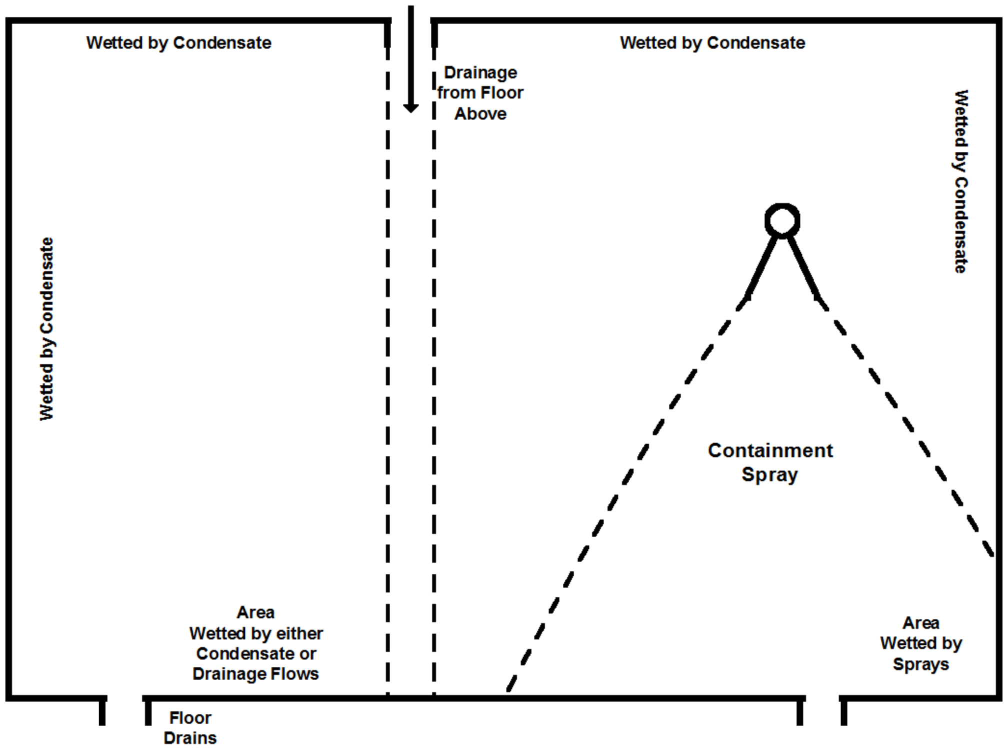

Figure 5.4-3. Schematic Diagram of Debris-Washdown Processes

The drainage of spray water from the location of the spray heads down to the sump pool is evaluated to provide insights for the transport analysis, such as identifying areas that would not be affected by the sprays, the water drainage pathways, likely flowpaths for drainage water to the sump pool, and locations where drainage water would fall from one level to the next. A key result of the washdown analysis is an estimation of how much debris is washed to the sump pool via each of the main drainage pathways (based on the assumption of the debris being uniformly mixed with the flows entering the pool). This information is typically needed for the evaluation of sump pool debris transport.

The spray and condensate drainage analysis can contribute to the upstream effects analysis, which addresses the potential holdup of drainage water in the upper containment to the extent that the holdup can adversely affect the sump pool water level, which in turn, can affect strainer submergence, vortexing, and the recirculation pump NPSH. The blockage of any water drainage could result in water holdup, but the primary locations of concern are the refueling pool drains because the refueling pool represents a substantial potential volume of water. An adequate understanding of the water drainage from the upper containment to the sump pool is needed to ascertain potential locations for water holdup, as well as debris washdown transport.

Certain types of insulation debris could potentially continue to erode to smaller debris during containment washdown. Experiments conducted in support of the DDTS analysis (NUREG/CR-6369) demonstrated that fibrous insulation debris could be eroded further by the flow of water. The primary concern of the DDTS analysis was LDFG debris that was deposited directly below the pipe break and, therefore, was inundated by the break overflow. Debris erosion in this case was substantial (i.e., ≈9%/h at full flow). Debris erosion due to the impact of the sprays and spray drainage flows was certainly possible but was found to be much less significant. The DDTS concluded that <1% of the LDFG was eroded due to the direct impact of the containment sprays. However, the debris caught within cascading flows of accumulated spray drainage could be subjected to more forceful erosion than the direct spray droplets. However, in many situations falling water flows could simply push the debris aside. Debris erosion due to condensation and condensate flow was neglected. Insulation debris still within its cloth cover was not expected to erode further. For RMI debris, erosion was not a consideration. For microporous insulations such as calcium silicate or Min-K, the degree of potential washdown erosion has not been determined, and the outcome could vary substantially with the type of insulation and even by the insulation's manufacture process (e.g., one vendor's calcium silicate readily dissolves while another's does not). The key PWR debris erosion process during washdown would be the erosion of debris impacted directly by the sprays and possibly debris layered on any gratings located below the break overflow. The erosion of debris on the sump pool floor would typically be evaluated under the sump pool transport processes, and most of the debris located directly below the break likely would be pushed away from the break area and be considered in the sump pool transport evaluation.

Because the result of the erosion process is additional very fine and easily transportable debris, the process should be evaluated. All erosion products should be assumed to transport to the sump pool. Further, this debris would also likely remain suspended in the sump pool until filtered from the flow at the sump strainers. Therefore, even a small amount of erosion could contribute to strainer blockage.

To estimate the volume of debris that was eroded, the volume of small and large debris that was impacted by the sprays should be estimated first. In the reference plant study, 1% of the small- and large-piece debris that was directly impacted by the sprays was considered to have eroded on the basis of the DDTS conclusion that erosion by sprays was <1%. Note that the 1% value was based on small-scale tests where the spray flow rates were scaled to the volunteer BWR plant. If the spray flow rate was increased, the erosion rate could possibly increase; however the 1% erosion represented a conservative conclusion for a minor rate of erosion. Even if the spray-driven rate of erosion was increased, its contribution to the overall erosion within containment would likely remain relatively minor compared to the recirculation pool erosion. Note that erosion does not apply to fine debris because it is already considered to be individual pieces incapapble of being eroded, and does not apply to intact debris because the canvas cover would likely protect the enclosed insulation.

Retention of debris on surfaces during washdown needs to be estimated for the debris (postulated to be deposited) on each surface (i.e., the fraction of debris that remains on each surface). The estimates would be based on a combination of experimental data and engineering judgment. Generic assumptions used in the reference plant study included:

- For surfaces that would be washed only by condensate drainage, nearly all deposited fine and small debris likely would remain there. The study assumed 1% of the fibrous debris would be washed away (99% retention on the surface) in a realistic central estimate, and 10% for an upper-bound estimate.

- For surfaces that were hit directly by sprays, the DDTS assumed 50% and 100% of small fibrous debris was washed away for the central- and upper-bound estimates respectively. Large and intact debris was assumed not be washed down to the sump pool (complete retention).

- For surfaces that were not sprayed directly but subsequently drain accumulated spray water, such as floors close to spray areas, the retention fractions are much less clear. These fractions likely would vary with location and drainage flow rates and, therefore, should be location specific, with more retention for small pieces than for fine debris.

- All erosion products are assumed to completely wash to the sump pool.

The overall blowdown/washdown transport fraction is the total quantity of debris entering the sump pool divided by the total volume of insulation generated within the ZOI.

In conclusion, the reference plant study in Appendix VI of NRC-SER-2004 developed a methodology that considered both transport phenomenology and plant features, and that divided the overall complex transport problem into many smaller problems that either are amenable to solution by combining experimental data with analysis or able to be judged conservatively based on the existing debris transport knowledge. The reference plant methodology resulted in predicted transport fractions that were conservative. The conservatism in the transport decisions is related to the availability of applicable data. Without data, the results should be conservatively hedged toward transporting the debris to the sump pool. The results also depended upon the analytical objective (i.e., bounding versus realistic results). Plant-specific analyses must consider a range of break locations. In performing blowdown/washdown analyses, it is important that (1) the debris-transport model correctly estimates the size and type of debris to match the characteristics of the debris-transport behavior, (2) the break region and the break region exits are analyzed in substantial detail because a significant portion of the debris capture may occur there, (3) the containment spray drainage patterns should be determined to support the washdown analysis, to determine where the debris would enter the sump pool, and to determine how the spray drainage would affect sump pool turbulence, and (4) the spray-drainage pathways, where potential debris blockage might occur, should be identified. The complexity of plant-specific methodologies could vary significantly from one plant to the next.

In general, for the fine LOCA-generated debris, it is likely that realistic analysis will show that a high percentage of the fines would be transported to the sump pool via the spray drainage flows. The fines retained in the upper containment would be the fines blown into areas not impacted by the containment sprays or the spray drainage. Transport fractions tend to decrease as the debris size increases. Realistically speaking, RMI might be expected to transport less readily than fibrous debris because it is more dense. During the resolution of GSI-191, the licensees typically chose to make highly conservative blowdown/washdown assumptions rather than perform the detailed analyses outlined herein. This conservative approach was not unreasonable, considering that the majority of the fines blown into the upper containment would be predicted to wash down to the sump pool, and that the majority of the larger debris residing in or entering the sump pool would typically settle in the sump pool rather than accumulate on the strainer.

5.4.2.3 BWR Blowdown/Washdown Transport

BWR Blowdown Containment Dispersion

The physical processes governing BWR blowdown dispersion are basically the same as the processes described in Section 5.4.2.2 for PWRs. Blowdown within a BWR containment results in primary system depressurization with flows through the downcomer vents to the suppression pool. Debris generated by a LOCA would be carried by these flows, with portions of the debris being captured along the way by deposition onto structures or by gravitationally settling onto equipment and floors. The blowdown dispersion within a BWR drywell was studied in the DDTS (NUREG/CR-6369).

The BWR containments differ from PWR containments in both size and design. The BWR suppression pools allow the BWR containment volumes to be significantly smaller than the PWR containments. The break discharge from a BWR primary system would cause flows toward the vent downcomers leading to the suppression pool. Gratings rather than solid floors typically separate the elevation levels in BWR drywells. A break above a continuous grating would trap the larger debris. Debris trapped on a grating directly below the break overflow would be subjected to substantial erosion. In addition to the break flows, the containment sprays would transport debris. Depressurization flows entering a vent downcomer may undergo turns, resulting in inertial debris capture at the vent entrances or debris may fallout onto the drywell floor. A pool of water would form on the drywell floor with its depth governed by the elevation of the entrances into the vent downcomers. The transport of debris in the drywell floor pool could be evaluated similarly to PWR sump pool transport. A CFD code was used in the DDTS to simulate the drywell floor pool for each of the BWR Mark I, II, and III designs. Debris transport within a BWR suppression pool is unique to BWRs and is discussed in Section 5.4.3.2.

The DDTS employed the logic-chart approach to decompose the overall transport process into individual steps, similar to the evaluation process described in the preceding section for PWRs. Typically, these charts treat each debris type and size category, and each break scenario separately. The analyst can choose the level of detail based on the application requirements and the information available.

A system level code, e.g., MELCOR, can be used to estimate containment conditions, flow dispersions, rates of flow, flow composition, condensation rates, etc. This information is useful when applying engineering judgment to transport models. The dominant debris capture mechanisms considered were inertial capture from fast moving flows and gravitational settling once flows slowed down.

Inertial capture of flow-driven fibrous debris was studied in the DDTS. The CEESI facility air jets were used to destroy fibrous insulation blankets and then to carry the debris downstream through a series of structural obstacles based on prototypical BWR containment congestion. The tests demonstrated the ability of structural components to capture debris. The average overall transport fraction for small debris in the CEESI tests was 33% of the total debris generated (i.e. ≈2/3 of the generated debris was captured, primarily by inertial impaction) within the test facility. Gratings were found to be the most effective debris catcher. Photographs of test debris capture on a grating were shown in Figure 5.3-2. Figure 5.4-4 shows a plot of the available debris capture data on a specific test grating, where the capture efficiency is plotted versus the debris loading approaching the grating. The capture efficiency did not seem to depend significantly upon the debris loading but did depend upon surface wetness. MELCOR analyses showed that steam condensation onto containment surfaces would happen relatively rapidly. The average fractions of small debris captured by each test structure component are shown in Table 5.4-1. The first continuous test grating stopped almost all of the larger debris but the capture fraction for that grating was not obtained due to the failure of the test mister system to adequately wet the continuous grating (i.e., this grating illustrated dry behavior). The subsequent two gratings in the test were successfully wetted and it was found that second of these two wetted gratings captured less efficiently than the first wetted grating (downstream of the first grating that failed to become wetted). This makes sense because the debris that had passed through the first wetted grating was smaller and more likely to pass through subsequent gratings. The 90-degree bend between two test chambers captured debris. The bend was maintained wet by a mister. About 17% of the debris entering the second auxiliary chamber was trapped on the chamber wall as a direct result of the bend. The pipes and I-beams captured a lesser, but still substantial amount.

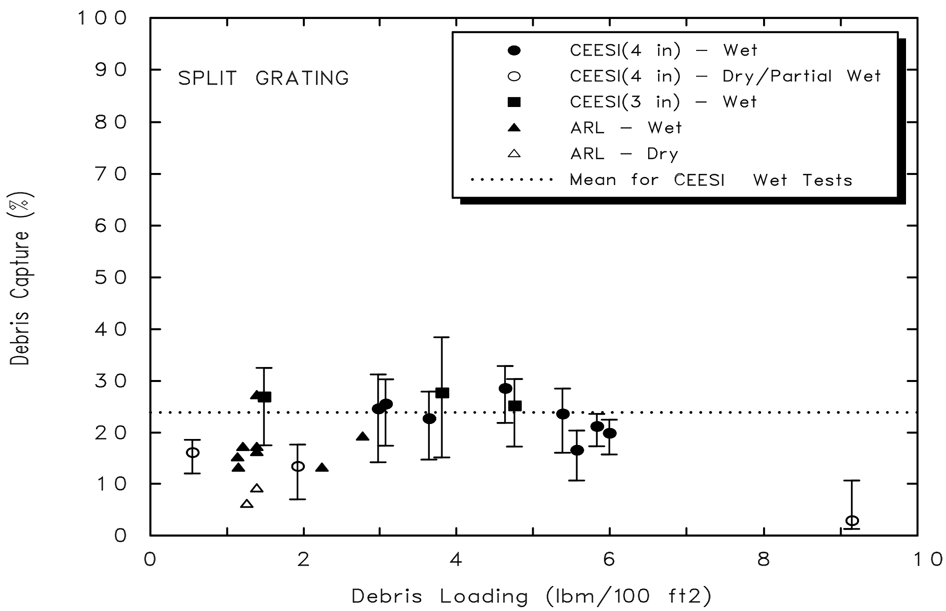

Figure 5.4-4. Capture of Small Debris by Grating

Table 5.4-1. Small Debris Capture Fractions

Structure Type	Debris Capture
I-Beams and Pipes (Prototypical Assembly)	9%
Gratings V-Shaped Grating Split Grating	 28% 24%
90o Bend in Flow	17%

Following the blowdown process, the containment sprays and/or condensate drainage would wash debris from surfaces and down into the drywell pool with overflow into the vent downcomers. Debris on surfaces hit directly by the sprays would be much more likely to transport with the flow of water than would debris on a surface that is merely wetted by condensation.

The washdown process in BWRs differs from that in PWRs, since elevations within the drywell of BWRs are, typically, separated by gratings rather than concrete floors. In PWRs, water would often flow across a floor to a floor drain but in BWRs the sprays pass through a grating from one level down to the next level. The DDTS included a small-scale experiment where debris was placed on top of a prototypical section of grating and then exposed to water spray. The purpose of the experiment was to study the erosion of the fibrous debris at various flow rates and to determine the ability of debris to remain on the grating. These tests are described in Volume 2 of NUREG/CR-6369. These tests demonstrated that nearly all of captured fibrous debris generally smaller than the grating openings would be washed through the grating, and that larger debris remaining trapped on top of the gratings would erode into finer debris, with the erosion fraction dependent upon flow rate. The debris directly under a simulated full break flow eroded at approximately 9%/hr. Debris erosion due to the impact of the sprays and spray drainage flows was found to be much less significant. The DDTS concluded that <1% of the LDFG was eroded due to the containment sprays. The spray experiments were carried out for 30 min, which was estimated to be the maximum credible time spray would be operated following a LOCA in a BWR. Further, the <1% result was based on tests with debris large enough to not be washed down through the support grating, thereby distinguishing erosion from the washdown transport fraction that was typically associated the fines and small piece debris. Debris erosion occurring because of condensation and condensate flow was neglected. Insulation within it cloth cover was not expected to erode further. These tests did not evaluate the erosion of microporous insulation debris.

The DDTS studied the turbulence levels within a drywell pool for each of the BWR Mark I, II, and III containment designs using a CFD code (Volume 3 of NUREG/CR-6369). The turbulence levels were correlated with debris settling by using the same CFD code to simulate flume tests that studied debris settling within a pool. That is, if the turbulence levels as predicted with this code were sufficiently high to keep debris from settling within the test flume, then the debris would not likely settle within the drywell pool at similar or higher turbulence levels. The turbulence levels were studied for scenario conditions where the drywell pool received full break-water overflow and for conditions where the break steamed so that the pool was driven by condensate and/or spray drainage. Under full flow the debris was predicted to likely transport into vent downcomers, but under more quiescent conditions, the debris was found more likely to remain in the drywell pool.

5.4.3 Pool Debris Transport and Recirculation

The blowdown/washdown analysis provides a debris source term for the evaluation of the debris transport to the PWR sump pool or the BWR suppression pool, which in turn, provides an estimate for debris accumulation on the strainer. The source term should include the quantities of debris by type and size classification and the locations where the debris enters the sump or the suppression pool. In addition, the blowdown analysis would provide an estimate for the quantities of debris deposited directly on the sump pool floor or in the suppression pool. The pool debris transport analysis estimates the quantities of debris by type and size classification postulated to accumulate on the recirculation strainers.

Re-suspension, the opposite of settling, is the phenomena by which debris or sediment located at the bottom of the suppression pool is picked up from the bottom and transported upwards. Re-suspension is possible when turbulence levels and/or recirculation velocities in the boundary layer are capable of providing sufficient upward drag on the debris to overcome gravitational forces. Analytically, the re-suspension mass flux can be calculated as a product of the sediment mass and a re-suspension coefficient that is a function of the sediment particle size and shape, the pool velocity profiles, and the pool turbulence levels. The re-suspension coefficient would transition from a value of one, associated with complete re-suspension during the initial highly turbulent blowdown phase, to zero or near zero during the post blowdown recirculation phase, which is relatively quiescent. In between one and zero, the coefficient would be governed by a time-dependent decay in the rate of re-suspension. This analytical technique was described in the BWR ECCS strainer blockage parametric study [NUREG/CR-6224] and implemented into the wetwell transport model of the BLOCKAGE 2.5 code (NUREG/CR-6371). Appropriate values for the re-suspension coefficient should be obtained from experimental studies where possible. Otherwise, conservative assumptions, based on achieving a conservative head loss result, are required.

Settling of debris within the suppression pool, reduces the debris available for accumulation on the strainers. The rates of debris sedimentation, also referred to as the "settling velocities," are a function of the debris characteristics of density, shape, and size, and the suppression pool dynamics of turbulence levels and flow velocity profiles. Analytical estimates of settling velocities are unreliable, even in still water, for complex undefined shapes characteristic of typical debris. The effects of pool turbulence on settling velocities are also difficult to predict analytically.

5.4.3.1 PWR Sump Pool Debris Transport

The sump pool debris transport evaluation considers two relatively distinct phases. The first phase involves the transport of debris as the sump pool fills, before activation of the recirculation pumps. The second phase examines the transport of debris within the established sump pool with the recirculation pumps operating. The further erosion of debris within the sump pool is considered to be a relatively long-term process and is, therefore, evaluated in the second phase rather than the first.

The information requirements for the sump pool transport analyses include the geometric shape of the pool including objects within the pool, the locations and rates of flows entering the pool, the location of and flow through the recirculation strainer, and the debris source terms from the blowdown/washdown analyses. The physical description includes any debris interceptors designed to preclude or reduce debris transport. The typical debris interceptor is a curb-like device designed to inhibit debris from moving across the sump pool floor, at least until sufficient debris piles up behind the interceptor to form a ramp that allows additional debris to slide over the top. Another type of interceptor is a grating or perforated plate across a flow pathway that traps debris at that pathway; once blocked by debris, the interceptor effectively reroutes flow over the interceptor or through a more torturous pathway to the recirculation strainer.

Sump Pool Formation Debris Transport

The PWR sump would begin to fill with water immediately after the LOCA break due to both RCS blowdown effluents and the drainage of the containment sprays. Filling of the pool continues until a relatively steady water level is achieved. Analytically, the sump pool formation period is generally assumed to range from break initiation to ECCS switchover to the recirculation mode. The analysis of transport after switchover is described in the sump pool recirculation debris transport section. The primary driving force for moving debris during pool formation, especially for the large debris, is sheeting flow as the initial water from the break spreads across the sump floor. This behavior was observed during the integrated debris transport tests (NUREG/CR-6773) in which debris, initially deposited on the floor, was observed to be pushed along with the wave front. These observations demonstrated that sheet-flow driven debris can be transported a considerable distance, even to the other side of the sump pool, and that once in motion, a piece of debris can readily gain enough momentum to carry it past openings where water would otherwise flow, such as a doorway from the primary sump area into an interior space such as the reactor cavity. Once the water depth becomes sufficient, drag forces of the water flow on the debris becomes substantially less dynamic than the original sheeting flow such that further debris movement is significantly decreased, especially for larger debris. Individual fibers continue to move as suspended debris in the water flow.

Substantial quantities of debris may be initially deposited on the floor of the compartment where the LOCA break occurred (e.g., a steam generator compartment), and the subsequent break compartment sheeting flow could transport substantial portions of that debris from the break compartment into other sump locations (e.g., the annular sump pool area via personnel access doorways). As the sump pool fills, water containing debris will flow into spaces located below the sump pool floor, such as the reactor cavity. However, in some situations, the pathway is sufficiently tortuous that larger debris would not transport in the space. When one of these spaces becomes completely filled and relatively quiescent, that space is referred to as an inactive pool or inactive volume. Once debris enters an inactive pool, that debris may be considered as permanently trapped there unless there is subsequent sufficient flow to once again entrain the debris. Once large-piece debris enters an inactive pool region, it is likely to remain there. The situation is less clear with respect to fine suspended matter because even natural circulation could allow the suspended matter to escape.

The debris entering the sump pool during the pool fill transport period would include debris initially deposited in the sump pool during blowdown and any debris washed back down into the sump pool by the containment sprays during this period. The sump formation period would likely be relatively short compared to the time it would take for the majority of washdown to occur; therefore most of the washdown debris would typically be expected to transport into the sump pool during the recirculation transport phase. While larger debris may be moved around during pool fill, such debris would likely remain on the pool floor, unless buoyant. Such debris would not accumulate on the strainer prior to switchover to recirculation and after switchover the strainer approach velocities would typically be too slow to lift the large debris from the floor and onto the strainer. Fine suspended matter would likely become relatively uniformly mixed within the pool, with the possible exception of the inactive pool regions.

The quantity of fine debris trapped within inactive pools has been estimated by multiplying the total quantity of fine debris estimated to be in the sump pool as a result of blowdown transport[8] by the ratio of the inactive pool volume to the total sump pool volume. Due to the associated uncertainties, the NRC staff limited the fraction of debris moving into inactive pools to a maximum of 15% of the blowdown source, unless analysis demonstrates otherwise. Regarding the distribution of the larger debris on the sump pool floor following pool fill, it is not conservative to assume that all such sump pool debris is uniformly distributed across the containment floor as settled debris. If it can be shown that debris of a specific size category would be settled debris, and that the subsequent sump pool velocities and turbulence were insufficient to cause such debris to accumulate on the strainers (i.e., entrainment), then the issue of debris distribution is of no consequence. Otherwise, an analysis with conservative assumptions will be required to determine the initial distribution of debris before switching to recirculation mode. For example, it could be conservatively assumed that the pool fill relocated all such debris near the recirculation strainers. A more detailed analysis could be used to relax the conservatism.

Sump Pool Recirculation Debris Transport

This phase in the debris transport evaluation estimates the quantities of debris, by type and size classification, that would arrive at the recirculation strainer for potential accumulation. The source debris includes the debris already in the sump pool when the recirculation pumps start

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[8]Because the transport of debris by the washdown processes are time-dependent, washdown debris will enter the sump pool both before and after the pool has filled and the recirculation pumps have started. Analytical capabilities have not been sufficiently developed to determine how much washdown debris enters before and how much enters after the pool has filled. Therefore, the only reasonable conservative assumption is that only the debris deposited in the sump pool area by blowdown processes can be transported into inactive pool volumes.

and the debris subsequently entering the pool due to washdown processes. The typical recirculation transport analysis estimates the overall potential quantities of debris transported, i.e., the transport processes are sufficiently complex that time-dependent analyses are not practical. However, if the only debris with the potential for accumulation on the strainers consisted of suspended matter such that settling and other forms of deposition could be neglected, and the time frame for the washdown processes was reasonably short compared to that for the recirculation processes, a first-order estimate of time dependency could be made based on a uniform concentration within the pool.

The three main types of debris that are considered to exhibit prototypical behavior for recirculation sump pool transport are: (1) suspended debris, (2) buoyant debris, and (3) settled debris. Suspended matter typically consists of fine debris (i.e., basically individual fibers and fine particulates). Although these fine debris types will settle in still or relatively calm water, the settling process can take substantially more time than the typical sump pool turnover times. For example, NRC staff has observed test tank water during vendor head loss testing that was completely obscured by fine suspended particulates, and after standing stagnant overnight, was still completely obscured the next day. In another example, chemical-effect precipitates (ICET Test 1) collected in a bucket took about three days to settle to the bottom of the bucket. An actual plant sump pool is not calm due to the continuous entrance of break overflow and containment spray drainage into the sump pool. This drainage added to the recirculation flow, especially at channels through passageways induces turbulence. In the absence of analysis that shows otherwise, it is conservative and reasonable to assume complete transport of the suspended fines to the strainer.

Debris that remains buoyant will float on the surface of the pool and, therefore, may tend to drift toward the strainer. Examples of buoyant debris are types of closed cell foam insulations where water penetration is unlikely. Typically, such debris would not be a strainer blockage problem because the typical strainer would be submerged. Hence, the buoyant debris is typically dismissed from further consideration. The exception, of course, would be the partially submerged strainer where the accumulation of the buoyant debris against the strainer could contribute to the potential blockage problem.

Settled debris may or may not transport to the strainer. The settled debris of greatest concern is typically shreds of fibrous debris. Dry fibrous debris will initially float because most of its volume is free space filled with air. But over time, water will infiltrate the fibers, and eventually the debris will sink to the pool floor, whether it is a small shred or a complete intact pillow (NUREG/CR-2982). The rate of water infiltration is highly dependent on the temperature of the water (surface tension effect). Whereas cold water can take hours to days to infiltrate fibrous insulation, hot water can saturate shreds of fibrous debris rather rapidly. If large-piece fibrous debris (or an intact pillow) remains buoyant for a sufficient time, it could float over the top of the recirculation strainer and then sink onto the strainer. However, the probability of this behavior resulting in significant blockage to the strainer is relatively small, i.e., the large piece would either simply lie across the top of the strainer or fall to the floor beside the strainer.

Once fibrous debris has settled to the sump pool floor, its mode of transport would be to either slide or roll along the floor toward the strainer. The debris could also be resuspended if it transports to an area of higher flow or turbulence. Floor transported debris would be subject to entrapment by obstacles such as curbs and debris interceptors. Small-scale testing has been conducted to measure the necessary velocities to cause the movement of various kinds of settled debris (e.g., NUREG/CR-6772).

For a given type and size of debris, a certain flow velocity is needed to move the piece of debris along the floor. A greater velocity would be needed to cause the debris to become sufficiently entrained to lift over an obstacle. If a piece of debris were to arrive at a strainer located above the sump floor, it may take a greater velocity to lift the piece onto the strainer resulting in accumulation. Further, for debris on a vertical strainer surface, a minimum velocity may be required to keep the debris attached to the strainer. Turbulence affects minimum transport velocities. Most separate-effects testing was conducted with uniform low-turbulent flows, and some testing has been conducted with turbulence induced. A flow assessment can estimate whether or not the flows approaching a strainer are sufficiently fast or turbulent to transport floor debris from the floor and onto the strainer. Some strainer configurations have a strainer recessed into a pit below the sump pool floor where the floor transported debris could simply fall into the pit and onto the strainer. Limited vendor-performed head loss testing in conjunction with debris transport to the strainer in facilities designed to replicate plant strainer approach velocities have shown a tendency for the heavier RMI debris and the typical paint chips to settle within the flume rather than accumulate on the test strainer, i.e., the flume test velocities were less than the debris transport velocities for debris that has settled to the flume floor. This vendor testing was plant-specific and therefore not generally applicable to all plants, however the noted trend would apply to a significant number of plants. There are exceptions to generic transport metrics. For example, a piece of RMI debris with an entrapped air bubble or a paint chip that floats may transport to the strainer. In addition, in vendor head loss testing, some fibrous insulation shreds remained buoyant and floated over top of the test strainer most likely due to air entrapment.[9] The final important aspect of floor debris transport is that some types of debris (e.g., fibrous and particulate insulation debris) are subject to erosion, resulting in additional suspendable fines that would likely be completely transported to the strainer. The erosion process is discussed in Section 5.4.4.

Determination of the transport fractions for floor-transportable debris requires an assessment of sump pool flow velocities and patterns, together with flow turbulence. The best method for this hydraulic assessment is the application of a computational fluid dynamics (CFD) code to the plant-specific sump pool. An example CFD application is the CFD study performed for reference plant, which is found in the Appendix III of NRC-SER-2004.

After a suitable CFD code is selected, a three-dimensional geometric model of the sump pool is developed. Models should include an appropriately detailed calculational mesh. The geometric model should be sufficiently detailed to include significant structures located within the sump pool and such details as stairwells and flow passageways. The height of the model should extend from the bottom of the pool to the maximum anticipated depth of water. Note that some CFD codes support the importation of CAD models. The locations and flow rates of water sources to the sump pool, including effluents from the LOCA break and containment spray drainage, are simulated. There should be sufficient detail to reasonably capture the locations of the incoming water to model its influence on flow and turbulence. The water drawn from the pool via the recirculation pump is simulated.

Analysts have typically focused on simulating the steady-state flows of a fully established pool but some have simulated the pool fill-up transient. A simulation typically requires appropriate

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[9]Vendor head loss testing was typically conducted with colder water that may not easily saturate fibrous debris. The usual test procedure would include a step were the fibrous debris was pre-saturated before introduction into the test tank typically using heated water. The floating fibrous debris noted during vendor testing was likely due to incomplete saturation.

boundary condition assumptions for surfaces, and inlet and outlet flows. Steady-state conditions must satisfy conservation of water mass within the pool; for example, the simulation might use a specified flow rate for mass inflow but then use a pressure boundary condition that allows the code to adjust the pressure at the bottom of the sump to balance the mass flow entering and exiting the pool without introducing numerical instabilities. Many CFD codes have user options for selecting numerical models for solving incompressible flow (Navier-Stokes equations), as well as for simulating turbulent kinetic energy and the dissipation of the turbulence. CFD codes that include features that model phenomena in sump pools should be selected. For example, codes should model specific sump pool flow behavior like turbulence dissipation of swirling flows. CFD codes require the analyst to specify appropriate initial conditions to initiate a simulation and to specify the numerical convergence criteria for the acceptance of a solution.

The CFD results are typically two-dimensional figures showing either the velocity flow patterns or the patterns of flow turbulence at particular levels within the pool. An example of a flow velocity pattern is shown in Figure 5.4-5 (Figure III-36 in NRC-SER-2004). The scale on the right side of the figure shows the color codes used for the pool velocities. Referring to Figure 5.4-5, shreds of LDFG debris located in the yellow or red zones (i.e. velocities greater than about 0.06 m/s (0.2 ft/s)) would most likely move with the flows, and the shreds located in the blue zones (i.e., velocities less than about 0.03 m/s (0.1 ft/s)) would likely remain at those locations, but the movement of the shreds located with the green zones is less certain. In addition, CFD results can include streamline plots that would indicate how fine suspended debris moves within the pool.

The scenarios that need to be simulated likely include both SBLOCAs and LBLOCAs and the various break locations, e.g., alternate steam generator compartments. Both the pumping flow rate and the pool depth can vary with the size of the break. Activation of the containment sprays is dependent on containment pressurization, which in turn, depends upon the size of break. In addition, the debris source term under evaluation may depend upon the size of the break, as well as break location.

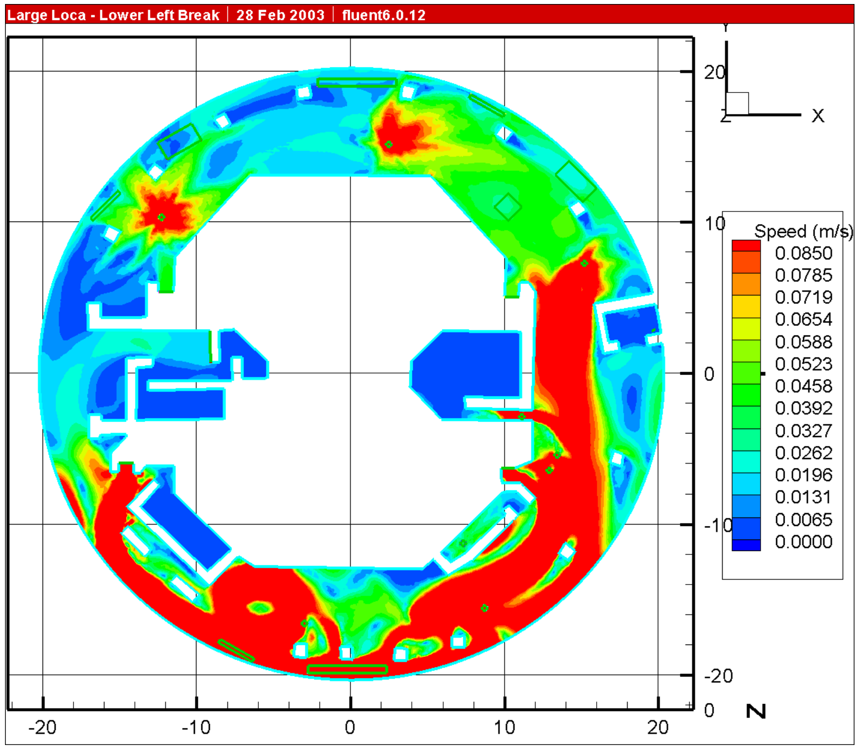


Figure 5.4-5. Example CFD Sump Pool Flow Velocity Pattern

With the pool hydraulics simulated, debris transport should be estimated by using the velocity and turbulence patterns and an assessment of the initial debris location in the sump pool. Unfortunately, no debris transport model has been developed in which a straightforward application of a computer code could be used to calculate the transport. The primary method in use involves the application of engineering judgment of the CFD results to estimate transport fractions. As such, it can be useful to establish CFD plot contours corresponding to threshold transport velocities that determine whether specific floor-settled debris would likely be transported.

Refer to the logic chart for the debris-transport model shown in Figure 5.4-1, as an example of transport assessment. This figure includes steps for debris transport during pool fill-up and during the recirculation phase for which the analyst could implement transport fractions based on analysis, experimental data, or conservative engineering judgment. During the evaluation of the fill-up phase, the chart shows that debris was either transported to the sump strainer, away from the sump strainer, or into an inactive pool. The debris transported to the strainer was added to the debris that was determined to be deposited at the strainer by the blowdown/washdown processes and the debris in the inactive pool was assumed to remain in the inactive pool. The fraction of debris predicted to be transported away from the strainer by the pool fill processes and that did not enter an inactive pool region would then be subjected to the recirculation transport processes. For material remaining in the active pool, the debris is either transported to the strainer or is predicted to stall in the pool, where it may then be subject to further erosion.

Pool velocity and turbulence characteristics determine the areas of the pool where debris may be entrapped. Flow streamlines can be used to determine whether debris entering the pool at a discrete location would likely pass through a potential entrapment location. During the integrated debris transport tests (NUREG/CR-6773), shreds of water-saturated fibrous debris were observed to accumulate in relatively quiescent locations within the simulated sump pool. Figure 5.4-6 is a photo showing debris stalled within a slow-flowing region from a one-tenth scale simulation of a plant sump annulus. Most of these shreds tended to remain in these locations for the relatively short duration of these tests. However, close observation showed an occasional shred exiting the low-flow area and was re-entraining in the surrounding flows. If such a shred subsequently encountered another quiescent location, it was likely to become stalled again. For a shred to be transported all the way to the strainer, a continuous transport pathway was needed where the flow velocities generally exceeded the minimum velocity required to keep the piece moving. This behavior suggests a method of estimating the fraction of debris transported along the floor within the sump pool.

CFD analyses can provide realistic descriptions of the flow conditions at floor level. By designating velocity contours based on experimentally measured thresholds for movement of the settled debris, the locations for debris entrapment become clearly indicated. By overlaying the CFD plots with the estimates for conservative debris placement at the start of pump recirculation and the locations where washdown debris enters the pool from above, a graphical integration can be performed to arrive at transport fraction estimates. Debris predicted to be located in a region of flow moving slower than the threshold for debris movement would be considered as not being transported. The transport fraction is obtained by summing these quantities and subtracting it from the total debris load to calculate the quantities transported, then dividing the obtained value by the original source terms. The actual calculation method could, for example, subdivide the pool floor into a fine mesh grid with each grid space independently assessed, the results of which are then combined.

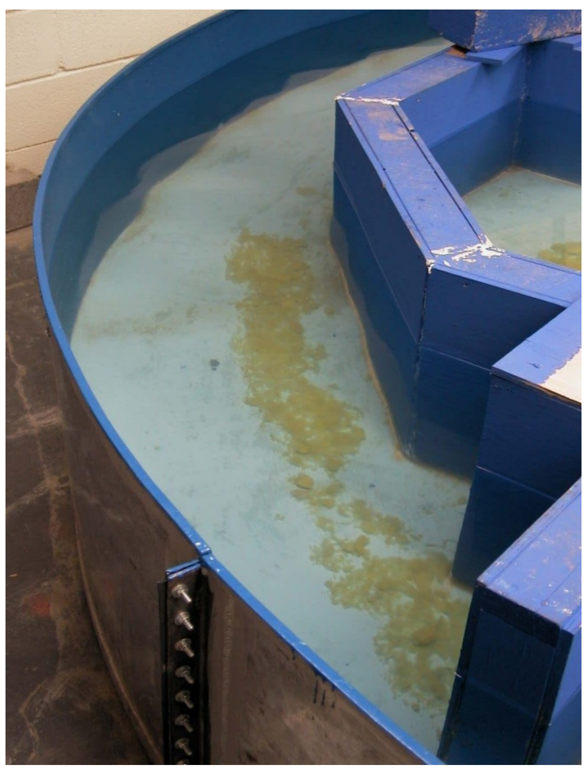


Figure 5.4-6. Debris Stalled in a Slow-Flowing Region of the Simulated Annulus
(Figure 6-3 in NUREG/CR-6773)

In addition to velocity contours, the streamline plots provide reasonable connecting pathways whereby a piece of debris would likely travel from its original location in the pool to the recirculation sumps. If a transport pathway passes through a slower portion of the pool, then debris moving along that pathway could stall and not be transported to the recirculation sump. Otherwise, transport to the strainer is more likely.

Effects of pool turbulence are more difficult to quantify. The transport results based on flow velocities may need to be adjusted by also overlaying the CFD-calculated turbulence level plots with the velocity plots. For example, turbulence levels may be relatively high near a location with a source of water plummeting into the pool. If high turbulence coincides with a flow velocity slower than the threshold transport velocity, it is prudent and conservative to assume that debris would be transported from that location. As noted above, stalled debris has been observed to resume movement, a behavior attributed to localized pulsations of turbulence that suddenly peaked at the position of that piece of debris. Although this behavior cannot be reasonably quantified, transport estimates should be modified to consider these effects because turbulence is capable of moving debris when bulk flow will not or keeping debris suspended to move with the flow at any velocity. One method of accounting for turbulence effects might be to decrease the threshold velocities for transport. In addition, a certain amount of engineering judgment may be required to arrive at a reasonable solution.

5.4.3.2 BWR Suppression Pool Debris Transport

During a postulated LOCA in a BWR, the suppression pool would be affected by the clearing of the vent downcomers of water as the drywell pressures rapidly increase. The suppression pool level will swell due to the vent clearing which will also induce significant turbulence in the pool. Debris transport within a suppression pool was studied and documented in NUREG/CR-6224. Steam and non-condensable gases from the drywell would be discharged into the pool. Initial large-scale turbulence would lead to re-suspension of a large fraction of any accumulated suppression pool sludge. Near the end of the drywell blowdown phase, oscillatory steam condensation could result in a chugging oscillation in the downcomers. Experimental data suggest that amplitude, frequency, and duration of the condensation oscillations are primarily functions of the mass flow rate, concentration of the non-condensables in the mass flow, downcomer submergence, suppression pool temperature, and break size. Pool turbulence would retard debris settling, and the high intensity turbulence would persist for the first approximately 50-100 sec for a LBOCA. After the pool turbulence dissipates, the pool would enter a longer term low-energy phase with recirculation flow patterns governed by the recirculation of water draining into the pool from the drywell and the recirculation pump draw. Debris located within the suppression pool would include suppression pool sludge and any other debris originally in the pool, and debris transported into the wetwell from the drywell both during the dynamic RCS depressurization phase and the post-depressurization recirculation phase.

The dynamics of the suppression pool turbulence provides a time-dependent behavior that would affect the accumulation of debris on the recirculation strainers. In addition, the recirculation flows may be throttled back according to operating procedures, which can also affect debris accumulation. BWR recirculation pumps start almost immediately following a LOCA and would therefore be operating during the initial period of high turbulence, which could cause larger debris, maintained in suspension by the high turbulence, to accumulate. Once the turbulence had dissipated, the larger debris would tend to settle to the bottom of the suppression pool rather than accumulate on the strainers. Then during the quiescent phase, debris accumulation would be due primarily to the suspendable fines. Suppression pool dynamics would vary among the Mark I, II, and III containment design.

The NRC-sponsored tests to study the settling rates for fibrous insulation debris and BWR suppression pool sludge in BWRs are described in NUREG/CR-6368. Settling velocities were found to depend upon the characteristics of the test debris. The test debris was based on the characteristics of debris expected to transport into the suppression pool. The fibrous insulation debris was prepared by passing fibrous insulation cut into large pieces through a leaf shredder. A sludge simulant was prepared using a mixture of iron oxide powders designed to match a BWROG characterization of suppression pool sludge. During the high-energy phase which lasts about 50 sec for a LLOCA and about 10 min for a MLOCA, these tests demonstrated that the turbulence would suspend all of the sludge initially contained at the bottom of the suppression pool and would keep both the sludge and the fibrous debris in suspension throughout the high energy phase. The turbulence would also further disintegrate the fibrous debris. After the high-energy phase, the residual turbulence in the pool is expected to decay to relatively quiescent conditions, allowing for sedimentation of the suspended debris. Note that these NRC sponsored tests did not include a simulation of the turbulence associated with the steady state operation of the recirculation flows Turbulence could maintain the finer debris in suspension. In the NRC experiments, the suppression pool was initially brought to a fully mixed condition by simulated chugging. After about 10 min the chugging was terminated, and the turbulence in the suppression pool was allowed to decay naturally. Visual observations revealed that soon after the termination of chugging, the debris began to settle to the pool floor. Water samples were drawn from five locations in the suppression pool at pre-determined intervals to measure debris concentrations. The debris concentrations were then used to estimate settling rates for each species, i.e. fibrous debris and particulate sludge. More than 60% of the total debris by mass exhibited settling velocities of less than 1 mm/sec, suggesting the that fibrous debris would require considerable time to settle in the suppression pool. The NRC experiments demonstrated that, on average, the sludge particles settle faster than the fibrous shreds. With the test particulate ranging from about 6 to 100 µm in diameter, about 30% by mass exhibit settling velocities in excess of 10 mm/sec, about 60% in excess of 2 mm, and the remaining approximately 10% of the sludge particles have settling velocities below 0.1 mm/sec. The median particle settling velocity was about 3 mm/sec.

Those applying the NRC-sponsored debris settling test results should consider that significant differences existed between the scaled test facility and the referenced plant suppression pool. The test facility mechanically simulated the condensation oscillations rather than the actual condensation. The mechanically induced turbulence was an approximation of a realistic postulated accident scenario. In addition, the tests did not include a simulation of the flow turbulence associated with the steady state operation of the recirculation flows. The sludge test debris had a larger size distribution than the BWROG-recommended distribution. The test results were judged to be characteristic of the types of behavior that could be expected within a suppression pool. When using the test results to predict plant behavior, the differences discussed above should be considered. Settling velocities would certainly be affected by these characteristics.

The NRC developed the BLOCKAGE 2.5 code (NUREG/CR-6370 and -6371) as a tool to evaluate licensee compliance regarding the design of suction strainers for ECCS pumps in BWRs as required by NRC Bulletin 96-03. This code includes scoping-level models for drywell debris generation and transport to the suppression pool (which are inferior to the latest PWR generation and transport models), a state-of-the-art suppression pool transport model, a strainer head loss model, and a probabilistic model that calculates a full range of postulated breaks to determine an overall plant probability of strainer blockage. The processes affecting debris accumulation are all time-dependent. These include drywell debris transport into the suppression pool, the re-suspension coefficient, the turbulence dissipation rate, the water temperature, and the pump flow rates. The code subdivides the size distribution into many groups, with each group having a group-specific settling velocity and head loss characteristics. The rate of debris accumulation on each active strainer is based on the time-dependent concentration of debris and the pump rate of flow. The calculations for strainer head loss are based on the head loss correlation in NUREG/CR-6224.

The conservative approach to modeling suppression pool transport with respect to maximum debris accumulation on the strainer was to assume complete re-suspension of debris and preclude sedimentation. Therefore all debris that is initially within, or later enters the wetwell, would be assumed to accumulate on the strainer or strainers. The NRC position in RG 1.82, Revision 3, and Section 2.3.2.4 is that credit should not be taken for debris settling until LOCA-induced turbulence in the suppression pool has ceased. However, the maximum head loss may not occur with the maximum quantity of debris, but may be associated with a debris bed composed of a smaller amount of fiber. Having less fiber can result in the particulate debris collecting in a smaller volume creating a denser debris bed.

5.4.4 Erosion of Containment Materials and Debris

The post-LOCA containment environment can potentially damage containment materials or further degrade LOCA-generated debris. The damage to containment materials could generate additional debris, and the degradation of existing debris could generate transportable fines from less transportable larger debris. Although, the erosion could be considered a debris-generation issue, it is addressed in the transport section because the assessment of such damage requires knowledge of the containment environment, such as locations of water pools, water flow patterns and the rates of flow.

5.4.4.1 Post-LOCA Damage to Containment Materials

The possibility of containment materials that were previously damaged by the LOCA being further degraded by the post-LOCA environment of containment sprays and flowing water should be considered. One degradation mechanism would be water flowing over such materials as insulation and fire barriers that were not protected by a cover or jacketing, such that the water could erode a surface, resulting in production of fine fibers or fine particles. Evaluation of this issue has typically not resulted in the prediction of the generation of significant additional insulation or fire barrier debris.

A key concern is the failure of coatings, other than those damaged directly by the break jet. Qualified coatings are expected to survive the post-LOCA environment because they are designed to withstand post-LOCA environmental conditions. Conversely, non-qualified coatings consisting of either degraded qualified coatings or coatings lacking qualification certification should be conservatively assumed to form debris, either as particulate or as paint chips. The coatings assessment is addressed separately under the coatings in Section 5.5.

5.4.4.2 Erosion of LOCA-Generated Debris

The subject of further erosion of LOCA-generated debris with respect to washdown debris transport was discussed in Sections 5.4.2.2 and 5.4.2.3. There, the postulated drivers for the erosion were the break overflow, the containment sprays, and/or spray and condensate drainage. The primary driver for erosion, however, is immersion in a pool of water, with water flowing over and around the debris. The types of debris of primary concern for erosion are fibrous debris and microporous particulate insulation debris.

Erosion of Fibrous Debris

Individual fibers will erode from larger non-transportable fibrous debris residing within a pool, then become readily transportable. This behavior was observed in the NRC-sponsored integrated debris transport tests (NUREG/CR-6773), which were designed to simulate the sump pool of a typical PWR plant. During four longer-term tests (3 to 5 hr durations), debris that accumulated on the simulated sump screen was collected every 30 min. Fine fibrous debris continued to accumulate on the test screen throughout these tests; the fineness of the eroded fiber is evidenced by the uniformity of the accumulation, which is illustrated in the test photo shown in Figure 5.4-7. The shreds (small clumps of fiber) typically accumulated in a heap at the bottom of the test screen. Sources of this fine fibrous debris included the initial fine fiber in the debris batches introduced into the test, as well as the eroded fibers. However, the initially suspended fibers would have been removed relatively early in the test, after a few turnovers of the tank volume. Therefore, the continued accumulation at a somewhat sustainable rate was concluded to have been primarily that of eroded fibers.

It was also apparent that the level of pool turbulence affected the rate of erosion, i.e., an increase in turbulence increased the rate of erosion. One test was conducted with a pool depth of 9 in. rather than the usual 16 in. but at the same volumetric rate of flow and the erosion rate was greater in the shallower pool. The water in the shallower pool flowed significantly faster with a corresponding greater turbulence than the deeper pool. In fact, the accumulation was about eight times more rapid for the shallow pool test.

Figure 5.4-7. Typical Accumulation of Fine Fibrous Debris
(Figure 6-7 in NUREG/CR-6773)

This test data for debris erosion in a sump pool strongly indicate a sustainable rate of erosion that is affected by the relative turbulence in the pool. Although these longer-term tests ran for several hours, they were of shorter duration than those of the LOCA long-term recirculation tests, which ran for up to 30 days. If it is assumed that the erosion rate remains constant beyond the measured erosion rate until the end of the mission time, a conservative fraction for the quantity of debris eroded can be calculated. The following extrapolation equation takes into account the steadily decreasing mass of debris in the pool:

$$F_{eroded} = 1 - (1 - Rate)^{Hours}$$

Based on the erosion rate of 0.3% of the current tank debris per hour, associated with the 16-in. pool tests and extrapolating to 30 days (720 hr), the analysis indicates that nearly 90% of the initial debris mass would become eroded. This conclusion is based on a constant erosion rate, which is unlikely to be realisitc in practice.

While the application of this 90% value, which was approved by the NRC staff in their safety evaluation of NEI GR 2004-07, to the overall transport results would be conservative, it may not be realistic. The calculation had substantial sources of uncertainty, including: (1) the integrated debris transport tests lasted only 3 to 5 hr, (2) flow turbulence would depend on plant-specific geometry and flow rates, and (3) the tests did not study large-piece debris (note that fibrous debris still enclosed within a protective cover is not likely to erode). The greatest uncertainties associated with the 90% value are the questions of whether the erosion rate declines with time, and whether the erosion rate measured for small shreds applies to large pieces of relatively intact insulation. It was expected that this 90% value could be reduced with better or more extensive erosion rate data.

Several vendors have conducted independent testing to justify reducing the erosion rate. One such test program, reviewed by the NRC staff, was sponsored by the licensee for the Salem plant, which conducted plant-specific erosion testing for Nukon® and Kaowool fibrous debris (NRC, 2008f). The licensee placed samples of insulation of various sizes within wire mesh baskets that were, in turn, placed within a linear flume. A turbulence suppressor and a flow straightener were used to condition the flow upstream of the sample baskets. Flume velocity was specified to approximately match a CFD-predicted maximum recirculation velocity for the post-LOCA sump pool. A nominal (average) flume velocity of 0.72 ft/s was used for the testing (greater than the velocities found in 98% of the containment pool). Note that this test velocity is much higher than the typical tumbling velocity for small pieces making the results conservative for debris lying on the floor unretained by some object, such as a debris interceptor. Debris samples were placed in the flume for a specific time period; removed, dried, and weighed, and then generally placed in the flume again later for one or more additional erosion test intervals (the intervals provided time-dependent information). The differences between the initial masses and the post-test masses were attributed to erosion. The Salem licensee extrapolated the measured erosion percentages for small and large pieces of NUKON® and Kaowool® debris from the test durations out to the 30-day test period, which resulted in a 30-day erosion estimate of 30% for NUKON® and 10% for Kaowool®. These numbers were conservatively increased to 40% for NUKON® and 15% for Kaowool® in its debris transport calculation. Although the NRC staff noted technical concerns with the test procedure and methodology, these results were considered acceptable for Salem based on compensating conservatisms in the Salem debris transport conclusion.

- The review of the Salem erosion testing provided points of guidance that should be observed whenever such erosion testing is conducted. These points include:
- The conduct of such erosion testing should ensure that the velocity and turbulence test conditions are prototypical or conservative with respect to the plant sump pool. Due to the turbulence associated with the often chaotic and multidirectional variations in prototypical flow conditions, a bounding flow velocity may not by itself guarantee the prototypicality of the turbulence.

- Preparation of debris samples should render debris prototypically representative of LOCA-generated insulation debris. For example, destroying insulation with a shredder would produce debris more prototypical of a LOCA than simply cutting insulation into pieces.
- The size distribution of the debris samples should be representative of or conservative with respect to predicted debris size distributions. It is conservative to hedge test samples to the smaller size because smaller pieces have a higher surface-to-volume ratio than larger pieces, which tends to increase the erosion rate.
- Placement and grouping density within the test basket should be prototypical of the plant sump pool, in that the grouping should not shield individual debris pieces from turbulence in a non-prototypical manner.
- If the measured erosion rates depend upon the size of the debris, then the overall erosion of the LOCA-generated debris necessarily would involve an integration of the rates with the predicted debris size distribution.
- Erosion test data are specific to the type of fibrous debris tested. There is no guidance regarding the adaption of erosion data for one type of fibrous insulation to another type of insulation.

Alion Science and Technology also conducted erosion testing on fibrous debris (ML101540221). Alion exposed submerged small pieces of Nukon low-density fiberglass insulation to water flows representative of a PWR containment sump pool following a LOCA. The test report concluded that a cumulative erosion percentage of 10% over a 30-day period following a LOCA is justified. The staff reviewed the Alion testing and considers the test recommendation of not less than 10% erosion over a 30-day period appropriate. It was concluded that it would be acceptable for PWR licensees to reference the Alion proprietary erosion test report for Nukon low-density fiberglass in their responses to Generic Letter 2004-02 if it was shown that the testing was applicable to their plant condition. Prior to application of the Alion proprietary erosion test results to their plant, PWR licensees should verify that the test conditions (e.g., velocity and turbulence levels, debris material properties) are applicable to their plant-specific conditions. The Alion testing demonstrated that the previous NRC assessment of 90% erosion based on extrapolating a few hours of test data out to 30-days was overly conservative for PWRs (similar data have not been developed for BWRs).

Regarding BWRs, the turbulence that would occur in the suppression pool during the high-energy depressurization phase would further disintegrate fibrous debris including the generation of individual fibers (NUREG/CR-6224). Such fragmentation behavior was observed in scaled suppression pool tests investigating debris sedimentation of LOCA-generated debris and sludge, but a method was not developed for quantifying the fragmentation (NUREG/CR-6368).

In the erosion of LOCA-generated debris, it is likely that destruction of the insulation leaves fibers rather loosely attached, so that moderate turbulence working these fibers back and forth will cause the fibers to detach. Testing during the DDTS (NUREG/CR-6369) showed that fibers will also erode from undamaged insulation, but that more turbulent energy is required to sustain erosion. Therefore, it is reasonable to expect that the rate of erosion for LOCA-generated debris would taper off with exposure time. As the more loosely attached fibers have been detached the increasing total eroded mass is expected to approach an asymptotic limit. As such, it may be possible and reasonable to extrapolate test results that demonstrate a tapering-off effect from shorter test durations out to a 30-day test period.

Erosion of Microporous Insulation Debris

Microporous insulation debris (e.g., calcium silicate, Min-K, and Microtherm) subject to post-LOCA environmental conditions can erode into fine particulates that could contribute to strainer head losses. During NRC-sponsored separate-effects testing, one type of calcium silicate (obtained from Performance Contracting, Inc.) was tested for its dissolution behavior in water (NUREG/CR-6772). In these tests, pieces of debris that had been created by shattering this calcium silicate insulation were dropped into water at both ambient and 80°C. The water was quiescent or was stirred to induce turbulence. Within 20 minutes in the stirred 80°C water, about 75% of the material became suspendable fines due to the disintegration process. This process was found to increase with temperature and turbulence.

Similar vendor conducted tests were reviewed by the NRC staff during the Indian Point audit (NRC, 2008e). This licensee sponsored the dissolution testing of two pieces of calcium silicate (identified as asbestos-bearing) that had been removed from the Indian Point Unit 2 containment. These two pieces were tested in 200°F (93.3°C) water for 2 hr with stirring added for 30 min. The data indicated that the erosion was very minor, after which the licensee assumed that all such pieces of calcium silicate debris would not further erode. However, the NRC staff concluded that the testing duration was too short to ascertain whether the disintegration that would occur over a 30-day period could be significant (e.g., 0.05% for 2 hr extrapolates to 18% in 30 days). The licensee's vendor noted another vendor dissolution test in which about 5% erosion occurred in 2 weeks for a type of calcium silicate similar to that found in the Indian Point containments. This information suggests that significant erosion would likely occur in 30 days.

The Indian Point vendor testing had substantially different results from the NRC-sponsored tests. During the onsite Indian Point audit, a calcium silicate insulation expert was consulted to help discern why the two sets of test results were so different. The primary reason for the behavior difference was attributed to the manufacturing process of the calcium silicate insulation i.e., either a press-shaping process or a molding-shaping process. The Indian Point asbestos insulation was manufactured by the press-shaping process, which is resistant to water erosion, whereas the calcium silicate used in the NRC-sponsored testing was manufactured by the molding-shaping process, which is apparently highly susceptible to water erosion.

The erosion rate depends on the type and manufacture of the calcium silicate, and it is apparent that at least some erosion would occur for any calcium silicate insulation. The same conclusion should be assumed for Min-K and Microtherm unless adequate research is conducted to support a different conclusion. When erosion tests are conducted, the tests should last for a sufficiently length of time to adequately determine the rate of erosion. The lower the rate of erosion, the longer the test duration needed to accurately determine the erosion rate. Even a low rate could be important over the long-term post-LOCA mission time of the containment sump. The conditions to which the test debris are subected should be prototypical (or conservative) with respect to the plant sump pool. In addition, steps should be taken to ensure that the samples are properly dried before weighing to ensure accuracy. Because the measured mass differences during the testing can range from hundredths to tenths of a gram, small variations in the quantity of water adhering to the samples at the time of weighing could easily influence differential mass measurements.

5.4.5 Characteristics of Debris Transported to the Strainer

The characteristics of the debris arriving at the strainer will differ from those of the as-generated debris. In particular, larger and heavier debris would likely not reach the strainer. The typical debris arriving at a PWR large passive strainer installed above the sump pool floor will likely consist primarily of suspended fines. Head loss evaluations, whether analytical or experimental, should be based on the debris expected to arrive at the strainer rather than on the as-generated debris, in particular the debris size distributions. For BWRs, the debris arriving at the strainer would be affected by the RCS depressurization induced turbulence in the suppression pool. Early on, the suppression pool turbulence would keep some larger debris in suspension and available for accumulation. Later in the event the suspended debris in the suppression pool would become finer as the larger debris settled. Characterizing the size distributions of debris arriving at the strainer would be at least somewhat time dependent, and therefore difficult to assess. Therefore BWR evaluations should maintain adequate conservatism to account for the unknowns. For PWRs, the typical debris arriving at a large passive strainer installed above the sump pool floor will likely consist primarily of suspended fines.

The strainer debris transport evaluation must conservatively interface with the head loss evaluation, i.e., the debris quantities (and properties) predicted to arrive at the strainer should match up with the debris quantities (and properties) used to initiate the head loss evaluation. The correlation between the head loss evaluation and transport evaluation should be based on head loss, rather than simply debris quantities. That is, smaller quantities of very fine debris can cause substantially higher head loss than larger quantities of bulkier debris. Different approaches are suitable provided that the transport and the head loss evaluations are compatible. If the transport analysis is to evaluate the debris approaching the strainer but not actually reaching the strainer, then the head loss testing would need to conservatively simulate the near field transport. If the transport analysis is to evaluate the debris actually accumulating on the strainer, then the head loss testing would not need to simulate the near field transport. For example, a PWR evaluation may assess the transport of floor transportable debris to the base of the a strainer positioned above the sump floor. If the transport evaluation demonstrated that the floor transported debris could be lifted from the floor and onto the strainer the head loss evaluation should consider that debris. However, the head loss evaluation should also be conducted for a debris load that does not include that debris in order to determine which condition results in a larger head loss. The more conservative value should be used in the plant evaluation because of the uncertainties associated with predicting debris transport. Specifically, some vendor head loss testing used agitation to force debris to accumulate on a strainer, to achieve a goal of conservative transport. The agitation may have resulted in some debris collecting on the stainer that would not have accumulated under prototypical conditions. The forced accumulation can preclude the formation of a worse case head loss debris bed (i.e., bed formed with fine tightly packed debris). Under these conditions a non-conservative assessments of the head loss can be made. The ‘common interface’ between the transport evaluation and the head loss evaluation is very important.

5.5 Coatings and Coatings Debris

5.5.1 Introduction

Painted industrial coatings are applied to a large number of systems, structures, and components housed in the containment of both PWRs and BWRs to protect the surfaces from corrosion, to facilitate decontamination, and to provide for wear protection during plant operation and maintenance activities. These coatings are of several types (primer, sealer, topcoat, surfacer, etc.) and encompass a great variety of chemical formulations. These chemical formulations commonly used include alkyd, vinyl toluene modified alkyd, epoxy, urethane, acrylic, styrenated acrylic, basic zinc carbonate, and inorganic zinc-rich materials. It has been estimated that a medium-sized PWR containment has approximately 650,000 ft2 of coated surfaces inside (NUREG/CR-6808). In a survey of conducted by EPRI, it was reported that 6% of the more than 11 million square feet of nuclear Service Level I coatings inside containments (represented by the survey) have shown signs of degradation (EPRI, 2006).

The NRC issued Revision 2 of RG 1.54, "Quality Assurance Requirements for Protective Coatings Applied to Water-Cooled Nuclear Power Plants," in October 2010 to provide updated guidance regarding compliance with quality assurance requirements for protective coatings applied to ferritic steel, aluminum, stainless steel, zinc-coated (galvanized) steel, and masonry surfaces. This guide encourages industry to develop codes, standards, and guidance that can be endorsed by the NRC and carried out by industry. The principal industrial standard cited in RG 1.54 is ASTM D 5144-08 (ASTM, 2008a). This top-level standard, in turn, incorporates by reference a number of other ASTM standards applicable to nuclear power plant coatings, as illustrated in Fig. 5.5-1.

Service Level I, II, and III coatings are defined in Revision 2 of RG 1.54 as follows:

a. Service Level I coatings are used in areas inside the reactor containment where coating failure could adversely affect the operation of postaccident fluid systems and thereby impair safe shutdown.

b. Service Level II coatings are used in areas where coating failure could impair, but not prevent, normal operating performance. The functions of Service Level II coatings are to provide corrosion protection and enhance decontamination in those areas outside the reactor containment that are subject to radiation exposure and radionuclide contamination. Service Level II coatings are not safety related.

c. Service Level III coatings are used in areas outside the reactor containment where failure could adversely affect the safety function of a safety-related SSC.

With noted exceptions related to quality assurance standards and the definitions of Service Levels I, II, and III coatings, the ASTM standards cited in the Revision 2 of RG 1.54 for the selection, qualification, application, and maintenance of protective coatings in nuclear power plants have been reviewed by the NRC staff and found acceptable.

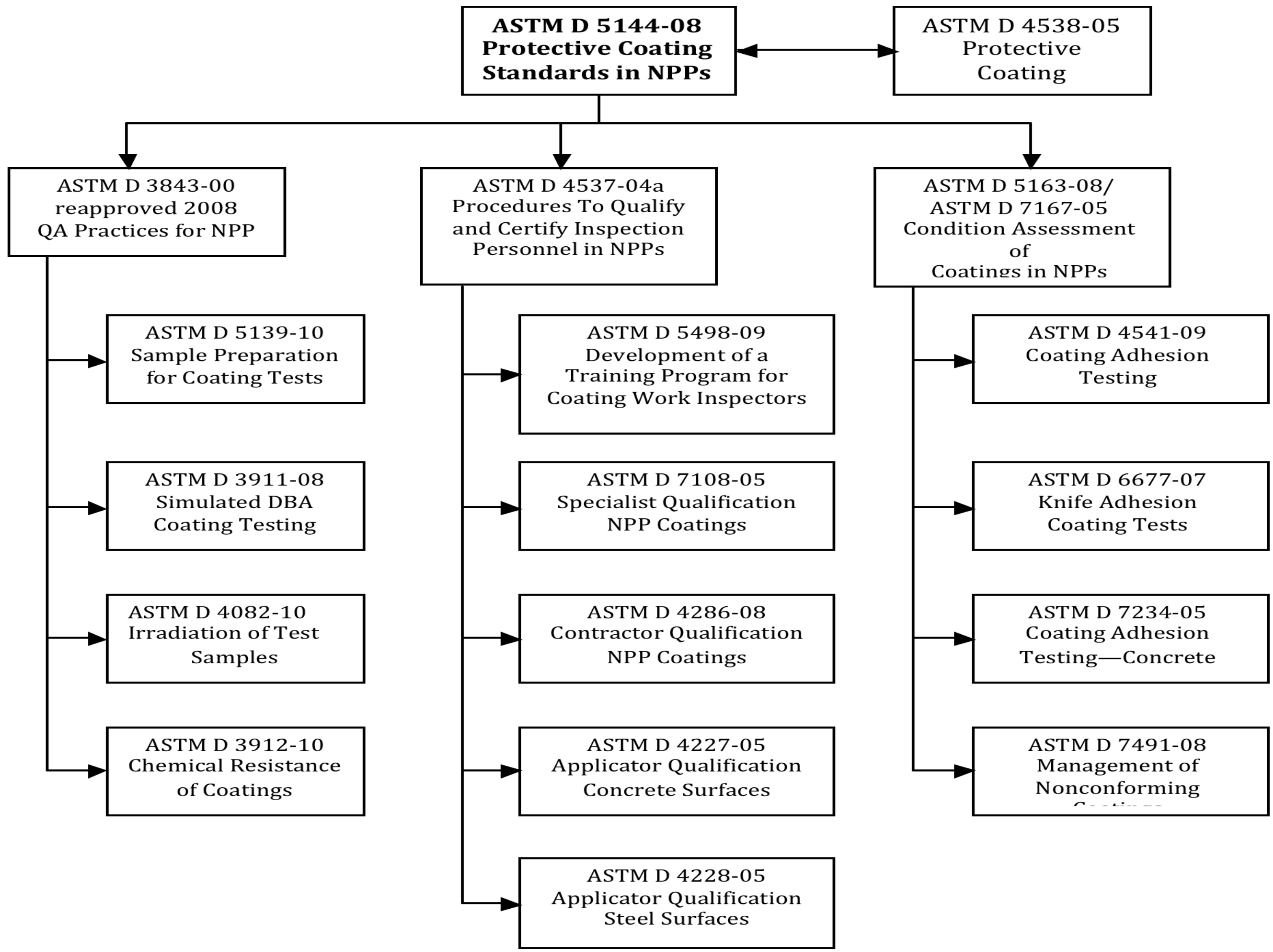


Figure 5.5-1. ASTM Standards Relevant to NPP Service Level I, II, and III Protective Coatings (NRC RG 1.54, Rev. 2).

For nuclear applications, the NRC has categorized those coatings that meet the requirements of ASTM D5144-08 as qualified coatings. Qualified coatings are expected to adhere to their substrates during a design-basis LOCA (DB-LOCA), unless directly impacted by the break jet, except for coatings that have received extensive irradiation (>109 rad) (ANSI, 1972). Coatings that do not meet the requirements of ASTM D5144 are classified as unqualified coatings. The NRC currently holds the position that 100% of design basis accident (DBA) unqualified coatings in reactor containments will fail (disbond from their substrate) during a LOCA and thus be available for transport to the ECCS sump.

A substantial quantity of unqualified coatings may be present in nuclear plant containments, and their presence represents a potentially significant contribution to ECCS sump clogging in the event of a LOCA. In addition, qualified coatings may also fail under conditions described above or because of improper application or maintenance, and the resulting debris from these coatings can also potentially contribute to sump clogging. The testing and failure of both qualified and unqualified coatings and the nature of the debris generated are summarized here.

5.5.2 Coating Failures in Operating Nuclear Plants

The Electric Power Research Institute (EPRI) has sponsored a research program designed to gain an understanding of the degradation of nuclear Service Level 1 coatings and to evaluate the effects of aging on the qualified coatings used inside containment. As a part of that program, EPRI report 1013465 documents the results of a survey of the U.S. nuclear industry to gather data regarding qualified coating degradation and failure inside reactor containment. This survey reported that the generic coatings systems with the highest percentage of area with signs of degradation involved modified phenolic epoxy coatings. Coating application issues (inadequate surface preparation, improper thickness of the applied coating, or insufficienct curing) were the most commonly reported causes of degradation. The most frequently reported visual evidence of coating degradation was delamination, followed by blistering, cracking, and flaking. Finally, the report concluded that aging is not a major degradation mechanism.

The related EPRI report (2007b) describes coating failures in industrial applications and compares them with coating degradation and failures in nuclear primary containments. The report compares industrial exposure environments with nuclear primary containment operating environments, presents case histories of industrial failures of coating systems that are similar to those used in nuclear primary containments, and discusses the relevance of industrial case histories to the nuclear coatings degradation described in EPRI report (2006).

As indicated in the two EPRI reports cited above, a significant number of coating failures in nuclear containments have occurred over the years. However, these two reports do not identify the specific nuclear plants that have experienced such failures. Summaries of some of the more significant failures reported in NRC communications are given in Table 5.5-1. It can be seen that these failures involve both qualified and unqualified coatings and that failures have occurred in both PWRs and BWRs. Where the cause of failure has been identified, it is most commonly attributed to the use of unqualified coatings and/or improper coating application.

Table 5.5-1. Summary of Selected Coating Failures in U.S. Nuclear Power Plant Containments as Reported in NRC Communications

Plant	Description of Failure	Reference
North Anna 1 (PWR), March 1993	During steam-generator replacement, it was discovered that most of the unqualified silicon aluminum paint covering the SGs had come loose from the exterior surfaces and was being supported only by the insulation jacketing. Paint pieces ranged in size from dust particles to sheets 0.61 m (2 ft) wide. This same paint on the pressurizer was also loose. The quantity of this coating in containment was estimated at 1,087 m2 (11,700 ft2).	IN-93-34
Indian Point 2 (PWR), March 1995	An inspection found that paint was peeling from the containment floor. The factors contributing to the delamination of the paint were: (1) the paint thickness exceeded the manufacturer's specifications by up to twice the allowed thickness; (2) there was excessive paint shrinkage caused by use of too much paint thinner; (3) the surface had not been cleaned and prepared properly before the paint was applied; and (4) appropriate inspection and documentation requirements were not implemented.	IN-97-13
Millstone 3 (BWR) July 1996	About 20 pieces of Arcor were found in the Train-A recirculation spray heat exchangers. Arcor is an epoxy coating material that was applied to the inside surfaces of the service water system piping. The Arcor chips were apparently swept into the recirculation spray heat exchanger channel during testing. The licensee also found 40 to 50 mussel shell fragments in the heat exchangers. The Arcor chips and mussel fragments were relatively small (on the order of 1 in.2). The licensee determined that the debris could have prevented the heat exchangers from performing their specified safety function. In addition, construction debris was discovered in all four containment recirculation spray system (RSS) suction lines, and gaps were found in the RSS sump cover plates.	IN-97-13 GL-98-04
Zion 2(PWR), November 1996	Inspections found that 40 to 50% of the concrete floor coatings showed extensive failure as a result of mechanical damage and wear, and that about 5% of the coating associated with the concrete wall and liner plate was degraded. Unqualified coatings had been applied to various surfaces, including instrument racks, struts, charcoal filter housings, valve bodies, and piping. Although adhesion tests showed acceptable adhesion strength in most of the locations tested, one test conducted on an unqualified coating system did not satisfy the acceptance criteria. Documentation was not found for over-coating (i.e., touch-up work) that had been applied to many of the liner plates and concrete wall surfaces.	IN-97-13

Clinton (BWR), July 1997	A significant quantity of degraded protective coating was removed from the containment because of substantial degradation in the wetwell and some degradation in the drywell. Because of the indeterminate condition of these degraded coatings, reasonable assurance could not be given that the coatings would not disbond from their substrates enough to clog the ECCS suction strainers during accident conditions.	GL-98-04
Braidwood 2(PWR), April 1999	During a refueling outage, the NRC resident inspector noticed a significant amount of paint peeling off the containment wall outside of the missile shield. This qualified coating system consisted of an inorganic zinc primer and an epoxy phenolic topcoat. The topcoat was coming off of the primer, with part of the primer adhering to the topcoat. The licensee's preliminary root cause for the degradation is that the primer was applied too thickly and is failing cohesively. Many of the paint chips were several inches square. Similar peeling was noted during the last several refueling outages. The peeling was initially observed in an area classified as outside of the ZOI for material blockage of the sump. However, there is a concern that the larger paint chips may block flow paths to the sump strainers.	NRC-SECY-99-127
Vermont Yankee 1(BWR), October 2001	Carboline Carbozine CX-11SG paint primer was applied to the drywell shell (inner wall) to the floor joint as part of a qualified seal design. The purpose of this seal is to provide a moisture barrier to mitigate water entering the shell to concrete interface. In preparation for and during subsequent applications of the primer, significant gelling/premature set-up of the paint was exhibited. Within 24 hr of the paint application, the paint began to lift and blister. The failure was most likely due to a moisture problem during manufacture.	NRC-Event Notification Report (ENR) 38408
Dresden 2 (BWR) Nov. 2001	An inservice inspection identified an area of missing coating and primer encircling the drywell shell adjacent to the basement floor. The area was 5-10 cm (2-4 inches) wide. In this area, the base metal of the drywell shell was found corroded. However, based on ultrasonic and visual examinations, the degraded area was found to be within the corrosion allowance for the drywell shell. The shell coating was repaired in this area to prevent further degradation.	IN 2004-09
Sequoyah 2 (PWR) May 2002	During an inspection, the NRC identified areas of the steel containment vessel (SCV) with degraded coatings and rust. One of the floor drains was clogged in the annulus area (1.5 m [5 feet] wide) between the SCV and the reinforced concrete shield building. Localized water ponding at the clogged drain had come in contact with a section of the SCV, causing deterioration of the SCV coatings and rusting of the SCV.	IN 2004-09

Oconee 1, 2, 3 (PWR), 2003-2004	During the Unit 1 refueling outage in Fall 2003, the inspectors discovered what appeared to be a significant amount of Service Level 1 coatings that were severely blistered, delaminated, peeling and falling off of the reactor building (RB) dome and liner, polar crane, and sprinkler grid support assembly. Similar degraded coating conditions were discovered by the inspectors during the Unit 2 EOC20 refueling outage and the Unit 3 forced outage following its February 26, 2004, reactor trip.	NRC-ONS 2004

5.5.3 Testing of Qualified Coatings

The Savannah River Technology Center (SRTC) has conducted an extensive experimental program on the potential for degradation and failure of qualified protective coatings applied to exposed surfaces within primary containment of nuclear power plants. The results of this program are summarized in a series of technical reports: WSRC-TR-2000-00079, WSRC-TR-2000-00340, WSRC-TR-2001-00067, and WSRC-TR-2001-00163 (Dupont et al., 2000a, 2000b, 2001a, and 2001b). Dupont et al. (2000b) describe results obtained for an epoxy-polyamide primer and topcoat (Amercoat® 370 over Amercoat® 370) applied to a steel substrate. The experimental approach involved a combination of (1) measuring critical coating materials properties at conditions representative of a post-LOCA period, (2) developing a predictive coating system failure model, (3) subjecting such coating systems to DBA conditions, (4) comparing model and test results to judge predictive capability, (5) documenting the degree of failure, and (6) characterizing the failed coating debris, for integration into the PWR sump blockage research program (GSI-191).

The research results reported in this report resulted in the following conclusions:

1 Properly applied qualified coatings systems can be expected to exhibit adequate adhesion strength to a steel substrate following exposure to simulated DBA conditions.

2 Selected samples artificially aged by exposure to gamma radiation to a cumulative dose of 109 rad in accordance with ASTM D-4082-95 (ASTM, 1995d), exhibited some near-surface degradation. This degradation appeared as a consequence of coating oxidation resulting from irradiation and temperature effects and would be expected to vary with oxygen availability and permeability in a particular coating system.

As part of the investigation, an Ameron Coatings System 5 epoxy and modified polyamide resins coating system (Amercoat® 370 over Amercoat® 370) was evaluated. A properly applied coating exhibited only blistering without detachment when subjected to a simulated LOCA, but it was projected that this coating system (if there were coating flaws that had entrapped moisture) could fail during the rapid containment cool down introduced by activation of containment spray systems.

In a second follow-on report (Dupont et al., 2000a), the same investigators describe the results of tests conducted on an epoxy-phenolic topcoat (Phenoline 305) over an epox (Starglaze 2011S) applied to concrete in accor -90 (ASTM, 1996e). This coating system, which was designated Coating System 2, is representative of coatings applied to concrete within PWR containments in the early to mid-1970s. Selected samples were again artificially aged by exposure to gamma radiation in accordance with ASTM D-4082-95 (ASTM, 1995d). In addition, both unaged and aged samples were exposed to DBA conditions specified in the ASTM D3911-95 (ASTM, 1995g) steam temperature profile for PWR containments, as well as other relevant DBA conditions, including a “pulse” steam temperature profile and a high temperature (up to 200°F) water immersion. This investigation resulted in the following conclusions:

1 Properly applied coatings that contain only minor defects and that have not been subjected to irradiation of 109 rad can be expected to remain fully adhered and intact on a concrete substrate following exposure to simulated DBA conditions.

2 Non-bonded embedded defects(or intentiontionally induced defect),greater than approximately 3.2 mm (1/8 in.) in diameter, are subject to cracking and failure during DBA exposure.

3 Properly applied coatings that have been subjected to irradiation of 109 rad exhibited profound blistering, leading to disbondment of a near-surface coating layer (0.025-0.05 mm [1-2 mils] of the 0.25-mm [10-mils] thickness) when exposed to elevated temperatures and moisture associated with DBA conditions. This failure of the coating produced a coating debris source term.

In the third stage of this research program (Dupont et al., 2001b) the same investigators tested an epoxy-phenolic topcoat (Phenoline 305) over an inorganic zinc primer (Carbozinc 11), which is representative of a coating system that was applied to steel substrates within PWR containment in the early to mid-1970s. The experimental approach was similar to that described above (Dupont et al., 2000a) and the following conclusions were reached:

1 Properly applied coatings that have not been subjected to irradiation of 109 rad, can be expected to remain fully adhered and intact on a steel substrate, following exposure to all simulated DBA LOCA conditions. In addition, no minor cracking in defect-free regions of the coating and regions near embedded defects was observed. This finding is in contrast to previous test results on a concrete system (Dupont et al., 2001b) and is predicted by the deformation modeling.

2 2. Properly applied coatings that have been subjected to irradiation of 109 rad exhibited profound blistering, leading to disbondment of a near-surface coating layer (0.025-0.05 mm [1-2 mils] of the 0.25-mm [10-mils] thickness) when exposed to elevated temperatures and moisture levels within the range of DBA conditions. This behavior is similar to that of the epoxy-phenolic topcoat/epoxy surfacer system described above and again produced a coating debris source term.

Finally, qualified coating specimensfrom the containment of four nuclear stations were evaluated for coating degradation and failure. These specimens included coating chips that had become disbonded during normal plant operation and intact coating specimens that were sectioned from steel components in the containment. These specimens were evaluated by several characterization techniques in the as-received (service-experienced) condition, and after irradiation-aging and simulated DBA-LOCA conditions to provide structural and chemical information.

The as-received coating chip specimens were found to have failed within the inorganic zinc (IOZ) layer. A non-uniform distribution of the ethyl silicate binder was observed that most likely caused poor adhesion within the IOZ. The failure was attributed to improper application, rather than in-service environmental degradation. The coating chips had a topcoat layer and a layer of IOZ. Exposure of the two-layer chip to simulated DBA-LOCA conditions resulted in extreme curling of the initially flat chip, apparently because of differential expansion/contraction between the two layers of the chip.

The intact coating specimens that were sectioned from plates and handrails from two plants were tested in the as-received condition. The coatings were found to be sound and strongly adhered following exposure to simulated DBA-LOCA conditions. The as-received condition of these materials represented 10-20 years of normal operational service. The intact coating specimens were also tested following irradiation aging to 109 rad (at 106 rad/hr and 120°F). Severe blistering and the formation of particulate debris occurred when these specimens were exposed to simulated DBA-LOCA conditions. This behavior is similar to that observed in coatings on laboratory specimens but the damage was more severe in the plant specimens.

A series of adhesion tests was conducted under EPRI sponsorship on existing qualified Service Level 1 coatings at four nuclear plants, namely, the San Onofre Nuclear Generation Station (SONGS) Unit 3, Waterford Unit 3, McGuire Unit 1, and Oconee Unit 2 (EPRI, 2007). The coatings tested included zinc-rich and epoxy primers, epoxy surfacers, and epoxy and phenolic topcoats applied to sound and degraded steel and concrete. The tests were conducted in accordance with (1) dry film thickness testing as stated in ASTM D4138-00 (ASTM, 2000) and/or ASTM D6132-04 (ASTM, 2004) as appropriate, (2) adhesion testing according to ASTM D4541-02 (ASTM, 2002), and (3) knife adhesion testing according to ASTM D6677-01 (ASTM, 2001). In all cases, coatings that exhibited no visual anomalies (flaking, peeling, chipping, blistering, etc.) continued to exhibit system pull-off adhesion at or in excess of the originally specified in the ASTM D5144 minimum value of 200 psi, even though the coatings had been in place for approximately 20-35 years.

5.5.4 Testing of Unqualified Coatings

Design basis accident testing has been performed on selected unqualified OEM coatings under EPRI sponsorship. The test samples consisted of 37 components of the sort typically found in PWR containments, all with the OEM-applied coatings. The NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Coatings Evaluation [ADAMS Accession No. ML080230462] issued in March 2008, noted that five of the 37 coatings in the EPRI tests showed greater than 80% failure, with some as high as 99% failure. These coatings included alkyds, moisture-cured urethane, and inorganic zinc-rich coatings. The Review Guidance document concludes that licensees would not be able to demonstrate, based on this report alone, that their coatings would not fail at these high rates and therefore would not be able to take credit for a reduced amount of unqualified coating debris. For specific coatings, the licensee might be able to justify a lower failure rate, based upon the EPRI data for that coating or upon results from plant- and coating-specific testing.

5.5.5 Coating Debris Generation

The amount of coating debris generated in a LOCA event depends upon the failure characteristics of the coating as well as the size of the region (i.e., the zone of influence or ZOI) over which coating failure is expected for a given accident scenario. The amount of this debris that actually reaches the ECCS sump further depends upon the transport characteristics of that debris under the accident conditions in question. These two points will be briefly considered here.

As noted above, the NRC issued the document “NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Coatings Evaluation” [ADAMS Accession No.

ML080230462] in March 2008. The purpose of this document is to provide guidance to NRR staff on what information is needed in a licensee's response to GL 2004-02 in the review area of protective coatings. In addition, the document provides guidance to licensees in preparing their supplemental responses to GL 2004-02 with respect to coatings. Six broad categories of information are described as sufficient to support closure of the aspects of the generic letter, as follows:

1 Summary of the type(s) of coating systems used in containment.

2 Description of the containment coating condition assessment program.

3 Description and the bases for coatings debris generation assumptions. For example, description of how the quantity of paint debris was determined based on ZOI size for qualified and unqualified coatings.

4 Description of debris characteristics assumed, i.e., chips, particulate, size distribution, and bases for the assumptions.

5 Description and bases for assumptions made in post-LOCA paint debris transport analyses.

6 Discussion of suction strainer head loss testing performed as it relates to both qualified and unqualified coatings and what surrogate material was used to simulate coatings debris. Discussion of bases for the choice of surrogates.

Most of these categories deal directly or indirectly with the issues of debris generation and transport resulting from coating failure, and category 3 deals directly with the question of ZOI size for the coatings in the region impacted by a pipe failure. The NRC-SE-2004 conservatively recommends an assumed coatings ZOI spherical equivalent of 10 pipe diameters, or 10D. The 2008 Review Guidance document described conditions under which the licensee may assume a less conservative ZOI of 4D or greater for qualified epoxy coatings and 10D or greater for qualified untopcoated inorganic zinc coatings (ML100960495).

The characteristics of failed coating debris have been examined by the BWROG for selected types of coatings and test conditions (Bostelman et al., 1998), as summarized by Shaffer et al. in NUREG/CR-6808. Test samples were prepared by first exposing the coating to a minimum radiation dose of 109 rad at an average dose rate of 1.65 Mrad/h at the University of Massachusetts Lowell Radiation Laboratory. The specimens next were subjected to a series of three LOCA tests at the testing department of the Carboline Company to investigate the post-LOCA failure mechanisms and the failure timing of the coating systems. Scanning electron microscopy was used to perform a detailed examination of pieces of debris. Microhardness measurements also were taken and compared for selected coating types. The coating debris examined ranged from powder residues to large, slightly curved pieces.

The hydraulic transport characteristics of coatings particulates under LOCA conditions were examined in a series of experiments conducted at the Carderock Naval Surface Warfare Center in 2006 (NUREG/CR-6916). Five coatings systems, typical of coatings applied to equipment and structures located in the containment buildings of PWRs, were tested. The effects of chip size, shape, density, thickness, stream velocity, water saturation of the coatings, and thermal curing on transportability were examined. Three types of tests were performed, quiescent settling tests, transport tumbling-velocity tests, and steady-state velocity tests. In the quiescent settling tests, coating chips were dropped onto the water surface under quiescent conditions. It was found that coating chips with a density close to that of water tended to remain on the surface indefinitely, and heavier chips tended to sink almost immediately. In the transport tumbling-velocity tests, the chips were placed on the flume floor under flowing water conditions. These tests demonstrated that all but the lightest chips and curled chips remained in their initial position at stream velocities in excess of 0.09 m/s (0.3 ft/s). In the steady-state velocity tests, the coating chips were released into the moving stream below the water surface. These tests found that, at a uniform water velocity of 0.06 m/s (0.02 ft/s), all but the lightest chips settled to the bottom before reaching the end of the flume.

5.5.6 Summary

In the event of a LOCA, the debris generated by failed coatings in the containments of nuclear power plants represent a potentially significant source of material available for transport to the ECCS sump. Furthermore, operating experience at a number of plants has demonstrated that coatings can fail even under normal operating conditions. Accordingly, Revision 2 of RG 1.54, "Quality Assurance Requirements for Protective Coatings Applied to Water-Cooled Nuclear Power Plants," provides guidance on the use and testing of these coatings. Both qualified and unqualified coatings have been extensively tested under simulated DBA conditions, and the debris characteristics and transport behavior have also been studied. In March 2008, the NRC issued the document "NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Coatings Evaluation," which provides guidance on what information is needed for a licensee's supplemental response to GL 2004-02 in the review area of protective coatings. The document also describes acceptable technical assumptions for those licensee responses based on research conducted by the NRC and the industry.

5.6 Latent Debris

5.6.1 Introduction

Dirt, fiber, and other foreign materials that are generally found in nuclear power plant containment buildings are referred to as "latent debris." Consideration should be given to the potential for latent debris to gather in containment during plant operation. This debris may transport to and affect head loss across the ECCS sump strainers. Therefore, it is necessary to determine the types, quantities, and locations of latent debris. Due to variations in containment design and size, latent debris sources should be evaluated on a plant-specific basis. It is unlikely that foreign materials exclusion (FME) programs can entirely eliminate sources of latent debris within containment. Reasonably conservative estimates for latent debris need to be included in the overall debris source term unless plant-specific walkdowns verify lower values. Plant-specific walkdown results can be used to determine a conservative amount of dust and dirt to be included in the debris source term. Walkdowns will not be able to directly measure the entire amount of latent debris. However, it is possible to quantify the amount of debris with additional steps. The following activities are recommended to quantify the amount of latent debris inside containment and are described in greater detail in sections below:

- Calculate the horizontal and vertical surface areas inside the containment. This calculation will determine the total area with the potential for accumulation of debris.

- Evaluate the resident debris buildup on representative surface areas within containment. Generally, samples of debris are taken at several locations.

- Define the debris characteristics. This information will be used in subsequent steps of the sump performance evaluation.

- Calculate the total quantity and composition of debris. This information will also be used in subsequent steps of the sump performance evaluation, such as evaluation of the transport of latent debris to the sump strainer and the resulting head loss. Detailed guidance is provided below for accomplishing the recommended activities for quantification of the amount of latent debris.

5.6.2 Baseline Approach

Latent debris is considered a contributor to head loss across the sump strainer and should be evaluated accordingly. Information is provided in the NRC staff SE on the NEI guidance report (SE NEI-04-07) to evaluate the quantity of latent debris with sufficient rigor to eliminate excessive conservatism. Note that in many cases, the contribution to head loss by latent debris will be small in comparison to that caused by debris from other sources, such as insulation materials. In these cases, latent debris will not determine the course of action for mitigating ECCS sump strainer issues. However, for cases where there is little fibrous debris generated by the LOCA jet, latent debris may have a significant effect on the head loss evaluation. If other debris sources create amounts of transportable debris much greater than that expected from latent debris a detailed latent debris evaluation should not be required. The impact on the results of the sump performance evaluation as a whole should be considered before performing a rigorous analysis of latent debris loading.

5.6.2.1 Estimation of Surface Area Inside Containment

Estimates are made of the horizontal and vertical surface areas. Vertical surfaces such as walls and sides of equipment are considered, although a significant amount of debris does not typically collect on vertical surfaces in the absence of factors that promote adhesion of solids to the surface. The list of items that should be included in the surface area calculation (floor area, walls, cable trays, major ductwork, control rod drive mechanism coolers, tops of reactor coolant pumps, and equipment, such as valve operators, air handlers, etc.) provides a starting point for licensees to consider for major inputs. The five steps provided for surface-area calculations (flat surface considerations, round surface area considerations, vertical surface area considerations, thorough calculation of surface areas in containment, and use of estimated dimensions when exact dimensions are unavailable) are considered informative.

5.6.2.2 Evaluation of Resident Debris Buildup

Although sampling of surfaces inside the containment at a number of plants indicated that the maximum mass of latent debris inside containment is likely less than 200 pounds for PWRs, a survey of each plant's containment is recommended, with the objective of determining the quantity of latent debris. Surveying the containment for latent debris ensures that higher-than-average debris loads are accounted for and will allow plants to take advantage of smaller latent debris loading if lower quantities are present. Note that it is recommended to perform periodic surveys (as part of outage efforts) to validate that there has been no significant change in the latent debris load inside the containment, especially if latent debris can contribute significantly to the head loss evaluation. The required rigor of these surveys is dependent on the effectiveness of the licensee's FME and housekeeping programs with respect to containment cleanliness. If the licensee has rigorous programs in place to control the cleanliness of containment and documents the condition of containment after an outage, it is adequate to perform inspections and limited sampling of surfaces. If the cleanliness of containment is not controlled through rigorous programs, or if the programs in place do not address all areas of containment, it is necessary to perform more comprehensive surveys.

The NRC staff guidance report (SE NEI-04-07) does not recommend direct measurement of latent debris thickness because (1) masses can be measured much more accurately than thickness, (2) comparison of dirt layers to reference thickness standards is subjective and prone to error because of heterogeneous small objects that may reside on the surface and because of non-uniform dust thickness across a surface like piping, and (3) in situ estimates of thickness do not characterize size distributions, particulate-to-fiber mass ratios, or densities that are needed to define hydraulic head-loss properties. These problems can be avoided by measuring total masses within a known surface area and then partitioning the fiber and particulate mass fractions either by physical measurement or by generic assumptions.

5.6.2.3 Surface Area Susceptibility to Debris Accumulation

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

It is appropriate to conservatively assume that the entire surface area is susceptible to debris accumulation. If it is unreasonable to use this assumption, then in addition to determining the total horizontal surface area inside containment, licensees must determine the fraction of the surface area of each component and surface that is susceptible to debris accumulation. To make this determination, evaluate the fraction of the surface area susceptible to debris accumulation on a component-by-component or surface-by-surface basis. The following guidance was recommended:

1 Assume that 100% of the surface area is susceptible to debris accumulation in inaccessible areas as well as in accessible areas that are not thoroughly cleaned and documented as clean per plant procedures before restart (e.g., cable trays, junction boxes, and valve operators), and floors with gratings positioned on flat surfaces.

2 Evaluate the fractional area susceptible to debris accumulation on smooth floor areas and on other surfaces cleaned per plant procedures before restart on a case-by-case basis. Considerations include the method of cleaning (e.g., pressure washing vs. vacuuming) and accessibility of areas. Because of wide variations in containment design and effectiveness of housekeeping and FME programs, evaluations should be performed on a plant-specific basis. For all cases in which the area susceptible to debris accumulation is reduced, a conservatively large fractional area susceptible to accumulation should be determined, and bases should be provided for the fractions used. The following guidance was given:

- Calculate the total surface area of the surface being considered.

- Calculate the area of the surface that is clean. Use simplifying assumptions that will result in a conservatively small clean area.

- Calculate the ratio of potentially dirty area to the total area.

5.6.2.4 Total Quantity and Composition of Debris

The final step in determining the quantity of latent debris inside the containment is to compute the total quantity of latent debris. Use the following guidance when performing the final calculations:

1 Perform calculations on an area-by-area basis, which will facilitate adequate representation of the debris densities and characteristics in the various areas inside the containment.

2 Compute the total quantity of debris for each area by multiplying the total surface area susceptible to debris accumulation by the debris layer thickness for the area of containment being considered.

3 Include quantities of other types of latent debris such as tape, equipment tags, and stickers.

4 Categorize and catalog the results for input to the debris transport analysis.

5.7 Debris Accumulation, Head Loss, and Vortex Evaluation

5.7.1 Overview

ECCS recirculation strainers are designed to prevent debris from entering the ECCS and CSS and causing damage to the pumps and other downstream components. However, debris accumulating on the strainers can cause head loss that, if sufficient, could result in pump degradation or failure by cavitation, air entrainment, or flow starvation. Air ingested into the strainer due to lack of full submergence or due to a vortex formation can result in similar pump issues. The pool water contains non-condensible gasses. The pressure decrease due to the water flow through the debris bed can cause deaeration-generated bubbles. In addition, when the water temperature is sufficiently close to the saturation temperature, flashing can occur within the debris bed or the strainer due to pressure decreases associated with flow induced head losses. These concerns are discussed in this section. Small debris penetrating the strainer may reduce flow to the core, cause equipment damage, or have other effects on downstream components. These potentials are evaluated in the section covering downstream effects.

The head loss and vortex evaluation requires assessment of the associated time-dependent variables that affect important phenomena associated with pump and strainer performance. Pump flow rates, water temperature, containment pressure, and sump or suppression pool water level, debris generation and transport, and the potential for chemical precipitation are key factors that should be included. Key aspects of the strainer design should be specified, including strainer area, surface geometry, and screen mesh or hole size. Debris generation and transport to the strainer should be assessed to provide the quantities of debris by debris type predicted to arrive at the strainer and the size distributions for each type of debris. Guidance requires that strainers be designed to accommodate the most problematic debris load. The most problematic debris combination may not be the greatest quantity of debris, but may be caused by a thin debris bed or some combination of debris types. Thin debris beds, or thin beds are created when a relatively small amount of fiber collects on a strainer with a significant amount of particulate debris. The particulate debris is concentrated in a small volume resulting in a dense bed that may be relatively highly resistant to flow. In a thicker bed, the particulate may be distributed among a larger volume of fiber resulting in a lower head loss. Several debris generation and transport scenarios may have to be considered to identify the most problematic debris combination for any particular strainer. All of this information is required to ensure that strainer qualification head loss testing results in a realistic or conservative design basis head loss for the plant specific debris load and hydraulic conditions. The head loss evaluation provides the design basis head loss and potential air ingestion amounts for the NPSH evaluation, and the maximum head loss for the strainer structural evaluation. The head loss evaluation may provide a head loss that varies with time or temperature. In general, head loss is lowest at the start of recirculation and increases as debris builds a bed on the strainer and pool temperature decreases resulting in increased water viscosity.

The bed porosity and the debris bed surface area through which the water flows are the debris bed parameters that most govern head loss. Flow rate though the debris bed and water temperature are also important variables. A comparison between pipe flow and the fiber bed may be useful in understanding debris bed head loss. The debris bed head loss is similar to the piping frictional pressure loss. The piping head loss is a function of flow area and the pipe surface area, typically specified by using the hydraulic diameter. As the diameter of a circular pipe is increased, the cross-sectional area increases, the flow velocity decreases, the surface area per unit of flow in contact with the flow decreases, and the pressure drop decreases. The shape of the flow channel also affects the pressure drop, e.g., a narrow rectangular conduit of the same flow area as a circular pipe would have a greater specific surface area in contact with the flow than the circular pipe, resulting in a higher frictional pressure drop. For a debris bed, the bed porosity roughly correlates with the hydraulic diameter while the debris bed surface area correlates with the pipe flow area. The pressure drop for flow through a debris bed increases with reduced porosity and/or a higher specific surface area. In general flow through pipes is turbulent. In many cases flow through a debris bed is mostly laminar due to the very small flow passages through the bed.

For a given porosity and surface area, head loss also increases with the thickness of the debris bed. This could be interpreted to indicate that a thicker debris bed would always result in higher head loss. However, bed porosity is also a function of how the debris accumulates. Debris arrival timing and sequencing can result in varying debris bed porosities. A thinner and tighter (less porous) bed can cause a higher head loss than a thicker and more porous bed. Of specific interest, a uniform thin debris bed formed of fine fiber and particulate debris can cause substantially higher head losses than a similar bed formed by larger fibrous shreds given the same particulate debris loadings. If a specific amount of particulate debris is distributed relatively evenly through fibrous beds of similar characteristics, but varying fiber amounts, frequently a bed with less fiber will result in higher head loss. This is because the particulates are trapped more closely together resulting in less porosity. It has been observed that up to a point debris beds with higher particulate to fiber ratios result in higher head losses. Uniform debris beds are generally associated with higher head losses than non-uniform beds containing the same amount of debris.

Other important aspects of debris beds include particulate filtration efficiency and bed structural strength. The size of strainer openings can affect the initial filtration efficiency of fibrous debris. Because the porosity of a layer of fibrous debris ranges from about 92% to 99%, fine particles can pass through the fiber bed while coarser particles are filtered. The fiber bed compresses due to increasing head loss. This increases filtration efficiency and reduces the bed porosity. As larger particulate is filtered, the overall filtration efficiency of the bed is increased and finer and finer particles are filtered. A typical thin bed of fine hardened particulate may have a porosity of about 80%. Coarse sand may have porosity as low as about 40%.

The slow buildup of a debris bed would first result in an accumulation of fibers, and then larger particles, followed by smaller particles until all debris is filtered from the fluid or the particles are too small to be filtered. Some of the more problematic materials with respect to head loss are microporous insulation (Microtherm, Min-K, and calcium silicate), and chemical-effect precipitates. Because these materials can be very small they sometimes pass through the debris bed without adding to head loss until filtration of the coarser materials increases the bed's filtration efficiency. This is an example of potential synergistic effects among debris types.

Another possible synergistic effect could be the structural strength of the bed, specifically for thin beds. Some debris beds have been observed to develop flow channels through the bed, referred to as "boreholes," as head loss builds. These boreholes relieve and limit head loss. Boreholes through a calcium silicate thin-bed layer can be observed in NUREG/CR-6874, Figure 3.18. Whether or not boreholes can develop within a bed of particulates likely depends upon the structural strength of the bed, which in turn likely depends upon the composition of the bed, such as types of particulate and the fiber composition. Although not observed in testing, it is possible that the addition of hardened particulate (such as coating particulates) to the calcium silicate (fragile crystallized particulate) beds tested in NUREG/CR-6874 could have affected the development of the observed boreholes.

Structural strength of a debris bed may be limited if there is inadequate fibrous debris present to support the bed. The staff has observed head loss tests that formed very thin uniform beds. In some cases pressure drop across the debris beds was limited by structural strength. Head loss was observed to increase up to a point at which is would suddenly decrease as bore holes developed due to the pressure drop. In some cases the head loss would increase and then suddenly decrease repeatedly due to bore holes being filled in by debris followed by additional bore hole formation.

The complexities of the debris bed formation and filtration, along with the many variables resulting from differences among plants, require that head loss tests be conducted for plant strainer qualification. Head loss testing has been conducted in small-scale apparatus and in larger-scale tests of plant strainer prototypes. The small-scale tests typically use a closed piping loop that sends water though a small flat screen and continuously recirculates the flow (e.g., NUREG/CR-6874). The prototype tests use a section of the plant strainer (e.g., for a stacked-disk strainer, the prototype would include a short section of the disks or one or more modules out of a multi-module strainer) with pumped water recirculation. The advantage of the small-scale closed-loop testing is simplicity. Prototype testing includes the geometric complexities of the plant strainer. However, when the debris bed is uniform, such that debris accumulation does not depend on screen surface orientation, the closed-loop test may provide head loss results similar to those of the prototype test. The small closed-loop tests are typically used in a separate-effects approach to ascertain debris head loss characteristics for specific types of debris.

Head loss and vortex evaluations use calculations to: (1) design a prototype strainer before conducting head loss testing, (2) conduct post-test scaling of test data to alternative conditions from the conditions tested, and (3) support testing and evaluation of the test results. Calculations may also be performed for other analyses. The available NRC-developed head loss correlations include the NUREG/CR-6224 correlation. Three NUREGs were developed in support of this correlation. They are NUREG/CR-6224 which developed the correlation, NUREG/CR-6371 which explains the use of the correlation as intended for BWRs, and NUREG/CR-6874 which developed parameters to be used in the 6224 correlation to predict the effects of calcium silicate on head loss. Another NRC correlation, presented in NUREG-1862, was developed in concert with the head loss tests at Pacific Northwest National Laboratory (PNNL), discussed in earlier reports (NUREG/CR-6917). The advantage of the NUREG/CR-6224 correlation is that it has been programmed into a user-friendly quality checked code and has undergone extensive technical review and application. The code is called BLOCKAGE. However, the NUREG/CR-6224 head loss correlation is an empirically derived equation that is dependent on water properties, flow velocity, and debris properties. The correlation assumes that temperature affects only the fluid properties and not the debris properties and characteristics. The correlation was developed to calculate single-phase pressure drop, and has not been validated and cannot be applied to two-phase flow conditions. The 6224 correlation was later updated for use by PWRs and the code was rewritten to include a module that could predict deaeration of fluid as it passed through the debris bed. Other issues with the NUREG/CR-6224 correlation is that it was developed and validated by tests that used a relatively small population of debris types, the tests used fibrous shreds instead of fine fibers which are more likely to transport, flow rates were relatively high, and thin beds were not validated. The newer NUREG-1862 correlation was developed to counter technical criticisms of the NUREG/CR-6224 correlation; however, this correlation was not developed into a user-friendly program and is only available through the NUREG-1862 report. It has not been used extensively for strainer evaluation.

Potential vortex formation was analytically correlated to the Froude number (NUREG-0897). Because a vortex can draw air from the pool surface to a significant depth below the surface and then into a strainer, plants often installed structures designed to physically prevent the formation of a vortex.

Prototype head loss testing cannot fully model prototypical plant conditions. For practicality, most prototype testing has been conducted at colder water temperatures than postulated accident pool temperatures. Subsequent temperature scaling of head loss test data has been based primarily on the temperature-dependent viscosities. The temperature-dependent viscosity scaling is based on head loss correlations, e.g., the NUREG/CR-6224 correlation, and is valid when the velocities through the debris bed are sufficiently slow that the head losses are linearly dependent upon the velocity rather than the square of the velocity. In the NUREG/CR-6224 correlation, the linear velocity term is proportional to the viscosity, but its velocity-squared term is not a function of the viscosity. If boreholes occur during testing it may be non-conservative to correct the measured head loss to a higher temperature because higher temperatures results in lower differential pressures. At lower differential pressures, the bore holes may not form. Any temperature correction to higher temperatures should be carefully reviewed.

Sometimes, the strainer design differs slightly from the tested prototype design. For example, the final design may result in an increase or decrease in strainer area. This would require that the effects of changes in debris loadings from the scaled loadings used in the prototype tests be reassessed. Because it is impractical to test strainers using plant conditions the use of analyses to estimate differences in head loss between the actual plant strainer and the tested prototype is necessary. The uncertainties associated with these estimates grow as the divergence between the actual plant strainer and the prototype strainer increase. Post-test calculations to scale head loss test results to the plant conditions should be carefully performed.

If the strainer is not fully submerged within the sump or suppression pool, the exposed strainer surface allows air to be drawn directly into the strainer. In this situation, if the debris bed head loss exceeds approximately one-half of the strainer submergence, as measured from the bottom of the strainer screen area to the pool surface, the water passing through the strainer will be inadequate to support the require pump flow rate and air can be sucked directly to the pump. For this reason RG 1.82 states that head loss should be limited to a maximum of one-half of the strainer submergence. To prevent this type of failure most strainers are designed to be completely submerged at the start of recirculation or soon thereafter. Some PWR strainers are vented to the containment above the sump water level. These strainers should be evaluated for the potential for air ingestion due to inadequate flow through the strainer surfaces as described above.

Even if a strainer is fully covered, air ingestion can still be caused by vortices and deaeration. Deaeration may occur as the water pressure decreases as it passes through a debris bed. At elevated temperatures flashing may occur. Flashing would likely have a much more detrimental effect than deaeration because the volume of gas formed by flashing is potentially much greater than that which could be caused by deaeration. During testing with colder water, deaeration typically results in a buildup of air immediately downstream of the test strainer, where the bubble-rise velocities exceed the pumped flow velocities. A similar air accumulation situation could occur within plant strainers. Increasing strainer submergence decreases the potential for flashing and deaeration because it increases the pressure on the water at the point that it passes through the debris bed. Colder water reduces the probability for flashing because it increases subcooling. However, as the water cools, head loss increases. Therefore colder water can result in the limiting condition for deaeration. Both flashing and deaeration should be evaluated for various conditions to ensure that they will not adversely affect the operation of the strainer or the pumps taking suction from the pool.

In response to NRC Bulletins 95-02 and 96-03, U.S. BWR licensees installed large capacity passive replacement strainers with total screen areas ranging from 475 to 6253 ft2 (Elliot, 2001). The BWR vendors conducted head loss tests on scaled design-specific modules to develop an analytical capability to estimate head losses on plant-specific strainers. The testing was not plant specific, but was intended to bound conditions that strainers could experience. The data from the testing was used to develop correlations that could be used to interpolate a plant's potential head loss based on its specific debris load. The NRC staff reviewed the test results from a number of these tests. The NRC staff also reviewed the head loss correlations and found them to be acceptable when applied with certain limitations.

In response to GL-04-02, U.S. PWR licensees installed large capacity passive replacement strainers with total screen areas ranging from 769 to 8275 ft2. Vendors conducted prototypical head loss testing to qualify the design of new replacement strainers. The NRC staff followed the industry's head loss testing through testing observation trips and plant audits. The NRC staff documented their positions in areas relating to head loss testing and evaluation including scaling, debris near-field settlement simulation, surrogate debris similitude requirements, test procedures, and post-test data processing and extrapolation. The intent of the staff work in this area was to establish appropriate evaluation criteria for the staff review of licensee corrective action associated with GL-04-02 and future strainer head loss analyses. The staff positions and the findings of many NRC and industry test programs provided a basis for writing review guidance for evaluations regarding strainer head loss and vortexing. This review guidance was issued in March, 2008 and may be found in ADAMS, ML080230038. Because of uncertainties regarding the head loss behavior of some debris types the staff determined that strainer head loss testing with plant specific debris loads should be conducted under most conditions.

The goal of prototypical head loss testing is to determine the strainer potential peak head loss that could occur during the postulated LOCA scenario during its mission time, considering the plant specific factors that could affect head loss. The mission time is considered to be the time from accident initiation to when the flow is permanently and substantially reduced by licensee emergency operation procedures (EOPs). In theory, head loss testing should continue until the mission time is reached, but practical considerations limit the period of testing. Because of the limited test time, peak head loss may be estimated by extrapolating the test head loss results from data whose values can be demonstrated to be approaching the final head loss reasonably closely. In prototypical head loss testing, the accumulation of debris depends on the filtration of the suspended debris within the test tank by the fibrous bed. The filtration, and therefore head loss, is dependent on the debris-dependent strainer filtration efficiency and may take some time to reach a value that is relatively stable. Assurance is needed that the test termination criteria are suitable to determine the potential peak head losses. In addition, there are potential time-related phenomena can affect debris bed head loss. For example, compression of the debris bed or material degradation may occur over time resulting in changes in head loss.

Prototypical head loss testing usually consists of a scaled strainer module tested in a representative fluid flow environment with scaled plant-specific debris loading. The strainer test modules are usually scaled-down versions of the plant replacement design or simply single modules of a multi-module strainer train. Specifically, the test module strainer surface areas are much smaller than the replacement strainers. Assurance is needed that the scaling between the test strainer module and the plant replacement strainer has been correctly evaluated and that scaling issues do not result in non-conservative test results. The primary scaling parameters include the screen area, the dimension of the strainer elements (e.g., disks), the level of submergence, the number of strainer elements, the debris amounts, and the local fluid flow conditions. These parameters affect the flow velocities approaching the test strainer and the velocities through the strainer and debris bed.

The debris surrogate material should be prepared and introduced into the test loop in a conservative or realistic way so that the debris accumulation on the testing module either represents the actual debris accumulation or bounds the realistic debris distribution.

The NRC staff positions on various aspects of head loss testing are discussed next. Section 5.7.2 discusses the role of head loss testing as part of the overall strainer design evaluation methodology and the staff's view regarding the uncertainties involved in head loss testing. Section 5.7.3 discusses the scaling of the plant replacement strainer design to the test strainer module. Section 5.7.4 discusses the similitude considerations for debris transport and debris accumulation on the strainer when a licensee proposes to take credit for near-field settlement. Section 5.7.5 discusses the similitude requirements for the surrogate debris. Section 5.7.6 discusses recommendations for developing conservative procedures for head loss testing. Section 5.7.7 discusses the criteria for terminating a head loss test. Section 5.7.8 discusses potential scaling of post-test data to actual plant conditions. Section 5.7.9 is a look back through the PWR resolution process to identify the governing aspects of head loss testing that should be the focus of future strainer qualification testing. The PWR methodology summary includes applicable resolution guidance information found in NRC-SER-2004, the supplemental March 2008 head loss guidance (NRC, 2008d), and relevant observations from the audit process. Additional head loss guidance is found in RG 1.82. Section 5.7.10 is a look back through the BWR resolution process. The BWR methodology is based on the BWROG URG (NEDO-32686) and the associated SE to the URG (NRC-SER-1998).

5.7.2 Role of Prototype Head Loss Testing in GSI-191 Resolution

5.7.2.1 Trends in Replacement Strainer Design

The primary trend in replacement strainer design has been replacement of passive strainers with significantly larger complex geometry strainers. The effects of replacing a strainer with a large strainer are to (1) distribute the debris over a larger area, resulting in thinner beds of debris accumulation, and (2) reduce the water flow velocity through the debris accumulation. Both effects reduce head losses through the debris. Vendor designs differ primarily on how large screen areas are incorporated into relative small volumes that can be tailored to fit within a containment sump or suppression pool. One distinguishing design feature is whether the internal strainer flow resistance is structured to enable uniform flow across the strainer surface. Most strainers incorporate disks, pockets, or some other geometry that allows the strainer surface area to volume ratios to be maximized.

Given a specific replacement strainer design, head loss depends primarily on the quantities, compositions, and distribution of the accumulated debris on the strainer. Some types of debris are relatively non-problematic. For example, pieces of crumpled RMI foil debris tends to be very porous, and the accumulation of relatively flat overlaying sheets of foils is not realistic at the low approach velocities expected with the new strainers. For BWRs, during periods of high turbulence RMI may transport more easily to the strainer. Some other types of debris are problematic and have caused serious head losses even at very low surface approach velocities. These types of debris include microporous insulation and chemical effect precipitates. Typical microporous insulation includes calcium silicate, Min-K, and Microtherm.

With the typical PWR screen approach velocity less than 0.01 ft/s, a fiber debris bed, lacking added particulate debris, accumulated on the screen would almost certainly be very porous. The primary threat to the typical large replacement strainer designs is a thin-bed formation that includes substantial quantities of particulate debris (e.g., calcium silicate or coatings) and/or precipitates from chemical effects. In addition, a thick bed accumulation of fiber with relatively large quantities of these particulates or chemical precipitates can potentially cause high head loss, especially if the strainer becomes engulfed with debris to such an extent that a circumscribed or transitioning debris bed is formed. A circumscribed bed is formed when the strainer is completely covered in debris so that the area through which the water flows is significantly reduced. For example the disks of a stacked disk strainer would be completely filled with debris. A transitioning bed is one that eliminates some of the surface area by partially filling in the complex geometry with debris.

For BWR strainers, the issue of thin-bed formation is less clear. Based on the BWR audit reports for the Limerick Generating Station (ML003684437), Dresden Nuclear Power Station (ML010930074), Duane Arnold Energy Center (ML012610017), and Grand Gulf Nuclear Station (ML012560213), the screen approach velocities are typically somewhat faster for BWR than for PWR strainers. However, the effects of BWR vent downcomer turbulence during primary system depressurization on the formation of the debris bed are not well understood. High turbulence can keep larger debris in suspension, which could disrupt the formation of a thin bed. The timing of the turbulence dissipation relative to the operation of the pumps could be a determining factor in whether a thin bed could be formed early in the event. Even if turbulence could preclude the formation of a thin bed during blowdown, once the turbulence subsided, the debris accumulation could be similar to that of a PWR. Once the heavier debris has settled, the fine suspended debris accumulates independent of gravity and, therefore, can accumulate uniformly on any strainer geometry.

For RMI and/or paint chips to result in high head losses on a large strainer in a PWR, the debris would have to be piled on top of and around the strainer in a circumscribed accumulation. For this type of accumulation, at typical low approach velocities, the strainer would likely have to be located inside a pit below the containment floor level such that the debris falls onto the strainer from above. It is unlikely that engulfing quantities of such debris would fall directly into a pit. However, the geometry of a strainer pit installation can enhance approach velocities toward the pit, resulting in velocities much higher than for strainers installed on the containment floor and thereby enhancing near-pit debris transport. Therefore the potential for this type of accumulation should be considered on a plant specific basis.

5.7.2.2 Inputs and Outputs of Prototypical Head Loss Testing

The overall resolution process based on head loss testing of strainer prototypes is represented schematically in Figure 5.7-1. This scheme is discussed in this section in order to put the steps in perspective before focusing on prototype head loss testing. This process was developed during the resolution of GL 2004-02 for PWRs. BWR testing was conducted more generically and correlations were developed to allow individual BWR plants to apply the test results to their particular conditions. Almost all PWRs conducted plant specific testing. The NRC staff is working with the industry to validate that the application of BWR testing to individual plants was conducted properly. Some of the areas discussed below may not have been addressed during the BWR testing in the 1990s.

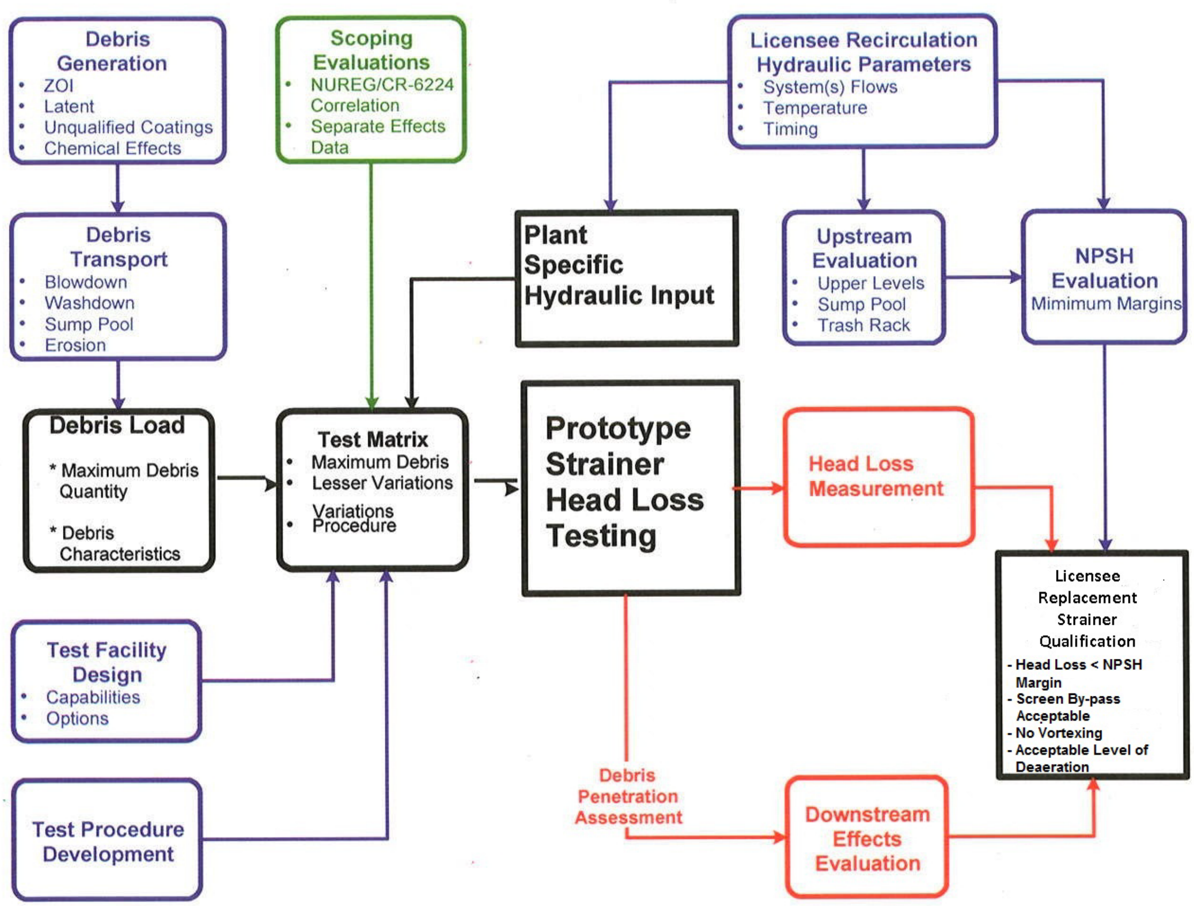


Figure 5.7-1. Schematic Diagram of Processes Used to Qualify Replacement Strainers

Head loss testing is performed with a reduced section of the licensee's replacement strainer design in a tank of water. The test strainer module is connected to a recirculation loop that pumps water from the tank through the test strainer and returns the water to the tank. A prototypical load of debris is introduced into the tank where accumulation on the test strainer usually results in measurable head loss. A water sampling method may be used to sample the flow downstream of the test strainer for subsequent analysis of debris bypassing the strainer. Test measurements include differential pressure across the strainer, flow rate, and water temperature. The challenge in prototype head loss testing is ensuring that the conditions within the test tank are prototypical or conservative with respect to the plant sump pool or suppression pool. These conditions include the postulated debris loading, strainer submergence, strainer flow velocity (or pump flow), and aspects of the various accident scenarios. Water temperature should be considered either in the actual testing or the subsequent analytical application of test data to strainer head loss determination. When adding turbulence to the test loop, care should be taken to preclude forcing debris to accumulate on the strainer that would not prototypically accumulate in an actual plant scenario or preventing debris from accumulating on some sections of the strainer. For example, if a shred of fibrous debris is predicted to settle to the pool floor and remain there, then the induced turbulence in the test tank should not cause such debris to accumulate on the test strainer. This condition is especially true in thin-bed head loss tests, where forced accumulation of such shreds can readily preclude the formation of conservative thin-bed formation. However, staff guidance has attempted to minimize or ensure conservative, the effects of having some debris transport to the strainer non-prototypically. Maximum debris accumulation does not always mean maximum head loss, especially for thin beds. The test matrix box shown in Figure 5.7-1 illustrates the input logic and information for the head loss test.

The NRC guidance on debris generation and transport provides a methodology to determine conservative bounds for the maximum quantities of various types of debris that could potentially reach the replacement strainers. A replacement strainer should be capable of handling the maximum potential debris load and any reasonable combination of lesser quantities as well. The strainer should retain acceptable head loss considering any realistic order in which the various types of debris could arrive at the strainers. The chaotic nature of debris generation and transport following a pipe break, the variety of post-LOCA debris types, and the extensive variation of break types and locations make it difficult to determine debris quantities and arrival sequences. In general, licensees determine the maximum debris quantities that could be produced for various breaks for use in full-load tests but also must conduct thin-bed testing based on minimal fiber accumulation and maximum particulate debris terms. For strainer testing, these maximum quantities are scaled down to the test strainer module, and either the actual plant material or a suitable surrogate is used to create prototypical debris for the head loss test.

The licensee specifications, often determined from accident analyses, provide the operating conditions for the sump strainer, including pump flow rate, sump pool water temperatures, and pool depths. An upstream analysis is conducted to ensure that a blockage of the flow of water into the sump or suppression pool cannot cause a reduction in the expected pool depth at the strainer after a LOCA. All of this information is used to determine prototypical hydraulic conditions for the conduct of the head loss testing. The licensee NPSH analysis determines how much debris-induced head loss can be tolerated across the replacement strainer.

The design of the test facility, in conjunction with the test strainer module, should be such that the hydraulic conditions within the test tank are prototypical or conservative with respect to the sump or suppression pool and plant strainer. These conditions include the flow velocities that transport debris and the turbulence levels that influence debris suspension and deposition on the strainer. The test specifications should be designed to determine the worst-case head loss from all the possible types of debris beds that could accumulate given the bounding quantities of debris analyzed to arrive at the strainer (i.e., thin-bed versus maximum debris accumulations and potentially stratified beds). Staff guidance is that, as a minimum, full-load tests and thin-bed tests that incorporate the full particulate load be performed. Testing experience has shown that a thin debris bed that includes a problematic particulate, such as calcium silicate, can become relatively non-porous, thereby causing very high head losses. Prior to conducting prototype testing, vendors used the head loss correlations, such as the NUREG/CR-6224 correlation to initially size the plant replacement strainer. Subsequently the prototype strainer was usually tested in accordance with the test matrix. The test results either provided the validation of the adequacy of the strainer design or demonstrated a need for a redesign.

Post-test evaluations are required in order to validate the head loss results, and apply the results to the replacement strainer, Results of head loss tests conducted with colder water are often scaled to the plant sump or suppression pool water temperatures. Sometimes scaling to an alternative approach velocity is performed. Scaling is discussed in Section 5.7.3 below.

The establishment of prototypical debris settlement within the test tank, referred to as the "near-field effect" or "near-field settling," has been problematic in prototype head loss testing. Debris accumulation on the test strainer should not be less than the corresponding expected debris accumulation on the plant strainer. At the same time, debris expected to settle in the plant sump or suppression pool should not be forced to accumulate, especially when conducting thin-bed testing. Some strainer vendors have agitated the test pool in an attempt to keep all debris in suspension and, therefore, make it much more likely to get all debris to the strainer. Other vendors did not agitate the pool, thereby allowing debris to settle. In some cases, agitation forced shreds to accumulate non-prototypically, thus precluding formation of a thin bed. It should be ensured that agitation does not prevent prototypical debris transport and that debris is not prevented from accumulating on the strainer as it would in the plant. The staff guidance for head loss testing is structured to reduce the effects of any non-prototypical debris transport during testing. For example, the guidance for thin bed tests states that fine debris should be added prior to larger debris and that this debris should be added in small batches. In addition, the guidance is to allow head loss to stabilize between debris batches. With this methodology, it is unlikely that larger debris pieces will disrupt a potential thin bed.

Sampling of flows downstream of the test strainer is sometimes conducted to determine the amounts and types of debris bypassing the strainer. This debris could potentially damage or clog components such as pumps, throttling valves, or the reactor core. The downstream debris characteristics are used to determine the likelihood that downstream blockage could threaten long-term core cooling or adversely affect other components downstream of the strainer. There is not a consistent methodology or staff guidance for determination of strainer bypass. However, the staff is working with industry to ensure that bypass testing results in realistic or conservative quantification of strainer bypass. The staff has noted that sampling of the fluid downstream of the strainer may not provide an accurate measure of bypass and that filtering of the full flow stream should be employed.

Some vendors use closed-loop flat-screen testing (rather than prototype testing) to determine head loss characteristics for test debris. In a closed loop test, essentially all of the debris accumulates on the test screen so the closed loop head loss can be correlated with the debris quantities and characteristics. Properly conducted flat screen tests result in very uniform debris beds. Based on debris-specific head loss tests, vendors can use a version of the NUREG/CR-

6224 relationship to correlate the measured head losses with debris quantities by backing out effective head loss parameters, such as the particulate specific surface area, so that the plant-specific head loss correlation reproduces the head loss test results. Subsequent application of the revised plant specific correlation to replacement strainer design has validity as long as the application conditions are close to the closed loop test conditions. Uncertainty occurs in the extrapolation to alternate conditions as variations from the closed loop condition occur. One approach to the evaluation of replacement strainers could be to use the validated correlation with parameters deduced from applicable closed-loop head loss testing to design the replacement strainer. A prototype of that strainer would then be tested to ensure the prototype functions as intended. Note that while the correlation is a useful developmental tool that because there are uncertainties in the applications of correlations to head loss, the staff position is that the final validation of the plant strainer should be based on head loss testing conducted under conditions that match the plant conditions as closely as possible. The staff may accept some extrapolations using the 6224 correlation, as long as the tested conditions are relatively close to the extrapolated conditions and some conservatism is included in the extrapolation.

5.7.2.3 Uncertainties and Conservatism in Head Loss Testing

The inputs to prototypical head loss testing can be divided into two categories. The first is plant hydraulic conditions, which use the maximum ECCS/CSS flow rate based on the worst-case single-failure assumption, the minimum containment sump pool subcooling, and the minimum sump level. The second is the debris load on the strainer based on debris generation and transport analyses. Rather than attempting to predict time-dependent debris transport, it is conservatively assumed that all the debris accumulated during the post-LOCA ECCS mission time for a given break location has accumulated on the strainer at the beginning of recirculation. The staff has allowed some analyses to credit delayed arrival of debris when evaluated conservatively. Additionally, the staff has allowed analyses to credit delayed precipitation of chemicals.

Conservatism has been built into the methodology for developing inputs to the head loss testing. In the area of plant hydraulic conditions at the beginning of recirculation, it has been assumed by many licensees that all ECCS and CSS pumps would be in operation for an extended period of time, up to 30 days. It is conservative to assume maximum flow through the strainer for head loss testing. For those plants whose design includes logic that shuts down the low-pressure safety injection (LPSI) pumps during switchover from the RWST to the sump, licensees may have to consider one LPSI train failure-to-stop, as the single active failure. This assumption leads to a conservatively calculated maximum flow rate through the screen. In addition, at the beginning of the recirculation phase, the sump or suppression pool subcooling is assumed to be at a minimum resulting in minimum NPSH margin. In reality, the NPSH margin increases significantly after the heat removal systems have removed significant heat from the reactor coolant system and the containment. The NPSH margin usually increases from its minimum value before the beginning of recirculation. Evaluations also assume the minimum strainer submergence which decreases NSPH margins, decreases flashing margins, and increases the potential for deaeration.

In the area of debris load input to the head loss testing, debris generation and transport are conservatively evaluated. The approved methodology conservatively assumes that all of the eroded fine fiber is present with other debris to cause head loss at the beginning of recirculation. In reality, erosion is a relatively slow process, and therefore the NPSH margin could increase significantly before all of the eroded fiber reaches the screen. There is a potential for debris agglomeration during transport to the strainer, thereby enhancing debris settlement, but this possibility is not considered in the transport analysis guidance.

With the key inputs to the head loss testing developed conservatively, the measured head loss is also expected to be conservative, as long as the test facility is scaled properly and the testing procedures are conservative. Specifically, the thin-bed test procedure should be carefully controlled to ensure it is conservatively conducted. Because test results are intended to be bounding no analysis has been performed to identify the uncertainty band of the measured head loss data. To ensure conservatism, guidance includes direction to design the test facility properly, conduct the test following conservative testing procedures, and perform a conservative evaluation of the test results.

5.7.3 Strainer Test Module Scaling

5.7.3.1 Strainer Vendor Scaling Approaches

Ideally, a scaled-down test facility is designed so that the debris transport and head loss processes that would occur in a plant following a postulated accident would also occur in a similar manner in the test facility. That is, the dimensions of the test facility would all be reduced by some common scaling parameter or parameters derived from that of the plant sump or suppression pool and replacement strainer based on the dominant processes. If the essence of the dominant processes is captured in one or more of the accepted dimensionless parameters, then the maintenance of the dimensionless parameters between the plant sump or suppression pool and the test facility can become the basis of scaling down the design. If scaling some aspects of the test are impractical or the required scaling is not well understood, the test facility and methodology should be designed to treat these areas so that realistic or conservative results can be expected.

For prototype head loss testing, several considerations tend to affect the options associated with scaling. These include:

- Strainer test vendors will likely construct only one test facility, or a limited number of such facilities, that can be modified to represent the various configurations of different plants.
- Plant replacement strainers are sometimes designed interactively with head loss testing, where the head loss measurements provide data critical to sizing the strainer.
- Strainer designs vary significantly in geometric configuration and size.
- Plant sump or suppression pool geometries, pool depths, and flow conditions vary considerably among plants.
- The types and quantities of postulated LOCA-generated debris vary with the plants.
- Head loss tests are generally conducted by using room-temperature or slightly warmer water rather than water at plant sump or suppression pool temperatures.

The typical geometrical scaling approach adopted by the nuclear industry is based on the ratio of areas between the plant strainer and the test strainer. Based on this principle, a full-size strainer module or a portion of a strainer module is placed in a test loop within which the total flow rate is determined by multiplying the total plant sump or suppression pool flow rate by the ratio of the surface area for the test module to that of the plant strainer array. In this way, the screen surface approach velocity in the test strainer is the same as that in the plant strainers. Debris loading for the test is also scaled on the basis of strainer surface area ratio with the assumption that debris accumulation is representative or bounding of the actual plant condition. In some cases, the debris loading and approach velocities may be based on the ratio of the circumscribed areas between the plant and test strainers. In general, this approach could be taken if the plant strainer can become completely engulfed in debris. However, for this case, an additional thin bed test is then run using the strainer surface areas for scaling.

The design of the flow channel upstream of the testing module or test tank surrounding the module varies among strainer vendors. Most test vendors do not scale the upstream flow path. Instead, testing procedures involve agitating the test pool so that most of the debris introduced into the test loop accumulates on the screen surface. However, for thin-bed testing in an agitated tank, the fibrous debris should be prepared prototypically fine to represent plant fibers that would not settle in the sump or suppression pool under plant conditions; otherwise, the formation of the thin bed is compromised. Some vendors have decided to take credit for near-field settlement and developed specific approaches to design the upstream flow path of the test loop. The design of test facilities that credit the settlement of debris can be problematic because it is difficult to evaluate the many complex flow paths in the plant and model them in a relatively small test facility. The velocity and turbulence in the test facility should be demonstrated to result in realistic or conservative transport with respect to the plant. The calculations required to demonstrate adequate transport in the test are complex and have been carried out using CFD models of the plant and test facility.

In addition to the geometrical scaling effort, the strainer vendors proposed various extrapolation schemes to address temperature scaling. This scaling is generally based on the ratio of the kinematic viscosity of water at the test and postulated plant temperatures. Some caution should be applied to temperature scaling to ensure that it is performed validly.

5.7.3.2 Theoretical Considerations

When scaling a large fluid field to a smaller test loop, dimensionless numbers are normally derived from the governing equations or are based on experience with and understanding of the dominant physical processes. A dimensionless analysis of the fluid flow associated with head loss testing primarily includes the Froude and Reynolds dimensionless parameters.

Reynolds number = ratio of inertial forces to viscous forces

Froude number = ratio of inertial forces to gravity forces

The debris transport and filtration processes that these forces influence include:

- The settling rate of debris within a relatively calm pool of water near the strainer
- The level of turbulence within a pool
- The thickness of the pool floor boundary layer

- The drag forces on debris residing on the pool floor near the strainer

- The lift forces on a piece of debris if the flow goes over a curb or if debris lifts from the floor onto a screen surface

Analysis of particles settling in calm or still water is usually treated by a Stokes Law approach in which the terminal settling velocity is inversely proportional to viscosity and directly proportional to the water density. Therefore, the relationship contains significant temperature dependence. Debris settling involves gravity; therefore, the Froude number is relevant. Because settling is also influenced by pool turbulence, which is typically correlated by using the Reynolds number, the Reynolds number is also relevant. Once a piece of debris has settled on the pool floor, a balance of drag and weight forces determines whether that piece of debris will move along with the flow toward the strainer. Flow velocity around the debris piece is affected by the thickness of the boundary layer relative to the debris height. Boundary layer models typically use the Reynolds number (e.g., to define the transitions between laminar and turbulent regimes). The force of drag on a piece of debris depends on the flow velocity, the debris dimensions, and a drag coefficient that is typically correlated by using the Reynolds number. Note that the length parameter (L) resides in the numerator of the Reynolds number but in the denominator of the Froude number, meaning that a decrease in L would decrease the Reynolds number but increase the Froude number.

The processes associated with scaling a test facility also have to consider the phenomena that generate a head loss across a bed of accumulated debris. The primary hydraulic parameters for head loss are the velocity of flow through the debris, and the viscosity of the water, and to a lesser extent, the water density. Another hydraulic aspect for head loss testing is thickness, compression, morphology, distribution, and porosity of the debris bed. Water temperature should be considered and adequately factored into the testing data extrapolation because of its effect on viscosity and density, which are inherently involved in the strainer fluid flow hydraulic processes.

Debris will settle significantly faster in still hot water than still cold water, which tends to make near-field settling in room-temperature head-loss tests somewhat conservative with respect to maximizing debris transport. However, as temperatures increase, viscosity will decrease, and hence, the Reynolds number will increase, which indicates more turbulence in the hotter sump pool than in the head loss test tank. More turbulence tends to keep debris suspended. This effect may tend to make room-temperature head-loss tests less conservative. The drag forces on floor debris will change somewhat due to an increase in Reynolds number as temperature increases. Colder water would enhance drag and increase the chance of debris being transported to the strainer. The complexity of the sump pool geometry relative to the head loss test tank must also be considered along with the variations in water returning to the sump or suppression pool from the break overflow and the containment drains. Staff guidance states that justification regarding the extrapolation of the room temperature near-field head loss testing should be provided if a credit is sought for near-field settlement. Computational fluid dynamics analyses of the sump pool and the test tank may be useful in the comparison of the test and predicted plant conditions.

Because the theoretical considerations associated with strainer head loss testing are complex it is frequently conducted in a conservative manner so that sophisticated evaluations are not required. Testing that credits debris settlement (near-field settling) requires significantly more complex evaluation than testing that attempts to ensure that most debris reaches the strainer through agitation.

5.7.3.3 Test Module Design - Area Ratio-Based Scaling

Typical designs for plant replacement strainers consist of strainer modules that are either interconnected along a common axis or connected to a common outlet plenum. A test strainer module typically consists of a single strainer module or a section of a strainer module. The test module must realistically or conservatively represent the array of modules or elements in the typical plant replacement strainers in both strainer design and prototypical conditions of flow approach velocities and debris accumulation. If the modules in a larger array have similar flow resistance characteristics, then under clean screen conditions, the modules closest to the pump suction will have more flow entering the modules than the modules farther away. Some strainer vendors compensate for this flow imbalance by including module-specific internal flow resistance that balances out module flows so that the approaching flow velocities tend toward uniformity. If the approaching velocities are uniform from one module to another, then under many conditions the debris accumulation can be expected to be relatively uniform from one module to another. (This expectation does not necessarily hold for pit geometries and may be challenged for flow conditions that are strongly influenced by external obstacles in containment.) However, if the approaching velocities are not uniform from one module to another, the module with the higher approach velocities will preferentially accumulate debris. This kind of debris accumulation also tends to shift the incoming flow to the modules farther from the pump suction as the head loss across the closer modules increases. This can result in sequential debris accumulation along the entire array. Other parameters that affect debris accumulation are debris distribution in the pool, debris characteristics, pool turbulence caused by flow entering the pool or objects in the pool, and distribution of velocities throughout the pool.

Prototype head loss testing procedures have typically specified the test flow rate and test debris quantities based on the average conditions for the strainer array. The average plant strainer conditions may be more applicable when the strainer has designed in flow controls that ensure a uniform approach velocity from one module to another. Whether the average flow rate may be applied to the test of a non-uniform velocity replacement strainer depends on the internal flow resistance of the strainer relative to the head losses caused by the actual debris accumulation. If internal flow resistance is relatively minor with respect to the postulated debris-driven head losses, then the average strainer conditions may be appropriate. If the internal flow resistance is not minor with respect to the postulated debris-driven head losses, then the average strainer conditions may not be appropriate or sufficiently conservative. In that case, the test should evaluate the postulated strainer conditions that will lead to conservative head loss results as opposed to testing with average conditions. Specification of the flow rate for the test strainer module may need to be based on a strainer module with an approach velocity greater than the average approach velocity for the plant.

The potential for vortex formation increases with the strainer approach velocity. Therefore, in a string of modules the strainer module closest to the pump suction intake has the greater likelihood of forming a vortex if uniform flow is not part of the strainer design. Therefore, the determination of whether a vortex could form should be based on the velocities associated with the module closest to the pump suction intake.

In summary, the important criteria for test designs that are based on screen area ratio scaling are: (1) the fiber and particulate amount based on the area-ratio scaling is not sufficient to form a circumscribed debris bed, and (2) the testing module screen surface approach velocity is equal to or higher than the average velocity. In cases where the strainer approach velocity varies significantly due to local flow patterns or due to variations in internal strainer head loss, it may be necessary to test with a somewhat increased velocity to ensure conservatism.

5.7.3.4 Test Module Design - Debris Accumulation Pattern

Pressure drop caused by a debris bed depends on the velocity of flow passing through the debris. The average velocity depends on the pump flow rate and the strainer area but localized velocities may vary due to localized variances in debris composition and localized flow resistance variations in the design of the strainer. For replacement strainers of relatively complex geometry, such as stacked disk strainers, debris can accumulate differently for very fine debris than for coarse debris. The accumulation pattern also depends on the total volume of debris that has accumulated and the types of debris present. For very fine debris, such as individual fibers or small particles, accumulation will likely be relatively uniform initially because this type of debris is typically suspended uniformly in the fluid. Fine debris is not significantly affected by the pull of gravity, and therefore, it will seek all screen surfaces through which water is flowing, relatively equally, regardless of the surface orientation. For example, for large PWR replacement strainers, in which the perimeter approach velocities are typically less than 0.1 ft/sec and the flow velocities through the screen surfaces are less than about 0.01 ft/sec, the debris arriving at the strainer can be characterized as suspended matter. If this fine suspended debris (typically fibers and/or particles) were to build up somewhat non-uniformly, the flows would be redistributed to follow the path of least resistance, thereby rerouting additional debris to locations of less accumulation. In this manner, a uniform thin layer of debris can accumulate over the entire screen area. This layer of debris will filter additional fiber and particulates, particularly smaller particulates that decrease the porosity of the debris bed and increase head loss. Such debris accumulation can lead to the so-called thin-bed effect where a modest layer of fibers forms a particulate filter. Subsequent particulate buildup within the bed results in a debris bed with porosity similar to a bulk accumulation of that particulate. For a thin uniform debris accumulation over the entire screen area, the test strainer approach velocity is appropriately determined by dividing the plant volumetric flow by the total plant screen area. Vendor prototype testing observed by the NRC staff has focused on this total screen area approach velocity, which is correct for thin-bed accumulations.

Suspension of non-buoyant larger debris would depend on the level of pool turbulence. For the BWR strainers, debris in the suppression pool would likely be maintained in suspension by the primary system depressurization flows of the turbulent vent downcomer until completion of the blowdown phase, after which the turbulence would rapidly decay, allowing all but relatively fine debris to settle (NUREG/CR-6368). The fine debris that would readily stay in suspension would become thoroughly mixed. Pool turbulence could also affect debris accumulation by disturbing debris already accumulated. For BWRs, the primary source of turbulence would come from the primary system depressurization. For PWRs, the primary source of turbulence would come from the drainage from the upper containment in proximity of the strainer.

Some types of debris, specifically coarser debris, can bridge the entrances into the interior gaps of the strainer and thereby accumulate on the outer perimeter of the strainer. It is also possible that a large volume of debris can fill the interior gaps of the strainer. This type of accumulation is referred to as "circumferential accumulation." Debris that could result in bridging of the gaps could include RMI debris, paint chips, or larger pieces of fibrous debris. Consider the case where a mixture of RMI, coatings, and miscellaneous debris were to pile up around a strainer to such an extent that the strainer was essentially fully engulfed. When the strainer is engulfed by debris the correct flow area to use for scaling is the circumscribed or perimeter area of the strainer. The correct velocity to use in estimating head loss is the circumscribed velocity determined by dividing the volumetric flow by the circumscribed strainer area. Test modules can preserve the circumscribed velocity either by using a full-scale module, with the same dimensions as the plant module, or by increasing the test module flow rate to achieve the average circumscribed flow.

Even fine suspended debris can accumulate non-uniformly, depending on the strainer design and sump layout configuration. Given a stacked disk strainer design, if the flow entering the gaps between the disks is fast enough (not typical of the large replacement strainers), it may push surface accumulations deeper into the gaps, filling the gaps from inside to the outside. Because the transport of debris deeper into the gaps clears the outer disk areas, the head loss is maintained relatively low. Non-uniformities can also prevent formation of a thin-bed accumulation. The correct test approach velocity for this type of non-uniform accumulation can vary from the total screen area velocity to the circumscribed velocity. Therefore, testing may have to focus on the two extremes. The simplest test strategy is to use a strainer module that has a total area to circumscribed area ratio that matches the plant strainer. This is described below.

For some proposed plant strainer designs, it may be possible to have testing similitude for both screen and circumscribed approach velocities simultaneously. Figure 5.7-2 schematically shows several modules connected end-to-end. In this figure, the ratio of the screen to circumscribed areas for a single module is reasonably close to the same ratio for the entire assembly. Therefore, during prototype testing of a single module, it is conceivable that similitude for both the total screen and the circumscribed velocities can be simulated simultaneously. For other strainer designs, it may not be possible to achieve similitude for both velocities simultaneously. Figure 5.7-3 schematically shows modules connected into a common plenum with the modules arranged in an array. In this type of arrangement, the center modules may only have one (or none if the top surfaces are not perforated) outer surface contributing to the circumscribed area. During prototype testing of a single module, the similitude for both the screen and the circumscribed velocities can probably not be simulated simultaneously. For these strainers, the test matrix may have to include tests in which the respective similitude is achieved piecemeal. A simple area-ratio-scaled head loss test may not be conservative. Alternately, the test facility could limit the volume around the test module to the minimum available for any module in the array by installing walls around the module. This would be a conservative method because it would allow a circumscribed bed to form with less debris than would be required in the plant. This type of test setup has to ensure that transport to the strainer is not non-conservatively affected by the structure surrounding the test strainer.

For high-fiber and high-particulate plants, the sump or suppression pool configuration plays a significant role in the debris accumulation pattern. For example, a design that has the strainer installed in a pit below the floor level could be a cluster of strainer modules with the interstitial volume higher than the estimated total debris volume. This type of design may experience a non-uniformly high debris accumulation at the top of the strainer array or at the entrance of the sump pit. Bridging may occur, and a debris bed may form over the top of the strainer at the entrance to the sump pit. The potential for this type of accumulation is that large debris may be transported by high velocity flow toward the below floor sump as it fills during washdown. In this case, high flow velocity could be expected through the debris bed, and the effective circumscribed area could be equivalent to the cross-sectional area of the sump pit opening. The head loss in this situation would be expected to be significantly higher than that measured by a testing module loaded with a scaled average debris load based on area-ratio scaling. For this type of configuration, the strainer surface area ratio based scaling practice is likely non-

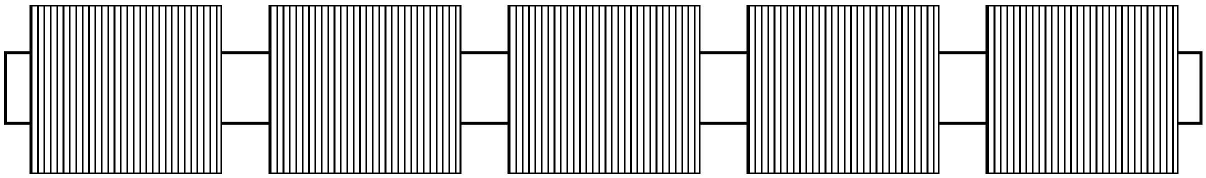


Figure 5.7-2. Schematic Diagram of Modules Connected End-to-End with Common Central Flow Plenum

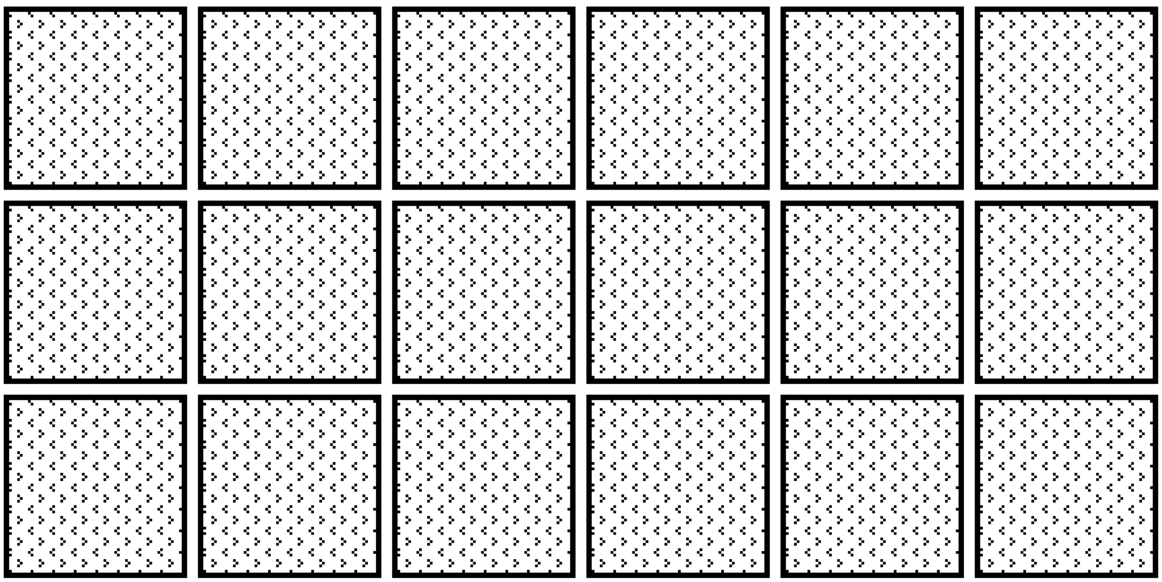


Figure 5.7-3. Schematic Diagram of Array of Modules Connected to Common In-Floor Plenum

conservative. Designs with this configuration should test at the circumscribed velocity or provide justification to demonstrate that the measured head loss using the area-ratio scaling (or other approach) is conservative.

A similar, although likely less significant issue, is the debris accumulation pattern experienced by a strainer array mounted in a shallow sump pit. If debris loading is high enough, the debris may form a thick circumscribed debris bed, and total head loss may be significantly underestimated by head loss testing that uses the area-ratio-based scaling approach.

In summary, the use of area-ratio-based scaling for head loss testing should be justified by evaluating the possible debris accumulation patterns. If severe non-uniform debris patterns are expected to cause significant circumscribed flow and pressure drop, head loss testing based on area-ratio scaling may be non-conservative.

5.7.4 Similitude Considerations for Near-Field Debris Transport on Strainer Accumulation

The concept of near-field debris settling was developed for the PWR sump pools. The debris transport within a BWR suppression pool would have considerable differences with respect to the debris transport within the typical PWR sump pool. When surrogate debris is introduced into a PWR test tank at some distance from the strainer, a substantial portion of that debris may settle within the test tank rather than accumulate on the test strainer module. In effect, if settling occurs the test combines the effects of debris transport with debris accumulation and head loss. Some strainer vendors and licensees considered this phenomenon as a realistic representation of the plant and took credit for debris settling during testing. The settling phenomenon is referred to as "near-field settling" or the "near-field effect." Tests that take credit for near-field settling should show that this settling is realistic for the strainer as installed in the plant. The main concern is that the test may result in unrealistic, non-conservative transport to the strainer. Assurance is needed that the near-field debris settling within the test tank is similar to or less than the settling that would actually occur within the plant following a postulated LOCA. Due to the complexities and uncertainties involved in predicting and creating realistic debris transport within a test facility, some conservatism should be applied to tests that credit near-field settling. An issue related to near-field settling is the prototypicality of the accumulation of debris on the strainer. For example, excessive turbulence in the test tank can drive debris onto the strainer non-prototypically or can wash or dislodge previously accumulated debris from the strainer. Some debris, particularly larger pieces of fibrous debris, may have the effect of reducing head loss by disturbing the uniformity of a thin layer of fine debris. Debris types not predicted to reach the strainer should not be forced onto the strainer by non-prototypical flow patterns or turbulence. The preparation and introduction of surrogate debris for the test can also affect debris transport and debris bed head loss. The design of a test that balances the prevention of near-field settling, by using agitation to keep debris in suspension, with prevention of non-prototypical transport is not trivial. However, the effects of non-prototypical transport can be limited by careful evaluation of the plant and test conditions and proper debris preparation and introduction.

The quantity of debris introduced into the test tank is usually scaled down from the bounding quantities determined from replacement strainer debris generation and transport analyses based on the area-ratio scaling approach. Because the test tank can, at best, only simulate the portion of debris transport relatively close to the plant strainer, the test should define an interface between the plant transport analysis and the debris introduction into the tank. The interface defines where the analytical evaluation of transport in the plant ends and the transport in the test begins. The interface could be a relatively short distance from the strainer perimeter, or it could be at the strainer surface. If, for example, the test tank was designed to simulate the debris settling and transport in the near field of the strainer, the methodology could require a transport analysis to determine the conservative bounding quantities of debris generated and subsequently transported to the interface. The method would then scale these quantities down to the appropriate test conditions based on the area-ratio approach. The interface-based scaling must also consider debris size, because debris such as RMI pieces may completely settle out before reaching the near field, but suspended fines would be expected to completely transport not only to the near field but also to the strainer. If the interface is specified at the strainer itself, then the analytical transport evaluation would be taken from debris generation to the strainer surface at which point the test debris amount would be calculated based on area-ratio scaling. Again the size distribution of the arriving debris should be determined for test specifications. For the typical PWR large replacement strainers, the debris arriving at the strainers would be, primarily, suspended fines although there may be exceptions. Consistency between the analytical/experimentally based transport analysis and the debris loads introduced into the prototype head loss tests is critical to test validity.

The near-field debris transport aspect within a BWR suppression pool is more dependent on timing than debris distribution. Spatially, the debris would enter the suppression pool at multiple locations through the vent downcomers some of which would be nearer a recirculation strainer than others. The duration and level of the depressurization flow-driven turbulence in the suppression pool depend upon the break size, break location, and plant design. Debris transport into the suppression pool is time-dependent. The activation times of the recirculation pumps are also scenario and plant dependent. Pumps activated prior to the dissipation of the turbulence could draw flows laden with larger and heavier debris than pumps activated after the turbulence has dissipated. The presence of turbulence would tend to maximize the quantities of debris accumulation, but the lack of turbulence would be more likely to accumulate a thin bed consisting of tightly compacted fines from suspended debris.

To ensure that replacement strainers are not undersized, the key aspects of head loss testing should be maintained prototypical (or conservative) with respect to the plant strainer and sump or suppression pool. The important aspects of the test include debris preparation, debris addition sequencing, debris introduction, debris characteristics, and debris transport within the test tank. This section addresses the testing aspects associated with the prototypicality of the debris transport from its introduction into the test tank until the debris either settles to the tank floor or accumulates on the strainer module. These aspects are (1) the methods used to achieve the hydraulic conditions within the test tank to achieve the prototypical conditions of the plant sump, (2) the analytical verification that prototypical conditions were achieved, and (3) the sequence of debris introduction into the test tanks.

5.7.4.1 Simulation of Strainer Upstream Hydraulic Conditions

The test facility for head loss testing consists of a test strainer module mounted in a sizable tank full of water. A piping loop with a recirculation pump draws water from the tank through the test strainer and then returns the water to the test tank at a location far enough away from the strainer to limit the impact of the associated turbulence on strainer debris accumulation. Debris introduced into the tank generally moves with the flow toward the strainer. Gravity tends to settle the debris and pool turbulence opposes the settling of the finer debris. With water continually being recirculated through test loop, the concentration of suspended debris decreases as it accumulates on the test strainer, but it may take many pool turnovers before the water clears of the finer suspended debris.

Various methods have been used to establish the hydraulic conditions within the tank, including flow channeling, water level control, adjustments to flow rate, water injection to cause pool turbulence, mechanical agitation, and installation of baffles or other mechanical obstacles to influence flow patterns. Some vendors have controlled flow velocities through the test tank by using specifically shaped flow channels that cause the water to change velocity as it approaches the test strainer to match the predicted plant condition. Paneling has been used to simulate plant features in the immediate vicinity of the replacement strainer, such as a nearby wall or sump or suppression pool installation. Flow velocity is controlled by the flow rate through the recirculation pump. This flow rate is usually established so that the strainer screen approach velocity matches that of the replacement strainer design for a specific accident scenario.

Tank water level is typically controlled to establish a prototypical level above the test strainer. In some cases, a vendor may implement a time-dependent water level corresponding to water buildup in the plant sump or suppression pool. Water-injecting downcomers have been used to introduce turbulence into the tank water pool in an attempt to represent the predicted sump or suppression pool turbulence or to artificially suspend debris within the pool. The pump, which takes suction downstream of the test strainer, discharges back to the test tank. The returning water can result in non-prototypical turbulence around the test strainer. Some test setups use baffles between the pump discharge and test strainer module to prevent this turbulence from disturbing the debris bed non-prototypically.

5.7.4.2 Analytical Verification of Prototypical Hydraulic Conditions

Analysis is needed to facilitate the establishment and verification of prototypical hydraulic conditions during head loss testing. For tests that credit near-field settling validation requires more than simply matching screen approach velocities. Similitude for debris transport should verify the prototypicality of transport velocities and pool turbulence levels for the test apparatus. The effects of structures near the replacement strainer that could affect debris transport and/or accumulation on the replacement strainer should be considered because such structures can create relatively fast-flowing channels approaching the strainer. If these structures are not represented in the test tank or otherwise accounted for, debris transport could be under-represented.

PWR licensees and vendors have used CFD codes to perform comparative flow analysis between the plant sump and the prototype tests. The key flow parameters that need to be prototypically represented in the tests are flow velocities and pool turbulence. Flow drag that could move settled debris across the test tank floor is a direct function of flow velocity. Pool turbulence affects the settling and potential resuspension of debris within a pool. Computational fluid dynamics codes provide a numerical modeling method of comparing both flow velocities and turbulence between the plant sump pool and the test tank. Although uncertainty exists in all such analytical evaluations, the CFD tools have proven to simulate reasonably well the key features of hydraulic flow. Use of the same CFD code and modeling options to simulate both the plant sump with the replacement strainer and the test tank with the prototype strainer should provide reasonable comparisons of both three-dimensional flow velocities and pool turbulence. The CFD simulations can account for flow channeling in the sump pool due to nearby structures. The CFD analyses should account for containment spray drainage flows into the plant sump pool and the LOCA break overflow into the pool, both of which could cause turbulence within the sump pool. The turbulence can suspend debris that would otherwise settle in a calm pool. The CFD analyses could also consider the effects of debris accumulation near or on the replacement strainer that could significantly alter subsequent flow patterns. Average flow velocities near the replacement strainer or at key sump pool locations can be determined from the CFD results. A CFD code could be used to perform similar analyses within a BWR suppression pool.

Unfortunately, simplified transport models are limited in capabilities, and the results likely have a relatively large uncertainty. These methods are limited, in general, to one-dimensional predictions of average flow velocity. Therefore, the best uses for these methods are in application to flow channels that are reasonably well defined. These methods cannot predict pool turbulence. Use of non-CFD methods will usually require a significant conservatism to account for the aspects of the flow stream that are not predicted by the model.

Simple flow calculations, such as estimating the average strainer approach velocity at the perimeter of the strainer, provide a rough characteristic velocity that can be compared to separate-effects data for debris transport. This information may be used to demonstrate whether settled debris reaching the base of the strainer could subsequently lift off the floor and accumulate over the surface of a strainer that is positioned above the sump floor. Further, average screen approach velocities can be compared to separate-effects data that measured the minimum screen velocity required to hold a piece of debris to a vertical screen surface. Such considerations could be used to determine whether heavier debris, such as RMI, could effectively accumulate on the strainer.

An additional complication with modeling of sump pools for strainer tests is the difficulty in either modeling an adequate number of flow paths to represent the pool flow toward the strainer or combining all of the plant flow paths into a single path for the test. Modeling of the entire area surrounding the strainer for a test would require a large test facility and the control of many boundary conditions to ensure that the test is an adequate representation of the plant. Alternately, analytically combining the sum of the flow paths approaching the strainer into one or more flow paths is complex and requires some conservatism to account for uncertainties involved in the analysis.

In summary, testing that takes credit for near-field settlement should realistically or conservatively simulate the strainer upstream flow and turbulent conditions. Proper analytical evaluation of the similitude between the test tank and the actual plant condition should be conducted. The NRC considers CFD codes to be useful tools to assist in the evaluation.

5.7.4.3 Debris Introduction with Respect to Hydraulic Conditions

A critical aspect of conducting prototypical head loss testing is to simulate the accumulation of the debris on the strainer if not realistically, then conservatively. Simulation of prototypical accumulation requires the debris surrogates, flow velocities, and flow turbulence near the test strainers to be recreated prototypically. The finer particulates and individual fibers, which are also capable of causing substantial head loss, will typically remain suspended in both sump pools and suppression pools. Suspension of fibrous debris is a real issue. Shreds of fibrous debris typically become saturated with water in a relatively short time within a pool of heated water. Without adequate turbulence the shreds may sink. The potential for the shreds to remain in suspension depends on the size of the shred, and the velocity and turbulence of the pool. Once on the pool floor, these shreds require adequate flow velocity and/or turbulence to again become suspended. A shred arriving at a strainer screen surface may not remain attached to a vertical or horizontally downward facing screen surface unless the associated velocities are relatively high.

The method of debris introduction into the test loop upstream of the strainer-testing module can significantly alter head loss measurement and debris settlement. Because of the variables and unknowns involved in a LOCA scenario it is not possible to identify a single realistic debris arrival sequence. Various debris introduction methods define the location, rate, and timing of debris introduction, as well as the sequence of the introduction of different types of debris. Some vendors typically introduce the debris well away from the test strainer and take credit for near-field debris settling. Other vendors introduced debris very close to the strainer to limit near-field settling. The advantage of introducing the debris immediately upstream of the strainer is that the licensee may be able to avoid analyses to demonstrate whether non-prototypical near-field debris settling occurred. However, a potential disadvantage of this approach is that the debris accumulation may become skewed, resulting in a nonprototypical accumulation compared to that in expected plant conditions. The staff is concerned that a non-prototypical, artificially skewed debris accumulation could affect the potential for thin-bed formation or have other unintended consequences. Conversely, introduction of debris well away from the strainer allows the finer suspended debris to become relatively uniformly distributed within the tank pool so that it follows the flow as the fluid seeks the paths of least resistance through the strainer debris bed.

Another important aspect of debris introduction is whether to introduce the debris before or after starting the recirculation pump. Following a LOCA, some debris would be deposited directly at the containment sump or suppression pool level, and some other debris that was initially deposited in the upper levels of containment would be washed down to the containment pool level by the containment sprays before the switch over to the recirculation mode. After the start of recirculation, debris would continue to wash down into the pool. Analytical capabilities are not sufficiently developed to accurately estimate the debris distribution in the containment pool before the operation of the recirculation pumps or to estimate how much debris would be located near the PWR containment sump or within the BWR wetwell. In addition, pool turbulence due to the break effluents and containment spray drainage can be substantial. A decision on whether debris is introduced before or after starting the test pump should be based on ensuring a realistic or conservative test.

If the debris is introduced into the test tank before the pump is started, turbulence modeling that associated with the LOCA break effluence and containment spray drainage should be present in the tank so that the debris does not settle unrealistically in the test tank. It would be non-conservative to introduce the debris into still water before starting the test pump. Further, introducing the debris before starting the pump can allow the debris to agglomerate non-prototypically. Agglomeration is of particular concern for the fine normally suspended debris such as fibers that erode from settled fibrous insulation over a relatively long period or those generated during the initial LOCA blowdown. In addition, vendor test flumes have not been designed to readily allow scaling of phenomena associated with transport modes other than flow rates. In general, the ratio of debris to water mass is much greater in a test facility than in a plant. A similar observation occurs for the amount of debris per floor area. Based on typical test scaling ratios, the debris amount added to a test flume before the start of the test pump could result in a debris layer on the floor of the test flume that is significantly thicker than that of the layer expected in the plant containment. This situation could result in greater agglomeration so that less transport will occur when the test pump is started. Similarly, the increased concentrations of suspended debris in the water may also tend to increase debris agglomeration. For these reasons, absent justification to the contrary, debris introduction before pump start has not been considered an acceptable approach for head loss testing.

If debris is introduced into the test tank after starting the pump, it should be shown that the introduction sequence is conservative. If less transportable debris is introduced first or mixed with fine fiber or particulate, the settled debris may trap the fine fiber and particulates, causing non-conservative settlement of fine fiber debris away from the strainer. Mixing fine debris with larger debris pieces may also result in non-prototypical debris agglomeration. This practice may cause a non-conservative measurement of head loss. Therefore, the staff considers a conservative introduction sequence of debris to be that the most transportable debris is introduced first and the least transportable introduced last.

The presence of particulate in the test pool affects the accumulation pattern of the fibrous debris. The initial accumulation of fibers would occur preferentially near the connection of the pump to the strainer because of higher flow velocities at this location. Without flow control designed into the strainer, the debris accumulates preferentially on the disk nearest the pump connection. Even when the strainer is designed with velocity flow controlling devices [e.g., Performance Contracting Inc. (PCI) strainers], the accumulation can preferentially occur near the center of the disks rather than evenly over the surface of the disks. As debris accumulates at the areas of high flow it causes head loss at the initial locations and flow in these areas decreases. The preferential accumulation locations move away from the pump connection until the whole strainer has debris accumulation. The accumulation pattern for fibrous debris without the presence of particulates can be substantially different from the corresponding patterns with particulates present because a fiber bed with particulates causes substantially greater localized head losses than a bed of fibrous debris alone. If a limited fibrous debris source term was added to a prototype test to determine whether the fiber was sufficient to form a thin bed, but the fiber accumulated preferentially at the areas of high flow velocity while leaving other portions of the strainer uncovered, it may be concluded that the fiber was not sufficient to form a thin bed. Conversely, with particulates available to be filtered by the fibers, the bed could cause sufficient localized head losses to shift the accumulation pattern toward initially uncovered portions of the strainer before the entire fibrous source is collected on the strainer. This could result in complete screen coverage and the formation of a thin bed. As such, the order of debris introduction can strongly affect the head loss outcome of the test. The conservative approach in head loss testing is to introduce the particulate before the fibrous debris.

In summary, proper debris introduction procedures should take into account that variations in the sequence and rate of debris introduction can potentially affect the head loss measurement. The introduction approach that is considered most conservative is to introduce the debris slowly into the test tank with the pump running and prototypical hydraulic conditions established. Particulate debris should be introduced before the fibrous debris, with the exception of the chemical precipitate that is predicted to be generated relatively late in the accident scenario. In general, the most transportable debris should be added first and the least transportable last. Other approaches may also be used if justified.

5.7.5 Surrogate Debris Similitude

For several reasons, test debris that exactly replicates the debris that would be formed in the plant following a LOCA cannot be obtained. The material may no longer be commercially available, or it may be too hazardous to handle from a practical standpoint. Therefore, surrogate materials are often used to simulate the postulated plant debris. Assurance is needed that the debris created using the surrogate materials is prototypical of the postulated plant debris.

The similitude considerations for the surrogate debris include selection of materials, preparation of the surrogate debris, and prevention of non-prototypical agglomeration of the prepared debris before and during the debris introduction process. For chemical effect precipitates, in addition to preparation of the precipitates, the potential for chemical interactions with other surrogate debris, such as coatings debris, should be considered.

For test strainer head losses to be considered representative of the plant strainer, the debris used in the test should represent the postulated plant debris prototypically or conservatively. Debris generation and transport analyses are used to estimate both the quantities and the characteristics of debris expected to arrive at the strainers. For each type of debris, a number of characteristics govern the behavior of that debris with regard to transport, accumulation, and head loss, and significant uncertainty is typically associated with estimating these characteristics (e.g., size distributions). Debris substitutions in testing add to the uncertainty in the head loss results. The important characteristics include debris settling tendencies, filtration, and head loss parameters.

To determine the similitude of surrogate debris, a licensee should first characterize the postulated debris as LOCA-generated, post-LOCA-generated, and latent debris. Second, the proposed surrogate debris should be characterized and compared to the expected plant debris. This comparison should be performed for each characteristic parameter that significantly affects strainer head loss to ensure either realism or conservatism. The characteristics include those parameters that govern debris transport, accumulation, and head loss. For example, fibers introduced into the test to represent latent fibers should not only be of characteristic diameters but should effectively be transported as individual fibers. The staff is unaware of any reasonable justification for latent fiber to accumulate and transport as clumps. Therefore, it is prototypical or conservative to assume individual fibers unless a different approach can be justified. If near-field settling is not credited during testing some of the surrogate debris characteristics may become less important.

Surrogates are frequently used to represent coatings debris. In paint chip form, the transport of coating debris depends on chip size, thickness, density, and shape. A conservative approach is to generate the debris in the form of particulate if chips are proved not transportable. If chips are transportable and may be generated during the event, separate or repeat testing may be needed to ensure that conservative head loss is measured. Reflective metallic insulation (RMI) debris should be manufactured from insulation samples if the manufacturing of replicated debris is not feasible.

Testing may require the introduction of chemical precipitates as part of the debris mix. The Integrated Chemical Effects Test (ICET) reports (NUREG/CR-6914) and the WCAP-16530 report form the basis for the types of chemicals and quantities added to the PWR head loss tests (NUREG/CR-6914). Methods of introducing chemicals into the test are discussed in the staff's review guidance for chemical effects. For example, chemicals precipitates can be introduced already formed or can be allowed to precipitate in the head loss apparatus. Additionally, the manner of controlling water pH and temperature should be considered.

Surrogate debris preparation should first render the material into debris that reasonably represents the size distribution determined by the debris generation and transport analyses. Once the debris has been generated, debris is typically pre-wetted to remove trapped air. The debris is usually added to a relatively large volume of water and mixed well to reduce subsequent agglomeration before introducing the debris into the test tank. For some head loss testing, fibrous debris is preheated to effectively age new insulation material so that it resembles insulation that has been installed at a plant for an extended period of time. This step is necessary only if the aging process significantly alters the head loss characteristics of the insulation material. Boiling or mixing the prepared fibrous debris in hot water can shorten the time required for entrained air to escape.

Of particular concern is preparation of very fine fibrous debris that would likely remain suspended, and therefore almost entirely accumulate on the strainers. Such fine fibers consist of a portion of the LOCA-generated fibrous insulation debris, eroded fibers from settled fibrous debris, and the latent fibers. In general fine fiber can result in higher head losses than coarser fibrous debris. Typically, vendors have used some form of shredded insulation debris to represent very fine fibers. This approach resulted in the concern that the debris may not be prototypically fine. A representative portion of the fibrous debris should be rendered into very fine pieces for maximum debris load testing. For thin bed testing, the finest fibrous debris present in the plant-specific debris size distribution should be used unless another approach is justified on a plant-specific basis. For plants that have a very small fibrous debris load, the fine fibers may not be adequate to result in a filtering debris bed during testing. The thin-bed testing for these plants may add all of the postulated fine fibrous debris, and then add sequentially larger debris to determine if a thin bed will form.

Specification of surrogate fibrous debris should consider filtration characteristics such as bed porosity and compressibility. The debris should be prototypical in the transport characteristics such as floor tumbling velocities and settling velocities. The specification of surrogate particulate and fibrous debris should consider head loss characteristics such as specific surface areas, porosity, compressibility, and fiber diameter. The debris surrogate should also consider the settling characteristics of the various sizes of debris. Settlement behavior of potential chemical surrogate materials should be considered during material selection and preparation process.

In summary, surrogate debris materials used in head loss testing should be either the actual plant materials or suitable substitutions. Substitutions should be justified by comparing the important characteristics of the plant debris sources and the surrogate to ensure that the debris preparation creates prototypical or conservative debris characteristics. Tests generally use the actual type of insulation installed in the plant for testing but use surrogates for coatings and other particulates. Surrogates for coatings include silicon carbide, stone flour, walnut shell flour, and tin powder (as a surrogate for zinc coatings).

5.7.6 Testing Matrix

Once the prototypical hydraulic conditions are established and the surrogate debris material is properly selected and prepared, the testing matrix should be developed to ensure control of the various testing input conditions and parameter variations that can affect the test results. That is, the test matrix include a range of tests that will ensure that a bounding head loss is determined for the conditions specific to the plant being evaluated. In principle, all test variables for a particular test case should be considered so that the effects of potential variations are understood. The important variables are addressed below. The variables should be controlled such that either a prototypical or conservative approach can be adequately specified.

The prototypical matrix for the head loss test should be based on the plant conditions expected during the postulated accident scenario. Specifically, the time-dependent ECCS hydraulic aspects of pump flow rates, water temperature, containment pressure, and sump or suppression pool water level, flow velocities, and pool turbulence. A basic understanding of the operation of the ECCS and CSS during the injection and recirculation phases is needed. Some test procedures make assumptions or use methodologies that result in conservative conditions so that some of these plant variables will not have to be considered carefully in the development of the test matrix.

Recirculation Sump Pool or Suppression Pool Water Level

The minimum water level of the recirculating pool should be used when testing clean strainer head loss and head loss across the debris bed accumulated on the screen. The minimum submergence of a completely submerged strainer is needed under both SBLOCA and LBLOCA conditions, which may need to be evaluated separately. Water depth above the top of the strainer affects the potential formation of vortices. The minimum water level should also be used for evaluations related to the strainer and the head losses determined during testing. The static water level affects the NPSH available to the pumps taking suction from the pool. Inadequate submergence can lead to flashing in the strainer or air ingestion into the ECCS and CSS pumps. The strainer submergence should be sufficient to preclude flashing, which depends on the temperature of the water, and the submergence should be adequate to preclude vortexing. For partially submerged sump screens, the water level affects the wetted screen area, which affects the water approach velocity, the area available for debris collection, and head loss.

Strainer Flow Rate

The conservative approach for determination of strainer flow rate is to assume maximum pump flows. The rate of flow through the screen, along with the screen area, determines the velocity of flow through the screen and the accumulated debris bed. Under certain conditions, pumps might be throttled back to a lesser flow rate. The maximum pump flow assumption removes the uncertainty that a lesser flow rate will be exceeded. If a lesser, throttled flow is assumed at some time during the scenario mission time, the basis for the lesser flow should be such that the throttling can be ensured to actually occur. This lower flow rate may be used during testing to measure a head loss for the low flow condition or a low flow head loss may be calculated based on test results. In general, the staff does not accept extrapolations to flow rates greater than those tested due to potential non-conservatism that could result. In some cases extrapolations to slightly higher flow rates have been accepted.

Recirculation Sump Pool or Suppression Pool Water Temperature

Water temperature is used in the head loss evaluation, the deaeration and flashing evaluation, and the NPSH evaluation. Temperature determines the viscosity of the water, which affects head loss. A lower water temperature increases the viscosity and, therefore, conservatively gives a higher frictional head loss across the debris bed on the strainer screens. The temperature dependence for the deaeration evaluation is more complicated because the water aeration depends on containment pressure and humidity, as well as the sump temperature and further, the quantity of air released within a debris bed depends upon the pressure differential across the bed, which in turn depends upon the temperature dependent viscosity. The flashing and NPSH evaluations are more conservative when a higher temperature is assumed. A conservative calculation would maximize the assumed temperature for the NPSH analysis and minimize the assumed temperature for the head loss analysis. The temperature range would be that predicted to occur during post-LOCA ECCS operation in recirculation. The maximum temperatures are taken from the LOCA analyses that conservatively maximize the temperature. The ultimate temperature is generally calculated using a conservatively cold ultimate heat sink temperature value.

An alternative approach is to evaluate these physical processes in a more realistic time-dependent fashion. That is, for multiple temperatures along the temperature transient, the head loss, deaeration, flashing, and NPSH are evaluated. These evaluations are then combined to determine a time-dependent NPSH margin. However, there are two time-dependent temperature evaluations, with and without the non-safety-related heat removal systems; therefore the appropriate temperature curve should be applied to each evaluation. The flow may also vary with time, as well as with the system status, depending on operating procedures. The maximum flow allowed by procedures should be used in these evaluations. Although debris accumulation is also a time-dependent process, debris transport evaluation capability is not sufficient to predict such a time-dependent accumulation; therefore the worst-case debris accumulation loads and processes should be assumed throughout the evaluation. There are two exceptions to this rule. First, some obviously conservative short-term delay in debris arrival has been accepted. Second, some plants have demonstrated that chemical effects will not affect head loss until temperatures are reduced below a plant-specific value due to precipitation properties specific to the plant. The time-dependent approach is a valid approach if properly evaluated, i.e., provided that (1) the flow rate remains that of the maximum pump flow, (2) the debris bed is the worst-case debris accumulation throughout the time-dependent temperature transient except as noted above, and (3) the pool temperatures are properly determined.

Containment Pressure

Specification of containment pressure is needed to evaluate the potential for flashing to occur within the debris bed and the potential for deaeration of water flowing through the debris bed, as well as for the NPSH evaluation. The level of containment pressure needed to preclude debris bed flashing depends on the water temperature. The containment pressure is also used in the deaeration evaluation. The head loss evaluation is not dependent on the absolute containment pressure. In general, containment accident pressure should not be credited for these evaluations. The staff has accepted the application of small amounts of containment accident pressure to suppress flashing when the amount credited is clearly conservatively bounded by LOCA calculations. NPSH calculations should be made crediting containment accident pressure only if the plant is licensed to do so. The best method to ensure that flashing will not occur is to maintain strainer submergence at a value greater than the head loss across the strainer. Having a greater strainer submergence also minimizes the potential for deaeration.

PWR Sump Pool or BWR Suppression Pool Characteristics

The pool flow velocities and turbulence affect the characteristics of the debris accumulating on the strainer. As discussed in the transport methodology section, debris transports as either buoyant material suspended in the flow or along the pool floor. The characteristic velocities include (1) the velocity through the screen surfaces, which affect debris attachment to the strainer, as well as the head loss, (2) the strainer perimeter velocities, which affect potential re-suspension of settled debris, and (3) the near-field velocities, which affect debris settling and transport within the pool. Buoyant debris may remain on the pool surface without interaction with the strainers unless the debris subsequently absorbs sufficient water to lose buoyancy. The turbulence level within a pool is influenced by water entering the pool, water pumped out of the pool, and water flowing between the points of entrance and exit. For PWRs, the main sources of turbulence are the break overflow, the containment spray, and condensate drainage from the upper containment. For BWRs, the main source of turbulence is flow passing through the vent downcomers, which initially includes the RCS depressurization flow. For both PWRs and BWRs some turbulence is created by water flowing in the pools toward the strainers. The amount of turbulence generated by these sources is plant specific. Turbulence can keep debris in suspension, and if the turbulence is near a strainer, it can affect debris accumulation. Information regarding turbulence is needed to either predetermine the types, quantities, and size characteristics of debris accumulation on the test strainer or to construct a flowing channel within the overall head loss test apparatus that is capable of prototypically recreating the postulated near-field debris transport and settling.

5.7.6.1 Consideration of Head Loss Testing Input Parameters

Prototypical head loss testing should test a sufficient number of postulated plant accident scenarios and potential debris strainer accumulation scenarios to ensure that the operation of the plant replacement strainers cannot be compromised by any combination or quantities of debris from the evaluated break locations. Given the plant post-accident operating parameters, including pump flow rates and water temperatures, the replacement strainer should be able to support operation of the required systems with the accumulation of the upper bound quantities of the various types of debris. In addition, the strainer should accommodate combinations of lesser amounts of debris, in any potential variation of time-dependent accumulation. Practical considerations for demonstrating this are discussed in the following subsections.

Break Selection for Testing

For each postulated LOCA break, the debris generation and transport analyses determine the bounding quantities of debris that could potentially accumulate on the strainer. These bounding quantities likely vary both in quantity and composition due to the variations in size and location of the postulated breaks. Typically, if a postulated LBLOCA is located near or within the same confined compartment as a postulated SBLOCA, then the quantity of debris that would be generated by the LBLOCA would bound the SBLOCA debris quantity making it unnecessary to consider the SBLOCA in the test matrix. The analysis should show that the potential debris compositions are comparable if a break is excluded based on another break's debris load. Typically, LBLOCA scenarios are postulated to occur within SG compartments. Some breaks are postulated to occur outside SG compartments where the jets could affect types of insulation other than those within the SG compartments. In such cases, it may be necessary to include this postulated LOCA debris composition in the test matrix. An example of a LOCA scenario that may have a different composition of debris than the typical SG LBLOCA is a break at the reactor vessel (RV) nozzles located within the shield wall surrounding the RV such that the RV insulation becomes a debris source.

In summary, the testing matrix should be developed to test a spectrum of break locations if it cannot be shown that a single break location can bound the rest of the break locations with regard to debris generation and transport. The test matrix may include bounding amounts of debris from several breaks to reduce the required number of tests performed. This practice is acceptable as long as the licensee can demonstrate that combinations of debris that result in limiting head loss are included in the test matrix. This is a common practice used to limit the number of head loss tests conducted for each plant.

Debris Configuration for Testing

The configuration of the debris accumulation on the strainer depends on a number of factors including quantities and composition of potential debris, relative timing of the arrival of debris, approach velocities and turbulence levels, and design of the strainer. The number of potential test scenarios to cover all possibilities is prohibitively large. Therefore, the test matrix should be carefully established and based on those debris configurations for which test experience has demonstrated the worst-case head losses are likely to occur. In general, the highest head losses have occurred in the thin-bed configurations or in fully loaded configurations.

Fully Loaded Case

A fully loaded debris bed configuration is based on the concept that the resultant head loss increases as the quantity of debris on the strainer is increased. The thickness of debris that the water must flow through is greater for a fully loaded bed than for a thin bed. An important consideration of fully loaded configurations is that the debris could completely fill the internal spaces between strainer components such as the gaps between disks in a stacked-disk strainer arrangement. When these internal spaces are filled, subsequent accumulation will occur around the strainer perimeter. This effect has been referred to as "circumscribed accumulation," in which the effective flow area is substantially less than that of the total strainer screen area. The lower-flow area results in increased flow velocity through at least a portion of the debris, which can increase head loss. Further, the strainer could be positioned in the plant in a closeted situation, for example, in a below-floor PWR sump pit. If the space housing the strainer were to fill with debris, then the approaching flow could be forced through debris over a relatively small area at the pit entrance; head loss at that point could become substantial. The test matrix should consider testing the upper bounding debris quantities and should account for any special surrounding geometry situations.

Thin Bed Case

The test matrix should consider situations in which debris quantities smaller than the maximum design basis load can cause a higher head loss than would the bounding quantities. An example of this condition is the thin-bed configuration, where a limited quantity of fine fibers filters and traps a layer of particulate on the strainer screens. With this debris mix, the bed porosity effectively corresponds to that of packed particulate, which is substantially less than a layer of fibrous debris. The thin-bed term originated because observations have been made in which a relatively thin layer of debris resulted in a large head loss.

For plants with minimal fibrous debris, a single test with the upper-bound fiber quantities may be able to test for both the thin bed and the maximum debris load. In this situation, the test matrix may consist of a single test per break scenario. The one consideration for plants that cannot generate a filtering fibrous bed is that it may be more conservative to add coating debris as chips than particulate. For low-fiber plants, in the absence of a plant-specific evaluation on the characteristics of coating debris, the licensee may need to test with paint chips to validate that head losses are not adversely affected by the chips. It may also be possible for plants to show that paint chips will not be transported to their strainers, in which case it would be conservative to test with coatings as particulate. If a licensee can demonstrate that the coatings will fail as chips and also that the chips will not transport to the strainer they would not need to be included in the testing. In general, the staff believes that testing with coatings, as particulate, will yield conservative head loss results. Unless there is significant bare screen, the NRC staff will accept the treatment of coatings as particulate as conservative.

Historically, the thin bed has been viewed as about a 1/8-in.-thick bed of fiber, but this assessment was not based on realistically suspended fibers and problematic particulates. Head loss testing, particularly, in the presence of particulate insulation, such as calcium silicate or chemical precipitates, much thinner fibrous beds have resulted in significant head loss. To date there has been no experimental or analytical work that has defined a minimum thickness at which a filtering debris bed cannot form. The effect of minimal fibrous debris with other plant specific debris can only be determined experimentally. Use of fibrous fines (as opposed to shreds) for thin bed testing will tend to decrease the bed thickness necessary to generate a filtering bed. The size of the screen mesh or the diameter of the strainer holes also affects the minimal thickness for thin bed formation. Some strainer modules with non-uniform approach velocities may require average bed thicknesses that are somewhat greater than those observed on flat plates or uniform flow strainers before a filtering bed covers the entire strainer.

For plants with the potential to generate relatively large quantities of fibrous debris, the test matrix should provide confidence that the peak head loss has been conservatively or prototypically determined. The preferred approach is to cover the thin-bed and fully loaded debris bed cases either in a single test or multiple tests. Even if the plant has enough fiber to form a thick fibrous bed, the accumulation process should pass from zero accumulation to bed thicknesses greater than the typical thin-bed thickness incrementally to ensure that the peak head loss is determined. During thin-bed testing, the fibrous debris should be added slowly, in small batches, so that the flows are allowed to transport the individual fibers and particles into the screen areas that have less debris to achieve uniform coverage. Head loss should be allowed to stabilize between batches. Once enough fiber has been added to ensure that the thin-bed thickness has been exceeded, the remaining fiber may be added somewhat faster but prototypical fiber deposition on the bed should be maintained. For high-fiber plants, the testing should ascertain the peak potential head losses associated with the thickness of fiber supporting the thin bed because the thin-bed head loss can depend on the quantity of supporting fiber, which is known to affect the filtration efficiency for the particulate. For high-fiber plants, the thin bed test can be performed during an early part of a thicker bed test, or it can be performed individually. Complications in performing only a single can test arises when chemical debris is added to the test loop or if all of the particulate debris filters onto the fiber before all of the fiber is added to the test. Because many potential interactions can occur between the chemical and non-chemical debris, a series of tests may need to be performed to ensure conservative bounding head loss.

The depressurization flow-driven turbulence within a BWR suppression pool could make the formation of a thin bed more difficult than has been observed in PWR tests. However, it is possible that a thin bed could form at some time during the event, especially given the variety of break scenarios. Therefore, BWR head loss testing should include tests with procedures conducive to forming thin beds.

In summary, the head-loss testing matrix should provide for high confidence that the testing bounds the potential peak head loss considering the plant specific conditions. It should, therefore, include both full load and thin-bed testing cases. If a given debris load does not have sufficient fiber to form a filtering bed, one full load case may suffice for both. If the fiber load is greater than the minimum amount of fiber to form a thin fiber bed, both the thin-bed case and the full-load case should be included in the testing matrix unless justification is provided to support a different approach. The debris introduction procedure should be designed to allow slow debris accumulation on the strainer surface to capture the potential for thin bed formation, including the filtration of the particulate debris. The potential for interaction of chemical debris with different debris bed thicknesses should be evaluated and tested if necessary.

5.7.6.2 Tailoring of Test Matrix to Test Objectives

Because of the large number of test parameters that can be varied in testing of prototypical strainers and the limited number of tests that can be conducted from a practical standpoint, the test matrix should be developed to ensure that significant variables are fully covered in the testing. The approach to specifying the test matrix will vary from plant to plant, but each set of head loss tests has the primary objective of showing strainer performance to be acceptable. Some of the test objectives, which if met may allow qualification, include:

- Determining whether sufficient fibrous material can accumulate on the plant replacement strainer to effectively filter particulate and chemical precipitates.
- Determining the worst-case head loss for a thin-bed accumulation.
- Determining the worst-case head loss for the maximum debris quantities on the basis of the licensee's conservative debris generation and transport analyses.

- Validation that vortex formation does not occur under minimum submergence conditions.

- The test matrix should be designed to achieve the primary specific test objective rather than to use a single test to complete all test objectives. The following sections discuss basic test procedures that should be considered when tailoring the test matrix.

- Validation of Insufficient Fiber to Filter Particulate

The primary sources of fibrous debris in containment are fibrous insulation, fire barrier materials, and latent fiber. Some plants in which the containment insulation is exclusively RMI or nearly so may not have enough fibrous debris sources to accumulate a fibrous layer sufficient to effectively filter particulates. In this case, the resultant head loss from fibrous and particulate debris could be well below the level of concern. However, even if a plant's insulation is exclusively RMI, latent fibers will exist in containment in some quantity. Other sources of fibers can include the fiber component in particulate insulations such as calcium silicate. If, for example, a plant had 100 lbm of latent debris and 15 lbm of that were fibrous, to the fiber could theoretically cover 600 ft2 of strainer surface with a 1/8-in. layer of fiber. Fibrous debris loads with a nominal thickness much less than 1/8 in. have resulted in significant head loss during testing when combined with problematic materials. Therefore, a validation of insufficient fiber to fiber particulate can only be experimentally determined using plant specific debris loads and conditions.

NEI Guidance Report 04-07, as accepted by the staff SE, recommended assuming a minimum of 1/8-in. fiber as the criterion for potential thin-bed formation. The source of this criterion was an observation made in NUREG/CR-6224 that included statements to the effect: "to form a uniform debris bed, a thickness larger than 0.125 in. was needed. For a lesser thickness, the bed does not have the required structure to bridge the strainer holes and filter the sludge particles." This observation was made from tests that used shredded NUKON® fibrous debris with approach velocities typically ranging from 0.2 to 1 ft/s, and screens typically either manufactured using 1/8-in. wire mesh screen or perforated plates with 1/8-in. holes. The SE noted that this 1/8-in. guideline may not apply for all types of fiber debris. During the NRC-sponsored calcium silicate tests (NUREG/CR-6874), a head loss of 14 ft was achieved at 1.4 ft/s flow with a layer of NUKON® and calcium silicate that was 0.11-in. thick (i.e., slightly less than 1/8-in.). The NRC staff has also observed high head losses during vendor testing of prototype strainers with calculated fiber bed thicknesses of much less than 1/8 in. These tests were conducted at prototypical plant approach velocities and used prototypical plant strainer modules, unlike the NUREG/CR-6874 testing described above. A debris bed accumulating from suspended individual fibers is formed more uniformly than a bed of shredded (larger) fibrous debris, for which the minimum thickness observation was made. High-density fiberglass insulations, such as Temp Mat are substantially less porous than NUKON®; therefore, a lesser thickness of Temp Mat may be needed to result in filtration compared with NUKON®. Some compression of NUKON® seems to be needed to effectively filter calcium silicate (alone, without other particulate), while less compression may be needed for Temp Mat or similar higher density fibrous sources. The particulate filtration efficiency for a layer of fibrous debris depends on the thickness of the fibrous layer, the porosity of the fibrous material, bed compression, approach velocity, and particle size distribution, as well as possibly the diameter of the screen holes or wire mesh size. Therefore, it is difficult to analytically evaluate whether a fiber bed is sufficient to form an effective filter for chemical precipitates and particulate debris. An indicator that a filtering bed would likely not occur would be that a significant portion of the strainer area remains completely free of fiber after all fibrous debris is added to the test flume and allowed to accumulate on the strainer. For this test the fiber should be suspendable fibers allowed to accumulate slowly in the presence of the particulate unless it can be shown that alternate debris characteristics or arrival sequences are expected.

A prototype strainer test designed to experimentally determine whether a fibrous layer could form should ensure that a conservative quantity of fibrous debris actually accumulates on the strainer. Given the very low screen approach velocities of the PWR replacement strainers, accumulation of fibrous debris over the entire strainer surface area would probably occur almost entirely due to suspended fibers or very fine shreds. In addition, the presence of particulate in the flow affects the uniformity of the fiber accumulation. The primary sources of suspended fibers include (1) latent fibers, (2) the fraction of the LOCA-generated fibrous debris that is destroyed into individual fibers or very fine shreds, and (3) fibers that erode away from larger fibrous debris in the sump pool. Latent fibers should be considered to transport completely as suspended fibers because they generally exist as individual or easily separable fibers in containmnet. When a fibrous insulation blanket is destroyed, a significant fraction of the debris is too fine to collect by hand (NUREG/CR-6369), and this component should be considered to transport as suspended debris. When fibers erode from small and large fibrous debris in the sump pool, they are transported as suspended debris (Appendix III.3.3.3 of NRC-SER-1998). This erosion occurs over hours, if not days, and is enhanced by pool turbulence. In BWR suppression pools, the depressurization flow-driven turbulence would further fragment fibrous debris resulting in more of the very fine fibers.

The NRC staff have observed tests, in which latent fibers were simulated in the test by using shredded NUKON®. The majority of the NUKON® shreds settled to the tank floor, where they remained. In these cases, only a portion of the NUKON® was accumulated on the strainer surface, and the accumulation of latent debris on the test strainer was considered neither realistic nor conservative by the staff. The staff made similar observations when fibrous debris classified as fines were added to the tests. The staff reached these conclusions because the fibrous debris used in the testing was not prepared to match the size of the debris predicted to reach the strainer by the transport calculation. In some cases, the flow was not prototypical or conservative with respect to the flow patterns expected in the plant. Test procedures should be designed to ensure proper latent and ZOI fiber debris preparation, especially the fine fibers, and a prototypical or conservative accumulation on the strainer before concluding that fibrous debris is not sufficient to form a filtering layer on the plant replacement strainer.

The NRC staff also witnessed a number of tests for which the fibrous debris size distribution was based on a generic debris preparation procedure. The size distribution of the generated debris was not verified to be representative of the size distribution of the debris predicted to reach the strainers by the plant-specific debris transport analysis. The staff expectation is that test procedures verify that the debris has a size distribution that is prototypical or conservative with respect to the plant-specific debris.

Peak Thin-Bed Debris Head Loss

Once it has been determined that there would be sufficient debris to form a fibrous layer that could efficiently filter particulate, the worst-case thin-bed head loss will generally have to be experimentally determined. Since all plants have some latent fibers and significant head loss have formed with minimum fibers in head loss tests with problematic particulates such as calcium silicate or chemical precipitates, a worst case thin-bed head loss test will generally have to be performed. . Even if the bounding maximum possible quantity of fiber debris would far exceed that needed to form a thin bed, the accumulation process in the testing should attempt to develop a thin bed to reflect the possibility that a smaller amount of debris could be generated, transported to the strainer, or that a thin bed could develop as an intermediate condition in a full-load case. The head loss in such a scenario can be significant. The limiting head loss in the plant can result from any amount of fibrous debris generation and transport, from a small amount up to the maximum postulated amount. Therefore, the thin-bed testing should cover the full range of potential debris generation in increments small enough to determine the limiting head loss for the plant-specific debris.

The following is guidance on testing to determine whether a thin bed will form. Variations from this guidance are acceptable as long as there is reasonable assurance that a bounding peak head loss for the plant specific conditions has been determined.

1 Analytically estimate conservative quantities of fine suspended fiber that could accumulate on the plant replacement strainer and then scale these quantities to the test strainer area.

2 Select the fibrous material(s) for head loss testing that have prototypical characteristics to the plant debris sources. NUKON® may be used for latent fibers and similar low-density fiberglass, but high-density fiberglass should be used for high-density fiberglass, mineral wool for mineral wool, etc.

3 Prepare the fine surrogate fibrous materials as fine debris that will tend to remain suspended with relatively little pool turbulence. Ensure that the concentration of the prepared debris slurry is adequate to prevent non-prototypical agglomeration of the fine debris before its addition to the test flume. The NRC staff has identified excessive debris agglomeration as a concern, and steps should be taken to avoid the agglomeration of fibrous debris associated with batching. The steps include debris dilution and slow introduction into the test tank.

4 The pump flow should be established before introducing the test debris, and the rate of flow should be scaled to provide similitude for the strainer approach velocity based on the total screen area.

5 The total amount of particulate debris should be added before introduction of the fibrous debris, with the exception of the later addition of the chemical effect precipitate. The particulate debris should be introduced as a wet slurry rather than as a dry powder to preclude non-prototypical agglomeration of the particulate.

6 The addition of fibrous debris should occur slowly in incremental batches, with the head loss allowed to stabilize between batches to ensure representative accumulation on the strainers. The first batch should be sufficiently small that the resultant fiber layer thickness is significantly less than the optimal thin-bed fiber thickness, which likely is somewhere between 1/8 in. and 5/8 in. This value tends to vary depending on the design of the strainer. The initial increments should be no greater than about 1/8-in. thickness equivalent per batch and should continue until the stabilized head loss does not increase significantly with additional fiber additions. If it appears that head loss is not increasing significantly after a batch is added, but it is indeterminate as to whether a thin bed has been formed another smaller batch (about 1/16 inch) can be added to validate whether or not a thin bed has been attained. If the total available fiber is less than 1/8 in., the total quantity can be added in the first and only batch.

7. When the fiber is added to the test flume, all of the finest fiber in the plant-specific debris size distribution should be added to the thin-bed test before larger sizes are added unless another approach is justified on the basis of plant-specific conditions. If all fine fiber is added and the thin bed has not formed, the small pieces should be added next, etc., until all debris that the plant-specific analysis shows would be transported to the strainer is added, or it can be demonstrated that the thin-bed region has been passed.

In summary, there is no realistic minimum fiber bed thickness that can be used as a criterion to determine whether a thin bed will form. Testing should be performed to support the determination of whether a thin bed can occur on a plant's strainer considering its specific debris load and flow conditions. Thin-beds are especially likely to form in the presence of chemical precipitates and particulate type insulations such as calcium silicate. Based on the observation of tests conducted with similar debris loads added in various sequences, the NRC staff has concluded that the debris introduction sequence has a large impact on thin bed head loss. During bed formation, the prompt accumulation of particulate in the interstitial areas of the fiber bed appears to create a thinner and more uniform bed. Without the particulate, the fibrous debris can preferentially accumulate toward the pump connection to the strainer or even toward the strainer central core, resulting in non-conservative non-uniformity. In this case, larger quantities of fiber are necessary to create sufficient localized head loss to redistribute debris-laden flow to clean areas of the strainer surface. Adding the fibrous debris before the particulate tends to result in the formation of a more porous layer of debris on the strainer surface and requires more fibrous debris for complete strainer coverage. Because the accumulation of fibrous debris in the absence of particulate debris is not expected to be prototypical of plant conditions, the staff expects that licensees will conservatively add the full particulate load that could be transported to the strainer before the fiber is added to the test unless an alternate debris arrival sequence can be justified.

The NRC staff has also observed that the preparation of fibrous debris and the near-field pool turbulence can have a significant effect on accumulation and resulting head loss. The debris should be prepared either prototypically or conservatively, and the near-field transport should be either prototypical or conservatively simulated. Agitation intended to enhance debris transport to the strainer can have the adverse consequence of forcing debris to accumulate that would prototypically settle in the plant pool. Such debris can disrupt the formation of a prototypical thin bed, resulting in non-conservative conclusions from head loss testing. For high-fiber loads, thin-bed testing should allow such debris to prototypically settle before reaching the strainer so that the incremental buildup consists of the suspended fibers. For low-fiber plants, such as all RMI plants where the fibrous debris consists primarily of the latent fibers, all of the fiber should be introduced as suspended fibers. Agitation may also adversely affect the formation of a bed on the strainer by preventing debris from collecting on some areas of the strainer. Turbulence should not affect debris bed formation non-prototypically.

Maximum Debris Loading Head Loss

Debris generation and transport analyses provide conservative or prototypical estimates for the maximum quantities of debris that could potentially arrive at the plant recirculation sump or suppression pool strainers. Except for thin-bed formation and possibly other bed stratifications, the worst-case head loss would generally be associated with the accumulation of maximum quantities of debris on the replacement strainers.

The typical large replacement strainer has interior gap volumes. Once these interior spaces are filled, the remaining debris must accumulate around the exterior of the strainer, a condition referred to as "circumscribed accumulation." Depending on strainer design, the head losses associated with maximum accumulations may be lower than with thin-bed accumulations. If a circumscribed accumulation occurs, then the effective flow area through the bed of debris is reduced substantially from that of the total screen area. The velocity of flow increases as area decreases. It is the velocity of flow as it passes through the debris, as well as the bed thickness and composition, that determines the resultant head loss. The circumscribed area is typically the strainer perimeter area. Therefore, the prototypical circumscribed velocity for a replacement strainer is the pump recirculation flow rate divided by the strainer perimeter area. If circumscribed accumulation occurs, then the recirculation pump flow rate for the test module should be scaled to achieve a prototypical circumscribed velocity. Further, the thickness and composition of the circumscribed layer should be prototypical of the plant replacement strainer. When a replacement strainer is located near a wall or in a small compartment, the walls could affect the debris accumulation and/or approach velocity by further reducing the effective flow area. Testing conditions should also account for the possibility of a circumscribed bed surrounding an array of strainers in that the spacing between the strainer modules may limit the volume where debris can collect. For these conditions, the test should simulate nearby obstructions so that the debris bed forms prototypically, or should otherwise account for the expected accumulation, potentially by adjusting the debris scaling.

1 The following is guidance on testing to achieve the limiting head loss for a maximum debris loading case. Variations are acceptable as long as reasonable assurance is provided that peak head loss for the plant specific conditions has been achieved.

2 Determine the maximum quantities of debris of various types predicted to reach the strainer. It is recommended to test with the actual materials if possible. Select suitable surrogate materials with prototypical characteristics when the actual debris sources cannot be used in the head loss testing. The amount predicted to reach the strainer is scaled based on the strainer area or the strainer perimeter area as appropriate to determine the amount required for testing.

3 Determine the fraction for each type of fibrous debris that should be simulated as individual fibers or very fine shreds (for latent debris, this fraction is one).

4 First prepare the fibrous debris as shreds to simulate LOCA-generated debris. Then further refine a fraction of these shreds as fine debris that will tend to remain suspended with relatively little pool turbulence, consistent with the calculation of plant-specific debris transport.

5 Prepare each type of particulate debris as wet slurry. Ensure that the debris is dilute enough that non-prototypical agglomeration does not occur before or during its addition to the test tank.

6 Establish the recirculation pump flow for prototypical flow conditions. If a circumscribed accumulation is expected, then scale the pump flow to achieve the circumscribed flow velocity of the replacement strainer. If the maximum fiber accumulation is not expected to approach a circumscribed accumulation, then scale the pump flow to the full-screen area approach velocity of the replacement strainer. Some test strainer modules may be designed to achieve both circumscribed and full-screen area approach velocities in the same test.

7 Introduce the debris slowly, with particulate and the most transportable fibers being added first until all debris that the plant-specific analysis shows would transport to the strainer is added. Chemical-effects precipitates predicted to be generated later in the accident scenario would be introduced last.

Potential debris-bed stratification can be explored by introducing some types of debris later in the test after other types have reached maximum accumulation. For example, if a specific particulate is intended to simulate an unqualified coating that is postulated to fail relatively late in the scenario, then this particulate could be added after the early debris accumulation reaches a steady-state condition. This could result in a higher concentration of the particulate on the outer surface of an existing bed, causing a relatively high head loss.

In summary, maximum-load head loss tests should ensure that the testing properly models the circumferential debris accumulation with a correct circumferential approach velocity, if applicable. If the full load test and the thin-bed test are to be the same test, then the thin-bed test guidance should be followed.

RMI and Coatings Paint Chip Debris Head Loss

Heavier debris such as stainless steel RMI and most paint chips may be transported along the floor of the PWR sump pool, depending on the velocity and turbulence in the pool. It is unlikely that significant quantities of debris of this type will accumulate on the strainer, with the possible exception of low density paint chips. Before this heavier debris can cause blockage problems in a large strainer, the debris must first be transported along the sump pool floor to the strainer and then accumulate on the strainer. For strainer designs positioned well off the floor, the flow velocities would have to be relatively high in order to lift the debris from the floor onto the strainer. For stainless steel RMI, testing indicates that the flow velocity would have to be at least 1 ft/s to lift a relatively small piece over a 6-in.-high curb. With many current PWR strainer installations, flow sufficient to lift such debris off of the floor and onto the strainer is unlikely. For this type of debris, complete lack of transport would be a realistic assumption. Exceptions to this situation could include strainers recessed below the sump floor where floor transported debris simply falls onto the strainer from above, or cases where strainers are located directly below sources of debris. In a BWR suppression pool, the depressurization flow-driven turbulence would tend to keep the heavier debris, including RMI and coatings chips debris, in suspension until the turbulence dissipates. The duration and level of turbulence would depend upon the break scenario and plant specific configuration.

If the debris transport analyses or testing clearly demonstrates that such debris will not accumulate on the strainer, it may be appropriate to simply omit it from testing so the test can focus on the remaining types of debris. On the other hand, if the strainer is recessed below the floor (in a pit), head loss testing should consider this type of debris because such debris can cover areas of the strainer and provide surfaces for fibrous debris deposition. This fibrous debris can then form a filtering bed with a surface area much smaller than the strainer surface area. The smaller area would result in a high velocity through the bed and potentially high head losses. The large debris should be included in tests for pit installations unless the floor transport analyses can clearly demonstrate that such debris cannot reach the strainer in sufficient quantity to cause a blockage problem. If the analyses indicate this heavier debris could accumulate on or around the strainer test module, then the head loss test should be prototypical enough to result in similar debris accumulation. In a situation where significant amounts of large debris can accumulate on or near the stainer the prototypical approach velocity for the strainer is most likely the circumscribed velocity.

The velocity in the test facility may have to be based on the flow velocity through the area of the pit opening in the containment floor if it is possible for the pit opening to be bridged with debris. If coating chips are light enough to transport as either suspended debris or can be easily moved across the floor and subsequently lifted onto the screen, these chips should be tested with the strainer prototype module under prototypical flow velocity and turbulence conditions.

In summary, both RMI and coating chips can be excluded from the head loss test if it is determined that they are not transportable to the strainer surface based on transport tests or analyses. However, the coating debris may need to be added into the test in a particulate form to conservatively account for unknown coating debris-size distribution. For pit strainer installations, strong justification should be supplied if the larger debris is excluded from the test. Testing for pit installations should ensure prototypical velocities approaching the strainer, prototypical paths for transport of larger debris, and prototypical test geometries that will allow simulation of plant debris accumulation. Test velocities should be scaled to be prototypical of the plant approach velocities.

5.7.7 Test Termination

The goal of head loss testing is to determine the plant specific peak head loss that could occur across a sump strainer during a postulated LOCA scenario over the strainer mission time. The mission time is the time from accident initiation to when the flow is permanently reduced by licensee EOPs. Ideally, the head loss testing would continue until the mission time is reached, but practical considerations may limit the period of testing. Also, conservatism in the testing procedure tends to mitigate the need to run a test through the full length of the mission time. Under certain conditions, the peak head loss can be estimated by the extrapolation of the test head loss results. Extrapolation is possible when the test head loss can be demonstrated to have approached the peak head loss value reasonably closely.

During testing, head loss may approach a steady state relatively soon after the majority of the debris has transported to the strainer. Once all debris has settled out or has been deposited on the debris bed, the water may appear clear indicating that the majority of fine particulate debris has been filtered onto the debris bed. In other situations, the filtration efficiency may be poor enough that the water remains cloudy. A final steady state head loss can sometimes require many pool turnovers as the filtration process gradually clears the water of finer and finer particles until the remaining particulate is too fine to be filtered or all of the particulate is removed. In addition, there are time-based phenomena that may result in longer-term head loss increases. Test termination and data extrapolation methods should consider this possibility as well. Some phenomena that can result in long-term head loss increases are bed compression due to differential pressure and physical or chemical degradation of debris bed components resulting in reduced bed porosity.

When pump flows are throttled, as would be typical of plant operating procedures, the head loss associated with the debris accumulated at that time will decrease. If testing simulates the flow reductions and debris is available to collect on the strainer, the test should continue until all debris has accumulated or demonstrated to settle and not be available for transport. In general, the approach used in head loss testing of prototype strainers has been to test at the full pump flow rate and ensure accumulation of the majority of the debris predicted to reach the strainer. This allows test durations to be much shorter than the typical times for throttling back the pumps while ensuring conservative results. Some tests have simulated reduced flow rates and delayed chemical precipitate arrival when it has been demonstrated that these assumptions are conservative for the specific plant condition.

In head loss testing that has been observed by NRC staff, criteria have been established to determine when the test has achieved a sufficient steady state that the test can be terminated. The typical criteria have involved specification of (1) a maximum increase in head loss over a minimum time period, and (2) a minimum number of pool turnovers. Typically, a basis for specifying the criteria has not been provided but appears to be the result of engineering judgment rather than experimental determination. The criteria for head loss increase generally assume that an asymptote is being approached and that the rate of increase will continually decrease. The staff has observed a number of tests in which head loss was continuing to increase at test termination, at a rate that appeared somewhat constant. Based on these observations, the staff is concerned that these criteria may not be sufficient to ensure the determination of peak head losses.

The processes that could cause the increase in head loss to continue for hours, if not days, include continuing filtration of the very fine particulate, erosion of the fibrous debris that is settled on the test tank floor, slow compression of the debris bed, and chemical changes. It is known that shredded NUKON®, for example, will continuously give up fibers in a turbulent pool for several hours, if not days (Appendix III.3.3.3 in NRC-SER-1998). For example, a longer-term vendor test conducted in 1992 (that tested 2-in of Nukon without particulate at 0.3 ft/sec and 9.4 pH) demonstrated that the head loss continued to increase at a somewhat constant rate until the test was terminated at 24 hrs (NUREG/CR-6808, Section 7.4.1). The NRC staff has reviewed vendor test data, which indicated that substantial overnight increases in head loss were likely attributable to achieving nearly complete filtration due to the extended testing period. Other vendor data have shown a rate of head loss increase that was approximately constant for about 12 days after which the test was terminated while the head loss continuing to increase.

Although it is not practical to conduct all head loss tests over a long term, the head loss results can be more reliable if selected key design basis tests are run for extended periods. Test termination criteria should be based on experimental observations rather than on engineering judgment. The achievement of steady-state head loss can be affected by test conditions and the time required to reach steady state can vary significantly. To illustrate this point, closed-loop head loss testing sponsored by the NRC was reviewed to ascertain the trend in how many times suspended debris circulated through the test screen before the head loss became effectively steady state. The tests that were reviewed included testing of calcium silicate (NUREG/CR-6874) and a surrogate for latent particulate debris (NUREG/CR-6877), both with fine Nukon fibers forming the underlying bed. Results of this review are reported in Table 5.7-1, which shows the number of flow circulations in the closed-loop apparatus, which correspond to pool turnovers in the vendor tests. First, all of the debris was introduced into the test loop upstream of the strainer screen, and then the pump rate of flow was incrementally increased after head loss reached a reasonable stabilization. The table shows the number of circulations needed to reach a relative steady state for each incremental increase in the flow. Whereas some vendor test criteria specified only a minimum of five pool turnovers for justification for terminating a test, the number of turnovers in Table 5.7-1 typically exceeded 10 circulations. Because incremental flow-increase No. 7 for Test 6H, conducted with NUKON® fibers and calcium silicate, required an excessive 150 circulations before head loss stabilized, some additional clarification is provided. This was a thin-bed test in which the nominal fiber thickness (without compression) was approximately 0.23 in. For the first six flow rates, the fibers did not effectively filter the fine calcium silicate so that bed head loss generally remained under 1 ft, however, in flow increment seven, compression of the fiber bed increased enough to substantially increase the bed filtration efficiency, resulting in a steadily increasing head loss over a period of about 90 min before head loss stabilized at approximately 13 ft. The period of 90 min corresponded to about 150 circulations of the test fluid volume. Such inefficient filtration behavior illustrates that in some situations, a relative long time is needed for test head losses to stabilize. However, it is possible that some of the increase in head loss was a result of time based effects instead of filtration. The number of turnovers as well as time under flow can affect debris bed head loss. Test termination criteria should be carefully specified.

Table 5.7-1. Number of Tank Turnovers to Reach Steady State

Flow Increase Increment	Number of Closed Loop Circulation (Turnovers)			
	CalSil Test 6B	CalSil Test 6H	Latent Test 11	Latent Test 19
1	9.4	4.3	8.0	11.8
2	14.8	7.7	7.8	11.1
3	18.3	8.7	10.0	4.4
4	13.6	11.9	8.6	-
5	-	13.6	-	-
6	-	18.0	-	-
7	-	150.3	-	-
8	-	15.9	-	-
Test Totals	56	230	34	27

The minimum number of pool turnovers was also analyzed. For the purpose of illustration, the following simplifying assumptions were made (which may or may not be applicable to particular test conditions); the strainer filtration efficiency is constant, the debris within the test tank is uniformly distributed within the pool, and no debris settles within either the tank or the recirculation piping. For this case, debris concentration within the pool could be represented by the following equation

$$c(t) = c_o \, e^{-\varepsilon N}$$

where c(t) = the time-dependent debris concentration
co = the initial debris concentration
ε = the strainer filtration efficiency
N = the number of pool turnovers

Based on this equation, the analytical decrease in tank debris concentrations vs. the number of pool turnovers is illustrated in Figure 5.7-4 at several filtration efficiencies. The figure shows that five turnovers are adequate to ensure filtration when the bed filtration efficiency is near 1, but many more turnovers are needed for the lesser filtration efficiencies that could be associated with finer particulates. Filtration efficiency for the debris bed and suspended material is dependent on the porosity of the bed, which changes with time. The results in Table 5.7-1 and Figure 5.7-4 are in general agreement that, depending on filtration efficiency, more than 10 turnovers may be needed before reaching a relative steady state in the head loss. The table and figure represent a simplified presentation of filtration as a function of tank turnovers. In test setups, other factors may influence the rate of filtration. Therefore, testing should use these other factors in addition to the number of tank turnovers for determining test termination.

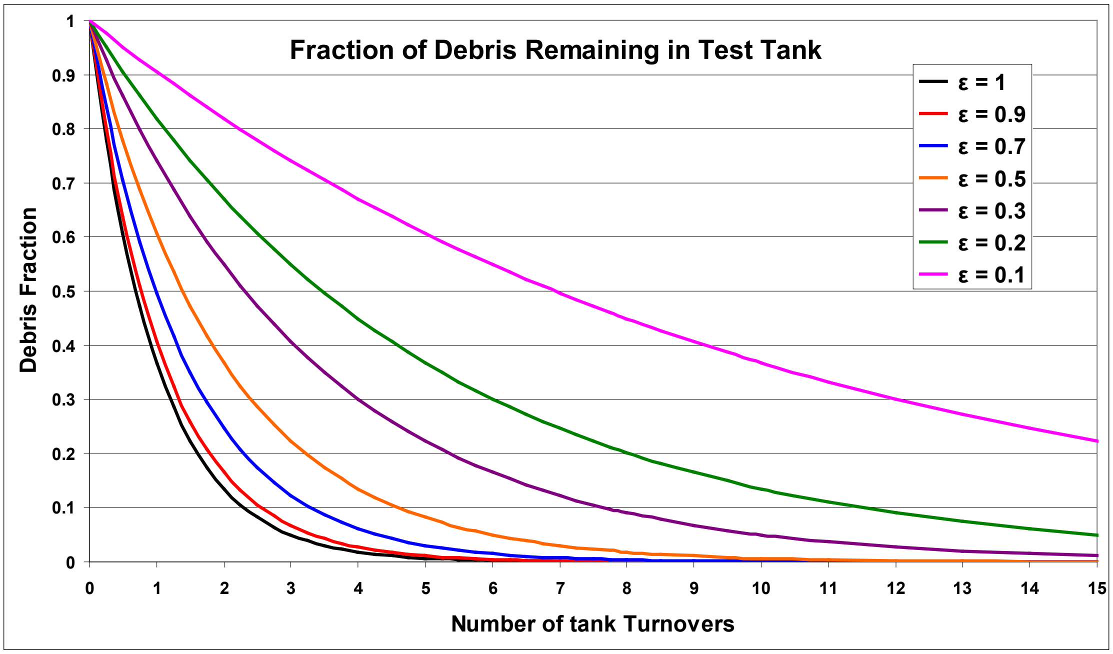


Figure 5.7-4. Analytical Debris Concentration as a Function of Pool Turnovers

If a head loss test is terminated on the basis of the rate of head loss increase dropping below a minimum criterion, but the head loss is continuing to increase, a method of estimating the head loss at the end of the strainer mission time would be required. The head loss test represented in Figure 7-23 of NUREG/CR-6808 is from a test in which head loss increased somewhat linearly throughout a 24-hr test period. The rate of head loss increase should be shown to be significantly decreasing at termination, or steady at a value below the test termination criteria, and the final head loss should be extrapolated appropriately. Alternately, the head loss may be decreasing at termination. For some cases, if the test has been run for an extended period and the head loss continues to increase relatively linearly, an extrapolation from that point may be appropriate. The staff generally considers linear extrapolation of the data near the end of the test to be conservative. Alternate extrapolation methods are to apply a curve fit to the test data or perform a more sophisticated numerical analysis of the test data. It is important that the test flow rate be tightly controlled when determining whether the head loss rate increase has decreased below a termination criterion minimum because a slight reduction in flow rate would also result in a lower rate of head loss increase. The extrapolation methodology should ensure that all data points collected during the test are enveloped within the curve.

It is also important to select a representative data range for performing the extrapolation. Data from much earlier in the test than those within the test termination criteria window may have to be considered because some tests have had relatively short periods of steady head loss or even short periods of decrease while increasing over the long term. The NRC staff has observed many longer-term tests that seemed to have no increase in head loss for significant periods, but actually had slowly increasing head loss. Variations in the time range of data used for extrapolation can result in significant differences in the extrapolated final head loss.
It may be beneficial to perform the extrapolation in real time on a lab test computer. Calculation of the second derivative of the head loss would illustrate whether the increase in head loss was actually slowing. Running a head loss test to the mission time would provide a more meaningful indication of test completion than would using extrapolation techniques. One test, run to the

mission time, could be compared to shorter tests (under similar test conditions) to determine an appropriate extrapolation method. The level of concern for this issue depends on the margins between the test design head losses and the licensee's NPSH and flashing margins. However, it is expected that extrapolations be conducted conservatively to account for uncertainties in the process.

In summary, final head loss values can be extrapolated or based on maximum head loss values obtained over a sufficient test period. Evaluators should ensure that they have considered sufficient information to have reasonable assurance that the head loss test evaluations have realistically or conservatively determined maximum strainer head loss over the required mission period. Test termination criteria should contribute to that high confidence. Criteria based on stability and predictability in test conditions are generally acceptable (e.g., specified number of turnovers, plus limits on changes in head loss in a given period). If a test reaches a maximum head loss value and the head loss decreases for a significant period of time the test may be terminated and the maximum value used as the design basis head loss. To estimate in the final head loss from the point of termination, the staff found that a linear curve fit and extrapolation of the head loss trend to the mission time (e.g., 30 days) are acceptable. It may be acceptable to use other criteria or methods if justified, as discussed above. Additional confidence can be gained by running the test for a period after the stability criteria are met. The staff's acceptance of linear extrapolation is based on the relatively little data available for longer term tests. Although some long-term head loss tests have been conducted, the behavior of debris beds over the long term is not well understood. However, the staff believes that the use of linear extrapolation provides a conservative extrapolation methodology.

5.7.8 Post-Test Data Scaling and Analysis

After completion of head loss testing, the resulting data may have to be scaled to alternative conditions from the specific conditions of the tests. The need to perform post-test data scaling or data extrapolation has included: (1) head loss extrapolation to the mission time if the testing was not extended to the mission time, (2) scaling of the head loss data to the postulated plant sump pool temperatures from the test temperature, and (3) scaling of the test data for deviations between the test strainer module and the actual replacement strainer design. In addition, it may be useful to perform post-test analysis to better characterize the performance of the surrogate debris in the test relative to the expected performance of the plant debris.

5.7.8.1 Temperature Scaling

Vendor head loss testing is typically performed with water that is at relatively low temperatures compared to the plant sump or suppression pool temperatures following a postulated LOCA. Methods for temperature scaling have ranged from simply applying the ratio of the water viscosities to applying a head loss correlation such as the NUREG/CR-6224 correlation. However, if the test debris bed incurred pressure-driven mechanical disruptions, such as boreholes, then the scaling of these head losses cannot be based on viscosity or the standard head loss correlations that are based on debris bed uniformity. If pressure driven bed discontinuities occur during testing, it may be difficult to show that these disruptions would occur at lower pressures associated with the higher water temperatures in the plant.
Because boreholes and channeling may not be easily observed or detected, it is recommended that flow sweeps be conducted at the end of the test to verify that the head loss varies relatively linearly with flow. Increasing the flow is more likely to create disruptions to the bed by increasing head loss. Therefore decreasing the flow at the end of the test is the preferred method to verify bed uniformity (flow and head loss change linearly). The primary temperature-

affected parameter is water viscosity, which increases at colder temperatures. Therefore, the test head losses are typically substantially reduced when applied to the plant condition at higher temperature. If the pressure drop across the strainer changes significantly more than linearly a viscosity based correction is likely not justified.

In summary, the temperature scaling method used to correct head loss data at test temperature should conservatively take into account the water viscosity change and any potential debris-bed morphology changes that occur during testing due to the higher differential pressures developed at lower test temperatures.

5.7.8.2 Deviations between Test Module and Actual Replacement Strainer

If the strainer test conditions did not accurately represent the plant replacement strainer, then scaling may be necessary to account for deviations. For example, if the design of the test strainer module was specified before the design of the replacement strainer was finalized, but the total area of the replacement strainer module was increased or decreased during finalization, then the test head loss may need to be scaled on the basis of screen area. In another example, the problematic materials had been included in the test specifications may be removed from containment. In this case, it may be desirable to scale the test head losses for the alternative but similar debris load, with respect to debris type and quantity. The scaling methods to account for these types of changes can be much more complex than simple temperature-based viscosity scaling. Scaling for a reduction in approach velocity should be relatively easy to justify. However, increasing approach velocity may be more difficult to evaluate due to the potential for bed compression caused by higher flow velocities. Scaling for significant differences in debris types and quantities is also challenging. In some cases, it may be conservative to analytically substitute a less problematic material for a more problematic material (e.g., coatings particulate for calcium silicate), but it would not be acceptable in any case to analytically substitute a more problematic material for a less problematic material (e.g., calcium silicate for coatings particulate). Due to the complexities involved in some scaling for situations that are not well understood, or that cannot be conservatively estimated by the scaling analysis, retesting with appropriate parameters is recommended. When analytical head loss scaling is performed, the greater the difference between the tested conditions and the plant conditions, the greater the uncertainty associated with the scaling.

In summary, scaling methods should conservatively correct the head loss data, taking into account the actual strainer debris loading and approach velocity. For most cases, if the plant debris loading is increased or the strainer hydraulic conditions worsen (e.g., increase in approach velocity), retesting is a conservative method of ensuring prototypical results. If conditions are only slightly more challenging than those tested, some conservative extrapolation of test results may be accepted, but adequate understanding of the change is required. Alternatively, if head loss is reduced due to removal of debris, decreased approach velocity, or increased strainer size, conservative calculations or retesting could be performed.

5.7.8.3 Post-Test Debris and Debris Bed Characterization

A licensee may find it useful to perform post-test analysis on its head loss data with the objective of better characterizing surrogate test debris, especially if the head loss behavior of a particular type of debris is not well understood. Such characterization would support the licensee's position that the surrogate is representative (or conservative) of the plant material it represents. An analysis of the behavior of specific materials may require more than one test with different debris combinations to collect sufficient data for the evaluation. Also, examination of the post-test debris bed could provide useful information regarding the debris bed morphology. If significant debris bed degradation occurs during the testing, the viscosity-based temperature scaling methodology should not be used. As discussed above, flow sweeps are useful for determining whether temperature scaling based on viscosity can be justified.

5.7.8.4 Clean Strainer Head Loss

Most strainer vendors calculate losses associated with portions of the plant strainer that cannot be modeled during testing due to size considerations. In general, the NRC staff has found the calculations to be performed in accordance with industry-accepted hydraulic calculations. Such calculations have been considered an acceptable methodology by the staff. However, some clean strainer head loss calculations have been based on testing, and the head loss did not follow theoretical head loss models. In some of these cases, the testing was performed on strainers that have significant geometrical variance from the strainers proposed for installation. The staff subsequently reviewed testing of strainers with similar geometries to those proposed for installation and validated that the correlations being used by the vendor provided conservative estimates of clean strainer head loss. If the clean strainer head loss cannot be calculated by accepted theoretical methods, testing should be provided that clearly demonstrates the head loss behavior of the clean strainer.

5.7.9 Qualification Testing of PWR Replacement Strainer Head Loss

At the onset of the GSI-191 resolution, there was no NRC staff accepted methodology for conducting strainer qualification testing. Each vendor independently developed its approach to head loss testing, with the NRC staff intermittently observing the vendor testing and providing comments. The process was one of evolution in which test observations resulted in new learning and ideas that were passed back to the vendors. This section discusses aspects of the qualification testing that turned out to be of lesser importance than originally anticipated, as well as the important aspects, all of which are integrated into this state-of-the-art methodology. This section is a review of the governing aspects that should be the focus of qualification testing.

At the beginning of strainer testing, vendors typically believed that thin-bed debris beds could not develop on their strainers due to the complexity of the strainer geometries. However, this thinking was largely based on previous testing with small strainers and associated faster approach velocities. Under these conditions large pieces of debris could accumulate on the strainer and debris could accumulate preferentially on selected surfaces due to approaching flow velocities and/or gravitational settling. Typical large passive PWR replacement strainer approach velocities are so low that the approaching debris consists primarily of suspended fibers and particles that are not significantly affected by gravity. Further, the very low velocities allow the debris to accumulate relatively uniformly even if the initial accumulations are nearer the pump connection to the strainer. As a result, thin-bed formations are not only possible on these complex strainers but they may be the most likely and problematic type of bed formation in PWRs.

The NRC staff has observed testing and/or seen test photos of instances in which substantial head loss was caused by a relatively thin and relatively uniform layer of debris (i.e., thin bed) on each of the PWR replacement strainer designs. Figure 5.7-5 shows a very non-porous thin-bed accumulation on a PCI replacement strainer prototype that caused 28 ft of head loss before the vendor reduced pump flow to avoid its damage (Smith, 2008a). This photo shows some bridging of the strainer disks by larger pieces of fibrous debris, but the primary cause of head loss was the relatively thin and relatively non-porous layer coating all screening surfaces. The vendor postulated that the head loss may have been higher than expected due to the use of walnut shell flour as a coatings surrogate. The GE strainer design is a similar stacked-disk strainer and the staff also observed thin-bed formation on a GE prototype (NRC, 2006) indicating that a thin-bed debris accumulation can cause severe head losses. Testing by Atomic Energy of Canada Ltd. (AECL) for their finned strainer design was based on thin beds causing the most severe head losses (ADAMS #ML062020596). AECL performed many scoping tests whose results indicated that thin bed accumulations were more problematic than thicker beds. The Alion top-hat strainer design is quite different from the disk or fin design, and thin-bed accumulations have been observed on this design, as well. (ADAMS #ML072420575). Another unique design is the Control Component Inc. (CCI) pocket strainer design, for which a thin-bed formation is shown in Figure 5.7-6. A chemical-effects thin bed caused a head loss that peaked at about 9 ft on a CCI strainer (ADAMS #ML072420572).

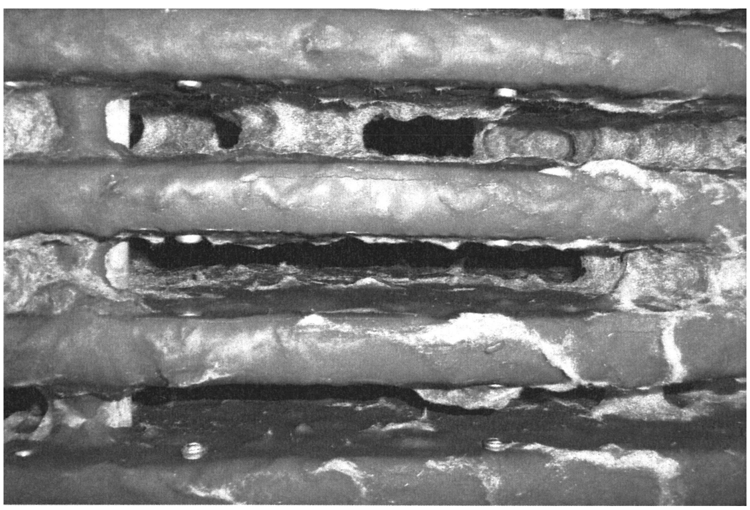


Figure 5.7-5. Non-Porous Thin-Bed on PCI Replacement Strainer(from Smith, 2008a)

Figure 5.7-6. Thin-bed on CCI Pocket Strainer Design

The process of developing the head loss test methodology included staff observations of vendor procedures that did not adequately test for thin-bed head losses which can be significant. In order to adequately test for the formation of a thin bed for a large PWR replacement strainer, testing must include features so that almost all of the debris approaching the strainer will approach the strainer as fine suspended matter. This is because the buoyant debris typically does not factor into the head losses and the floor transported debris will essentially remain on the floor. Although, this trend is typical, outlier situations can require alternative considerations, such as a strainer in a pit where floor-transported debris may fall onto the strainer or strainer/debris load combinations that do not have enough fine debris to fully cover the strainer surface.

Therefore, the key feature of simulating realistic debris accumulation is to ensure that the suspended matter is prototypically or conservatively represented. Further, the non-suspended matter must not be artificially forced to accumulate on the strainer by non-prototypical agitation or debris addition methods that affect debris accumulation on the strainer. Testing has demonstrated that the most severe head losses are associated with a relatively slow accumulation process that allows the debris to systematically seek the locations of higher flow through a debris bed and slowly plug these locations. Rapid bulk accumulations can leave channels within a bulky debris bed that would not exist for slow accumulations. Moreover, the fiber bed accumulates more uniformly in the presence of particulates than without the particulate because particulate filtration increases localized head losses and forces the flow toward uncovered surfaces. In conclusion, thin-bed head losses are accurately simulated with only suspended matter approaching the strainer, with the particulate added first and the fibrous debris introduced very slowly. Given the large number of uncertainties associated with head loss testing and its inputs, the assurance of strainer qualification should include a thin-bed test based on these features. In the absence of a thin-bed test the acceptance of vendor qualification testing requires judgment that can add considerable uncertainty to the strainer acceptance. Examples of inappropriate testing practices observed by the staff have included:

- Testing in which the intended suspendable fibrous fines were simulated with larger shreds of fibrous insulation. In one case the only fibrous debris was latent fibers and these fibers were simulated with NUKON® shreds, resulting in a potentially severe underrepresentation of latent fiber accumulation because the shreds did not transport to the strainer (NRC, 2007a). Other observations of non-prototypically coarse fiber preparation were common prior to the NRC providing expectations for fine debris characteristics in testing.

- Use of non-prototypical agitation to force fibrous shreds to accumulate on the strainer rather than settling to the tank floor, with the objective of maximizing debris quantities on the strainer. This practice has been observed to prevent the formation of a thin bed in tests that were intended to identify thin bed head losses. When a relatively large fibrous shred enters a gap between disks, within a cylinder, or an interior pocket it can settle onto a horizontal surface because the agitation that drove it to the gap is no longer influencing the shred. This creates a non-uniform accumulation with respect to the surfaces of other orientations. In one situation, accumulations of debris that settled between horizontal disks created a damming effect. The result was a pressure differential that was subsequently relieved by the dam being forced inward clearing a portion of screen of debris and relieveing the overall strainer head loss (NRC, 2008a). This test did not adequately represent the intended thin bed, and the observed phenomenon was likely non-prototypical of what would occur in the plant.

- Similarly, fibrous shreds have been introduced directly in front of strainers to enhance debris accumulations, also with the effect of negating the formation of an effective thin bed. In this situation, the shreds entering the pockets settled to the horizontal surfaces of the strainer. This condition created non-uniformities between the horizontal surfaces and the surfaces of other orientations, thereby precluding the formation of an effective thin bed (NRC, 2008f).

- Particulates were observed to be introduced as buckets of dry powder that appeared to agglomerate, thereby under-representing the suspended particulate (NRC, 2006).

- The staff has observed cases where the debris preparation did not match the results of the transport evaluation (fiber pieces too large or not assured to be conservatively fine).

- Flow in test facilities have been observed to be non-conservative with respect to the plant resulting in non-conservative transport.

- Agglomeration of debris resulting in non-conservative transport and head loss has been observed.

Head-loss testing experience has shown that the large PWR replacement strainers with their inherently slow screen approach velocities, typically less than 0.01 ft/s, cannot be effectively blocked by fibrous debris alone due to the high porosity of the fibrous debris, even if the strainer was to become completely engulfed in fibrous debris. Regarding particulates, not only are thin beds capable of causing severe head losses, but the type of particulate is important. A thin layer of fine hardened particles, such as latent debris or coatings, which would have a bed porosity in the neighborhood of 80%, is not too likely to cause the severe head losses. Coarse particulates would cause substantially less head loss than would the fine particulates. The primary issue is the more problematic particulates, such as calcium silicate, Microtherm, Min-K, and chemical-effects precipitates. Confidence that a specific strainer blockage issue has been resolved can be greatly increased when these types of particulates are not present in the containment in significant quantities.

5.7.10 Qualification Testing of BWR Strainer Head Loss

The BWROG developed the strainer resolution methodology referred to as the Utility Resolution Guidance (URG) (NEDO-32686), which the NRC staff reviewed and subsequently issued a safety evaluation report (NRC-SER-1998). The URG included technical support documentation addressing strainer head loss. The BWROG sponsored head loss testing of a variety of test module designs, including a truncated cone strainer, a small PCI stacked disk strainer, a large PCI stacked disk strainer, a 20-point star strainer, a 60-point star strainer, and a self-cleaning strainer. The BWROG developed a head loss correlation based primarily on fiber and sludge (fine corrosion products typically found in suppression pools) but also included “bump-up” factors to account for other miscellaneous types of debris. The URG stated that the bump-up factor correlation was only valid at lower debris loadings (without explicitly defining “lower debris loadings”). The staff review found the BWROG bump up factor correlation to be unreliable, incomplete, and unacceptable for plant analyses. Other vendors including General Electric (GE), Enercon, and ABB (Asea Brown Boveri/Combustion Engineering) conducted scaled strainer module tests and developed head loss correlations that were considered applicable to their respective strainers. Based on knowledge that emerged from PWR testing the BWROG and NRC are reviewing the need to re-evaluate BWR strainer head loss on a plant specific basis.

Whereas the PWR strainer head losses were determined by performing strainer module tests using plant-specific debris types and loads, BWR head losses were typically determined using head loss correlations based on generic vendor tests. In at least one plant, the strainer qualification was based entirely on head loss analyses. The NRC staff reviewed the results of head loss testing conducted by the BWROG as presented in the URG, a test report by GE, and head loss testing reviewed during the auditing process. The NRC staff conducted formal audits of four licensees, including (1) the GE strainer installed at Duane Arnold (Mark I BWR containment); (2) the PCI strainer installed at Dresden (Mark I); (3) the ABB strainer installed at Limerick (Mark II); and (4) the Enercon strainer installed at Grand Gulf (Mark III).

Based on these audit reports, it is clear that the licensees and vendors typically believed that thin beds could not develop on their respective strainers due to the complexity of the strainer geometries. The fact that thin beds were discovered to have occurred in the Perry and Limerick incidents (which were part of the reason for the regulatory actions to improve strainer performance) was attributed to the simpler strainer designs that existed at that time. PWR strainer testing has subsequently shown that the complex strainer designs cannot preclude the formation of a thin bed. For BWRs, evaluation of thin-bed formation is complicated by the effect of the vent downcomer depressurization turbulence.

The BWR resolutions did not address the potential severity of particulate insulation debris, e.g., calcium silicate. Due to the very fine nature of pulverized calcium silicate dust, it was generally assumed that this fine dust would not be filtered; therefore head loss testing with calcium silicate like particulates was not performed until late in the resolution process. Licensees typically screened out smaller quantities of calcium silicate debris as being unimportant compared to the larger quantities of other debris types, and/or performed analyses using assumed head loss properties that may have underestimated head losses associated with calcium silicate like particulates.

Chemical effects were not considered during the BWR resolutions in the 1990s. Although the BWR post-LOCA environments are less likely to result in significant chemical products, the potential extent of chemical effects should be determined and accounted for if necessary. Head loss testing and strainer qualification conducted during the BWR resolution was performed to a different set of standards than during the PWR resolution. Because of the lessons learned during the implementation of strainer improvements at PWRs, the BWROG and NRC staff are currently revisiting several areas to determine whether further actions are required at BWRs to ensure adequate strainer performance. One of the main areas being evaluated is strainer head loss testing which also includes issues regarding the debris included in the vendor tests, the debris preparation, and whether the debris used in testing adequately represents the plants' conditions.

5.8 Debris Head Loss Correlations

The NRC developed the head loss correlations presented in NUREG/CR-6224 and NUREG-1862. The NUREG/CR-6224 correlation was developed as an analytical tool to support the resolution of the BWR strainer issue but was also used during the GSI-191 resolution as an analytical scoping and test data extrapolation tool. The NUREG-1862 correlation was developed during the GSI-191 resolution specifically to address concerns raised by the ACRS regarding analytical estimation of head-loss-associated debris beds containing calcium silicate.

The NUREG/CR-6224 correlation was implemented in two separate user-friendly software packages and made available for industry use, as well as the NRC staff. These software packages are the NUREG/CR-6224 Correlation and Deaeration Software Package, and the BLOCKAGE 2.5 code. The first development was BLOCKAGE 2.5, which includes a fairly complete set of BWR strainer blockage evaluation models, as well as the NUREG/CR-6224 correlation (NUREG/CR-6370 and NUREG/CR-6371 are the Blockage 2.5 User and Reference Manuals). The models include drywell and wetwell debris transport and probabilistic models that calculate debris accumulation and head loss on multiple suppression pool strainers at the same time. The probability model calculates an overall plant strainer blockage probability based on user input weld break probabilities and the code's determination of whether or not each specific weld break would lead to a blocked strainer. A key component is the model for suppression pool debris resuspension and settling. This model calculates debris concentrations for each type and size categorization, which are subsequently used to predict debris accumulation on each strainer based on the debris concentrations and pump flow rates. The NUREG/CR-6224 Correlation and Deaeration Software Package was developed by extracting the head loss correlation model from the BLOCKAGE 2.5 code and adding models to estimate deaeration from flows passing through a bed of debris. Both software packages have a user-friendly graphics user interface. The NUREG-1862 correlation was not developed into a software package.

There are basic limitations for the use of all such analytical correlations. Specifically, the head loss predictions are only as good as the correlation input parameters. At least two of the input parameters can only be determined by using an applicable head loss correlation to deduce the parameter from applicable head loss data. These two parameters are the debris bed porosity and the debris bed constituent specific surface areas. Since these parameters should be deduced using an appropriate head loss correlation, they should then be used in conjunction with that correlation. To make matters more complicated, a typical strainer blockage calculation will have multiple types of debris (such as fibrous insulation, latent fibers, coatings particulates, calcium silicate, dirt, etc.), and the experimentally determined head losses will include synergistic effects among the debris types that are difficult to simulate analytically. Therefore, the analytical correlations are useful for scoping purposes such as the initial sizing of a new strainer design or the extrapolation of head loss test data from the test conditions to alternate conditions, such as a slightly smaller or larger strainer area. The greater the variance between the calculation parameters used in the correlation and the corresponding validating test parameters, the greater the uncertainty introduced into the correlelation results.

It should also be pointed out that each of these correlations has inherent assumptions built into their respective developments. For example, both correlations assume that particulate debris cannot be deformed under the range of pressures encountered in a strainer debris bed. Particulates such as dirt or iron oxide corrosion products can be observed to be very rigid when observed under a microscope. When these particles are compressed in a solid layer they do not deform once the particles make complete contact such as in a thin layer of dirt particles. Some materials, such as calcium silicate derived from limestone and diatomaceous earth (fossilized plankton), has a fine crystalline structure that can undergo shape changes under pressure. These changes can affect head loss correlation predictions involving calcium silicate (i.e., the bed porosity and specific surface area could have a pressure dependency which is not modeled).

The NUREG/CR-6224 Correlation and Deaeration Software Package is presented first because this package had greater use and a wider peer review. Second, the BLOCKAGE 2.5 code is briefly presented followed by the more recent NUREG-1862 correlation.

5.8.1 NUREG/CR-6224 Correlation

5.8.1.1 NUREG/CR-6224 Correlation and Deaeration Software Package

The NUREG/CR-6224 head loss correlation was originally developed during a volunteer plant parametric study, completed in 1995, for the resolution of the BWR ECCS strainer blockage issue. For this study, the correlation was implemented into a computer program named BLOCKAGE 2.5 (NUREG/CR-6370, NUREG/CR-6371), which included models for debris generation, debris transport, risk assessment, and debris head loss. In 2004, for use in the resolution of the GSI-191 PWR sump strainer blockage issue, the basic NUREG/CR-6224 head loss correlation, as programmed into BLOCKAGE 2.5, was extracted and implemented as a stand-alone program that solved only the head loss calculation. A user-friendly graphical user interface was also developed. In 2005, this program was expanded to include a deaeration model to estimate the deaeration that occurs when the pressure of the water deceases as the water flows through a bed of debris. This final program, referred to as the “NUREG/CR-6224 Correlation and Deaeration Software Package,” was publically released by the NRC in June 2005 via the NRC Public Document Room. Program installation also installs a user’s manual, sample problems, and reference materials, along with the executables.

NUREG/CR-6224 Head Loss Correlation

A semi-theoretical NUREG/CR-6224 correlation was developed for predicting head loss through fibrous debris beds based on the fundamental principles of porous media filtration and hydraulics (NUREG/CR-6224). The correlation was developed for single-phase water flow and for a uniform-thickness homogeneous layer of fibrous debris with or without interspersed particulate, but it is also applicable to a layer of particulate debris supported in place with minimal fibers overlaying a strainer mesh or strainer holes, sufficient for effective filtration (i.e., a “thin bed” of debris). The general equation, valid for laminar, transient, and turbulent flow regimes, is formulated as

$$\frac{\Delta H}{\Delta L_o} = C\left[3.5 S_v^2 (1-\varepsilon_m)^{1.5}\left[1+57(1-\varepsilon_m)^3\right]\mu U + 0.66 S_v \frac{(1-\varepsilon_m)}{\varepsilon_m}\rho_w U^2\right]\left(\frac{\Delta L_m}{\Delta L_o}\right)$$

where C = 4.1528×10^{-5} (ft-H_2O/in.)/(lbm/ft^2-s^2) [units conversion constant]

S_v = specific surface area = 1.71×10^5 ft^2/ft^3 for NUKON™

εm = mixture porosity

μ = dynamic viscosity (lbm/s-ft)

U = velocity (ft/s)

ΔH = head loss (ft-H_2O)

ρ_w = water density (lbm/ft^3)

ΔL_o = uncompressed fiber bed thickness (in.)

ΔL_m = actual bed thickness (in.)

The first term of two on the right-hand side, which is linear with flow velocity, reflects the viscous effects associated with pressure loss, and the second term, which is a function of the square of the velocity, reflects the effects of inertia. In the laminar flow associated with large passive strainers, where the velocities through the debris bed are typically less than 0.01 ft/s, the pressure loss is dominated by the first term. The ratio of the actual bed thickness (ΔLm) to the uncompressed thickness (ΔL_o) reflects the compressibility of the fibrous debris bed under pressure (the larger the pressure differential, the greater the bed compression).

The supporting constituent equations, which complete the correlation, include an equation for the compressibility of the fibrous debris bed, an equation that provides a material contact compressibility limit, and equations for calculating the mixture properties of porosity, specific surface area, and densities. The mixture porosity depends upon the porosities of the uncompressed fiber bed, the entrapped particulate, and the bed compression and is calculated from:

$$\varepsilon_m = 1 - (1 + \frac{\rho_f}{\rho_p}\eta)(1-\varepsilon_o)\frac{\Delta L_o}{\Delta L_m}$$

where ρ_f = density of an individual fiber (175 lbm/ft3 for fiberglass)

ρ_p = density of each individual particle

η = ratio of the mass of particulate to mass of fiber in the bed

ε_o = uncompressed fiber bed porosity

The next equation is used to estimate the compressibility of the debris bed.

$$c = \alpha c_o \left(\frac{\Delta H}{\Delta L_o}\right)^{\gamma}$$

where c_o = the "as-fabricated" bulk fiber density (2.4 lbm/ft3 for NUKON® fiber)

c = actual bulk fiber density under pressure (lbm/ft3).

The coefficients α and γ can be specified in the software package input by the user. The values developed for these coefficients during the NUREG/CR-6224 study were α = 1.3 and γ = 0.38.

There is a practical limit to the fiber bed compression, particularly whenever significant particulate is embedded in the fiber matrix. The particulate cannot be compressed beyond its bulk granular density (e.g., approximately 65 lbm/ft3 for BWR suppression pool sludge consisting of iron oxide corrosion products). The limiting compression equation incorporated into the software package is:

$$\Delta L_m = \Delta L_o \frac{c_o}{c_{gran}}(\eta + 1)$$

where, c_{gran} = the bulk granular density of the particulate (lbm/ft3).

For thin-bed debris beds, the bed porosity is limited to correspond to the porosity of the granular particulate, which is:

$$\varepsilon_m = 1 - \frac{c_{gran}}{\rho_p}$$

The solution of the general NUREG/CR-6224 correlation equation and its supporting equations require an iterative solution, which is discussed in NUREG/CR-6371.

Programming Verification and Correlation Validation

Correlation programming verification was conducted for the BLOCKAGE 2.5 code (NUREG/CR-6371) by comparing code results to the results of analytical solutions. This verification is extended to the NUREG/CR-6224 Correlation and Deaeration Software Package, since the applicable correlation programming is common to the two programs.

The validity of the NUREG/CR-6224 correlation was assessed against limited experimental data involving NUKON® and BWR suppression-pool iron oxide sludge during the NUREG/CR-6224 study and the correlation was shown to perform reasonably well against that data. Validation against experimental data involving NUKON® and calcium silicate particulate (NUREG/CR-6874) proved more challenging. Calcium silicate particulate has a crystalline structure subject to potential deformation, whereas iron oxide particles behave like small, hardened rocks and are unlikely to deform under differential pressures expected across strainers. During the calcium silicate tests, the fiber bed compression was measured, whereas it was not measured during the iron oxide testing; therefore, the compression function was not independently validated during the earlier NUREG/CR-6224 study.

The validity of the correlation predictions depends upon knowing appropriate values for input into the correlation. One important property that should be experimentally determined is the specific surface area of the particulate. The specific surface area strongly affects hydraulic flows through the particulate, as does the bed porosity. The experimental determination is done by adjusting this input parameter and others and comparing the results to the experimental data until the correlation fits the data reasonably well. Once agreement is reached the input values in conjunction with the correlation can be used with reasonable success to predict head losses for comparable debris compositions. Note that the densities can typically be independently predetermined to a reasonable accuracy. The test data from a thin-bed test provide a reasonable basis for ascertaining the particulate specific surface area because the bed compression and fiber properties are not issues for the thin-bed case. Calcium silicate is a substantially more difficult type of particulate for which to determine the appropriate correlation input values than less deformable particulates like iron oxide. The iron oxide particulates are hardened particles that will not change shape under the kinds of pressures found in a typical debris bed, whereas calcium silicate particulate with its crystalline structure could change shape under debris bed head loss pressures (i.e., the surface area could become somewhat dependent on head loss).

An independent ACRS technical assessment of the correlation identified deficiencies, with which the NRC staff generally agreed, in the formulation of the correlation. The assessment pointed out that there were variations in the trends of the results when the correlation, as originally formulated, was applied to the head loss test data for calcium silicate in NUREG/CR-6874, which was intended to ascertain the specific surface area for calcium silicate. The three identified formulation deficiencies listed in Table 5.8-1 could have contributed to these variations.

First, the denominator in the porosity expression of the inertia effects term should have been cubed, i.e., instead of $(1- \varepsilon m)/\varepsilon m$, it should have been $(1-\varepsilon m)/\varepsilon m3$. The primary reason for this change was to put the formulation in agreement with the more classical theoretical forms, such as the Ergun equation. An NRC comparison with test data indicated that the more classical form was a somewhat better fit to the data. The inertia effects term, which is a function of the velocity squared, has the most impact when the flows are faster and turbulent in nature. For the large passive strainers, the flow rates through the debris bed are generally much too slow for this correlation correction to have a significant effect on the calculation estimates.

The second and third formulation deficiencies related to the correlation's ability to predict the compression of the bed of fibrous debris. The second deficiency dealt with the formulation of the compression function that related pressure to the bed compression ratio, and the third deficiency dealt with the formulation of the compression limiting equation. The compression function of the NUREG/CR-6224 correlation related the bed compression ratio to the head loss per unit bed thickness whereas the ACRS review stated that it would be more correct to relate the compression ratio only to the head loss. In addition, the ACRS review noted that the compression function did not calculate a compression ratio of one when the head loss was zero (which, in addition to not being correct, caused difficulties with the iterative numerical solution of the correlation's set of equations). This deficiency suggested a compression function of a different form that would go to one when the head loss is zero, i.e., $\Delta Lo/\Delta Lm=1+\alpha\Delta Lo\varphi\Delta H\gamma$. The ACRS noted that the compression-limiting equation had been oversimplified for debris types such as calcium silicate and provided a more detailed derivation, as presented in Table 5.8-1.

Table 5.8-1. Deficiencies Identified in Formulation of NUREG/CR-6224 Correlation

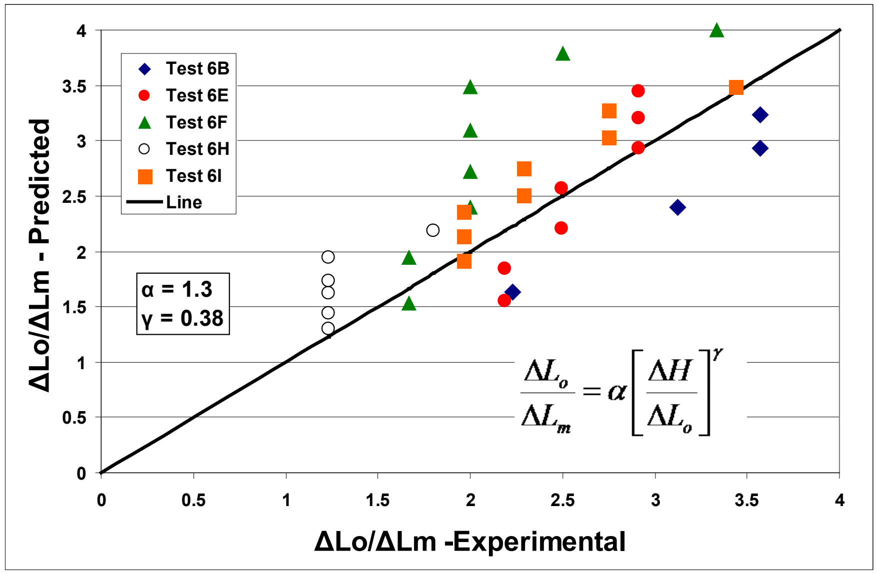
Specific Concern	NUREG/CR-6224	ACRS Comment
Porosity expression in inertia effects term, specifically, εm in the denominator should be cubed	$(1- \varepsilon_m)/\varepsilon_m$	$(1- \varepsilon_m)/\varepsilon_m^3$
Formulation of compressibility function	$\Delta L_o/\Delta L_m=\alpha(\Delta H/\Delta L_o)^\gamma$	$\Delta L_o/\Delta L_m=\alpha\Delta H^\gamma$
Formulation of compression limiting function	$\Delta L_m/\Delta L_o= (c_o/c_{gran}) (\eta+1)$	$\Delta L_m/\Delta L_o=(c_o/c_{gran})(\eta+c_{gran}/\rho_f)$

The most appropriate form of the compression function really depends upon which form does the best job of predicting the head loss data and could depend somewhat on the type of fiber. The data reduction of the calcium-silicate head loss data presented in NUREG/CR-6874 (for the final and most valid series of tests) applied the correlation to a thin-bed calcium silicate debris bed, where the bed compression was not an issue, to ascertain an effective specific surface area for the calcium silicate particulate. Then, the correlation was applied to other test series to determine how well the correlation was performing overall. The comparative results for the original NUREG/CR-6224 correlation with the test data are shown in the upper plot in Figure 5.8-1, where the horizontal axis represents the experimentally measured compression ratio, and the vertical axis represents the calculated compression ratio. If a data point was correctly estimated by the correlation, then that point in the plot would reside on the 45° line. This upper plot shows substantial data scatter both above and below the 45° line. Using the compression formulation suggested above (i.e., $\Delta Lo/\Delta Lm = 1 + \alpha \Delta Lo^{\varphi} \Delta H^{\gamma}$) along with the other two ACRS suggested formulation corrections, the data scatter is greatly reduced, as shown in the lower plot in Figure 5.8-1. Given the quality of the test data compression measurements, this is a reasonably good result. Obtaining quality head loss data for calcium silicate was more difficult than for suppression pool sludge due to issues with particle filtration and particle deformation associated with calcium silicate; therefore, these comparisons represent a reasonably good test of the correlation's capabilities, both as originally programmed in the software package and the potential improvements to the original correlation.

Applicability of Correlation

The head loss predictions of the NUREG/CR-6224 correlation are only as good as the validity of the input parameters and depend upon whether or not a realistic debris bed can be treated as one-dimensional, uniform thickness, and homogeneous, with single phase water. Further, the most appropriate formulation of the compression function and associated coefficients may depend somewhat upon the type of fibers in the debris bed. The large passive strainers in use at the plant have varied strainer geometries that may affect debris bed uniformity and one-dimensionality. Instead of forming in a homogeneous manner, the bed could contain stratification due to the relative timing of arrival of the various debris constituents. Under some conditions, debris beds can develop channeled flow through bed penetrations known as boreholes. Realistic plant debris beds may consist of multiple fiber types and particulate types so that even if the appropriate correlation input parameters are developed for each debris type, the agglomeration of debris could have synergistic effects not accounted for by means of testing with individual components. Additionally, complex geometry strainers are likely to collect debris non-uniformly with the degree of non-uniformity depending on the strainer design and debris transport. The correlation assume a uniform debris bed. Although the NUREG/CR-6224 correlation is certainly suitable for scoping calculations, given all these uncertainties, the qualification of plant strainers should necessarily be based on experimentation. However, when properly applied, the correlation can often be used to extrapolate experimental data from the test conditions to alternative conditions not too far removed from the test conditions such as a different water temperature, a variation in debris load, or strainer flow velocity. However, the further the extrapolation from the test condition, the greater is the uncertainty.

Original NUREG/CR-6224 Correlation



Revised NUREG/CR-6224 Correlation

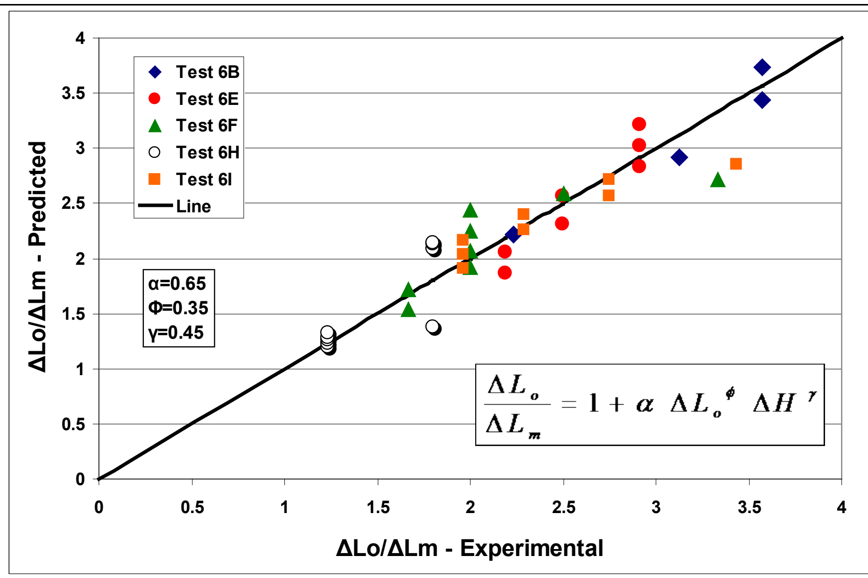


Figure 5.8-1. Performance Comparison of Original and Revised Correlations

The ACRS identified deficiencies in the formulation of the NUREG/CR-6224 correlation listed in Table 5.8-1 do not significantly affect the predictions for thin-bed debris beds associated with the typical large plant strainer, where the velocity of flow through the bed of debris is typically less than 0.01 ft/sec. At these low velocities, the inertial velocity squared term with the εm3 correction becomes irrelevant. Because a thin bed consists of very little fiber, the two deficiencies associated with fiber bed compression do not apply either. Since thin beds tend to form from the fine suspendable fibers and particulates, which are not significantly affected by gravity, they tend to form relatively uniformly on surfaces of all orientations. As such, the quality of the head loss prediction depends upon knowing the appropriate specific surface areas of the agglomerated particulate. If the debris bed forms uniformly the performance of a complex geometry strainer can perform in a manner quite similar to the flat-plate strainer. In this situation, head loss data taken with a small-scale closed loop head loss test apparatus may closely approximate similar debris loads on complex strainers.

The set of constituent equations used in the correlation to combine the input properties of density and specific surface area for multiple components into a single set of numbers for use by the main correlation equation is based on the assumption of hardened materials that do not deform under pressure. Particulates that can deform under pressure (or with moisture absorption) can pack into the small spaces among the hardened particulate, thereby creating a low porosity medium for which this correlation will most likely underpredict the associated head loss. The user should beware of this limitation.

Deaeration Model

A deaeration model was added to the software package to estimate the evolution of dissolved air as the water flows through a bed of debris. The software was designed to calculate conservative estimates of deaeration given plant specific conditions. The containment sump pool water will contain dissolved air due to its contact with the containment atmosphere. As pumped recirculation water flows through the recirculation strainer and debris bed, the pressure decrease can be significant enough for dissolved air to evolve from the flow, thereby generating air bubbles consisting of both air and water vapor. Excessive voiding can result in pump cavitation. In addition, the void fraction, if high enough, could invalidate the head loss predictions from the NUREG/CR-6224 correlation or those attained during plant specific tests under conditions other than those predicted for the plant. Deaeration has been observed in both NRC-sponsored and industry-sponsored head loss testing, which is typically conducted at temperatures much colder than would be expected in a plant sump pool. This deaeration resulted in substantial air buildup immediately downstream of the test strainers. At higher water temperatures, the vapor contribution can increase substantially.

The complete deaeration model (see Information Systems Laboratories, 2005) is included in the software package installation. The key assumptions included in the deaeration model are:

1 Henry’s law and the ideal gas law are both applicable.

2 The dissolved air composition is based on standard composition dry containment air.

3 The concentration of the dissolved air in the containment sump water is always at its equilibrium saturation level both before and after the sump strainer.

4 The decompression process through the strainer debris bed is isothermal.

5 The void gases are saturated with water vapors.

6 The hydrostatic pressure downstream of the strainer equals containment pressure plus sump pool hydrostatic head minus strainer and debris head losses.

A key limitation to this deaeration model is the isothermal assumption. If substantial water vaporizes while passing through the debris bed, the water temperature will begin to drop accordingly. Therefore, in a situation where the sump-pool water temperature begins to approach the boiling point, a debris bed depressurization could cause sufficient vaporization that the prediction from the Henry’s-law based deaeration model prediction would not be valid due to the isothermal assumption. In addition to the input parameters required to solve the head loss correlation, this deaeration model requires input of the containment pressure and the depth of the pool above the sump strainers to calculate the hydrostatic pressure at the sump strainer surface. For conservatism, the height of the water above the minimum submergence for the entire surface of the strainer should be used for pool depth in the deaeration calculation.

5.8.1.2 BLOCKAGE 2.5 Code

The BLOCKAGE 2.5 code was developed by the NRC as a tool to evaluate licensee compliance regarding the design of suction strainers for ECCS pumps in BWRs, as required by NRC Bulletin 96-03. The BLOCKAGE code was developed to predict whether or not accumulation of debris on the pump suction strainers, following a LOCA, would lead to loss of ECCS pump NPSH in a BWR. The code included a transient temperature-dependent suppression pool model to credit sedimentation, the ability to simultaneously track multiple debris types accumulating on the strainers associated with multiple pumps and multiple common headers and estimated head losses on each strainer employing user-selected optional head loss correlations, including the NUREG/CR-6224 correlation.

BLOCKAGE 2.5 allows the user to simulate debris generation and the subsequent transport of multiple types of debris, including fibers, particles, and metal shreds by specifying the characteristics of each debris type. The debris could originate from target destruction in the drywell (e.g., insulation), non-target related drywell sources (e.g., latent), and wetwell sources (e.g., latent sludge). The user can specify a given quantity of debris for transport or use a three-zone destruction model to calculate the generation of insulation debris from insulation targets based on the user input of target diameters, lengths, and locations. The user specifies a destruction fraction for each of the three zones. The debris transport from the drywell to the wetwell can be modeled as location-dependent and time-dependent and is split between two discrete time intervals referred to as the “blowdown period” and the “washdown period.”

The debris entering the pool immediately becomes suspended in the pool where it can be deposited onto a strainer, pass through a strainer and be trapped within the primary system, or settle to the floor of the wetwell. Debris existing in the wetwell at the time of the pipe break is assumed to initially reside on the wetwell floor, where it is subject to resuspension by the turbulent primary-system depressurization flows. The wetwell debris transport model accepts debris transported from the drywell by debris type, subdivides the debris of each type into settling velocity groups, and independently determines the transport of each velocity group for each debris type within the suppression pool. The terminal velocity at which debris settles in a still pool of water is a function of the size of the individual debris pieces and the type of debris. The BLOCKAGE models require that the terminal settling velocity function be subdivided into discrete intervals or groups for each type of debris. The user enters a table of characteristic settling velocities associated with each size grouping in the debris size distribution.

The debris transport within the suppression pool, including the deposition of debris on the strainers and the debris concentration within the pool, is calculated separately for each discrete debris size for each debris type. The suppression pool is treated as single volume of water (i.e., debris concentration does not vary with location within the pool). Several model parameters supplied by the user, which are time-dependent, include the calculational time step, the pump flow rates, the drywell debris transport rates, the suppression pool temperature, and the suppression pool resuspension and settling rates.

Several independent ECCS pumping systems can be modeled simultaneously, with each system consisting of multiple pumps on a common header attached to a single equivalent strainer. The ECCS pump and header models in BLOCKAGE 2.5 allow the user to tailor the strainer blockage calculation to the plant specific ECCS pumping systems. As many as eight independent pumping systems could be modeled in a single calculation. A single pumping system consists of multiple pumps (or a single pump) attached to a common header that draws water from a single strainer. The strainer areas of the multiple strainers attached to a common header are combined and represented as the single strainer, and the flow through the equivalent strainer is the combined flow of the operating pumps attached to the common header. As many as four pumps could be attached to the common header. Each pump attached to a common header is modeled with a separate flow capacity and a separate NPSH margin, but all pumps use a common time-dependent flow multiplier. Each pump provides ECCS flow to the reactor until strainer blockage head losses exceed its available margin of NPSH, causing the pump to fail and its flow to cease. Each pump is considered to fail due to cavitation when the strainer head loss exceeds its temperature-dependent NPSH margin. The calculation of the strainer head loss is based on the total flow of the pumps still operating on the common header, but the cavitation failure of each pump is determined independently of the other pumps.

A debris bed filtration model determines the quantity of debris entrained in the pump flow that is deposited on the strainer and the quantity of debris that passes through the strainer and may be retained within the primary system. The fraction that is deposited onto the strainer is called the "strainer filtration efficiency." The filtration efficiencies are a function of the type and size of debris and the thickness of fibrous debris bed already deposited onto the strainer. The debris passing through the strainer and debris bed will be carried by the ECCS flow to the reactor vessel and associated piping, where some debris will likely be trapped and other debris may be returned to the drywell or suppression pool. The retention efficiency determines how much of the debris passing through the strainers is retained in the primary system and not returned to the containment. One minus this efficiency is immediately returned to the pool. The retention efficiency is a function of the type and size of debris.

Debris accumulation on the ECCS strainer resists further flow through the strainers, thereby impeding the delivery of ECCS coolant to the reactor core. The BLOCKAGE code contains models to estimate the flow resistance, referred to as "pump head loss." The head loss for each strainer is calculated independently of the other strainers. BLOCKAGE 2.5 contains four optional head loss correlations, which may be selected by the user to model the head loss for a debris cake consisting of fibrous and particulate debris. One correlation should be selected and is applied to all of the strainers in the model throughput the entire calculation. The four correlations are the semi-theoretical NUREG/CR-6224 correlation, the empirical BWROG correlation (Boiling Water Reactor Owners Group, 1994), and two generic correlations. The NUREG/CR-6224 correlation was discussed in Section 5.8.1. The two generic correlations allow the use of user-supplied coefficients that allow users to implement their own solution. The BWROG correlation represented early work that is now be considered obsolete. BLOCKAGE 2.5 also contains an additive term for estimating head loss due to metallic debris on the strainer, which can be added to any of these four head loss correlations. The failure of the ECCS to provide long-term cooling to the reactor core is flagged whenever the total ECCS flow capability drops below a user-specified minimum flow rate.

The BLOCKAGE code can evaluate a single-break scenario or a large number of break scenarios to determine plant-wide risk. Two sizes of pipe break scenarios are considered, large and medium LOCAs. The BLOCKAGE code has two models for calculating the pipe weld break frequency for particular welds. These models are referred to as the "weld method" and the "plant method." The weld method specifies the weld break frequencies as a function of pipe diameter and weld type. The weld break frequencies are input to the calculation by the user as a list of break frequencies that are a function of the pipe diameter and the type of weld. The diameters are grouped into classes to reduce the size of the table. The plant method specifies the break frequencies for all weld breaks for a specific diameter pipe. Then the break frequency for an individual pipe weld break is determined by using weighting factors that are specified by the diameter class and the weld type. When selected by the user, the code writes several probability reports that provide information regarding the plant-wide strainer blockage probabilities correlated by pipe diameter, piping system, and break location. The code's graphical user interface can be used to create a wide variety of time-dependent plots.

5.8.2 NUREG-1862 Correlation

The NRC sponsored head loss testing of debris beds consisting of fibers and calcium silicate insulation debris to determine the head-loss characteristics associated with calcium silicate insulation debris (NUREG/CR-6874). Experiments confirmed that calcium silicate insulation could degrade into very fine particulates in the containment environment after a LOCA, and that debris beds formed by a combination of fine calcium silicate particulates and fibrous insulation on a sump strainer can cause substantial head loss across the sump strainer.

Analysis of the test data using the NUREG/CR-6224 correlation recommended that head loss parameters such as particle density, the sludge density, and the specific surface area, be used in conjunction with the correlation for analysis of debris beds containing significant calcium silicate. The analysis noted uncertainties associated with the test parameters and also variability in the manufacture of the particular brand of calcium silicate insulation tested. A technical review by the ACRS raised concerns regarding the application of the NUREG/CR-6224 correlation and the NUREG/CR-6874 methodology for calculating head loss through debris-covered sump strainers. The concerns specific to the formulation of the correlation were discussed in Section 5.8.1.1. The ACRS also expressed concerns with the NUREG/CR-6874 methodology use of a different specific surface area for calcium silicate when the correlation was applied to a thin bed rather than when applied to a thicker bed containing a higher ratio of fiber to particulate debris. These concerns launched an effort to develop a new and improved head loss correlation that was largely based on debris beds of fiber and calcium silicate. This new correlation became the NUREG-1862 correlation. The NRC also sponsored additional testing conducted at PNNL (NUREG/CR-6917). The data from the PNNL tests formed the basis for validation of the NUREG-1862 correlation.

The NUREG-1862 correlation consists of a set of equations derived to calculate the pressure drop for flow across a compressible porous debris bed composed of thermal insulation such as fiberglass fibers (NUKON®) and calcium silicate (CalSil) particles. The equations account for the kinetic and viscous contributions to pressure drop. The compressibility of the porous medium debris bed is considered by initially assuming an irreversible, inelastic process followed by elastic behavior with constant compressibility. Semi-empirical relations and constants required to solve the flow and compression relations were determined from available test data.

The solution of the set of equations involves an iterative procedure developed to estimate the pressure drop across a debris bed composed of one debris type (e.g., fibers) by applying the flow and compression relations to a one-volume, homogeneous debris bed model. This iterative solution procedure was successful in providing estimates of an upper bound pressure drop for the available test data for a debris bed composed of two types of debris using a two-volume, nonhomogeneous model in which the particles are assumed to concentrate or saturate a part of the fiber bed. The pressure drop across a debris bed composed of two debris types (e.g., fibers and particles) depends on the distribution of the two debris types in the bed. For a debris bed composed of two debris types, procedures have been developed to estimate the lower bound pressure drop by using the one-volume, homogeneous model, and to estimate the upper bound pressure drop by using a two-volume, nonhomogeneous model in which the particles are assumed to concentrate or saturate a part of the fiber bed.

Whereas the NUREG/CR-6224 correlation was based on the assumption that the debris bed could be treated as a homogeneous distribution of fibers and particles in a single layer of uniform thickness, the NUREG-1862 correlation allows the debris bed to be divided into two separate homogeneous layers with different particulate concentrations. For the correlations in NUREG-1862 to be valid, the pressure downstream of the strainer must remain above the saturation pressure at the sump water temperature.

The pressure drop (Δpdebris bed) in a debris bed of thickness ΔLdebris bed consisting of a single debris type is given by a modified Ergun equation:

$$\frac{\Delta p_{debrisbed}}{\Delta L_{debrisbed}} = \mu V S_V{}^2 \frac{X^3}{K(X)(1+X)^2} \frac{(1-\varepsilon)^2}{\varepsilon^3} + \frac{b\rho V^2 S_y}{6} \frac{1-\varepsilon}{\varepsilon^3} \left[\frac{(1-\varepsilon)\mu S_y}{6\rho V} \right]^c \qquad (5.8.1)$$

where b = 1.95 for a cylindrical fibrous bed, 3.89 for a spherical particle bed
c = 0.071 for a cylindrical fibrous bed, 0.13 for a spherical particle bed
S_v = specific surface area
ρ = fluid density
μ = fluid absolute viscosity
ε = porosity
V = approach flow velocity upstream of strainer

$$X = \frac{Vol_{void}}{Vol_{solid}} = \frac{\varepsilon}{1-\varepsilon} = \text{Void ratio}$$

K(X) = a dimensionless permeability function

For flows perpendicular to a cylinder axis with ($X>1\times10^{-4}$ and $\varepsilon<0.995$)

$$K(X) = -0.5 + 0.5\ln(1+X) + \frac{1}{2-2X+X^2} \qquad (5.8.2)$$

and for a bed composed of spherical particles with ($X>1\times10^{-4}$ and $\varepsilon<0.995$)

$$K(X) = 2 - \frac{3}{(1+X)^{1/3}} + \frac{5}{3(1+X)^{5/3}+2} \qquad (5.8.3)$$

Equation (5.8.1) can be rewritten as

$$\frac{\Delta p_{debrisbed}}{\Delta L_{debrisbed}} = \frac{\mu V S_V{}^2}{K(X)} \frac{m_{solid}}{A\Delta L_{debrisbed}\rho_{solid}} \frac{(1-\varepsilon)^2}{\varepsilon^3} + \frac{b\rho V^2 S_y}{6} \frac{1-\varepsilon}{\varepsilon^3} \left[\frac{(1-\varepsilon)\mu S_y}{6\rho V} \right]^c \qquad (5.8.4)$$

where m_{solid} = mass of solid material in the debris bed= $\rho_{solid} Vol_{solid}$

ρ_{solid} = density of solid material in the debris bed

A = debris bed cross-sectional surface area= $\frac{Vol_{solid} + Vol_{void}}{\Delta L}$

The viscous term (first term on the right-hand side) of the head loss Eq. (5.8.1) or Eq. (5.8.4) is the dominant contributor to pressure drop for sump strainer approach velocities that are less than 0.061 m/s (0.2 ft/s). The viscous term contributes more than 90% of the total pressure drop for all of the calculational results provided in NUREG-1862. At approach velocities of less than 0.0305 m/s (0.1 ft/s), the viscous term contributes an even larger percentage of the pressure drop. Consequently, it can be argued that the kinetic term could be omitted from the head loss calculation for typical PWR large strainer approach velocities.

For a homogeneous bed consisting of two debris types (NUKON® and CalSil), the total pressure drop is obtained by adding the two pressure drops similar to Eq. (5.8.1) or Eq. (5.8.4), one using Eq. (5.8.3) and the cylindrical fibrous bed constants for NUKON® fibers and the other using Eq. (5.8.4) and the spherical particle constants for CalSil.

Debris Bed Properties

The calculational procedure developed in NUREG-1862 employs pressure drop calculations across a debris bed composed of either one or two calculational control volumes. The one-volume method should be used for calculating head loss across a debris bed composed of a single debris type. The one-volume approach does not represent the best calculational method for beds with multiple debris types and non-homogeneous debris distributions because hydraulic and mechanical pressures can vary non-uniformly within the debris bed. The two-volume method overcomes this limitation by calculating the debris bed flow and compression by assuming the presence of two compressible calculational control volumes for the debris bed.

Testing has shown that a bed can be initially formed at an approach velocity of 0.1 ft/s (0.0305 m/s) with conditions close to a uniform NUKON®/CalSil distribution. However, the uniform condition was not maintained with flow passing through the debris bed, when the particles tend to redistribute from a uniform condition to one in which the particles are concentrated in the fiber in a portion of the debris bed. Testing has shown that the homogeneous debris bed produces the lower bound head loss. This condition (homogeneous unsaturated debris bed) can be modeled using the one-volume calculational approach. The homogeneous debris bed with a uniform distribution of NUKON® fibers and CalSil particles can be modeled by using Eq. (5.8.1) or Eq. (5.8.4) to calculate the debris bed pressure drop.

A heterogeneous locally saturated debris bed represents a more stable reconfiguration of particles in a fiber bed. The upstream portion of the debris bed is considered to be composed entirely of fibers, and the downstream portion is considered to contain the maximum concentration of particles that the fiber bed can hold under a specific flow condition.
(The maximum particle concentration volume can be located anywhere within the debris bed; however, for calculation purposes, the maximum particle concentration volume is assumed to be present on the downstream side of the debris bed.) Testing has shown that this bed configuration typically results in a larger upper bound head loss. The two-volume calculational method should be used to model this bed configuration to account for the two different debris distributions within the debris bed.

A homogeneous saturated debris bed is a subset of the locally saturated debris bed. In this configuration, the fiber bed is completely saturated with particles. In other words, every part of the fiber bed contains particles. The one-volume method can be used to model this configuration because the saturated debris bed is closest to a true homogeneous condition with uniform distribution of fiber and particles. However, if the debris bed is heterogeneous and locally saturated with particles, a two-volume approach is proposed to calculate the head loss. In either approach, the initial bed conditions, flow parameters (determined from experimental studies and described in NUREG-1862), and material parameters need to be known to calculate the pressure drop across a porous medium debris bed.

A heterogeneous oversaturated debris bed represents the case where the debris bed contains more particles than are required to saturate the fiber bed. It is postulated that the downstream portion of the bed is composed of fiber saturated with particles. The upstream portion of the bed is composed entirely of particles. The two-volume calculational method should be used to solve for this condition because of the various debris distributions in the bed.

To apply the calculational approach recommended in NUREG/CR-1862, several debris bed initial conditions, parameters, and material parameters should be known. The following specific information is needed to calculate the pressure drop across a porous medium debris bed:

- Constituent masses of the material in the test debris beds
- Initial thickness of the debris bed at bed formation
- Debris material properties such as density and specific surface area, as well as the multipliers and exponents in the kinetic term of the porous medium pressure drop equation
- Maximum concentration of particulate debris in a fibrous debris bed, a condition called the “maximum particle concentration”
- Material-specific compression parameter, necessary to predict the porous media debris bed compression and expansion
- Flow velocity

The values for these parameters were obtained by comparing the predictions made using the calculational approach with head loss data from tests at PNNL (NUREG/CR-6917), Los Alamos National Laboratory/University of New Mexico (LANL/UNM) (NUREG/CR-6874), and Argonne National Laboratory (NUREG/CR-6913).

Compressibility of a Debris Bed

The material compressibility, a measure of the mechanical strength of the material, affects fluid flow in a porous medium. Gels and fibers are compressible materials that present unique problems in relating fluid flow and applied pressure because bed porosity can change throughout the bed as conditions vary. The geometry of a porous medium can change because of (1) deformation of the solid matter, (2) rearrangement of the individual particles or fibers as a result of movement, bending, or slipping, and (3) disintegration and subsequent rearrangement of the solid material. Bending, slipping, and disintegration are essentially irreversible processes. Therefore, these deformation mechanisms produce non-recoverable volume reductions. The degree of non-recoverable deformation is especially pronounced during an initial compression and decreases as the deformation is increased.

A porous medium composed of material such as fibers, particles, or gel exhibits hysteresis during compression-recovery cycles. This phenomenon is difficult to model in a numerical calculation; therefore, the assumption is made in NUREG/CR-1862 that the first compression is an irreversible process, and that after first compression, the porous medium is elastic with constant compressibility. Further, by assuming the volume of the solid material to be incompressible, the compressibility of the porous medium can be related entirely to the void volume instead of the total volume.

Initial Bed Thickness

The above considerations allowed the derivation of the initial thickness for a NUKON®/CalSil bed at a reference approach velocity:

$$\Delta L_{initial} = \frac{(X_{nukon}+1)}{A}\frac{m_{nukon}}{\rho_{nukon}} + \frac{(X_{Calsil}+1)}{A}\frac{m_{Calsil}}{\rho_{Calsil}} \qquad (5.8.5)$$

where $\Delta L_{initial}$ = debris bed thickness at a reference bed formation approach velocity of about 0.0305 m/s (0.1 ft/sec)
A = is debris bed cross-sectional surface area
m_{NUKON} = NUKON mass in the debris bed
m_{CalSil} = CalSil mass in the debris bed
ρ_{NUKON} = NUKON (fiber) material density
ρ_{CalSil} = CalSil (particle) material density

The values for the initial void ratios of the solid constituents at bed formation were determined from tests conducted at PNNL; these are X_{NUKON} = 30 and X_{CalSil} =6.2. These constants, together with Eq. (5.8.5), provide a reasonable prediction of formation debris bed thickness for NUKON-only and NUKON/CalSil debris beds at an approach velocity of 0.0305 m/s (0.1 ft/sec) over the range of temperatures from about 19 to 82°C (66.2 to 179.6°F). The assumption of constant compressibility allows the void ratios and bed thickness after the first compression to be calculated from the compressibility model.

Debris Bed Material Properties

For predictive calculations, the material densities of the NUKON fibers and the CalSil particles were assumed to be the same as those recommended in NUREG/CR-6874. Because PNNL verified the appropriateness of these density values, they are recommended for predictive calculations. CalSil insulation can include fiber material such as fiberglass and cellulose. The CalSil fibers are assumed to possess the same material density as fiberglass.

If the specific surface area (S_v) is calculated using the manufacturer-specified fiber diameter and the geometric definition for a packed bed composed of cylindrical fibers oriented perpendicular to the flow direction, $S_v = 4/\Delta_p$, the following values result.

S_v = 4 / 0.00026 in. = 605,694 m^{-1} = 184,615 ft-1 without binder material
S_v = 4 / 0.00028 in. = 562,430 m^{-1} = 171,429 ft-1 with binder material

PNNL performed independent measurements of the NUKON fiber diameters. These measurements indicated that the fiber diameters range between 5 and 15 μm. The diameters result in the following range of SV values.

S_v = 4 / 5x10-6 m = 800,000 m^{-1} = 243,840 ft^{-1} for 5-µm-diameter fibers
S_v = 4 / 15x10-6 m = 266,667 m^{-1} = 81,280 ft-^{1} for 15-µm-diameter fibers

However, not all of the fibers in a NUKON debris bed are expected to be oriented perpendicular to flow. Consequently, the Sv value that results from the assessment of test data (which is recommended for application in the developed calculational method) can differ from the theoretically calculated value. Based on re-analysis of the PNNL data, NUREG-1862 recommends the following values of S_v:

984,252 m^{-1}/ 300,000 ft^{-1} for NUKON fibers
2,132,546 m^{-1}/ 650,000 000 ft^{-1} for CalSil particles
984,252 m^{-1}/ 300,000 ft^{-1} for fiberglass fibers in CalSil

The equations used for determining the first irreversible compression of the debris bed equation and the elastic relaxation of the debris bed after the first compression employ a material specific parameter, N. The value of the parameter should be determined from test data. A value of 0.236 was recommended for N, which was determined by using data obtained from testing at PNNL, from the tests performed by LANL at UNM, and from the ANL testing.

Comparison with Data and Conclusions

The iterative procedure developed to solve the flow and compression relations using a one-volume model for a homogeneous debris bed has been successful in conservatively estimating the pressure drop for PNNL, ANL, and LANL/UNM tests with regard to flow across a debris bed composed of one debris type (e.g., NUKON fibers).

The one-volume head loss predictions for a homogeneous NUKON/CalSil debris bed provide a reasonable lower bound pressure drop when compared to available test data. For debris beds composed of particles and fibers, the two-volume calculational method can predict upper bound pressure drops for larger CalSil concentration and can provide an adequate estimate of pressure drop, in the correct order of magnitude, for debris beds with lower CalSil concentration.

Pressure drop across a debris bed depends on water temperature as well as on the flows and temperatures to which the debris bed has been exposed. The developed calculational method, generally, predicts higher pressure drop at lower liquid temperature, a result that follows classical theory expectations.

5.9 Chemical Effects

5.9.1 Introduction

The NRC initiated this study in response to a concern raised by the ACRS during its review of staff activities related to the resolution of GSI-191 in February 2003 (NUREG/CR-6868). Specifically, the ACRS raised the concern that chemically induced corrosion products have the potential to impede ECCS recirculation after a LOCA. Under this study, several small-scale head loss tests were conducted to determine whether debris generation and sump strainer head loss can be affected by chemical interactions between the ECCS recirculation water and exposed metal surfaces. Head loss flow tests were conducted in a small-scale (10 liters), vertical, closed-loop circulation, hydraulic test system built for measuring the head loss across a fiber-laden strainer. The principal conclusions of this study are that it is possible for gelatinous materials, if formed, to transport to PWR sump strainers, and that such materials can increase head loss across a fibrous debris bed. These results lend credibility to the concerns raised by the ACRS. Figure 5.9-1 shows head loss vs. materials concentration. The measured head loss increases with the metal concentration. In Figure 5.9-2, the measured head loss with chemical precipitates was normalized by the head loss without chemical precipitates. In the case of aluminum, the head loss with chemical precipitates is almost two orders of magnitude higher than that without chemical effects.

Even though this study showed the significance of chemical effects, the scope is limited; only sodium hydroxide was used as a pH buffering agent, metal salts (as nitrate forms) were added to the test loop, and the corrosion/leaching tests for zinc were not successful because of the quiescent condition. This study included only separate-effects tests for each potential stage of the progression (i.e., quiescent-immersion corrosion/leaching tests, and artificially induced saturation/precipitation combined with transport/head loss flow tests) (NUREG/CR-6868). As a result, this study did not include integrated tests to demonstrate the complete progression of chemical effects from metal corrosion to the ultimate formation of precipitation products. As an independent peer review panel recommended, integrated chemical effects testing was needed. Three NUREG reports described in the following sections are follow-on studies to implement the findings in this study.

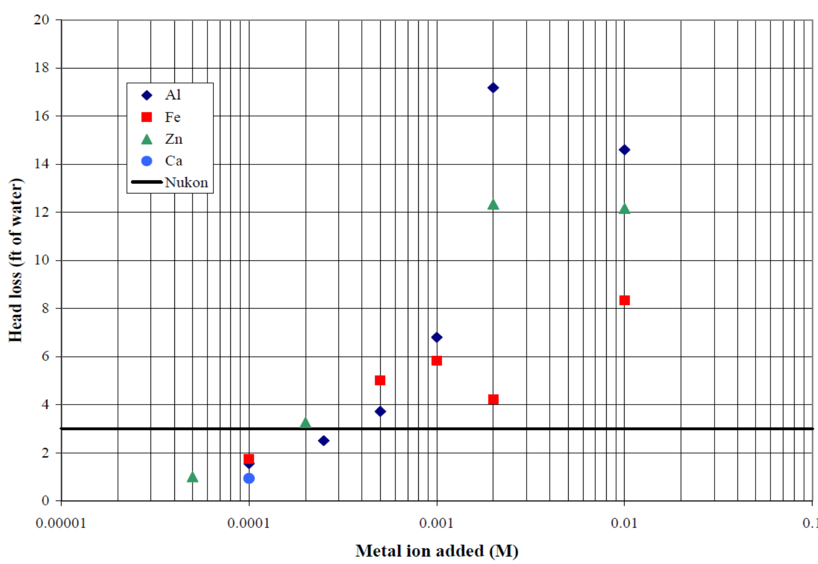


Figure 5.9-1. Head Loss versus Materials Concentration (NUREG/CR-6868)

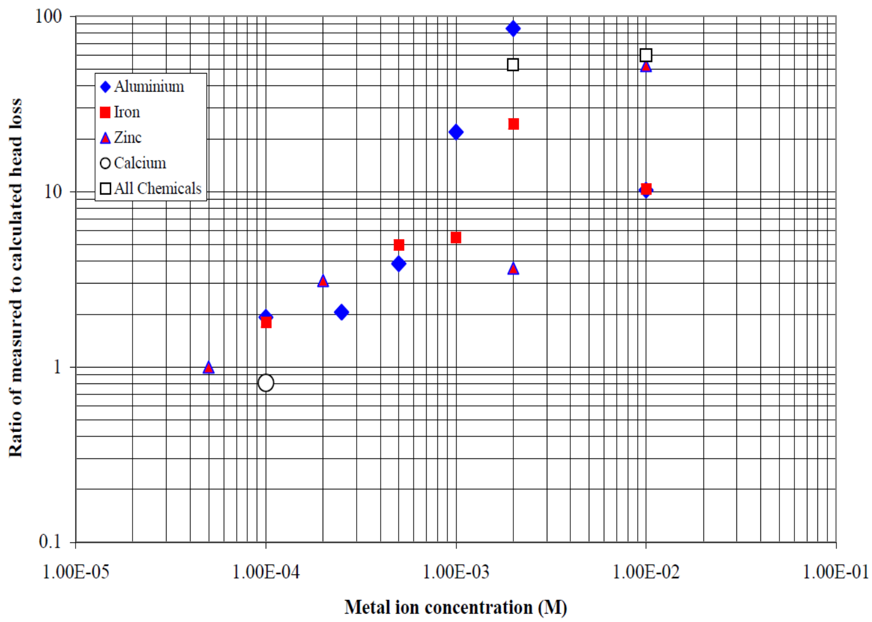


Figure 5.9-2. Ratio of Measured Head Loss With And Without Chemical Precipitates as a Function of Metal Ion Concentration (NUREG/CR-6868)

5.9.2 Integrated Chemical Effects Test

The Integrated Chemical Effects Test (ICET) project was a joint effort by the NRC and the nuclear utility industry (NUREG/CR-6914). The ICET attempted to simulate the chemical environment in a containment water pool after a LOCA and monitored the chemical system for 30 days to identify the presence, composition, and physical characteristics of chemical products that formed during the tests. The primary objectives were to (1) determine, characterize, and quantify chemical-reaction products that may develop in the containment sump under a representative post-LOCA environment, and (2) identify and quantify any chemical precipitates that might be produced during the post-LOCA recirculation phase. No measurements of head loss were made in the tests. This section is primarily based on an earlier review documented in the Appendix B of NRC Staff Review Guidance (NRC, 2008c).

5.9.2.1 Test Conditions

All of the ICETs were conducted in an environment that attempted to simulate containment pool conditions during recirculation. The tests included an initial 4-hr spray phase to simulate containment spray interaction with the unsubmerged materials. The materials present in this environment typically included higher ende amounts of submerged and unsubmerged aluminum, copper, concrete, zinc, carbon steel, and insulation samples. Representative amounts of concrete dust and latent debris (dirt) were also added. Insulation samples consisted of NUKON fiberglass and calcium silicate (CalSil) material. Water was circulated through the bottom portion of the test chamber during the entire test to achieve representative flow rates over the submerged specimens.

The amounts of material in the test were scaled to the liquid volumes of the test chamber and the containment sump volume. For most materials, scaling was in terms of the surface area of material to the sump volume, but for insulation materials, the scaling was in terms of the volume of material to the sump volume. The relative amounts of material were based on an informal survey of a number of plants (NUREG/CR-6914). More-detailed plant survey information made available after testing indicated the amount of insulation (e.g., CalSil) in these tests may have been too high to be representative. The ratios of material to sump volume are in most cases larger than would be expected for a typical plant, although the values are not necessarily bounding. The ratios of the material quantities to sump water volume are summarized in Table 5.9-1.

The physical and chemical parameters that defined the tank environment are summarized in Tables 5.9-2, 5.9-3, and 5.9-4. Of the chemical parameters listed, only boric acid, lithium hydroxide, and hydrochloric acid were present in all five tests. Hydrochloric acid (HCl) can be formed from the degradation of cable insulation material. The initial test solution pH was different in each test, and it varied from ≈7.3 in. Test 2 to ≈9.8 in. Test 4. The predetermined amounts of chemicals were added for each test, and no attempt was made to control or alter the resulting pH during the test.

Table 5.9-1. Material Quantity/Sump Water Volume Ratios for ICETs (NUREG/CR-6914)

Material	Ratio Value (ratio units)	Submerged Material (%)	Unsubmerged Material (%)	Comments
Zinc in galvanized steel	8.0 (ft^2/ft^3)	5	95	Accounts for grating and duct work that might be submerged.
Inorganic zinc primer coating (non-topcoated)	4.6 (ft^2/ft^3)	4	96	Addresses both non-topcoated zinc primer applied, as well as zinc primer exposed by delamination of a topcoat.
Inorganic zinc primer coating (topcoated)	0.0 (ft^2/ft^3)	-	-	Epoxy-based topcoats prevent interaction of the zinc primer with sump and spray. Exposure of zinc primer to sump and spray fluids due to local failures of epoxy-based topcoats is accounted for in the non-topcoated zinc coatings.
Aluminum	3.5 (ft^2/ft^3)	5	95	Aluminum is generally not located at elevations inside containment where it may be submerged.
Copper (including Cu-Ni alloys)	6.0 (ft^2/ft^3)	25	75	Majority of surface area associated with CRDM coolers and instrument air lines (containment fan coolers for Cu-Ni alloys).
Carbon steel	0.15 (ft^2/ft^3)	34	66	
Concrete (surface)	0.045 (ft^2/ft^3)	34	66	The submerged value accounts for limited damage to floor and wall surface areas that will be submerged due to primary RCS piping being elevated above the containment floor.
Concrete (particulate)	0.0014 (lbm/ft^3)	100	0	
Insulation material (fiberglass or calcium silicate)	0.137 (ft^3/ft^3)	75	25	The submerged value accounts for most of the fiberglass remaining in areas where it will wash down into the sump pool.

Table 5.9-2. Physical Parameters for ICETs (NUREG/CR-6914)

Physical Parameters	Test Value
Tank Water Volume	949 L (250 gal)
Circulation Flow	100 L/min (25 gpm)
Spray Flow	15 L/min (3.5 gpm)
Sump Temperature	60°C (140°F)

Table 5.9-3. Chemical Parameters for ICETs (NUREG/CR-6914)

Chemical	Concentration
Boric acid (H_3BO_3)	2800 mg/L as borona
Trisodium phosphate (TSP-$Na_3PO_4 \cdot 12H_2O$) (Tests 2 & 3)	As required to reach pH 7 in simulated sump fluid
Sodium hydroxide (NaOH) (Tests 1 & 4)	To reach pH 10 in simulated sump fluid
Sodium tetraborate [Borax] (STB-$Na_2B_4O_7 \cdot 10H_2O$) (Test 5)	To reach boron concentration of 2400 mg/L in Test #5
HCl	100 mg/L[a]
LiOH	0.7 mg/L[a]

[a]Concentrations applicable to Tests 1-4. Concentrations for Test 5 were 2400 mg/L boron, 43 mg/L HCl, and 0.3 mg/L LiOH.

Table 5.9-4. Test Series Parameters (NUREG/CR-6914)

Test	Temp (°C)	pH Control	pHa	Boron (mg/L)	Notes
1	60	NaOH	10	2800	100% fiberglass insulation test. High pH, NaOH concentration as required by pH.
2	60	TSP	7	2800	100% fiberglass insulation test. Low pH, trisodium phosphate (TSP) concentration as required by pH.
3	60	TSP	7	2800	80% calcium silicate/20% fiberglass insulation test. Low pH, TSP concentration as required by pH.
4	60	NaOH	10	2800	80% calcium silicate/20% fiberglass insulation test. High pH, NaOH concentration as required by pH.
5	60	STB	8 to 8.5	2400	100% fiberglass insulation test. Intermediate pH, sodium tetraborate (Borax) buffer.

[a]Values shown were the target pH for Tests 1-4. Value for Test 5 is in the expected range.

The materials described in Table 5.9-1 were introduced to the tank as 373 flat-metal coupon samples (40 submerged) and one submerged concrete sample. Flow rate and temperature were controlled to maintain target values of 25 gpm and 60°C. The value of 25 gpm was chosen to yield fluid velocities over the submerged coupons from 0-3 cm/s. Daily water samples were obtained for measurements of pH, turbidity, total suspended solids, kinematic viscosity, and shear-dependent viscosity, as well as for chemical analyses. In addition, microscopic evaluations were conducted on water-sample filtrates, precipitates, fiberglass, CalSil, metal coupons, and sediment.

When the water reached the desired temperature, test-specific chemicals were dissolved into the water. Latent debris, concrete, test coupons, and insulation samples were then placed in the tank. Once the solution temperature reached 60°C, the test commenced with initiation of the tank sprays. During the 4-hr spray period, additional chemicals were added if required. The tests ran for 30 days. Water samples, insulation samples, and metal coupons were analyzed after the test.

5.9.2.2 Overall Results

Solution samples from Tests 1 and 5 produced precipitates upon cooling to room temperature, whereas samples from Tests 2, 3, and 4 did not. A precipitate formed at the test temperature of 60°C in Test 3. The Test 1 precipitates occurred much more quickly and were present in greater quantities than the Test 5 precipitates. Except for precipitates seen on the first day of Test 3, no precipitates were visible in the test solutions at the test temperature of 60°C. Turbidity measurements were taken at 60°C and 23°C. In Tests 2, 3, and 4, measurements at both temperatures produced similar results, consistent with the assumption that the turbidity is due to physical particulates and independent of temperature. During the first 4 hr of Test 3, a large increase in turbidity was seen, and corresponded to the visible precipitates in that test. In Tests 1 and 5, turbidity at 23°C rose higher than the 60°C values, consistent with the presence of a precipitate at the lower temperature.

The precipitates in Tests 1 and 5 are primarily amorphous forms of Al(OH)3, which is supported by x-ray diffraction (XRD) measurements and earlier literature referenced in the same report NUREG/CR-6915). The precipitate in Test 3 is a calcium phosphate (NUREG/CR-6914). Calcium phosphate is the name given to a family of minerals containing calcium, phosphorus, and oxygen (and sometimes hydrogen). They are all highly insoluble in the moderately alkaline solutions of interest.

Daily samples were analyzed for aluminum, calcium, copper, iron, magnesium, nickel, silicon, sodium, and zinc. The solution samples were completely mixed before the inductively coupled plasma (ICP) atomic emission spectroscopy (AES) measurements. Thus, the results are representative of the solution plus any precipitate present. In Test 1, aluminum and sodium were present in greater concentrations than were all other tested elements. In Test 2, silicon and sodium were the dominant elements in solution. Silicon, sodium, and calcium were present in the greatest concentrations with the Test 3 solution. In Test 4, silicon, sodium, calcium, and potassium were present in solution in the greatest concentrations. Sodium, aluminum, calcium, and silicon were the elements of highest concentration in the Test 5 solution.

Turbidity was measured to study suspended solids. In all of the tests, turbidity peaked within the first few hours of testing and decreased to lower values within 24 hr. By the second day of testing, the turbidity decreased to very low values. The turbidity measurements remained at these low values for the duration of the tests. Tests 3 and 4 had higher values of turbidity early in the test than did the other tests because CalSil particulate was added to the tank before test initiation. Turbidity reached a very high peak early in Test 3 due to the formation of a calcium phosphate precipitate .

Insulation debris, which was composed of fiberglass or a mixture of fiberglass and CalSil, was analyzed after completion of each test. Three types of deposits were found on the fiberglass samples: flocculants, films, and webbing. Particulate deposits were confined to the exteriors of the samples and were physically attached or retained. Flocculent deposits were found throughout the samples and were more prevalent on the fiberglass interior. It is likely that the film or webbing deposits that were observed in Tests 1 and 4 were caused by the drying process since new fiberglass dipped in solution produced a similar film appearance. The amounts of deposits seen on the fiberglass insulation varied from test to test because of differing solution chemistry. The greatest deposition occurred in Test 3, followed in order by Tests 1, 4, and 2. Test 5 samples had the fewest deposits. Test 1 experienced the largest amount of corrosion on the submerged coupons. No significant corrosion of the submerged coupons was observable in Tests 2-5, except for the aluminum coupons in Test 5. None of the tests showed significant corrosion on the unsubmerged coupons. Sediment on the tank bottom at the end of the tests also varied. Tests 3 and 4 had the most sediment, most of it attributable to the large amount of crushed CalSil added to the tank. In Test 3, there were also significant amounts of chemical precipitate. Tests 1, 2, and 5 produced the least sediment, which was composed largely of materials from the insulation used (fiberglass) and debris added to the tank.

5.9.2.3 Solution Chemistry

Each test had a target pH that was attributable to specific chemical requirements, as given in Table 5.9-4. The actual measured pH values are shown in Figure 5.9-3 and are relatively constant throughout the tests except for Test 3. In Test 3, the pH increased from the initial pH by approximately 0.8 units. In this test, the formation of Ca3(PO4)2 removed phosphate from the solution early in the test, which diminished the buffering capacity of the system. Without adequate buffering, the system pH could be more easily affected as varying chemical reactions occurred.

The only metal coupons that showed significant corrosion in any of the tests were the aluminum coupons in Tests 1 and 5 and the uncoated carbon steel coupons in Test 1. It should be noted that the post-test weight loss measurements listed in NUREG/CR-6914 were performed after air drying without cleaning the coupons. The measured aluminum concentrations during Tests 1 and 5 are shown in Figure 5.9-4. Aluminum concentrations in the other tests were below the detection limit of the ICP measurements. The pH in both Tests 1 and 5 was in the range of high aluminum solubility. Test 1 had a higher pH, which is consistent with the higher observed corrosion rate. In both Tests 1 and 5, the aluminum levels increased fairly steadily for about 15 days, and then stayed relatively constant for the remainder of the test. Although the pH in Test 4 was also high, the aluminum levels in solution were less than 1 mg/L. As will be discussed later, this low level of corrosion is probably due to the presence of high amounts of Si in solution from dissolution of the large amount of CalSil insulation in Test 4. The pH in Test 2 corresponds to a solubility minimum for Al(OH)3, which is consistent with the very low levels of dissolved aluminum in this test.

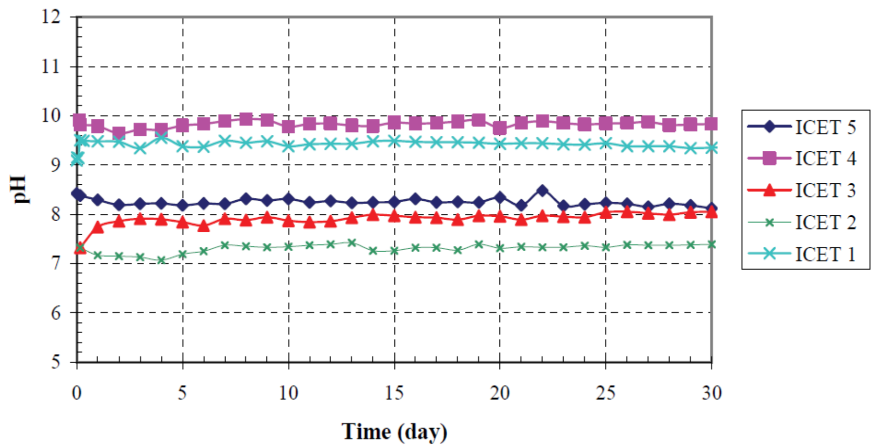


Figure 5.9-3. Measured pH During ICETs (NUREG/CR-6914).

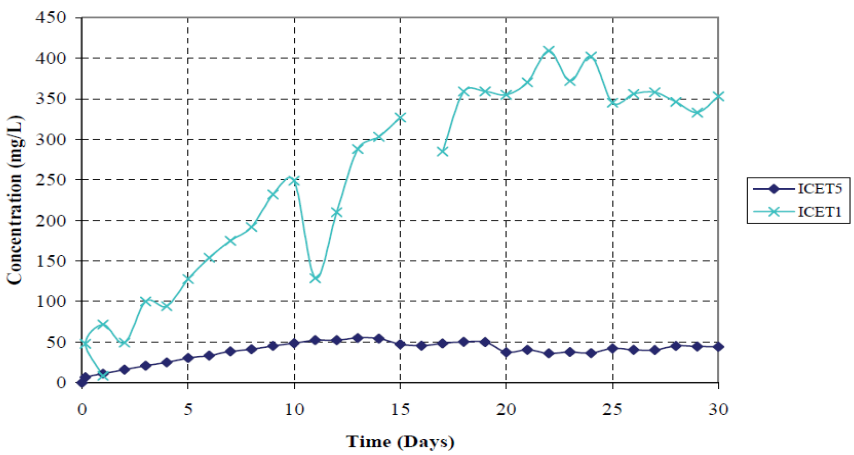


Figure 5.9-4. Measured Aluminum Concentrations in Tests 1 and 5 (NUREG/CR-6914).

The concentrations of zinc and copper were very low compared to the concentrations of aluminum in Tests 1 and 5. Neither zinc nor copper appeared as either adsorbed or precipitated species in these tests. Calcium levels were high in Tests 3 and 4, due to the addition of a large amount of CalSil in those tests. The solubility of CalSil (mostly calcium silicate $CaSiO3$) decreases with increasing pH. This may partly explain why the dissolved Ca levels at long times are lower in Test 4 than in Test 3 (see Figure 5.9-5). However, the higher pH in Test 4 may also lead to increased dissolution of fiberglass, and the resulting increase in dissolved siliconlevels (Figure 5.9-6) may also result in a decrease in dissolved Ca. The dissolved calcium in the tests without CalSil additions is probably due to leaching from concrete dust and other concrete sources. The drop in the calcium level early in Test 3 is due to the removal of Ca from solution by precipitation of $Ca3(PO4)2$. The amount of TSP added in Tests 2 and 3 is about 4 g/L. Fully dissolved, this would give P levels greater than 300 mg/L. For CalSil loadings greater than about 2 g/L, the amount of $Ca3(PO4)2$ that can be formed is limited by the amount of phosphate available. Thus, in Test 3, the measured phosphate levels from day 1 to day 30 were less than 1 mg/L. All the phosphate has been removed from solution by precipitation of $Ca3(PO4)2$. Although the precipitation of $Ca3(PO4)2$ removed Ca from solution

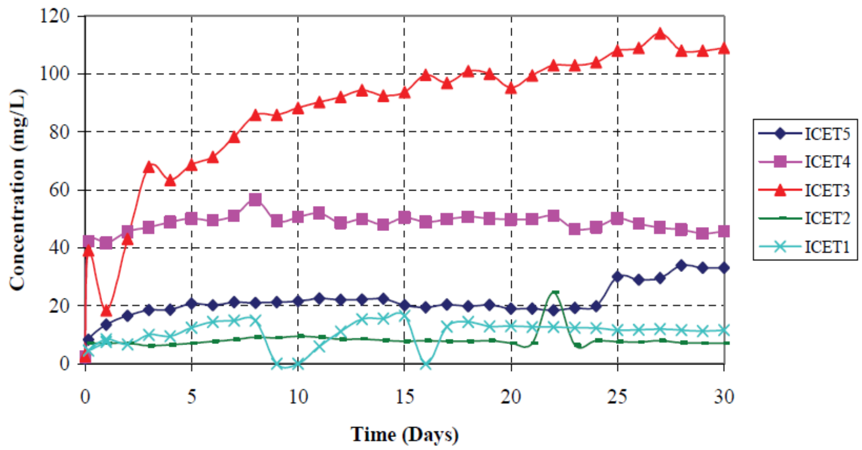


Figure 5.9-5. Measured Calcium Concentrations in Tests 1-5 (NUREG/CR-6914).

early in Test 3, because of the large amount of CalSil present in the test (19 g/L), dissolution of the CalSil continued until reaching the equilibrium solubility limit corresponding to the pH.

Measured silicon concentrations are shown in Figure 5.9-6. They are high in Tests 3 and 4, as expected from the large amounts of CalSil in those tests. The silica concentration is also high in Test 2, which has only fiberglass insulation and a TSP buffer. It is extremely low in Tests 1 and 5, and this was somewhat unexpected. Fiberglass solubility increases with pH, and separate effects testing (5-6 and 5-7) would suggest significant dissolution of fiberglass in Test 1 and somewhat less in Test 5. It appears that dissolved aluminum quickly reacted with the fiberglass to coat it, inhibiting further corrosion of the fiberglass (NUREG/CR-6914).

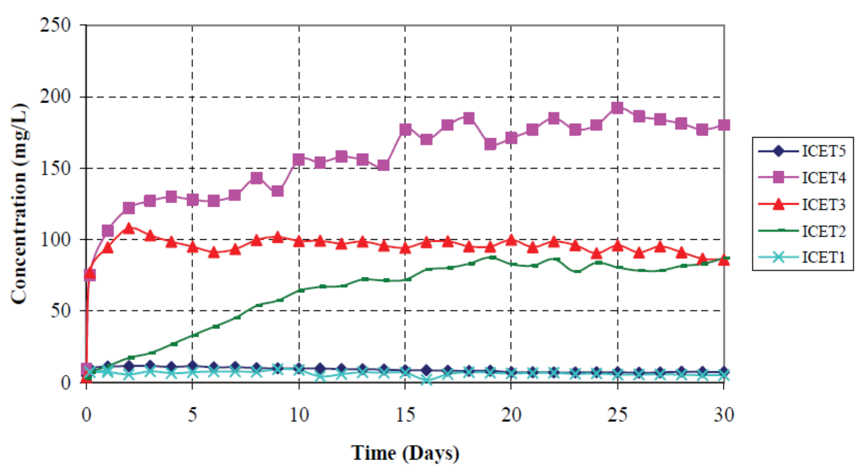


Figure 5.9-6. Measured Silicon Concentration in Tests 1-5. Note that although expressed in NUREG/CR-6914 as silica (SiO2) concentration, it is probably silicon (Si) concentration because that is what would be directly measured by ICP.

5.9.2.4 Precipitation

The two major chemical precipitates observed in the ICETs are $Ca_3(PO_4)_2$ in Test 3 and some form of $Al(OH)_3$ in Tests 1 and 5. The formation of the $Ca_3(PO_4)_2$ precipitate in Test 3 occurred very quickly with the addition of TSP through the sprays and is easily replicated in separate effects tests when phosphates are added to solutions that contain dissolved calcium. No precipitates were observed in Test 2, which also used TSP, but had no CalSil. Concrete would be a potential source of dissolved calcium. Figure 5.9-5 shows that the dissolved calcium level in Test 2 is lower than that in Test 5. Because leaching of calcium from concrete increases with decreasing pH (Lane et al., 2006), this is somewhat unexpected. It is possible that some of the calcium was removed from solution by formation of Ca3(PO4)2. Because this compound would form almost immediately as the calcium was leached from the concrete, it would probably not be visible as a precipitate in the solution, but would add to the sediment. Behavior of the precipitates in Tests 1 and 5 is more complicated. White precipitates were observed in solution samples for these tests as the solutions cooled to room temperature, whereas no precipitates were observed at 60°C. In Test 1, precipitates became visible after the first 8 hr of testing, when the test solution was cooled to room temperature. The amount of visible precipitation at room temperature increased, and the precipitates formed more quickly during cooling as the test progressed. In Test 5, the precipitates took longer to form (several days at room temperature), and the quantities were much smaller than in Test 1. In addition, the quantity of Test 5 precipitates was relatively unchanged throughout the test.

The ICP-AES results indicated that the precipitates were composed largely of aluminum and boron. Calcium and sodium were also present in smaller amounts. The ICP analysis cannot detect the presence of either oxygen or hydrogen in materials. The precipitates from Tests 1 and 5 have similar chemical compositions. The precipitate in Test 1 may have a somewhat greater proportion of aluminum than in Test 5. The precipitate in Test 5 appears to have a larger concentration of calcium. These results are consistent with the relative amounts of aluminum and calcium in solution (Figures 5.9-4 and 5.9-5). Transmission electron microscopy (TEM) and XRD analysis of the precipitates from Test 1 indicated that they were primarily amorphous rather than crystalline, although it was insisted that the XRD refinement revealed pseudoboehmite (poorly crystalline AlOOH) (NUREG/CR-6915), and the fundamental particle size was about 10 nm. However, much larger agglomerations of these basic particles were observed. It should be noted that the poorly crystalline AlOOH identified by XRD was performed after drying the precipitate.

Precipitate was not detected visually at the test temperature, 60°C, at any time during Test 1. However, the turbidity measurements are supportive of a precipitation in the Test 1 solution at room temperature. As the solution cooled from 60 to 23°C, the turbidity was observed to increase in a 10-min period from 0.3 NTU at 60°C to significantly higher values at 23°C becoming more than 133 NTU during the later stages. Precipitate was also visually observed to have formed as the fluid cooled during the draining process at the end of the test. The tank fluid appeared cloudy as it exited the drain hose into the post-test holding tank. A surrogate precipitate was produced by titrating aluminum nitrate solution with pH 9.5 containing 2800 mg/L boron and sodium hydroxide at 25°C. Nuclear magnetic resonance (NMR) analysis was performed on this surrogate precipitate, which indicated that a complexation between aluminum and boron occurred when the solution cooled below 40°C. Thus, the description of the precipitate as Al(OH)3 or AlOOH is a simplification of a more complex situation.

5.9.2.5 Passivation of Aluminum in ICET Solutions

In both Test 1 and Test 5, dissolved aluminum concentrations increased approximately linearly with time during the initial part of the test, but then reached pseudo-steady-state values (See Figure 5.9-4). Such behavior could be associated either with reaching a solubility limit or passivation of the metal coupons.

Hydrogen is generated as part of the corrosion reaction of aluminum with water. Generation of hydrogen is an indication of an ongoing corrosion process. There were some problems with the hydrogen measurements during Test 1. However, the data from day 20 until the end of the test are at least qualitatively accurate. The hydrogen generation decreased from day 21 to day 26, which corresponds to the leveling off of aluminum concentration on day 25 in Test 1. Similarly, the decrease in the hydrogen generation associated with Test 5 at about day 17 is consistent with the leveling off of the aluminum concentration in that test. These measurements thus support an argument for passivation, not a solubility limit, as the mechanism that produces the leveling off of the dissolved aluminum concentration in these tests.

The results in Test 4 suggest passivation by aluminum silicates, which was evidenced by a benchtop Al corrosion coupon testing and x-ray photoelectron spectroscopy analysis (NUREG/CR-6915). Passivation by aluminum silicates requires a source of soluble silicates. In Test 4, considerable leaching of Si from the fiberglass appears to have occurred, but the presence of dissolved aluminum in Tests 1 and 5 appears to significantly inhibit leaching from the fiberglass. The initial dissolved silica levels of 100 mg/L in Test 4 seemed to rapidly produce passivation of the aluminum. At the dissolved Si levels of ≈8 mg/L seen in Tests 1 and 5 (Figure 5.9-6), many days are required for passivation to occur, and it is possible that these low levels of silica may not have affected aluminum passivation in these tests.

5.9.2.6 Summary and Discussion

Aluminum hydroxides, Al(OH)3 or related forms, and calcium phosphates are the primary chemical precipitates in the ICET tests. Significant dissolution of aluminum was observed in solutions with pH of 8.0 or greater. The isothermal nature of the ICET tests produces nonconservative estimates of the potential corrosion of nonsubmerged materials in the containment and the corrosion that occurs early in the accident. Calcium phosphates were formed in solutions with TSP and CalSil.

Concrete and other insulation materials are other potential sources of dissolved Ca that could react with TSP to form calcium phosphate. No visible precipitates were observed in the Test 2 fluid, which had TSP but no CalSil. The measured Ca levels suggest that some calcium phosphate may have formed. Rapid formation of calcium phosphate precipitate may be especially detrimental because NPSH margins are typically at a minimum near the switchover to ECCS recirculation.

In the plant, the recirculated water is cooled by heat exchangers (e.g., shutdown cooling HX in CE plants, RHR or RHR + CS HXs in Westinghouse plants or decay heat coolers in B&W plants) The lower temperature in terms of solubility or reaction kinetics can affect formation of a precipitate product. Therefore, the temperature-cycling effect by heat exchangers on precipitation may need to be further investigated; it was partially investigated by ANL work (Bahn et al., 2008b) suggesting that the rapid thermal cycling does not appear to affect chemical precipitation.

The initial aluminum precipitation product is amorphous. Eventually, it will transform to the more stable, much less soluble, crystalline form. The crystalline form is much less soluble than the amorphous form, and any portion of the precipitate that is transformed would be much less likely to redissolve at higher temperatures. However, it is noted that this transformation would take time, depending on temperature and solution chemistry.

The ICET results show that solution chemistries observed in complex multicomponent environments are not always consistent with those predicted on the basis of tests in simpler environments. Levels of dissolved silica in Test 1 are much lower than would be predicted from tests on fiberglass in solutions with comparable pH value (NUREG/CR-6873). Aluminum in solution inhibits the dissolution of fiberglass. Low levels of dissolved aluminum in Tests 3 and 4 provide strong evidence for the potential for passivation of aluminum in solutions with large amounts of Si in solution. In this respect, the large amount of CalSil in the ICET tests is non-conservative. Westinghouse Electric data reported in WCAP-16530-NP (Lane et al., 2006) indicate a 75 ppm threshold silica inhibition level for passivation, with a marked decrease in aluminum corrosion at a 50 ppm concentration. Aluminum phosphates are also highly insoluble, making phosphates a candidate inhibitor (if no CalSil is present) (Lane et al., 2006). Passivation also occurred in Tests 1 and 5 after 15 to 20 days. At the low levels of dissolved silica in these tests (≈ 8 ppm), it is not clear whether the mechanism of passivation in these tests was in any way related to the formation of aluminum silicates. It is also not clear how to "credit" passivation in such environments based on the various ratios of aluminum surface area, fiberglass volume, pH, other materials, etc. When passivation occurs, use of the average corrosion rate over the whole test period gives non-conservative estimates of the amount of corrosion that will occur during active dissolution, before the material becomes passivated.

5.9.3 ICET Aluminum Chemistry

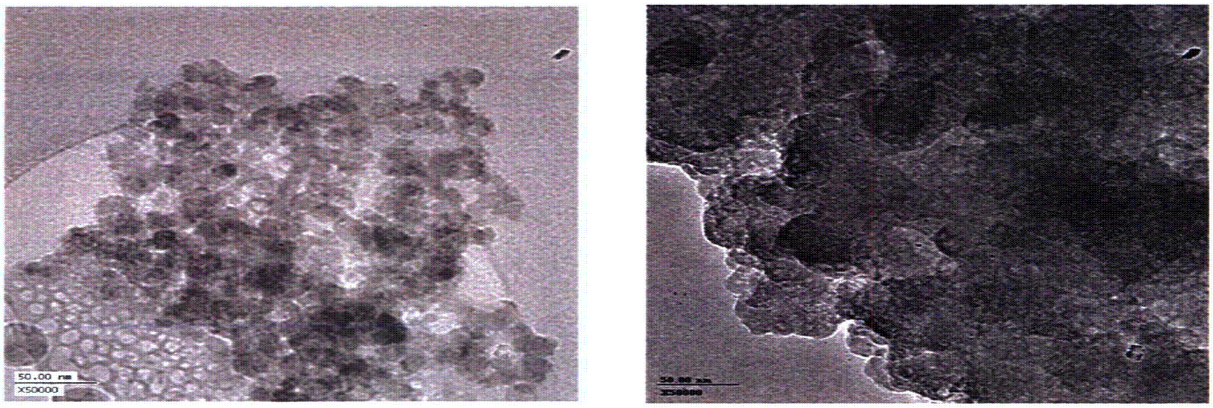
5.9.3.1 Bench-Scale Experiments

The report NUREG/CR-6915 describes the results of an extensive literature search and bench-scale experiments that were performed to gain a better understanding of the corrosion of aluminum and the formation of precipitation products in environments similar to ICET Test 1 and ICET Test 5. It also includes results from a comprehensive examination of both the test solutions and precipitates from these two tests. The precipitates were visually examined by using both scanning electron microscopy (SEM) and TEM. Supplemental analytical measurements were performed with XRD, NMR (both liquid and solid state), and light scattering.

5.9.3.2 Summary of Important Results

The precipitates that form as the ICET 1 and 5 solutions cool are agglomerations of nanometer-sized particles. The size of the agglomerations grows with time. The precipitate is highly hydrated, consisting of about 90% water by mass.

The XRD and TEM analyses of the precipitates of ICET 1 and 5 indicate that the precipitates were largely composed of amorphous aluminum hydroxide, with a substantial quantity of boron adsorbed onto the surface, although the XRD refinement revealed pseudoboehmite, poorly crystalline boehmite (AlOOH). Figure 5.9-7 shows TEM micrographs of precipitates formed at room temperature in ICET Test 1 solution, suggesting that the constituent particle size is about 10 nm. The amorphous form is to be expected because of the high concentration of anions in the solution; such high concentrations of anions are known to retard crystallization at temperatures below 60°C. Also, as discussed in the report NUREG/CR-6915, earlier literature showed that the crystallographic phase of aluminum hydroxide precipitation in alkaline solution depends on a degree of supersaturation; this is further discussed in an ANL letter report in terms of aluminum solubility in alkaline solution (Bahn et al., 2009a). Chemical analysis results indicate that up to 35% of the boron from the initial solution may have been adsorbed onto the amorphous aluminum hydroxide precipitate. The NMR measurements showed complexation between aluminum and boron. This finding corroborates the hypothesis that complexation was responsible for impeding the crystallization of aluminum compounds.



(a) (b)

Figure 5.9-7. TEM Micrographs of (a) Day-15 and (b) Day-30 Filtered Test Sample from ICET 1 Solution (NUREG/CR-6915).

Figure 5.9-8 shows the particle size distributions for the aged and precipitated ICET Test 1 solution at room temperature. As indicated in Figure 5.9-7, the size distribution suggests that the precipitates are highly agglomerated. To evaluate the possibility that tiny and colloidal particles were present in the ICET Test 1 solution at 60°C, surrogates were prepared by adding aluminum coupon into NaOH/boron solution. As shown in Figure 5.9-9, light scattering measurements of particle sizes in surrogate solutions simulating ICET Test 1 showed that they contain particles with a bimodal size distribution peaking at ≈30 and ≈500 nm. However, this result suggests that nanometer-sized aluminum hydroxide precipitates can be formed in NaOH/boron solution at 60°C within a relatively short time. The report also states that precipitates were noted at 60°C in the surrogate solution after several weeks. Thus, although at 60°C and pH 9.6, the estimated solubility limit for amorphous aluminum hydroxide is much higher than ≈375 mg/L, the solution may contain colloidal and tiny particles dispersed in solution rather than only aluminate ions (Al(OH)4–). In acidic solutions, aluminum in solution can exist as Al3+, AlOH2+, and Al(OH)4+. In alkaline solutions, aluminate ions (Al(OH) 4–) are the only stable form of aluminum. The solubility is a function of the solid hydroxide phase present (amorphous or crystalline) and increases with pH in alkaline solutions. The presence of some organics and inorganics can increase the aluminum solubility. Solubility can also be affected by the particle size presented in the solution.

A review of the literature shows that sodium silicates are effective inhibitors of corrosion of aluminum, with an inhibition efficiency of almost 100%. The inhibition is due to the formation of an amorphous aluminosilicate film on the metal surface. Microstructural analysis performed on the Test 1 and 4 aluminum coupons indicate that the major components are aluminum, oxygen, silicon, sodium, and calcium, with small amounts of carbon and magnesium. Silica was present to a much larger degree in ICET Test 4 than in Test 1. Thus, in ICET Test 4, the corrosion of aluminum was inhibited by the dissolution of calcium silicate.

A bench-scale test was performed to provide a direct comparison between aluminum corrosion in a boric acid/NaOH solution and a boric acid/NaOH with silicates. The silicate addition produced virtually instantaneous passivation of the aluminum, and no measurable corrosion could be detected. The concentration of the silicate inhibitor is cited as 88.7 mg/L, but it is not clear whether this is the concentration of Si or silica (SiO2).

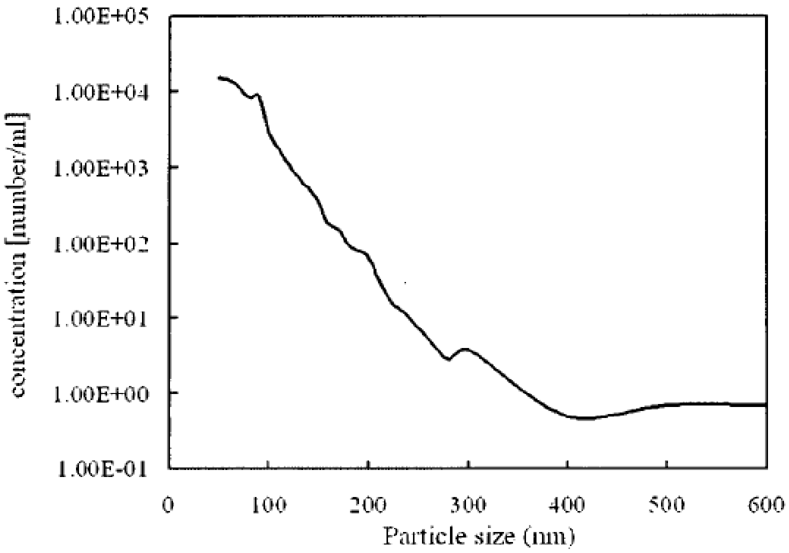


Figure 5.9-8. Particle Size Distribution for Test 1 Solution at Room Temperature after 4-Month Aging (NUREG/CR-6915).

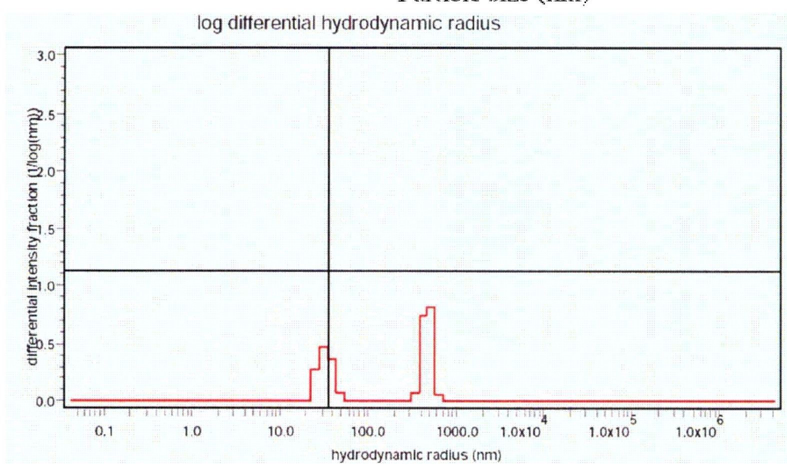


Figure 5.9-9. Particle Size Distributions for Aluminum/Boron Metal Dissolution Surrogate Solution at 60°C after 8 hr (NUREG/CR-6915).

5.9.3.3 Summary and Discussion

The amorphous forms of Al(OH)3 are more highly hydrated than the crystalline forms. The rate of transformation to the more crystalline form is controlled by the rate at which hydroxyl anions replace water in the amorphous solid. This may mean that per mole of aluminum, an amorphous precipitate may be more effective in producing head loss than a crystalline precipitate. Because aluminum in solution exists in different forms in acidic and alkaline solutions, it is not clear that the process for producing surrogates such as outlined in WCAP-16530-NP (Lane et al., 2006), which starts from an acid solution, will produce precipitates comparable to those that could potentially form in an alkaline sump environment (NUREG/CR-6915). An ANL letter report showed that the crystal phase of aluminum hydroxide surrogate by WCAP-16530-NP appears amorphous with weak indication of poorly crystalline bayerite (Shack, 2007).

The presence of silicon in solution can lead to inhibition of the corrosion of aluminum. The large amount of CalSil in ICET-4 probably produced a concentration of dissolved Si that was not representative of what would be found in the post-LOCA environment. Passivation needs to be demonstrated for conditions representative of plant-specific conditions.

Complete inhibition of aluminum corrosion was demonstrated in a bench test with a concentration of silicate inhibitor at 88.7 mg/L. This finding is in reasonable agreement with WCAP-16785-NP values (Reid et al., 2007).

Because aluminum hydroxide precipitates in NaOH/boron solution can exist as colloids, the aluminum content of a solution is not a complete measure of the likelihood of precipitate formation as a solution is cooled. Although the aluminum concentration in ICET Test 1 remained relatively constant from Day 15 to Day 30, precipitates formed much more readily as the solution cooled during the later part of the test.

5.9.4 ANL Head Loss Testing

5.9.4.1 Overview

A test loop was constructed at ANL to study the effects of the chemical products observed in the ICET tests on head loss (NUREG/CR-6913). This study considered the effect of head loss at a CalSil loading of 19 g/L (ICET 3), along with much lower CalSil loadings lower (0.5 g/L and less), which would be more representative of most plant situations.

Most tests in the ICET 3 environments were integrated, and the chemical products were formed by the dissolution of calcium silicate insulation reacting with dissolved trisodium phosphate (TSP) buffer in the test loop water In the ICET 1 and 5 environments, surrogate chemical products were used. Use of the surrogate forms was justified by comparisons with the chemistry and other physical characteristics, such as the amorphous structure of the products formed in the integral ICET.

A diagram of the ANL test loop is shown in Figure 5.9-10. Piping in most of the loop is chlorinated polyvinyl chloride (CPVC); the clear test section containing the test strainer was either LEXAN or clear polyvinyl chloride (PVC). LEXAN has better high-temperature strength; PVC is more resistant to NaOH solutions. The heater and cooler sections are stainless steel. During operation, temperatures around the loop are typically ±0.6°C (1°F). Loop velocities can be controlled over the range from 0.02 to 2 ft/s. The inside diameters of the LEXAN and PVC sections are 6.5 and 5.625 in., respectively. Fluid volume in the loop is 119 L (4.2 ft3). At 0.1 ft/s, the transit time around the loop is about 4 min. The sump strainer in these tests is a flat perforated plate; two different perforated plates have been used. Differential pressure transducers measure the differential pressures across the strainer and bed.

In scaling the results from the ANL test facility, the mass of chemical product and physical debris per unit area of strainer should be considered. The mass of chemical product produced scales with fluid volume, while the potential for head loss is characterized by the product mass per unit strainer area. A 15 g loading of debris in the LEXAN section corresponds to a loading of 0.7 kg/m2. To maintain the same loading per unit area in the PVC section requires 11.5 g of debris.

Physical debris and chemicals are introduced to the loop through a charging port at the top of the loop. The horizontal configuration of the strainer is not intended to reflect a realistic strainer configuration, but rather to permit the development of uniform beds with well defined characteristics. Head loss behavior for such beds may not characterize the local head loss behavior of more complex, non-uniform beds that might form on realistic strainer geometries.

In the basic test procedure, the test loop was filled with deionized water and heated to 54°C (130°F). Boric acid, LiOH, and a pH control chemical (NaOH, TSP, or STB) were added to reach desired concentrations and pH. The loop was held at temperature overnight to deaerate the liquid. NUKON and CalSil were used to create the physical debris bed. The insulation materials were added as slurries. The NUKON was shredded and processed in a blender; the CalSil was ground with a mortar and pestle. Liquid was added to form a slurry. In some cases, the slurry was held at temperature for a time before being added to the loop. Pressure drop across the bed, flow velocity, and temperature were monitored continuously. In ICET 1 environments, aluminum nitrate solutions were added to the loop after the physical debris was formed. The pressure drop across the bed before addition of the aluminum nitrate solution provided a baseline value for pressure drop without chemical effects. In the ICET Test 3 environments, tests were run without TSP additions to get baseline values for the pressure drop due to the physical debris alone.

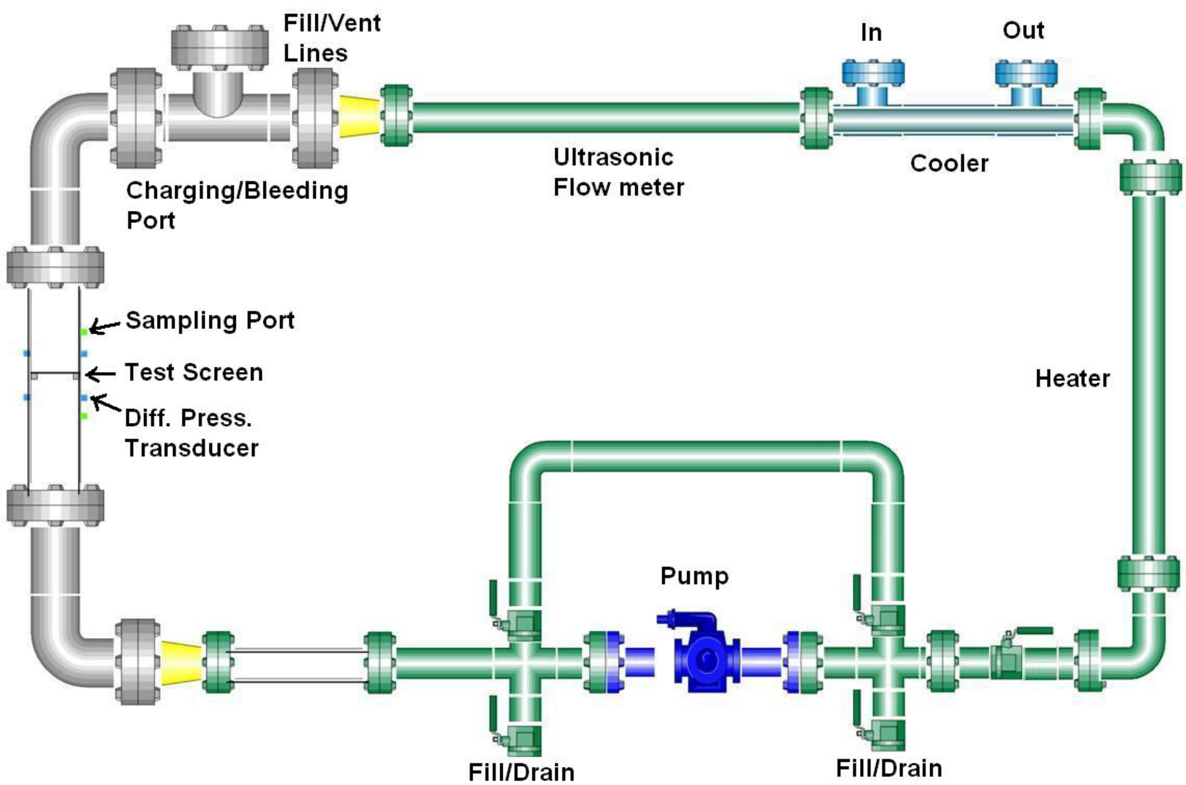


Figure 5.9-10. Schematic Diagram of ANL Test Loop (NUREG/CR-6913).

5.9.4.2 Solution Chemistry

A series of tests (ICET-3-1 to ICET-3-11) was performed to evaluate the potential for head loss due to chemical effects in a TSP-buffered environment. Test conditions are summarized in Table 5.9-5. The tests were designed to explore conditions corresponding to a range of debris amounts, containment sump residence times, and TSP dissolution times. The two basic physical parameters that are affected by these variables are the degree of CalSil dissolution that will occur before the formation of the debris bed, and the interaction between the chemical products and the physical debris during bed formation. Unlike the ICET-3 integrated test (NUREG/CR-6914), these tests have excess phosphate available, i.e., the amount of calcium phosphate that can form is limited by the amount of calcium available from dissolution of the CalSil.

Benchtop, small-scale dissolution tests of CalSil were performed to identify the potential effects of the TSP dissolution rate on the dissolution of CalSil and the subsequent formation of calcium phosphate precipitates. Three different histories of TSP addition were studied, with the intention of encompassing the range of histories of TSP dissolution expected within an actual containment sump:

1 Add TSP before CalSil addition (instantaneous dissolution of TSP).
2 Titrate TSP over 1-hr period into solution after CalSil addition (nominal case).
3 Titrate TSP over 4-hr period into solution after CalSil addition (very slow addition of TSP).

Surrogate solutions for ICET-1 environments were developed using aluminum nitrate, Al(NO3)3·9H2O. Because in ICET-1 the solutions arise from the dissolution of aluminum in a basic solution containing boric acid, the surrogate solutions were prepared by dissolving commercial aluminum nitrate, Al(NO3)3·9H2O, powder in a base solution containing 2800 ppm B added as boric acid, 0.7 ppm Li as LiOH, and NaOH sufficient to reach a pH of 9.6. Aluminum hydroxides, nominally Al(OH)3, make up the principal chemical product with potential to cause head loss observed in ICET-1 and -5 environments. Detailed characterization of the products formed in ICET Test 1 showed that they are most likely amorphous (NUREG/CR-6915).

Samples of surrogate solutions containing 100, 200, and 375 ppm Al form precipitates at room temperature. The precipitates are too fine and too dilute for direct measurement of structure. However, when samples were taken through heating and cooling cycles, the sediments would redissolve at high temperatures. This finding, together with measurements of the Al level in the supernate, suggests that solubility behavior is similar to that expected for amorphous Al(OH)3, which suggests that the sediments are amorphous or at least act like amorphous Al(OH)3.

The tests performed in ICET-1- and ICET-5-like environments are summarized in Table 5.9-5. For the ICET-1 environments, the dissolved Al levels ranged from 100 to 375 ppm. For the ICET-5 environment where the pH is lower, a dissolved Al level of 50 ppm was used (for the final portion of this test, this value was raised to 100 ppm).

5.9.4.3 Precipitation

Significant effects on head loss due to chemical products were observed in environments with CalSil and TSP buffer (ICET-3) and in environments with significant dissolved aluminum and NaOH for pH control (ICET-1).

In ICET-3 environments, the head losses associated with purely physical debris beds of NUKON and CalSil are generally much lower than those that occur across debris beds in which some of the CalSil has been replaced with a corresponding amount of calcium phosphate precipitate. For a thin NUKON bed (≈3 mm), very large pressure drops were observed for the lowest tested CalSil loading, 0.47 kg/m2. However, with thicker NUKON beds (≈12 mm), little chemical effect could be observed for CalSil loadings ≤ 0.47 kg/m2. These results show that the relationship between head loss and fiber loading for a given particulate loading is highly nonlinear and not monotonic. Beds in which no NUKON was present were also examined. In this case, a significant portion of the strainer remains open for the highest strainer loading of CalSil tested, 1.2 kg/m2. The pressure drops are very low with this open area.

The dissolution of CalSil and, hence, formation of calcium phosphate would be retarded if all TSP could be dissolved before the CalSil addition (i.e., simulating instantaneous TSP dissolution). However, even with instantaneous TSP dissolution, the equivalent dissolved Ca will exceed 75 mg/L after a few hours for CalSil concentrations as low as 0.5 g/L. Such an equivalent dissolved Ca concentration was shown to produce pressure drops on the order of 5 psi at an approach velocity of 0.1 ft/s across a 0.71 kg/m2 NUKON debris bed.

Amorphous aluminum hydroxides in the ICET-1 environment can have significant effects on pressure drop. Pressure drops much greater than would be expected from corresponding debris beds in an inert environment have been observed in environments with NaOH buffer for dissolved Al levels of 375 and 100 ppm. These high pressure drops can occur with no visible precipitates.

Table 5.9-5. Conditions for Head Loss Tests in ICET-3 Environment (NUREG/CR-6913)

Test ID	NUKON (g)a	Cal Sil (g)	30 min Presoak	TSPb	Additional dissolved Ca (ppm)	Comment
ICET-3-1	15	15	No	Initially in loop	200	Simulates initial conditions in ICET-3; precipitates arrive after bed forms
ICET-3-2	15	15	No	Initially in loop	10, 25, 50 ppm Cad	Parametric test starting with 1/20th dissolved Ca of ICET-3: precipitates arrive after bed forms
ICET-3-4	7	25	Yes	1/8th initially in loop; 7/8th metered in	None	Minimal CalSil dissolution before initial bed formation; continued dissolution as test continues
ICET-3-5	7	25	Yes	None	None	Baseline physical debris only
ICET-3-6	15	15	Yes	1/8th initially in loop; 7/8th metered in	None	Minimal CalSil dissolution before initial bed formation
ICET-3-7	15	15	Yes	None	None	Baseline physical debris only
ICET-3-8	15	0	No	Initially in loop	43.5c	CaCl2 and NUKON added simultaneously; maximum CalSil dissolution before bed formation
ICET-3-9	15	0	No	Initially in loop	9, 18, 27 ppm Cad	CaCl2 added after NUKON bed stabilizes; maximizes arrival time of precipitates to bed; maximum CalSil dissolution before arrival at the bed
ICET-3-10	15	15	Yes	½ metered presoak; ½ metered	None	Intended to represent a “typical” degree of CalSil dissolution before bed formation
ICET-3-11	Replicates ICET-3-7					
ICET-3-12	15	5		½ metered presoak; ½ metered	None	Lower CalSil loading
ICET-3-13	15	5	Yes	None	None	Baseline for ICET-3-12

ICET-3-14	ICET-3-7 & 11					
ICET-3-15	15	10	Yes	None	None	Baseline physical debris only
ICET-3-16-A1	15	10	Yes	½ metered presoak; ½ metered	None	Lower CalSil loading
ICET-3-17-A1	Replicates ICET-3-10					
ICET-3-18-A1	5	10	Yes	½ metered presoak; ½ metered	None	Thinner NUKON bed
ICET-3-19-A2	-	25	Yes	½ metered presoak; ½ metered	None	CalSil/calcium phosphate precipitate only debris

[a]1 g of debris corresponds to a strainer loading of 47.6 g/m^2.
[b]The total amount of TSP in each test where TSP was added was always 3.4 g/L. Some fraction was either dissolved initially in the test loop or metered in during the presoak period. The remaining fraction was metered in during a 30-60 min period after the debris was added to the loop.
[c]Calcium equivalent to full dissolution of 15 g CalSil.
[d] Calcium additions made incrementally to sequentially reach values of dissolved Ca listed.

Table 5.9-6. Summary of ICET-1 Head Loss Tests with NaOH and STB (NRC, 2008c)

Test ID	Description	Test Section	Strainer
ICET-1-3	NUKON 15.0 g; NaOH; 375 ppm Al	A	1
ICET-1-1-B2_100ppm	NUKON 15.0 g; NaOH; 100 ppm Al	B	2
ICET-1-2-B2_200ppm	NUKON 11.6 g, NaOH; 200 ppm Al	B	2
ICET-1-3-B2_375ppm	NUKON 11.6 g, NaOH; 375 ppm Al	B	2
ICET-1-1-B2_100ppm repeat	NUKON 11.5 g, NaOH; 100 ppm Al	B	2
ICET-1-1-B2_100ppm repeat 2	NUKON 11.5 g, NaOH; 100 ppm Al	B	2
ICET-5-1-B2_042606	NUKON 11.5 g, STB 1248 g; 50 ppm Al	B	2
ICET-3-STB1-A2	NUKON 15.0 g; CalSil 15.0 g; STB 1248 g; 50 ppm Al	A	2

A: LEXAN test section.
B: PVC test section.
1: Perforated plate with 51% flow area and 3/16 in. holes with 1/4 in. staggered centers.
2: Perforated plate with 40% flow area and 1/8 in. holes with 3/16 in. staggered centers.

Sodium tetraborate buffers seem more benign than NaOH or TSP. A submerged aluminum area and sump volume that results in a 375 ppm dissolved Al concentration in a NaOH environment results in 50 ppm dissolved Al with a sodium tetraborate buffer. No significant head loss was observed in a test that lasted ≈11 days with 50-ppm aluminum and a STB buffer. A test with a NUKON/CalSil debris mixture and STB buffer produced much lower head losses than observed in corresponding tests with TSP, although tests were not performed over the full range of CalSil loadings of interest.

5.9.4.4 Head Loss in ICET Environments

Pressure drops across the bed for tests with physical debris of 15 g NUKON/15 g CalSil and TSP present (ICET-3-6 and ICET-3-10) are compared with the baseline test ICET-3-11, which had 15 g NUKON/15 g CalSil but no TSP, in Figures 5.9-11a and b, respectively. In ICET-3-6, no TSP was added to the presoak to limit the possible dissolution of the CalSil. This scenario was intended to give a lower bound for the amount of calcium phosphate precipitate arriving as the debris bed is formed. As expected, the initial pressure drop behavior in ICET-3-6 is very similar to the baseline case ICET-3-11, in which no chemical precipitates are present (Figure 5.9-11a). However, a comparison of the maximum pressure drops reached in ICET-3-6 and ICET-3-11 shows that the difference in the pressure drop increases with time. The increased pressure drop with time in ICET-3-6 is attributed to the continuing dissolution of CalSil and additional formation of calcium phosphate precipitates.

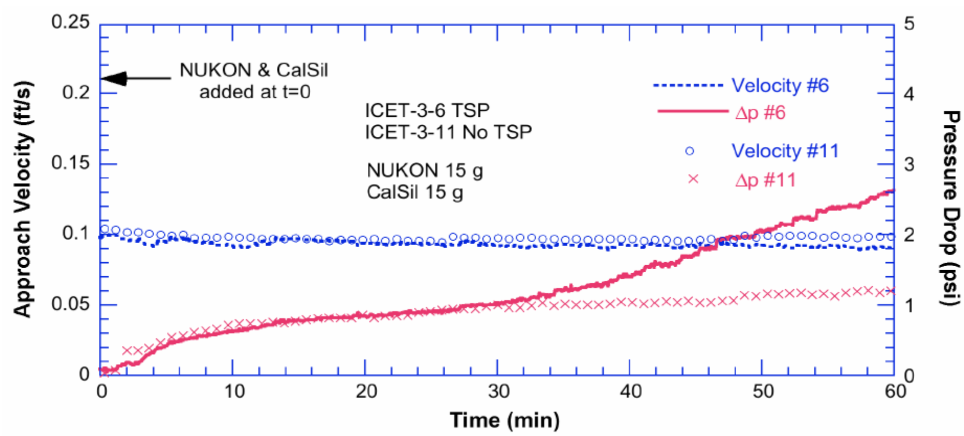
In Test ICET-3-10, some TSP was added during the presoak. This test was intended to give a more "typical" amount of calcium phosphate precipitate arriving as the debris bed is formed. This results in a much more rapid increase in head loss than in ICET-3-6 (Figure 5.9-11b), although the pressure drop in ICET-3-6 eventually approaches the steady-state value obtained in ICET-3-10. Pressure drop across a 15 g NUKON bed at 0.1 ft/s is about 0.2 psi. With the addition of 15 g of CalSil, but no chemical reaction, the pressure drop at 0.1 ft/s is about 1.2 psi. With the addition of TSP, pressure drop across the bed increases to greater than 5 psi even though the velocity decreases to less than 0.05 ft/s.

The degree of dissolution that would occur before the debris reached the sump strainer in a prototypical situation would presumably be bounded by the ICET-3-6 and ICET-3-8 limiting cases, and may be most similar to the ICET-3-10 case. The test results suggest that variability in the degree of CalSil dissolution is likely to have a relatively small effect on the chemical effects of head loss in this system. Differences in debris transport time would probably have a much larger effect on the rate at which the pressure drop increases. The actual amount of head loss for a plant-specific case is also dependent on many additional factors such as sump strainer debris loading, uniformity of the strainer debris loading, propensity for flow bypass (i.e., jetting) through the debris bed, debris bed strainer approach velocity, and transport of chemical precipitate not addressed in these tests.

Test ICET-3-18 used debris loading of 5 g NUKON and 10 g CalSil. This resulted in a thin debris bed about 3-4 mm thick. The bed approach velocity and differential pressure across the strainer as a function of time for test ICET-3-18-A1 are shown in Figure 5.9-12. This test resulted in a rapid buildup of head loss. After 10 min, flow velocity could not be maintained at 0.1 ft/s and gradually decreased. The thinner bed plugged more rapidly than in either ICER-3-10 or ICET-3-17, which had 15 g NUKON and 15 g CalSil and was about 12 mm thick. This test result is consistent with the classic thin bed head loss behavior observed elsewhere (i.e., a thin fiber bed that becomes saturated with particulate can result in high head loss).

Test ICET-3-9 was performed with CaCl2 additions. The pressure drop history in ICET-3-9, shown in Figure 5.9-13, suggests a strongly nonlinear relationship between the amount of the calcium phosphate precipitate and the pressure drop. The first two additions of CaCl2 in ICET-3-9 produced relatively small increases in pressure drop. The third addition resulted in a very rapid increase in pressure drop. The total inventory of dissolved Ca added in ICET-3-9 is equivalent to complete dissolution of 9 g of CalSil or a CalSil loading of 0.4 kg/m2 of strainer. However, the results from ICET-18 (Figure 5.9-12) show that the loading that results in high pressure drops will also depend on the thickness of the fiber bed.

A test was also run with debris loading of 25 g CalSil with no NUKON. The 25 g of CalSil used in this test corresponds to a strainer loading of 1.2 kg/m2, which is probably conservative for most plants after their sump strainers are updated. Although a portion of flow area was blocked by the CalSil, a significant portion of the strainer remained open with this loading. The pressure drops were very low as expected with a significant open area. It appeared that, even with a heavy loading of CalSil, another source of fiber is necessary to form a bed that can trap the CalSil particulate and the associated chemical product.



(a)

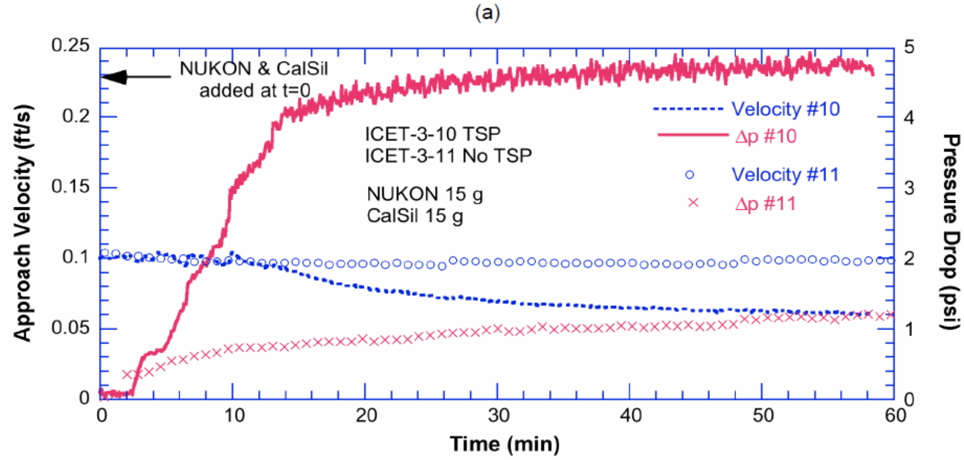


Figure 5.9-11. (a) Bed Approach Velocities and Differential Pressures across the Strainer as a Function of Time for (a) Test ICET-3-6 and -11 and (b) Test ICET-3-10 and -11 (15 g load = 0.7 kg/m2) (NUREG/CR-6913).

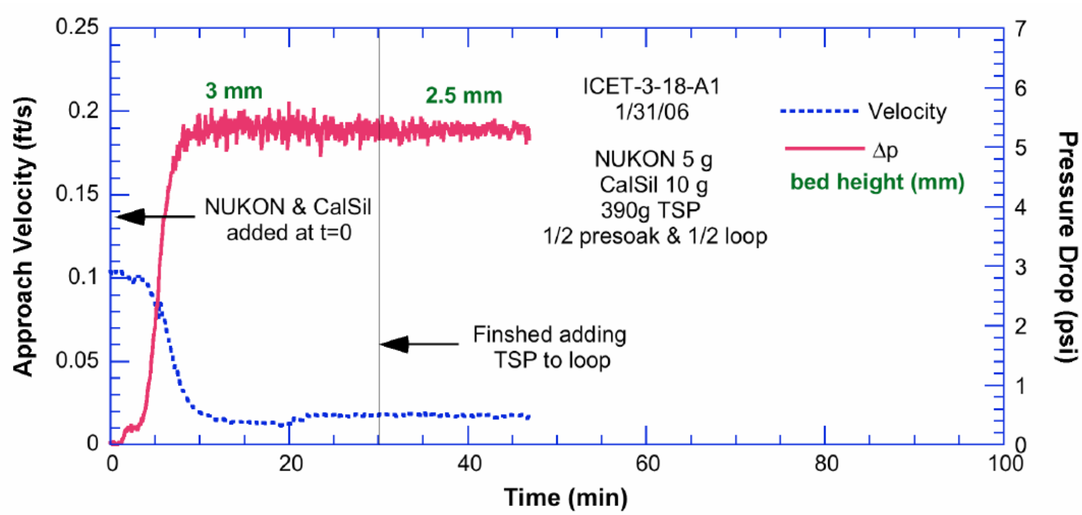


Figure 5.9-12. Bed Approach Velocity and Differential Pressure across the Strainer as a Function of Time for Test ICET-3-18 (NUREG/CR-6913).

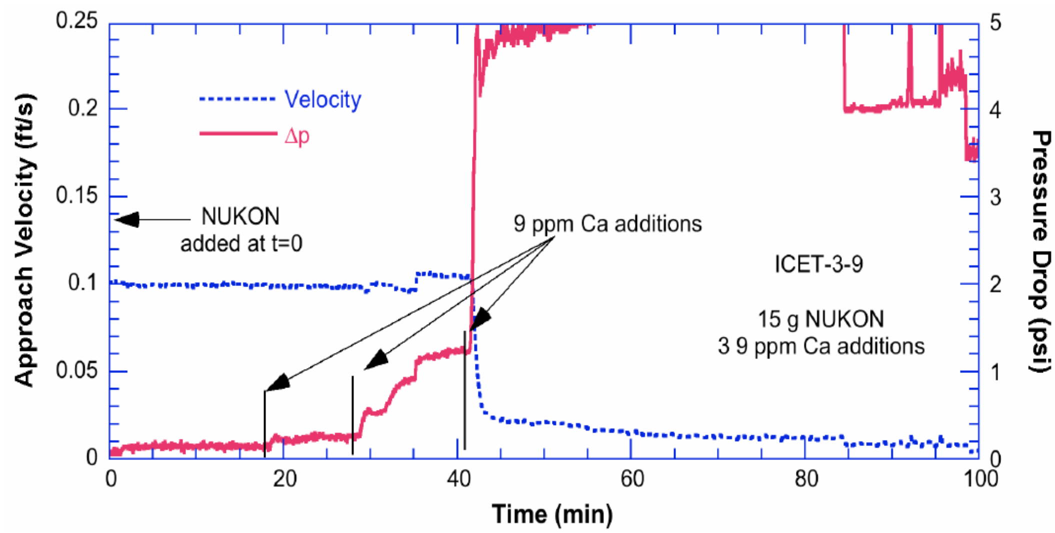


Figure 5.9-13. Bed Approach Velocities and Differential Pressures for ICET-3-8 and -9 (NUREG/CR-6913).

Because the dissolution rate of CalSil is pH dependent (dissolution is more rapid at lower pH), it will depend on the rate at which TSP is added to the system. Tests were performed with TSP dissolved in the solution before any addition of CalSil ("instantaneous" dissolution of TSP) and with TSP metered in over 1-hr and 4-hr periods. The TSP dissolution history had a larger effect at a CalSil loading of 1.5 g/L than at 0.5 g/L. It took substantial time (approximately four days) to achieve full dissolution for the 1.5 g/L CalSil loading, while dissolution of the 0.5 g/L loading appears to be complete within approximately 1-3 days. However, for both CalSil concentrations, substantial Ca dissolution (>75 mg/L) has occurred within a few hours regardless of the TSP addition rate.

In the head loss loop tests, virtually all the calcium phosphate precipitates that form are transported to the bed. In an actual sump, the precipitates can settle before they reach the sump strainer. Settling tests were performed to determine settling rates for calcium phosphate under conditions with no bulk directional flow. Tests were performed in a settling tower with an effective height of 71.5 cm. The tower was filled with a solution containing LiOH (0.7 ppm Li), and boric acid (2800 ppm B), and TSP (3.4 g/L). A CaCl2 solution was then added to the tower. The dissolved Ca reacts with the TSP in the solution to form calcium phosphate precipitate. The solution is stirred to get a uniform mixture, and then the precipitates are allowed to settle. Two different CaCl2 concentrations were tested. One produced a dissolved Ca inventory equivalent to 300 ppm, and the other an inventory equivalent to 75 ppm. The 300 ppm inventory is roughly equivalent to full stoichiometric dissolution of a 1 g/L concentration of CalSil; the 75 ppm inventory is roughly equivalent to full stoichiometric dissolution of a 0.25 g/L concentration of CalSil. The settling rate was dependent on concentration. For the 75 ppm calcium test, which is more representative of the concentrations of interest, the settling velocity was estimated to be 0.8 cm/min.

Pressure drops much larger than would be expected from corresponding debris beds in an inert environment have been observed in environments with NaOH buffer for dissolved aluminum levels of 375 and 100 ppm (ICET-1 and -5 environments). These high pressure drops can occur with no visible precipitates. The increases in pressure drops are much larger than those expected due to the small changes in bulk fluid properties, like viscosity, for these solutions.

In short-term laboratory testing with surrogate solutions, the kinetics of the formation of chemical products can lead to substantial test-to-test variability. Both tests with 375 ppm dissolved Al concentrations resulted in large pressure drops. No high head losses were observed in two short (8-10 hr) tests with 100 and 200 ppm Al in solution, respectively. However, two longer (6-8 day) tests with 100 ppm Al did result in large pressure drops. The pressure drop history in one of these tests (ICET-1-1-B2) is shown in Figure 5.9-14.

Samples of the solutions from all the loop tests formed emulsions that settled to the bottom of the sample containers when allowed to remain at room temperature for some time. Measurements were made with ICP/AES to determine the Al content of the clear supernate solutions above the emulsions. Although the solutions appeared perfectly clear, this finding does not preclude the possibility that some fine precipitates remain. Thus, the measurements may somewhat overestimate the solubility of amorphous Al(OH)3 at room temperature and nominally pH 9.6 in sump solutions. The measured values were 32-63 ppm. The variability in the results is probably due primarily to small variations in pH. Literature estimates of the solubility at room temperature give values of 37-59 ppm for pH values 9.4-9.6, which are consistent with the results from the loop tests.

The observation that the solutions in the head loss loop can remain supersaturated for a substantial period is consistent with results from ICET 1 (NUREG/CR-6914). Although the concentration of aluminum remained constant over the 10-15 days of the test, precipitates formed more rapidly and in greater volume as the solution was cooled as the test progressed.

The head loss test in the ICET-5 environment was conducted for ≈11 days. No increase in head loss due to precipitate formation was observed. Sodium tetraborate buffers seemed more benign than NaOH or TSP. A submerged Al area and sump volume that resulted in a 375 ppm dissolved Al concentration in a NaOH environment resulted in a 50 ppm dissolved Al concentration with a sodium tetraborate buffer. The 375 ppm concentration resulted in high head loss in 0-2 hr. Interaction with NUKON/CalSil debris mixtures produced much lower head losses than observed in corresponding tests with TSP, although tests were not performed over the full range of CalSil loadings that might be of interest.

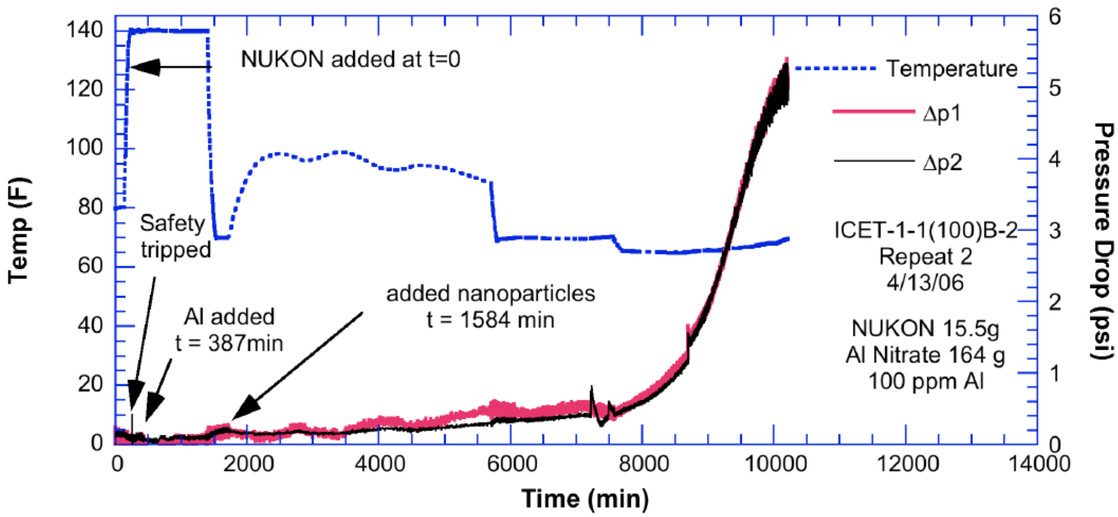


Figure 5.9-14. Pressure and Velocity History in Test ICET-1-1-B2 (100 ppm, repeat 2) (NUREG/CR-6913).

5.9.4.5 Relationship of ICET to Plant Environments

Although the final level of dissolved Al in ICET 1 was ≈ 375 ppm, actual plant levels of dissolved Al for the same environments would "scale" with the amount of Al exposed, which is plant specific. In addition, the ICET 1 was run isothermally at a temperature of 60°C (120°F), whereas the actual temperatures will vary considerably over the whole course of the accident. The amount of Al exposed to the environment depends strongly on whether the sprays are on. In most plants, the amount of submerged Al would be a small fraction of the total Al in containment. To obtain a better estimate of the range of Al that may be expected in the recirculating water, calculations were performed using more realistic thermal histories for 17 plants for which estimates of the amount of Al in containment were available (NUREG/CR-6914, Vol. 1, Appendix C).

The results suggest that the dissolved Al concentration in ICET-1 is conservative, and most plants with NaOH buffering would be expected to have dissolved Al concentrations at 30 days below 100 ppm. Because of the large amount of aluminum that is exposed to sprays but not submerged, one plant, based on the survey results and the preliminary calculations, could have a concentration 65 ppm after one day, rising to 80 ppm after 30 days. Although comparable time-temperature dissolution history calculations were not performed, the dissolved Al concentration in ICET-5 is probably similarly conservative. Based on the corrosion rates inferred from ICET-5 and the relative amounts of Al in containment compared to ICET-5, most plants with STB buffering would be expected to have dissolved Al concentrations at 30 days below 15 ppm.

5.9.4.6 Comments and Observations

Significant effects on head loss due to chemical products were observed in environments with CalSil and TSP buffer (ICET-3) and in environments with significant dissolved aluminum and NaOH for pH control (ICET-1).

CalSil dissolves quickly in prototypic environments. The dissolved calcium concentration was greater than 75 ppm within a few hours even with 0.5 g/L concentrations of CalSil.

Uncertainties in TSP dissolution rates and degree of dissolution of CalSil before bed formation have relatively small effects on the dissolution rate of CalSil for CalSil loadings of interest. Solubility of calcium phosphate is low over temperature and pH ranges of interest in the sump. Thus, precipitate will occur simultaneously with dissolution of CalSil and TSP. Significant amounts of precipitate are likely to occur in a relatively short time for TSP plants that have sufficient amounts of dissolved calcium in a post-LOCA containment pool.

Tests with the vertical head loss loop showed that dissolved calcium levels of 10-20 ppm (corresponding to 0.03–0.06 g/L of CalSil) had significant increases in head loss due to precipitation of calcium phosphate. These test results are consistent with those of WCAP-16785-NP (Reid et al., 2007) regarding the highly insoluble nature of calcium phosphate. The level of dissolved Ca required for high head loss in environments with TSP depends strongly on fiber bed thickness, sump volume, and strainer area. Thin fiber beds (≤3 mm) show a much higher head loss.

If the results from a test facility are scaled up to plant-specific parameters, the mass of chemical product and physical debris per unit area of strainer should be considered. The mass of chemical product produced should be proportional to the fluid volume while the potential for head loss is characterized by the product mass per unit strainer area. Even with a heavy loading of CalSil, a source of fiber is necessary to form a bed that can trap the CalSil particulate and the associated chemical product.

The ICET-1 environments gave high losses in tests with Al concentrations down to 100 ppm. Post-test measurements suggested that approximately 50 ppm remained in solution at ≈ 75°F, pH ≈ 9.6. No visible precipitate was observed in tests with 100 ppm aluminum in solution, even though head loss was high. This finding is consistent with results from ICET-1 that precipitates are very small. Argonne measurements on filtered/unfiltered solutions in bench tests with 0.2-μm filters showed no differences in aluminum concentration. The Al(OH)3 precipitates are difficult to characterize.

Results from TEM suggest that precipitates consist of agglomerations of ~10 nm constituent particles. ANL measurements gave 19 μm without ultrasonic deflocculation and 2 μm with deflocculation, which is consistent with the LANL observations of agglomerates. High hydration of products increases effectiveness in plugging of debris bed formed on the strainer. The kinetics of Al(OH)3 precipitation are complex. Solutions can maintain a significant amount of supersaturation for significant amounts of time (days), and then a relatively rapid increase in head loss can occur. The behavior of precipitated aluminum in ANL loop tests and in ICET-1 is consistent with an ongoing process of nucleation and growth of products too small to be detected visually. In these tests, a large amount of aluminum was removed from solution (more than 50 ppm). Subsequent ANL conducted tests with WCAP-16530 AlOOH surrogate product, corresponding to 5 ppm aluminum in solution, also showed high head loss (Bahn et al., 2007). However, a loop test with a STB buffer suggested somewhat large amounts of product (10–30 ppm) were required to get high head loss.

Although all the tests were run with a standard thickness of NUKON bed, it is expected that the level of dissolved aluminum required for high head loss is expected to depend strongly on fiber bed thickness, sump volume, and strainer area. Thin fiber beds could produce a much higher head loss for the same mass of chemical product than a thicker bed.

Head loss tests in the ICET-5 environment showed no measurable increase in head loss due to chemical effects with 50 ppm dissolved Al for tests of 12-20 days. An increase of dissolved aluminum to 100 ppm resulted in high head loss. A test with a NUKON/CalSil + STB resulted in a head loss characteristic of NUKON/CalSil without chemical effects. The head loss slowly decreased with time consistent with dissolution of the CalSil (thus reducing its effectiveness as a physical particulate) with no formation of a precipitate product (at a concentration of CalSil of 0.12 g/L).

5.9.5 Thermodynamic Modeling

5.9.5.1 Thermodynamic Simulation Studies

A study was initiated before the ICET program to determine the need for a pressurized test loop for ICETs (NUREG/CR-6873). In addition, to assess whether gelatinous products could form following a LOCA, gain insights into important parameters, and attempt to predict the ICET results, this study performed computer-based thermodynamic simulations of chemical effects. The report NUREG/CR-6873 documents the results of experiments to determine corrosion rates for metals and leaching rates for concrete and fiberglass, which were used as input parameters to the thermodynamic model. Based on the measured corrosion rates, estimated exposed surface area, and exposure time, the thermodynamic simulations indicated that the formation of dominant solid phases was controlled by the presence of NUKON, aluminum, and concrete. The predicted dominant solid phases consisted of potentially amorphous silicate phases such as sodium aluminum silicate ($NaAlSi3O8$), calcium magnesium silicate ($Ca2Mg5Si8O22(OH)2$), calcium silicate ($CaSiO3$), and silica ($SiO2$). The formation of $NaAlSi3O8$ in the presence of alkaline solutions could lead to gel formation, which could result in clogging of debris-loaded sump pump suction strainers. The thermodynamic simulations indicated that, in alkaline simulated containment water at pH 10, corrosion product formation does not differ as high-temperature and -pressure conditions during the initial stages of a LOCA event approach steady-state atmospheric pressure conditions, which could support the validity of ICETs without a pressurized water loop.

This study provided initial understanding of the evolution of solution chemistry and possible solid phases. However, as identified in the report, there were assumptions and simplifications to the thermodynamic model. One simplification is that the model does not consider reaction kinetics, which is a common weak point of thermodynamic equilibrium modeling. Another weak point is that the modeling results such as chemical speciation entirely rely on what kinds of information are included in the code database, for example, the reaction equilibrium constant (K) as a function of temperature. In this study StreamAnalyzer© Version 1.2 was used. The modeling results need to be benchmarked by one simulation program with those by another thermodynamic program, which might contain a different thermodynamic database or experimental observations. For this purpose, a follow-on study to compare simulation results with ICET observations was conducted by the same authors. The follow-on work was documented in a separate NUREG report, as described in the following section.

5.9.5.2 Commercial Simulation Codes

To gain insights into important test parameters and develop the predictive capability of ICET results, the NRC initiated a study to evaluate the feasibility of utilizing commercially available thermodynamic simulation computer codes to predict the formation of chemical species in a typical post-LOCA PWR containment environment (NUREG/CR-6912). As an initial step, not only OLI Systems StreamAnalyzer, which had been used in the previous work (NUREG/CR-6873), but also three other computer codes were used: EQ3/6, PHEEQC, and Geochemist's Workbench REACT. After the code comparison exercise, three of the codes, EQ3/6, OLI

Systems StreamAnalyzer, and PHEEQC were further examined in more detail. The simulations by three codes were benchmarked to the ICET experiments, corresponding to five representative post-LOCA environments at 60°C (140°F) for times up to 720 hr. After a couple of trial predictions, a complete set of blind and informed predictions was attempted using a single modeling program, PHEEQC, which provided modeling advantages in terms of its flexibility in suppressing the precipitation of specified solids and the ease with which its thermodynamic database could be modified. The authors tried to simulate the evolution of water chemistry over a 30-day period by dividing the time into multiple steps and at each step providing different input data based on corrosion/release rates for each element. Because the corrosion/release rates were predetermined and constant over the time period, the code could not address properly the time-dependent effect observed in ICETs, such as inhibition effect or metal surface passivation, which led to the decrease of the corrosion/release rates.

Results of this study demonstrated that thermodynamic simulation modeling software is broadly useful in assessing the potential effects of post-LOCA interaction on sump strainer blockage. However, its predictive capability is often hindered by insufficient thermodynamic data for relevant phases and aqueous species in the code database, as well as limitations in the kinetic data for dissolution of reactive materials in the presence of co-dissolving materials. Based on those findings, this study provides some insights for predicting what would happen in environments outside ICET tests, although the modeling alone is insufficient to make blind predictions with confidence. When thermodynamic simulations were refined using ICET data and experimental observations, the predictions broadly agreed with experimental results. Overall, prediction of chemical byproduct concentrations and species is most accurate when the analytical models are properly benchmarked with experimental data.

5.9.6 Peer Review of Chemical Effects Studies

The chemical-effects peer review assessment process and a summary of its significant findings are discussed in NUREG-1861. Each peer reviewer was asked to provide an individual evaluation, based on his or her particular area of expertise. The research projects addressed by the peer review included ICET and ICET-follow-up testing and analysis conducted at LANL (NUREG/CR-6914, -6915) chemical speciation prediction conducted through the Center for Nuclear Waste Regulatory Analyses (CNWRA) at SwRI (NUREG/CR-6873 and NUREG/CR-6912), and accelerated chemical-effects head loss testing conducted at ANL (NUREG/CR-6913). The chemical-effects peer review evaluated the technical adequacy and uncertainty associated with the NRC-sponsored research results, and identified outstanding chemical effects issues. Subsequent to the peer review assessment, ANL conducted additional testing on chemical effects (Bahn et al., 2007, 2008a, 2008b, 2008c, 2008d, 2009). One head loss test was also conducted with in-situ corrosion of aluminum coupon instead of adding chemical chemical precipitates (Bahn et al., 2008c), as has been recommended by the peer review.

5.9.6.1 Integrated Chemical Effect Tests

The review focused on a predetermined set of ICET-related technical questions. Those questions and the related responses from the peer reviewers are summarized as follows:

Question 1: Have the principal sump pool variables, which affect chemical byproduct formation environment, been adequately simulated?

Response: The majority of the reviewers agree that the types of materials that are present in PWR containments have been appropriately selected. They also stated that the concentrations of chemicals used during the operation of a PWR are approximately in the range of anticipated chemical concentrations. The reviewers also noted that other chemical constituents have not been simulated, the analysis lacks consideration of redox effects and radiolysis, and the tests did not adequately model the steep cyclic temperature transients of recirculating coolant or the hot fuel cladding and pressure vessel surfaces.

Question 2: Many ICET variables were held constant during the experiments. How would changes in the most important constant variables affect chemical product formation?

Response: In general, the reviewers suggest comprehensive evaluation of the physical, chemical, and mineralogical properties of the observed precipitates during the experiments, along with detailed evaluation of all of the data to better understand the effects of chemical product formation. Some of the reviewers suggest that temperature has a significant effect on solubility and the types of compounds that will form. They recognize temperature as a difficult aspect to model and recommend further work.

Question 3: What variables or materials not simulated by the ICET testing may have the most impact on chemical product formation (e.g., coatings, free insulation, flow through sediment and other materials on sump strainer, and galvanic effects), and how should their effect be characterized by testing or by analysis?

Response: In general, the reviewers think that field visits to operating PWR facilities could unearth limitations or omissions not otherwise anticipated. Considerations from the reviewers are diverse and are summarized as follows:

- A failure to control or monitor CO_2 uptake, which could deviate significantly from the actual post-LOCA environment in a PWR
- Presence of suspended solids from the RCS and how they could change their chemical form
- Effects of organic coatings to estimate the quantities of coatings involved, their properties, and the secondary effects of radiation and hydrothermal reactions (reactions with hot water) on the organic materials
- Effects of high- and low-temperature heat transfer surfaces on collection and dissolution of solid phases to determine the importance of surface deposition
- Effect of liquid coming into contact with fuel in the reactor vessel to understand heat and radiolytic effects
- Effects of silica in the water storage systems and RCS on the total mass of material precipitating
- Simulation of the production of hydrogen peroxide (1-20 2, to determine redox potential) and nitric acid (HNO_3, lowers the pH of the solution)

Question 4: Were the methods used within the ICET program to characterize and analyze chemical byproducts sufficient?

Response: The reviewers agree that the methods used within the ICET program were not sufficient to characterize and analyze chemical byproducts. Much more serious work needs to be done to characterize the physical, chemical, and mineralogical properties of the precipitates and coatings as a basis for subsequent conceptual and computer modeling. Some XRD and TEM work was performed during the course of ICET or during follow-up work, but in general, the tests should have incorporated the following analytical techniques as part of their standard analysis:

- Particle size distribution (PSD)
- Fourier transform infrared spectroscopy (FTIR)
- X-ray diffraction (XRD)
- Transmission electron microscopy (TEM)

5.9.6.2 ANL Head Loss Testing

The review focused on a predetermined set of technical questions related to chemical effects head loss testing. Those questions and the related responses from the peer reviewers are summarized as follows:

Question 1: Is the accelerated head loss testing approach viable for evaluating the effects of multiple chemical environments quickly?

Response: The majority of the reviewers agree that the current head loss testing facility is insufficiently flexible for evaluation of multiple chemical environments or replication of tests to establish reproducibility, and the test loop does not provide the same type of stagnant environment that would be encountered in the submerged portion of the containment building. Some recommendations are as follows:

- Use multiple small bench-scale facilities that could be run simultaneously, with stepped variations in critical parameters, so that the sensitivity and magnitude of potentially adverse conditions could be rapidly mapped as a function of these parameters.
- A smaller test loop might be designed to model the operation of a vertical strainer, rather than the tested perpendicular dead-end strainer.
- A smaller test loop would also allow easier testing at temperatures that vary with time and might allow exposed high and low temperature surfaces.

Question 2: What is the best method for incorporating time-dependent effects (e.g., material aging, evolving chemical environments) in simulation testing?

Response: The reviewers suggest various methods to incorporate time-dependent effects in simulation testing:

- With the variability in individual PWR designs and differing operating histories, there is a need to concentrate on the most critical parameters and efficiently study their effects though small-scale bench tests. Once the degree of variability and its importance are established, small-scale loop and head-loss tests could be conducted on a suitable range of variably aged samples.
- The effect of temperature should be studied through small bench-scale tests, followed by limited small-scale loop and head-loss tests. Confirmatory tests using the present facilities should be conducted only after assessing the impact of all relevant parameters.
- Kinetic models, coupled with thermodynamic codes, should be considered, making sure that the codes accurately simulate radiolysis and redox effects.

Question 3: What metrics are most appropriate for evaluating the results of simulated chemical products with those that formed during the ICET program?

Response: The reviewers identified various metrics for evaluating the results of simulated chemical products:

1 In the filtration/head-loss testing, the aluminum corrosion product was introduced by neutralizing aluminum nitrate [Al(N03)3] with sodium hydroxide (NaOH). This method is not representative of the way aluminum solids arise in the post-LOCA cooling water system. It is proposed that the aluminum be introduced in another manner, either by corroding a coupon of aluminum in NaOH or by adding sodium aluminate solution [NaAl(OH)4].

2 The testing performed for the ICET program showed the importance of pH, CalSil dissolution, borate, aluminum corrosion, phosphate, NUKON fiberglass, and concrete on solids formation. The head loss testing could focus on varying these components, plus studying the effects of temperature differentials and hot and cold surfaces, to create the solids present in the post-LOCA environment.

5.9.6.3 Thermodynamic Modeling

The review focused on a predetermined set of technical questions related to prediction of chemical speciation. Those questions and the related responses from the peer reviewers are summarized as follows:

Question 1: Is the speciation analysis expected to provide reasonable predictions of chemical product formation over a range of possible sump environments?

Response: The reviewers agree that even though this chemical speciation analysis represents a significant improvement over earlier work, it does not exploit existing capabilities of the selected codes to their fullest advantage. Specifically, two physical effects not modeled were the radiation field from the fuel, and the layer of corrosion products on the interior surface of the RCS. The reviewers note that concessions had to be made for the seeming lack of CO2 to form low-solubility carbonates. Reaction rates (kinetics) also are not handled well by the modeling software; therefore, the models may not reflect the evolving concentration profiles. As the models are refined, they should provide closer matching of the observed ICET concentrations, the concentrations observed in the supplemental CNWRA testing, and the concentrations in systems not replicated in the ICET experiments. In addition, the non-equilibrium concentration of radiolysis products (and even species in the absence of radiolysis) cannot be addressed by the selected codes.

Question 2: Is the plan for benchmarking these codes using small-scale testing and the ICET results appropriate?

Response: The reviewers agree that the plan for benchmarking codes is satisfactory, provided that the actual processes are accurately simulated. Some reviewers think that the capabilities of the codes currently being used are not being used to full advantage and, as a result, the value of the associated experimental studies is diminished. In addition, the reviewers note that small-scale testing is a valid approach to gain more information, especially on the kinetic and equilibrium behaviors of the key solutes and solid phases.

Question 3: What is the most appropriate way to measure the uncertainty associated with these codes?

Response: The reviewers suggest various ways to measure the uncertainty associated with the codes, noting that it is difficult to measure the overall uncertainty of the output of any multi-component chemical simulation, because a large number of parameters are involved with widely varying levels of accuracy. First, a sensitivity analysis of empirical or deterministic models is suggested. Second, comparison of the code predictions against the results of targeted small-scale tests is a feasible way to strengthen the codes and identify and measure their uncertainties. Third, the most realistic values should be utilized, and runs should be replicated using Monte Carlo methods to determine variations in parameters deemed to have the greatest uncertainties and considered to be most critical to model output. The cumulative variation in outputs can then be adopted as a measure of uncertainty.

5.9.7 Industry Approach to Evaluate Chemical Effects

5.9.7.1 Overview

The Westinghouse report WCAP-16530-NP (Lane et al., 2006) provides a consistent approach for plants to evaluate the chemical effects, which may occur post-accident in containment sump fluids. The results of this evaluation are intended to provide input on the type and amounts of chemical precipitates that may form post-accident.

Based on containment materials survey for 69 U.S. PWRs, ten material classes were selected for dissolution testing at pH values of 4.1, 8.0, and 12.0, in solutions that contained boric acid (4400 ppm B) with added TSP, STB, and sodium hydroxide. The dissolution tests were conducted at temperatures of 88 and 129°C (190 and 265°F). The dissolution of each element from representative materials was estimated by ICP, and precipitation testing was, subsequently, conducted by sampling and cooling the dissolution-test solution. The settling rates and filterability of precipitates were measured, which provided baseline data for surrogate chemical precipitate qualification. The WCAP-16530-NP chemical model was developed based on the dissolution testing results. Instructions were provided for preparation of three chemical (surrogate) precipitates.

5.9.7.2 Summary of Important Results

Containment Materials Survey

The containment materials provided on the plant surveys can be divided into fifteen (15) material classes based on their chemical composition. Ten of these material classes were selected for the dissolution testing, and eleven representative materials were tested, as shown in Table 5.9-7.

Table 5.9-7. Containment Material Classification Summary (from WCAP-16530-NP)

Material Class	Materials in Class	Representative Material
Aluminum	Aluminum alloys, aluminum coatings	Aluminum (pure)
Aluminum silicate	Cerablanket, FiberFrax Durablanket, Kaowool, Mat-Ceramic, Mineral Fiber, PAROC Mineral Wool	FiberFrax Durablanket
Calcium silicate	Asbestos, CalSil insulation, Kaylo, Marinite, Mudd, Transite, Unibestos	CalSil insulation
Carbon Steel	All carbon and low alloy steels	SA 508 Cl 2
Concrete	Concrete	Ground Concrete
E-glass	Fiberglass insulation, NUKON, Temp-Mat, Foamglas, Thermal Wrap	NUKON, Unspecified Fiberglass
Amorphous Silica	Min-K, Microtherm	Min-K
Interam E Class	Interam E Class	Interam E-5
Mineral wool	Min-Wool, Rock Wool	Min-Wool
Zinc	Galvanized steel, zinc coatings	Galvanized Steel
Copper	All copper alloys	None
Nickel	All nickel alloys	None
Organic Mastics	CP-10, ThermoLag 330-1	None
Other Organics	Armaflex, Kool-Phen, Benelex 401, RCP motor oil	None
Reactor Coolant Oxides	Nickel ferrite and other oxides	None

Dissolution Testing

Eleven containment materials were dissolution tested: seven insulation materials, plus aluminum, zinc, carbon steel, and ground concrete. The total time for the dissolution testing was 30, 60, or 90 minutes at either 88 or 129°C (190 or 265°F).

Elemental analysis was performed using ICP for Al, Fe, Zn P, S, Si, Ti, Mg, and Ca on all materials tested. The ionic material of greatest concentration after the equilibration tests was aluminum followed by silicon and calcium, as shown in Figure 5.9-15. For this figure, the total mass of each element release in the design matrix dissolution tests was calculated by summing the releases for all times, temperatures, and pH levels. Released mass of Al increased with solution pH. Figure 5.9-16 shows the total mass releases from each tested materials.

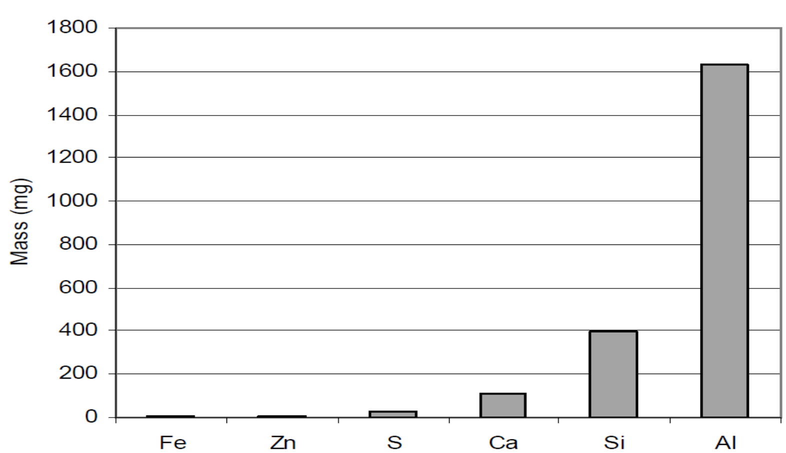


Figure 5.9-15. Comparison of Total Mass Released during Dissolution Testing by Element (Lane et al. 2006).

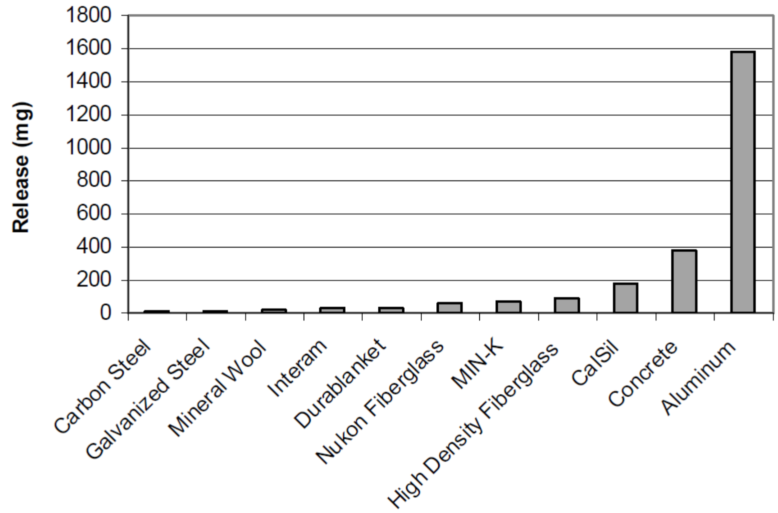


Figure 5.9-16. Comparison of Total Mass Released from the Tested Materials (Lane et al. 2006).

Precipitation Testing

Precipitation testing was performed following the dissolution testing. The solution from the dissolution testing was transferred and cooled down, or the solution was mixed with other pH-buffering agents, such as TSP or sodium tetraborate. Precipitate formed in thirteen of the sixty tests performed, and none of the 13 precipitates settled rapidly; thus, all of the precipitates would be expected to be transported to the sump strainer. Analysis of the 13 precipitated materials with SEM and energy dispersive x-ray spectroscopy (EDS) identified their chemical compositions. The "best guess" for the precipitates identified six different types: hydrated aluminum oxyhydroxide (AlOOH), sodium aluminum silicate ($NaAlSi_3O_8$), calcium aluminum silicate, calcium phosphate, sodium calcium aluminum silicate, and Zn_2SiO_4 (willemite). Among them, the major chemical precipitates were determined to be aluminum oxyhydroxide, sodium aluminum silicate, and calcium phosphate. The precipitate identification is based on chemical composition analysis by SEM/EDS, but any TEM or XRD analysis to characterize crystallographic phases was not reported. Therefore, for example, "aluminum oxyhydroxide (AlOOH)" in WCAP-16530-NP (Lane et al., 2006) should be considered as a common name for the aluminum hydroxide family, including the amorphous phase. Precipitate filterability was also assessed, by calculating filter cake coefficients.

Chemical Model

For each chemical species, concentration data generated during dissolution testing at specific conditions were used in a regression analysis to develop release rate equations as a function of temperature, pH, and the concentration of that species. Release rate equations were developed for each predominant containment material for each chemical species. For example, different functions were used to calculate calcium release from calcium silicate and concrete. Using the WCAP-16530-NP (Lane et al., 2006) chemical model for precipitate formation, CalSil dissolution is greatest at pH values between 5.6 and 8.5, and decreases above 8.5. However, this is offset by a reverse effect with pH seen by aluminum corrosion. Aluminum release was highest at pH 12.0 and lowest at pH 4.1.

The chemical model conservatively assumes all dissolved aluminum precipitates as hydrated AlOOH and/or sodium aluminum silicate and all dissolved calcium in phosphate solutions precipitates as calcium phosphate. This assumption appears reasonable for calcium phosphate because of the low solubility but highly conservative for aluminum because ICET 1 and 5 testing (NUREG/CR-6914), ANL solubility tests (Bahn et al., 2008b), subsequent Westinghouse solubility study (Lane et al., 2006), and other publications suggest that a significant amount of dissolved aluminum would not precipitate but may stay dissolved in solution or form extremely small-size colloidal particles, which would not induce head loss across the debris bed on the sump strainer.

Since corrosion of aluminum resulted in the greatest mass released during the dissolution testing, the release rate equation for aluminum incorporated into the chemical model needs to be carefully evaluated. Equation 6-2 in WCAP-16530-NP, the expression for aluminum, is a fit to a combined data set including ICET 1 average release rate. As shown in Figure 5.9-17, the WCAP-16530-NP chemical model underpredicts the aluminum release for the active corrosion part of ICET 1. However, since the 30-day total aluminum release is conservative compared with ICET 1 and the WCAP-16530-NP chemical model assumes 100% precipitation of released aluminum, using this chemical model to estimate the 30-day total mass of chemical precipitates for chemical-effects head loss testing appears to be reasonable if the total precipitates are added at the beginning of the testing.

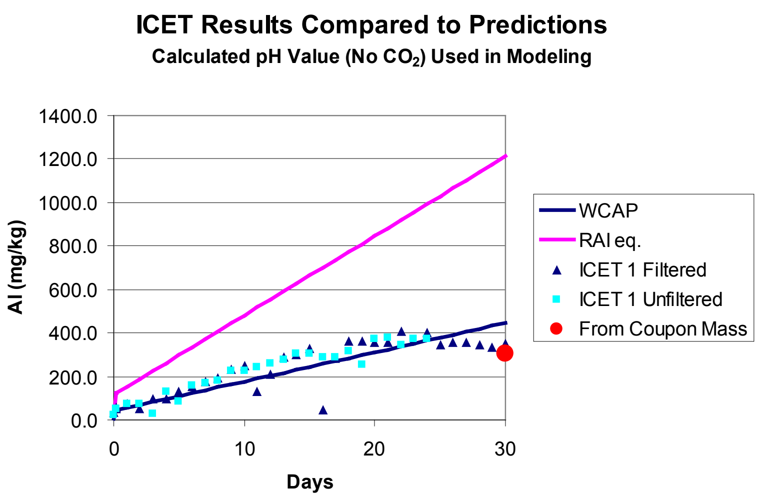


Figure 5.9-17. Aluminum Concentrations with Time Estimated by WCAP-16530-NP Chemical Model in Comparison with Actual Measured Concentrations in ICET 1 (Lane et al. 2008).

The WCAP-16530-NP chemical model assumes that sodium aluminum silicate would precipitate first if there is dissolved silicate, and then the remaining aluminum would precipitate as AlOOH, which is based on the thermodynamic analysis in NUREG/CR-6873. As discussed in a previous section, the thermodynamic analysis suggested sodium aluminum silicate precipitation if aluminum, NUKON, and concrete are present together. This analysis might be correct but needs to be carefully evaluated because the ICETs did not indicate any formation of sodium aluminum silicate precipitate, and thermodynamic modeling is highly dependent on the adequacy of its thermodynamic database. However, if the filterability of the sodium aluminum silicate is comparable with that of AlOOH, which is claimed in this Westinghouse report, the assumption of sodium aluminum silicate formation in the model would be acceptable. Comparison of two precipitates in terms of filterability was performed by ANL head loss testing and is further discussed in one of the following sections.

The chemical model is based on single effects and does not consider multiple materials effect. The ICETs indicated some multiple materials effects, such as Al corrosion inhibition by dissolved silicate (ICET 4) and Si release inhibition by dissolved Al (ICET 5). However, the enhancement of release rates by the multiple materials effect was not evidenced. Therefore, the chemical model based on single effects appears reasonable.

Surrogate Chemical Precipitate

This Westinghouse report provides instructions on preparing chemical surrogates for three major chemical precipitates (AlOOH, sodium aluminum silicate, and calcium phosphate) and qualification criteria for the settling rate of these surrogates. If the settling rate is too high, the prepared surrogate should not be used in head loss testing. The way to prepare surrogates is relatively simple and convenient to follow, but an identification analysis to confirm the surrogate's crystallographic phases was not provided. Rough estimation for surrogate size is available, but size distribution measurements in solution are needed, for example, by using a laser light scattering method. Argonne letter reports suggest that the AlOOH surrogate in WCAP-16530-NP is most likely amorphous (Bahn et al., 2007).

To prepare AlOOH surrogate, aluminum nitrate is added into water, followed by sodium hydroxide. Since in actual post-accident sump conditions aluminum would precipitate in alkaline water, it would be more prototypical if sodium hydroxide were added into water first, followed by aluminum nitrate. This reverse procedure might raise other issue because of strong caustic condition by dissolved sodium hydroxide. As long as the AlOOH surrogate is efficient in inducing head loss across the debris bed, this procedural modification may not be necessary.

Summary and Comments

Important containment material classes were selected on the basis of survey results. Eleven representative materials were tested for dissolution and precipitation. From these tests, three major chemical precipitates were identified: hydrated AlOOH, sodium aluminum silicate, and calcium phosphate. Settling rates and filterability were measured for formed precipitates. However, the measurement of filterability, in this study, was not reliable since the model used to calculate the filter cake coefficient was determined by calculating a precipitate mass measured after drying. These calculations assumed the same degree of hydration between different batches of precipitate and between different precipitates. This may not be a valid assumption. The chemical model was developed from dissolution testing and can predict total precipitate mass during the 30-day mission time under plant-specific conditions. The model assumes that all dissolved aluminum would precipitate, and all released calcium would precipitate in phosphate solution, which is highly conservative for aluminum precipitation. The WCAP-16530-NP report provides instructions on preparing each chemical surrogates and qualification criteria for the settling rate. The chemical surrogates were poorly characterized in terms of crystallographic phases and particle size distributions. However, if these surrogates are highly efficient in inducing head loss across the debris bed, detailed surrogate characterization might not be necessary.

5.9.7.3 WCAP-16530 Follow-on Study

Description of Tests and Procedures at CNWRA

The tests in the follow-on study were conducted at CNWRA. These NRC-sponsored tests (McMurray and He, 2006) focused on a more detailed evaluation of the dissolution characteristics of specific insulation materials and concrete resulting from post-LOCA solutions. They also had the objective of attempting to reproduce the results of the Westinghouse tests in WCAP-16530-NP (Lane et al., 2006). Original models used by Westinghouse assumed that dissolution rates for the same material classes (e.g., different types of fiberglass insulation) had similar dissolution characteristics. The CNWRA tests used different materials (than in the Westinghouse tests) from the five insulation classes, recorded their dissolution rates, and then compared them to the assumptions made in WCAP-16530-NP. A test was done for a concrete coupon in this test. The concrete coupon should be contrasted with a concrete "powder" that was used in the WCAP-16530-NP testing regime. The concrete surface area used in this report is representative of the upper bound of uncoated concrete in U.S. PWRs.

Each of the materials was soaked in 4400 ppm boric acid solutions at pH values of 4.1, 8, and 12 at 265 and 190°F for 90 min. The solutions at pH 8 and 12 were adjusted to their respective pH values using NaOH. The test vessels were allowed to cool for approximately 2 hr before undertaking chemical and SEM measurements and visual observations of the solutions. Additional visual observations of the solutions were made after equilibration at room temperature continued for one day and 85 days.

No settled precipitates were visually observed at the end of the cool down phase of the test. However the CalSil solutions were cloudy. Only one chemical compound was positively identified, Na_2CO_3 on the surface of the Microtherm material. The exact chemical identity of the species creating the cloudy solutions was not ascertained.

Summary of Important Results

The CNWRA tests were a repeat of some of the WCAP-16530-NP methodology tests (Lane et al., 2006) and also some new tests to complement these studies. Both groups performed tests at the same temperatures and at the same three pH values (4.1, 8.0 and 12.0). We contrast the differences results of these tests here.

The first of these differences is the cooling rates afforded to the solutions in contact with the simulated containment materials. The Westinghouse methodology maintained the solutions in equilibrium with the separate test materials at the test temperature (either 190 or 265°F) while performing in-situ filtration through a 0.7 μm filter. The first sets of tests were to determine the concentration of various compounds leached from the test materials. Once these samples were taken at 0.5, 1.0, and 1.5 hr, another volume of liquid was transferred into settling cones at a temperature of 80°F. This second test was to determine the precipitation rate of the cooling solutions. These solutions did not have the containment materials in contact with them either when sample aliquants were removed or when they were in the cooldown phase. The total contact time of the materials with the solutions was 90 min.

In the CNWRA tests the materials were brought to test temperature (either 190 or 265°F) for 90 min. The cooldown was achieved by equilibration of the sample containers with ambient laboratory temperature. These solutions remained in contact with the simulated containment materials during the cooldown. The cooldown took approximately two hours, yielding a total contact time of the solution with the materials of ≈3.5 hr. At the end of the cooldown period, 1 mL aliquant was withdrawn through a 0.45 μm filter. The remainder of the leachate solution was then decanted from the test vessel and put into separate vessels to observe the settling rates at day one and day 85.

The WCAP-16530-NP tests used Teflon containers at 190°F and stainless steel containers at 265°F, as there were container integrity problems with poly-tetrafluorethylene (PTFE) at 265°F. The CNWRA tests were also performed in PTFE vessels at both temperatures andno container integrity problems were noted with this material. The WCAP-16530-NP methodology attempted to provide mixing effects by having the reaction vessel placed on a shaker table during the 1.5 hr equilibration period. Additionally, the WCAP-16530-NP tests fully submerged the materials in the solutions at the start of the tests. The CNWRA tests allowed the samples to sink to the bottom of the test vessel based on material wetting and gravity. The CNWRA tests also did not include any device to enhance mixing or stirring.

The WCAP-16530-NP methodology employed ground, aged concrete for their tests. The CNWRA methodology used solid blocks of concrete. There was no attempt in the SwRI studies to use materials identical to the ones in the WCAP studies. In fact, different materials of the same insulation class were specifically chosen to see if the tests would bear out the hypothesis that all classes of materials in the same insulation type would react the same way.

No precipitates were observed in any of the test vessels after the 2-hr cooling period. Plant-specific materials were used in all of these solutions. However, the solutions with CalSil were cloudy due to the presence of “disaggregation” of the insulation, although there was no visual evidence of physical change to the solid material. Following an equilibration period of 85 days, none of the solutions had precipitates in them. The CalSil solutions were still cloudy, and the only “solid” materials on the bottom were small pieces of the insulation. For the amorphous silica class of insulation materials, significant quantities of silica were released from the pH 8 and 12 solutions vs. the pH 4.1 solutions. For the E-glass classes of insulation materials, greater amounts of silica were dissolved at pH 12 than at pH 4.1. For the aluminum silicate class of insulation materials, higher concentrations of silica were observed in the pH 12 than in the pH 4.1 solutions. The two insulation materials from the aluminum silicate class, Kaowool and Durablanket, reacted to the chemical leaching tests the same way. In high pH solutions of Microtherm insulation, Na_2CO_3 formed. It was only found in the pH 12 solution, but the time of formation is not known because the hydrated form of the solid is transparent. This compound was discovered during the EDS analysis of the Microtherm surface due to the high sodium concentration. It was not identified in any of the other solutions.

Calcium silicate materials demonstrated higher solubilization of calcium at pH 4.1 than pH 8 or 12, and higher concentrations of potassium and silica at pH 8 and 12 than at pH 4.1. Concrete dissolution tests showed that calcium is significantly solubilized at pH 4.1, whereas at pH 12 the principal materials solubilized were silica and potassium. All three pH solutions had sulfur identified in the ppm range (chemical species was not determined).

Comments and Observations

Both of the CNWRA and WCAP-16530-NP methodologies (Lane et al., 2006) provide information regarding the solution chemistry. The slower cooling in the CNWRA tests better represents cooling of a post-LOCA containment pool, while the more rapid cooling in the WCAP-16530-NP tests better represents cooling that may occur in an RHR heat exchanger. In the WCAP-16530-NP tests, the removal of the containment materials from the solution before cooldown is non-conservatem, as it does not represent what happens to the material on the sump strainers where the debris will have cooled in the presence of the post-LOCA pool. Although materials of the same manufacturer were used for both tests, the materials were not of the same production batch. The difference is of some importance, as the insulation is made from mined materials with very little chemical treatment to remove natural impurities. These impurities would not affect the insulating properties of the material but may make their chemical composition slightly different.

The SEM measurements of the fibers from all the solutions (except Microtherm) after the CNWRA test showed no difference with the images of the same materials taken before the test. Specifically, SEM observations showed no evidence of dissolution of the material or precipitation of other substances. No information on how quickly the turbidity in the solutions from CalSil was formed is available in the report with the exception that the cloudy appearance of the CalSil solutions was present after the 2-hr cool down and remained even after 85 days. These materials were referred to as a “disaggregation” of the bulk insulation and not a precipitate. No tests were performed on the filterability of these solutions. No measurements were made of pressure drop during the testing period. The chemical tests of the Microtherm solution and the SEM of the material indicated that a significant amount of silica had dissolved, and an apparent outer layer was formed on the surface of the fibers. Additionally at pH 12, the Microtherm had a deposit that was determined by XRD to be Na_2CO_3. However, it is unclear if this material formed during the dry-out of the insulation or if it was formed in situ from solution.

5.9.7.4 Description of Technical Letter Report on WCAP-16530-NP

This technical letter report (TLR), prepared at ANL (Shack, 2007), reviewed WCAP-16530-NP (Lane et al., 2006). It includes some criticisms of the release equations for Al developed in WCAP-16530-NP and some comments and observations on the surrogates for $Al(OH)_3$ produced by the procedures described in the report. It also summarizes literature results on the solubility of $Al(OH)_3$ in various crystalline and amorphous forms.

For the most part, the calculations of releases proposed in WCAP-16530-NP seem appropriate. The model for calcium release includes a saturation term that is not relevant if phosphate is present, but this has little practical effect for the levels of calcium that would be experienced in the post-LOCA environment. The release rate models in WCAP-16530-NP are based on “one-material-at-a-time” dissolution tests and thus may miss important interactions that can occur in more complex environments. For example, straightforward application of the silica release equation in WCAP-16530-NP would greatly overestimate the release of silica in ICET-1.

There is excellent agreement between the results of the WCAP-16530-NP aluminum dissolution tests and the observed dissolution rate in ICET-1 for days 1–15. However, when comparing predictions of the release rate models with data from ICET-1, the average dissolution rate over the whole 30 days of the test is used. The recommended Al release model in WCAP-16530-NP (Equation 6-2) significantly underestimates releases in ICET-1 over the first 15 days of operation (predicted 11.5 mg/L/day and observed 20.8 mg/L/day) and underestimates the dissolution data in the tests reported in WCAP-16530-NP. It also underestimates somewhat the release rates in ICET-5 (predicted 2.4 mg/L/day and observed 4.1 mg/L/day).

An alternative release model is given in WCAP-16530-NP (Equation 6-1) that seems to better reflect the available data. It should be noted that the coefficients for this equation in Rev. 0 of the report are incorrect. Corrected coefficients in the TLR (Shack, 2007) are in excellent agreement with the WCAP-16530-NP dissolution data and ICET-1 day 1-15 data. This release model seems to over-predict releases in STB environments (predicted 9.4 mg/L/day and observed 4.1 mg/L/day). The assumption in WCAP-16530-NP that all dissolved calcium in TSP environments forms precipitates is reasonable. The assumption that all dissolved aluminum forms precipitates is quite conservative in Al/NaOH and Al/STB environments (ICET-1 and ICET-5, respectively). Some crystalline forms of $Al(OH)_3$, such as gibbsite, have very low solubilities, but the solubility of amorphous forms in the pH range of interest for sumps is significant. However, accurate prediction of solubility limits is difficult since they are sensitive to the choice of the solubility constant and pH. For amorphous materials, literature citations on Al/NaOH solubility have values of 14-54 ppm at 25°C and pH 9.5.

Confirmatory tests at ANL showed that the surrogate $Al(OH)_3$ produced by the procedures described in WCAP-16530-NP produces very fine precipitates that produce high head loss in loop tests. The TLR notes that WCAP-16530-NP does not provide other information, such as solubility under changing pH or temperature conditions that might provide information on whether the products are crystalline or amorphous.

Comments and Observations

The report WCAP-16530-NP (Lane et al., 2006) provides useful data/information, especially on a wide range of insulation materials not included in ICET. However, care should be taken in interpreting the results as they are single-component effects. The study only tests single-effect dissolution; in most cases, only one material in the alkaline NaOH/boric acid solution was tested. The Equation 6-1 release rate in WCAP-16530-NP (with corrected coefficients) gives conservative rates for Al release in all stages of ICET-1 and ICET-5. The Equation 6-2 release rate in WCAP-16530-NP (with corrected coefficients) gives non-conservative rates for Al release in ICET-1 and ICET-5 before passivation of the aluminum. The assumption in WCAP-16530-NP that all dissolved calcium in TSP environments forms precipitates is reasonable. The assumption that all dissolved aluminum forms precipitates is quite conservative in Al/NaOH and Al/STB environments.

5.9.7.5 Description of Technical Letter Report on WCAP-16530-NP Surrogates and STB

In the TLR (Bahn et al., 2007), the procedure given in Westinghouse report WCAP-16530-NP (Lane et al., 2006) for preparing precipitates representing several insoluble aluminum precipitates was used to prepare aluminum oxyhydroxide surrogate product and the properties of this product were studied. Only limited characterization of the product was actually performed, since a head loss test demonstrated that it is very effective in producing head loss. Small-scale tests were also performed to determine the solubility of aluminum in STB solutions as a function of temperature at a pH of approximately 8.3. A long-term (35 days) head loss test with STB buffer was performed to confirm earlier test results.

The solubility of aluminum in NaOH solutions has been studied extensively. Although the crystalline forms such as gibbsite are thermodynamically more stable, experience with ICET-1 suggests that over the time frames of interest, the solubility is controlled by the formation of amorphous products.

For the pH range of interest the most significant soluble aluminum species is aluminate ion, $Al(OH)_4^{-1}$. The equilibrium reaction between the solid phase and its supernatant solution is given by:

$$Al(OH)_3\ (s) + H_2O\ (aq) \rightarrow H+\ (aq) + Al(OH)_4^{-1}\ (aq)$$

The $Al(OH)_4^{-1}$ concentration at equilibrium is a function of pH:

$$\log Al(OH)_4 - = \log K - \log H^+ = \log K + pH$$

Values of the solubility product constant log K are given by Van Straten et al. (1984) and Langmuir (1996) and can be inferred from experiments by ICETs at LANL (NUREG/CR-6915), and ANL bench top and loop tests (NUREG/CR-6913). The data cited in the above research papers are for aluminum/NaOH systems with no other added chemicals. The data from the LANL and ANL tests are for systems with 2800 ppm B and LiOH. The "best estimate" value for log K based on experiments in environments containing boron (present as boric acid) is about 12.2 at room temperature.

The ICET Test 5 suggests that at a pH of 8.4 the solubility of aluminum in STB solutions is about 50 ppm at room temperature (70°F). This value is also consistent with the result of ICET-5-1-B2 (the initial ANL loop test with STB buffers), in which no head loss was observed with 50 ppm after about 12 days of operation at 70°F. These concentrations are much higher than suggested by the literature data under these conditions (≈4 ppm), and this anomaly provides motivation for the small-scale tests on solubility described WCAP-16530-NP.

Studies on the WCAP-16530-NP Surrogates

The procedure in WCAP-16530-NP (Lane et al., 2006), in particular the limitations on the concentrations and the requirements on the settling rates, does seem effective at producing fine precipitates. However, the concentrations in the mixing vessels are still very high compared to the concentrations expected in the post-LOCA sump, ANL 100 ppm loop tests, or ICET-1 tests. No arguments or data are available to show that they are in any physical sense equivalent to the suspensions that would be produced under conditions more representative of those that might occur in a post-LOCA sump. Limited X-ray spectra on surrogates similar to those developed by the WCAP-16530-NP process suggest that they are most likely amorphous but with some indication of crystalline phase.

A head loss test was conducted using the WCAP-16530-NP aluminum oxyhydroxide surrogate. The amount of surrogate precipitate added to the test loop would be equivalent to an original concentration of aluminum of 5 ppm and that completely precipitated from the 119-liter test loop. The pressure increase during the test was extremely rapid, starting just after the few seconds necessary for transport of the injected surrogate solid from the mixing tee to the plate with the NUKON bed. The pressure drop capacity of the system was exhausted almost immediately. No precipitate was visible (≈595 mg was added as solid) in the water approaching the bed, and no buildup of precipitate was visible on the bed.

Studies with STB Buffers

Two series of small-scale tests with initial solutions of STB were performed. In the first test series, Al(NO3)3 was added periodically to solutions held at constant temperature resulting in nominal aluminum concentrations ranging from 10 to 90 ppm. The solutions were carefully examined visually for evidence of the formation of precipitates. In the second test series, sufficient Al(NO3)3 was added to the solution to cause precipitation and have solid material in equilibrium with the supernatant solution. If all the aluminum added would have stayed in solution, this condition would have yielded a nominal aluminum concentration of 400 ppm. The solutions were then held under isothermal conditions for over 22 days. If the solution reached equilibrium with the precipitate during the test, the dissolved aluminum concentration would be equal to the solubility of Al(OH)3 under the given conditions.

In the solubility tests at 80°F, visual observation suggested that precipitation began to occur at concentrations of aluminum in the range of 55 to 66 ppm. The amount of precipitate at these levels was very small and difficult to observe. At levels of 80 ppm and greater, the precipitate was easy to see and clearly evident. In the solubility tests at 100°F, visual observation of precipitation was evident at a concentration of 77-80 ppm. Although precipitates were observed in the 80°F test at 55-66 ppm of Al, the measured concentration in the supernate increased as the nominal concentration was increased.

This finding suggests that either the kinetics of precipitation is sluggish or the precipitate particles are initially smaller than the 0.22 μm filter used to filter the supernate. In the solubility tests at 100°F, the increase in the measured concentration as the nominal concentration was increased was smaller than in the case of the test at 80°F; this difference may indicate that the kinetics of precipitation are faster at the higher temperature.

Precipitation

In the precipitation kinetics tests, all the test solutions were cloudy at the beginning of the tests, but the sample at 120°F looked less cloudy than the samples at 80 and 100°F. After 9 days, the sediment in 80 and 100°F had largely settled, but the 120°F test was still cloudy with no sedimentation. The 120°F test did not show visible sedimentation until 20 days after the test started. The solution pH was 8.3-8.4 for all the tests. The ICP analysis of samples from the tests at the three temperatures shows that after 22 days the solutions had not reached equilibrium concentrations.

The tests were shut down after ≈104 days, but unfortunately, the last samples were taken at 22 days. Because room temperature is not too different from the test temperature for the 80°F test, a sample was taken at 134 days from this solution. Since the higher temperature solutions were allowed to cool, no long-term data were available.

Therefore, the concentrations at 100 and 120°F at 134 days were estimated assuming an exponential decrease in the supernate concentrations. Figure 5.9-18 plots the measured values of aluminum concentration at 22 days for the 80, 100, and 120°F tests, the measured value at 104 days for the 80°F test, and the extrapolated long-term data for the 100 and 120°F tests as a function of temperature. The predicted aluminum solubility based on data in NaOH and boric acid solutions is also plotted. The measured results are much higher than the predicted results. The reasons for these differences are not clear. Previous small-scale tests with NaOH and boric acid at the pH ranges of 9.5-10.0 indicated good agreement with the predicted aluminum solubility data (NUREG/CR-6913).

The predicted results show a monotonic increase of aluminum solubility with increasing temperature, but the measured aluminum concentrations in the supernates after 22 days showed the highest concentration at the lowest temperature. Rather than a difference in solubility, it is likely that the STB solutions can be highly supersaturated at 80°F because the precipitation kinetics is slow. For the 100 and 120°F solutions, the kinetics would be faster so that the observed aluminum concentration in the supernate could be lower than at 80°F. The solubility tests also suggested that the precipitation kinetics is slower at 80°F than at the higher temperatures. The processes could also be made more complex by changes in the kinetics of the transformation of the precipitates from their initial amorphous form to crystalline forms. Because of the slow kinetics, longer-term tests would be needed to get better quantitative estimates of aluminum solubility by this approach.

Since initial head loss tests with STB buffer (NUREG/CR-6913) showed no pressure drop at 50 ppm dissolved aluminum and a large pressure drop at 100 ppm dissolved aluminum, a second head loss test with a STB buffer (ICET-5-2-B2) was performed to evaluate interim concentrations. The temperature and pressure history during the test is shown in Figure 5.9-19.

The test was run with 50 ppm aluminum at approximately 80°F for ≈ 21 days. No increase in pressure drop was observed in the initial test period. After ≈21 days, $Al(NO_3)_3$ was added to increase the nominal dissolved aluminum concentration to 60 ppm. The test was continued for about a day. Then, $Al(NO_3)_3$ was added to increase the nominal dissolved aluminum concentration to 70 ppm. At this aluminum concentration, a notable pressure increase occurred even at 120°F. The pressure drops increased as the temperature was dropped to 100°F and then 80°F. The significant increase in pressure drop between 120°F and 80°F with 60 ppm is consistent with that expected due to the change in viscosity (≈50 percent). The initial increase in pressure drop between 120 and 100°F with 70 ppm (≈20 percent) is also consistent with the change in viscosity (≈20 percent). However, the continued increase in pressure drop with time at 100°F and 70 ppm is indicative of precipitate formation. The increase in pressure drop as the temperature is decreased from 100°F to 80°F (≈30 percent) is consistent with that expected from viscosity alone (≈30 percent). The growth in pressure drop with time at 120°F with nominal 80 ppm Al is clearly faster than with nominal 70 ppm aluminum. The jump in pressure drop as the temperature is decreased from 120°F to 100°F with a nominal 80 ppm aluminum (≈40 percent) is somewhat greater than would be expected from viscosity alone (≈20 percent). The jump in pressure drop as the temperature is decreased from 100°F to 80°F with nominal 80 ppm aluminum (≈40 percent) is again somewhat greater than would be expected from viscosity alone (≈30 percent). The pressure drop increased from ≈0.2 psi at 80°F with a nominal 50 ppm Al to 1.3 psi with 80 ppm Al, and the difference was still increasing when the test was terminated.

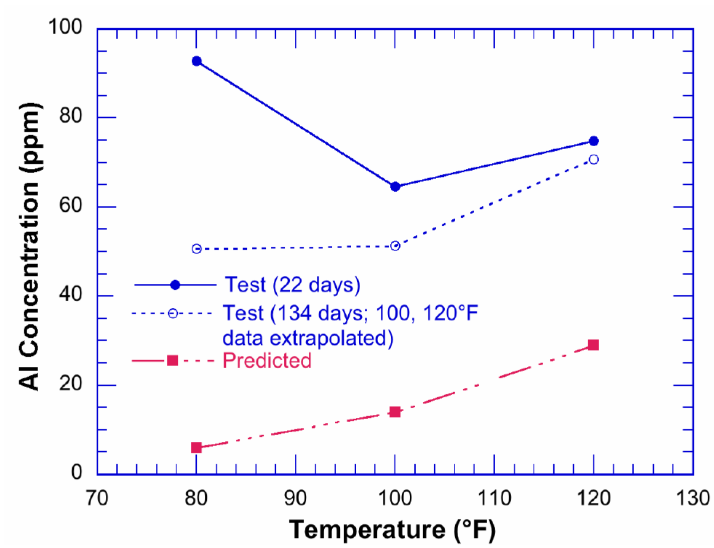


Figure 5.9-18. Measured Al Concentration in the Supernate after 22 Days from the 80, 100, and 120°F Precipitation Kinetics Tests, 134-day Extrapolated Values, and Predicted Solubility (NRC, 2008c).

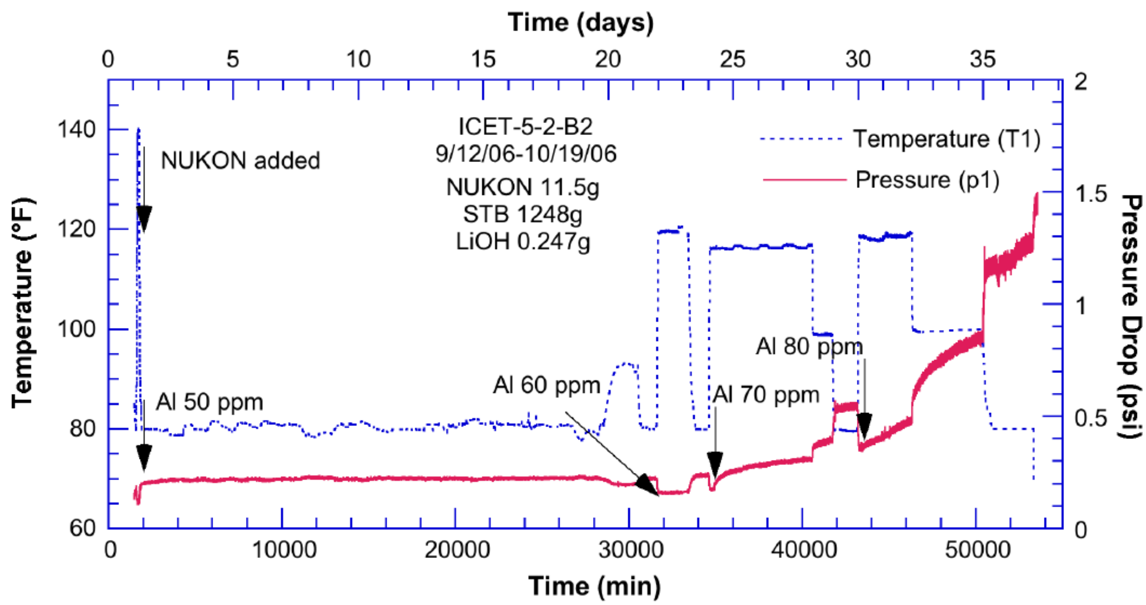


Figure 5.9-19. Pressure and Temperature History during Head Loss Test ICET-5-2-B2 (Bahn et al., 2007).

Comments and Observations

The $Al(OH)_3$ surrogate was prepared at ANL according to the WCAP-16530-NP procedure (Lane et al., 2006). It was tentatively concluded that the precipitate had a fine crystalline structure rather than being truly amorphous. However, regardless of structure, the aluminum oxyhydroxide surrogate that was produced was effective in producing head loss. An amount of surrogate equivalent to the precipitation of 5 ppm dissolved aluminum resulted in immediate blockage of the vertical head loss loop.

A head loss test with STB (pH ≈8.3) with 50 ppm dissolved aluminum showed no measurable head loss increase after 20 days of testing at 80°F. An increase to 70 ppm resulted in the first measurable increase in head loss, and an increase to a dissolved aluminum level of 80 ppm produced more significant head loss. Tests confirm results seen in an earlier head loss test at ANL. The equilibrium solubility limit for aluminum in STB and boric acid solutions with pH ≈ 8.3 is less than ≈ 50 ppm, but kinetics of precipitation are very sluggish, especially at temperatures as low as 80°F.

5.9.7.6 Description of Technical Letter Report on AlOOH and SAS Surrogates

Argonne performed additional testing related to GSI-191 chemical effects as part of technical support provided to the NRC (Bahn et al., 2009a). The purpose of these tests was to evaluate the properties of chemical precipitates that are used in sump strainer head loss testing by certain nuclear industry test vendors. Argonne conducted vertical loop head loss tests to evaluate precipitate filterability and bench-type tests and to investigate precipitate characteristics such as particle size and settlement rate and solubility. Specific precipitates that were evaluated included aluminum oxyhydroxide (AlOOH) and sodium aluminum silicate (SAS) prepared according to the WCAP-16530-NP directions (Lane et al., 2006), along with precipitates formed from injection of sodium aluminate, calcium chloride, and sodium silicate according to the plant-specific test approach.

Head Loss Testing

Argonne had previously performed a vertical head loss loop test with the WCAP-16530-NP AlOOH precipitate. An additional head loss test using the WCAP-16530-NP AlOOH surrogate but at lower concentration was performed. The test confirmed that the surrogate is very effective in increasing the head loss across a glass fiber bed. The test result is consistent with that of the earlier ANL head loss test with the WCAP-16530-NP surrogate. In the ANL loop, only 1.5 ppm Al equivalent of surrogate (29.6 g/m2) can completely plug a glass fiber bed, as shown in Figure 5.9-20.

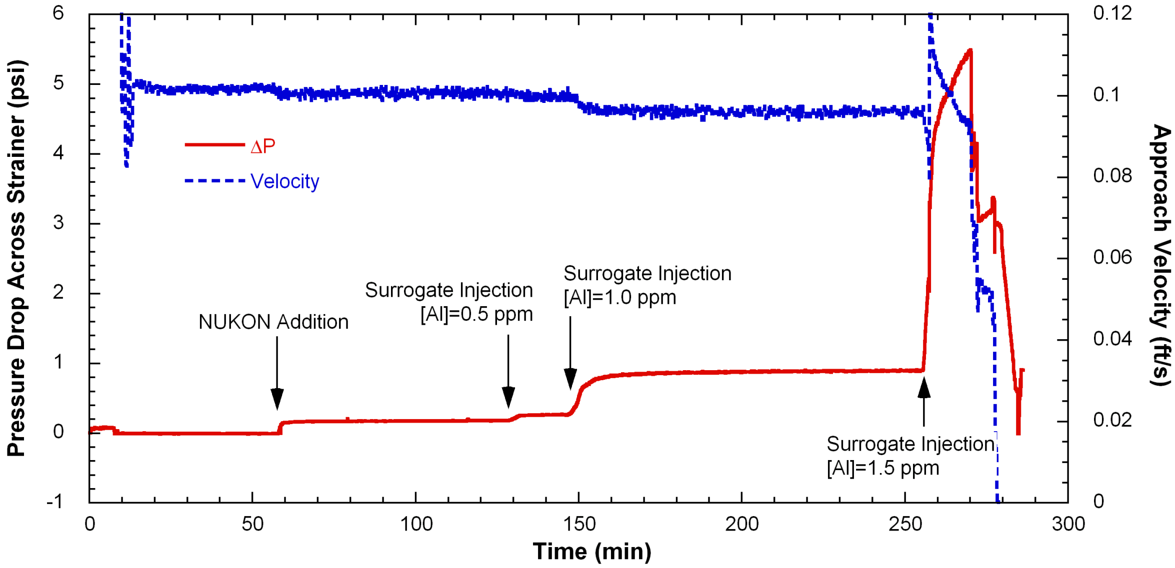


Figure 5.9-20. Pressure Drop and Strainer Approach Velocity vs. Time in a Loop Test using the WCAP16530-NP Aluminum Hydroxide Surrogates (Bahn et al., 2008a).

Tests with the SAS surrogate showed that it is not quite as efficient as the WCAP AlOOH surrogate in increasing head loss. At low levels, the SAS surrogate tends to dissolve, especially in high purity water. However, in tap water, only 2 ppm Al equivalent SAS surrogate (172 g/m2) is needed to generate a significant head loss. Therefore, both surrogates are quite effective in the increase of head loss with a glass fiber debris bed.

Particle Size

The median particle sizes of the WCAP-16530-NP AlOOH surrogates were 13-72 µm, depending on the Al concentration in the mixing tank. For the same mixing concentration, the particle sizes of the SAS surrogate are larger than those of the AlOOH surrogate. The settling rates of the surrogates are strongly dependent on particle size, and the rates are reasonably consistent with those expected from Stokes Law or colloid aggregation models. The particle size distribution of these surrogates was significantly shifted by ultrasonic vibration (i.e. the size became smaller) suggesting that the binding energy between particles in surrogates is relatively low so that the flocculated particle can break apart into smaller particles by external forces. Compared with the precipitate size formed in the ICET-1 solution at room temperature, the WCAP-16530-NP AlOOH surrogates are highly flocculated, but the total Al concentrations are different (375 ppm vs. 1000 ppm). The particle size distributions of various surrogates are universal, consistent with the predictions of reaction-limited colloid aggregation theory.

Plant-Specific Approach

Surrogates were also created using the plant-specific procedure. Although aluminum and silicate were both added to the solution, the aluminum precipitate formed by the procedure probably consisted primarily of aluminum hydroxide, since it would tend to form first in this plant-specific procedure. The characteristics of the precipitates strongly depend on whether in the solutions are made using high purity or ordinary tap water and whether silicates are present or not. In borated and silicated high purity water the aluminum hydroxide precipitates form extremely small particles with sizes of 100-300 nm depending on the total Al concentration. These particles are much smaller than the WCAP-16530-NP surrogates. This finding suggests that the sodium silicate that is present in the plant-specific procedure could act as a deflocculant for the aluminum hydroxide precipitates. In tap water, the aluminum hydroxide precipitates are much larger than those formed in the solutions using high purity water, although they are still somewhat smaller than the WCAP-16530-NP surrogates. The effect of tap water on precipitate size may be attributable to the relatively high ionic strength of tap water due to dissolved cations like Ca^{2+}, Mg^{2+}, Na^{+} and the presence of anions like $SO4^{2-}$, Cl^{-}, etc. The loop head loss tests showed that extremely small aluminum hydroxide precipitates (100-300 nm) produced by using borated/silicated high purity water do not cause significant head loss while the 5.7 ppm Al equivalent of the plant-specific type precipitate made in tap water exhausted the pressure drop capacity of the ANL vertical loop.

5.9.7.7 Description of Technical Letter Report on AlOOH Surrogate Stability at Elevated pH

One acceptable method to the NRC staff for conducting chemical effects head loss testing is to follow the methodology for creating chemical surrogate material as described in WCAP-16530-NP (Lane et al., 2006). Many licensees have employed this method. An assumption in WCAP-16530 is that the water used in head loss testing remains close to a neutral pH. However, during head loss testing, materials such as insulation can leach chemicals that may elevate the pH of the water. The NRC staff requested that ANL evaluate the potential impact that elevated pH may have on the chemical surrogates created using the WCAP-16530-NP methodology (Bahn et al., 2009a).

Bench-scale and loop head loss tests for $Al(OH)_3$ precipitates that can potentially form in sump solutions with high levels of dissolved aluminum (Al) have been performed at ANL with aluminum oxyhydroxide (AlOOH) surrogates prepared as described in WCAP-16530-NP and summarized in a previous section. In previous ANL tests (Bahn et al., 2008a), the characteristics of this surrogate were explored only at near neutral water chemistry. The main objective of these tests was to evaluate whether or not AlOOH surrogates generated using the WCAP-16530-NP procedure are affected by elevated pH.

The stability of the AlOOH surrogate was evaluated by measuring dissolved aluminum concentration as a function of time at different pH values. The solubility of the AlOOH surrogate in tap water increased with pH. In samples filtered through a 0.02 μm filter, 2.3 ppm Al was detected at pH=8.7, while at pH=8.0, the Al concentration was less than the detection limit of 0.5 ppm. As the solution pH decreased over test time because of carbon dioxide from air, the dissolved Al concentration decreased. At pH=9 dissolution occurred rapidly with peak values of the dissolved Al found at times less than 4 hr. The dissolution kinetics were somewhat slower at pH=8.5.

At pH=9.0, the surrogate appears to have a lower solubility in high purity water than in tap water, presumably because the higher ionic strength of tap water enhances the Al hydroxide solubility.

The surrogates made with tap water followed the reaction-limited-colloid-aggregation theory. Although the WCAP-16530-NP AlOOH surrogate particles made with tap water were larger than those made with high purity water at the same pH and total Al concentration (2.2 g of AlOOH/L), the constituent particle size was smaller than that in high purity water. Reaction-limited-colloid-aggregation theory suggests that, although the overall solubility is increased, the higher ionic strength of tap water may enhance the nucleation of Al hydroxide precipitates.

A vertical-loop head loss test at room temperature with solution pH=9.0 was performed with the AlOOH surrogate made with tap water. Figure 5.9-21 shows the pressure drop and flow velocity as a function of time. An AlOOH surrogate addition equivalent to the precipitation of 3 ppm Al from solution caused a 2.5-psi head loss increase. At this pH and temperature, the head loss was very stable over 5 days, even though the bench-scale tests suggest that this amount of Al would be soluble under these conditions. In a previous head loss test with the AlOOH surrogate at neutral pH, a 1.5 ppm Al equivalent addition was enough to plug the bed. This finding suggests that the efficiency of the surrogate on plugging a bed is less at pH=9.0 than at neutral pH, as would be expected from the variation of solubility with pH. Dissolution of the AlOOH surrogate at an initial solution pH=9.0 to a steady state Al concentration occurred quite rapidly. The steady-state concentration was quite stable over time periods on the order of five days. After 5 days the solution pH decreased to 8.91. It was further decreased to 7.60 by addition of nitric acid. The decrease in pH resulted in an increase in head loss of an additional 3 psi for a total head loss of 5.5 psi, but then the head loss gradually decreased and stabilized at 4 psi after 2 days. This decrease in head loss was unexpected because of the decreased solubility of AlOOH at the lower pH. This result may be due to the higher ionic strength induced by the nitric acid addition or the effect of precipitate aging making the precipitates less effective in producing head loss or perhaps some debris bed re-distribution over time.

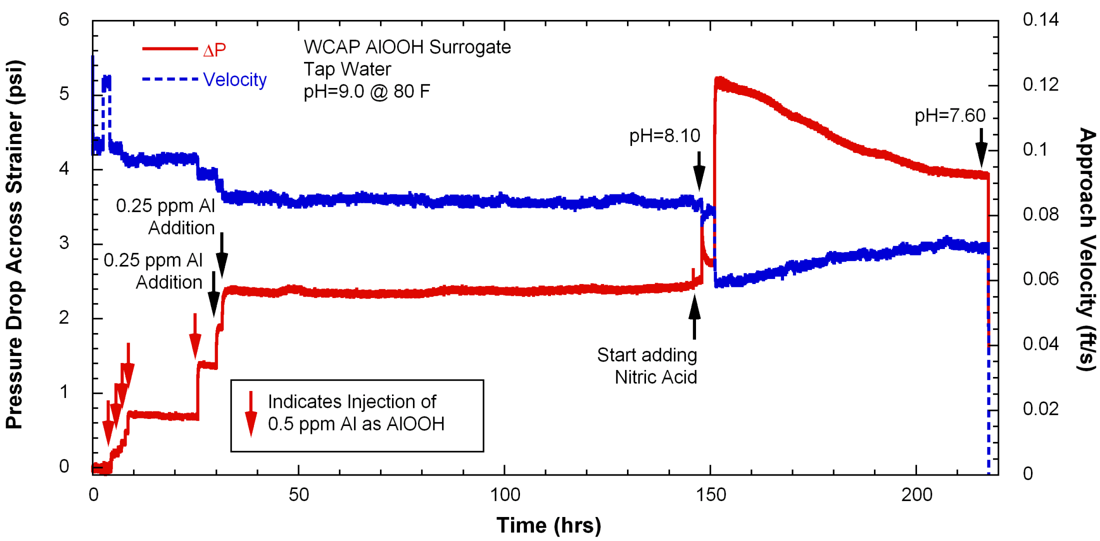


Figure 5.9-21. Pressure Drop Across the NUKON Bed and Approach Velocity as a Function of Time for a Vertical-Loop Head Loss Test with Tap Water at Initial pH=9.0 (Bahn et al., 2009).

5.9.7.8 Description of WCAP-16785-NP and WCAP-16530-NP Refinement

Description of Tests and Procedures

The chemical dissolution model developed in WCAP-16530-NP (Lane et al., 2006) was intended to be generic for all PWRs. In this follow-on report, Westinghouse describes the results of tests which further evaluate the inhibition of corrosion in aluminum and aluminum alloys in the presence of silicates and phosphates at temperatures of 100 and 200°F. The specific areas chosen for testing were silicate and phosphate inhibition of aluminum corrosion, the variability in corrosion rates between aluminum alloys, and the solubility of key precipitates containing aluminum, silica, and phosphate.

This study uses the generic Westinghouse chemical model and applies to it the ICET program parameters to predict the amount of chemical precipitates that will form. This computed result is then compared to the results of the ICETs. Task 1 tested the passivation of aluminum corrosion by silica (at concentrations of 0, 50, 75, 100, and 125 ppm) at a pH of 8.0 and 200°F. The passivation concentration minimum was then tested at various pH values (6.0, 8.0, and 11.0) and temperatures (150 and 200°F). This task also tested the effect that silica had on the passivation of aluminum in the presence of phosphate. Task 2 tested the corrosion rates of various aluminum alloys at pH 8.0. Task 3 measured the passivation of aluminum and its alloys by phosphate at pH 8.0 and 200°F. Task 4 measured the solubility of calcium and aluminum precipitates at various pH values and temperatures and in the presence of silica.

Summary of Important Results and Conclusions

The WCAP-16530-NP (Lane et al., 2006) investigated the solubility of aluminum silicate, aluminum oxyhydroxide, and calcium phosphate precipitates over the range of temperature and solution chemistry anticipated in the post-LOCA environment. It also investigated the inhibition of corrosion (i.e., passivation) of aluminum metal in environments containing TSP and silica. The investigation was focused on aluminum as the major contributor to the ionic content of the post-LOCA environment as a result of aluminum corrosion. Aluminum as the major contributor to dissolved ionic species following a LOCA is supported by WCAP-16530-NP as well as the ICET work documented in NUREG/CR-6914.

All tests were conducted in solutions containing 2500-ppm boron. This was used as the primary "test solution." The range of temperatures and pH conditions tested was selected to bound the long-term equilibrium conditions under which the bulk of the material release and subsequent precipitate formation occurs.

With this as the test objective, the pH of test solutions was adjusted to the following values: 4.5, 6.55, 8.0, or 11.0 at the onset of the measurement process. The lowest pH value (pH 4.5) occurred in the test solution when a small amount of TSP was added (Task 3). The pH value of 6.55 was realized when sodium silicate was added such that the silicon concentration was 75 ppm (Task 1). The pH of ≈8.0 was realized when TSP was added to the solution of boric acid (Task 3). The solutions for this test only used TSP for pH adjustment (i.e., no NaOH was added to these solutions). For tests of passivation, a separate test solution was adjusted to each of the test pH values (using NaOH or TSP), and the temperature was adjusted to either 150 or 200°F before inserting test coupons. These were used in Tasks 1, 3 and 4.

Task 4 measured the solubility of sodium aluminum silicate, aluminum oxyhydroxide and calcium phosphate. In the absence of TSP, with a concentration of 60 ppm aluminum and 178 ppm silica, a precipitate formed at both 80 and 140°F at pH 8.0. Solutions containing 99 ppm aluminum and 294 ppm silica, with TSP used as a buffer, formed precipitates at pH 8.0 and 200°F.

Aluminum and silica were added to a solution of 2500 ppm B (pH 8.0 using NaOH) at a temperature of 200°F. The precipitate solubility was calculated by incremental additions of the aluminum and silica solutions until precipitation occurred. The limit of solubility for $NaAlSi_3O_8$ at 80°F is between 40 and 60 ppm aluminum with 119-178 ppm silica.

At a solution temperature of 200°F and a maximum aluminum concentration of 98 ppm, no precipitates were observed for 30 days at any pH value. No precipitate was observed in the 140°F test solution at 40 ppm aluminum for up to 30 days at pH 8.0. Solutions of AlOOH just below the solubility limit were cycled between 200 and 80°F over a four-day period. No details were provided concerning the rate of temperature change during cycling. No precipitation occurred. Additionally, the pH was varied from 8.0 to 7.0 and from 8.0 to 9.0 at constant temperature (200°F), and no precipitate formation occurred. Calcium phosphate was found to be insoluble at all pH, concentrations and temperatures tested.

The corrosion coupons were immersed for a total of either 12 or 24 hr. Task 1 in this study showed the 24-hr corrosion rate of aluminum was lower than the 12-hr corrosion rate of aluminum (this is a usual circumstance in corrosion rate measurements) in both solutions adjusted with the different buffers. The aluminum corrosion rate decreased over the concentration range of 0 to 75 ppm silica from 9.5 mg/m2/min. where it leveled off at <2.0 mg/m2/min after a 24-hr period.

Similar passivation of aluminum by silica was observed using the same test conditions as above with TSP added as the buffer (bringing the solution to pH 8.0). This task also demonstrated that the corrosion rate of aluminum in silica solution increased greatly with increasing pH for both 150 and 200°F tests.

Task 3 tested the ability of only phosphate to passivate aluminum alloy 1100. At pH 8.0 and at 200°F, the amount of aluminum dissolved decreased by a factor of 3.6 using TSP. Reductions in corrosion were realized at a pH 9.0 as well as at higher temperatures when compared to solutions with no phosphates.

WCAP-16785-NP (Reid et al., 2007) developed an equation for multi-variate aluminum release rate for inhibition by silicate and a similar equation for phosphate, which they claim to be valid in the pH range of 4.5 to 9.0 and below 200°F. Above pH 9.0, the equation for original aluminum release rate should be used.

Additional tests in Task 1 identified that the Westinghouse model for aluminum corrosion in WCAP-16530-NP (Lane et al., 2006) was more conservative than the actual measured corrosion rates, evaluated at both temperatures. Task 2 measured the corrosion rates of three aluminum alloys: 3003, 5005, and 6061. The corrosion tests were performed for 12 and 24 hr at a temperature of 200°F in 2500 ppm boron solution adjusted to pH 8.0 using NaOH. The corrosion rates were compared to the rate of aluminum alloy 1100 corrosion.

The conclusion presented in the WCAP-16530-NP report is that the difference in corrosion rate of aluminum alloys (as compared to aluminum metal) under identical conditions as in Task 1 was negligible. Another conclusion was that, due to the variety of aluminum alloys used in plant applications, the net reduction in aluminum-generated precipitates would be low.

Task 3 tested the passivation of aluminum in TSP-buffered boric acid solution without added silica. The aluminum corrosion with silica was one-fifth that without silica. The tests also showed a significant decrease in passivation when the TSP solution is brought to pH 9.0. Westinghouse again developed a multi-variate equation to model the corrosion as a function of pH and temperature. This model, as before, showed that there is significantly less passivation from the model than from actual testing.

Comments and Observations

Additional testing was performed to study TSP and silica inhibition of aluminum corrosion. Based on the overall application of inhibition and alloy-specific corrosion rates, it may be possible for an individual plant to use these results to demonstrate a lower aluminum release rate compared to the WCAP-16530-NP base model (Lane et al., 2006). During corrosion testing, however, the aluminum coupons were placed on the bottom of the Erlenmeyer flask. This creates a crevice between the flask and coupon over part of the sample, affects the surface area of the coupon exposed to the bulk solution, and could introduce variability in results.

The temperatures and pH values at which measurements were made were not exactly the same as those of other studies and within this study itself. It was very difficult to make direct comparisons of different corrosion rates for aluminum for this reason. As an example the silicate inhibition tests were run at 150 and 200°F and at pH values of 6.55, 8.0, and 11.0. The pH of 6.55 resulted from the addition of basic sodium silicate. Other passivation tests were performed at pH 4.5. The pH of all the solutions was measured after precipitation and was at the target pH (with the exception of the 6.55 value). This finding indicates that TSP was not the limiting reagent in the precipitation reactions. No confirmatory analyses (e.g., XRD) were performed on the precipitates. It was assumed that sodium aluminum silicate, aluminum oxyhydroxide, and calcium phosphate were the precipitates that formed in those tests, and no others.

As a preliminary effects study, this is a good basis. However, there is a tacit assumption that other materials that will be present in the sump environment will have no effect on these measurements. Based on the experimental evidence here identifying that the theoretical model originally used overestimates the mass of precipitates formed, the assumption of no synergistic effects is not justified.

5.9.7.9 Aluminum Chemistry and Aluminum Corrosion Products

Previous ANL head loss tests for $Al(OH)_3$ precipitates that can potentially form in sump solutions with high levels of dissolved Al have been performed with surrogates proposed by industry or by forming precipitates in situ with $Al(NO_3)_3$ as the source of dissolved Al (Bahn et al., 2008c). In a post-LOCA environment, the precipitates would be formed in situ with the source of the Al being dissolution of Al due to corrosion of Al metal, and NO^{3-} would not likely be present in amounts comparable to those encountered when $Al(NO_3)_3$ is the source of dissolved Al. The current head loss tests were performed with the source of Al being corrosion from Al alloy plates. The objective of these tests was to compare head loss associated with precipitate formation from aluminum coupon corrosion with those using WCAP-16530-NP precipitates or with precipitates formed in situ as a result of chemical injection.

The head loss tests were performed in the ANL vertical loop with 6061 Al alloy and "commercially pure" 1100 Al plates immersed in borated solution. The Al release rate from 6061 Al alloy in borated water at a pH=9.35 (at room temperature) and 140°F with a flow rate of

0.1 ft/sec was similar to predictions based on data from bench-top tests and low-flow rate tests with 1100 and 3003 Al alloys. However, the Alloy 1100 corrosion rate was higher than predictions based on data from benchtop tests and appears to be flow dependent.

Figure 5.9-22 shows the pressure drop across the debris bed and temperature as a function of time. Alloy 6061, when allowed to corrode in a flowing loop, created a significant head loss at an Al concentration of 116 ppm with a pH of 9.35 and a temperature of 140°F. An additional increase in the head loss was observed when the temperature was lowered from 140 to 80°F. Post-test examination revealed that grayish black particles were trapped in the glass fiber bed. Stagnant bench-top corrosion tests with Alloy 6061 also showed grayish black particles, which were released from the coupon surfaces rather than being generated as a precipitate from the solution. Based on microscopic analyses, it was concluded that the grayish black particles were intermetallic particles present in the alloy that were released by corrosion of the alloy matrix. The intermetallic particles were primarily (FeSiAl) ternary compounds ranging in size from a few tenths of a micrometer to 10 µm. The ANL bench-top tests and other loop tests showed that the solubility limit for $Al(OH)_3$ at pH=9.35 (at room temperature) and 140°F is significantly greater than 116 ppm Al. This result indicates that the head loss at 140°F was induced by the intermetallic particles present in the 6061 Al alloy. As the temperature of the loop was decreased, additional head loss occurred due to the formation of $Al(OH)_3$ from the decrease in temperature (i.e. the dissolved aluminum exceeded its concentration limit at the lower temperature).

Another head loss test was conducted with 1100 Al plates. Figure 5.9-23 shows the pressure drop and temperature variation with time. With an Al concentration of 118 ppm in the loop from corrosion of 1100 Al plates, no significant increase in head loss was observed at 140°F. Post-test examination for the glass fiber bed and bench-top test results confirmed that Fe-Cu enriched intermetallic particles were present in the 1100 Al, which were released and captured in the bed during the loop test. The differences in head loss behavior associated with the intermetallic particles may be attributed to the sizes of the intermetallic particles in 6061 Al alloy being typically larger than those in 1100 Al alloy. At the Al concentration of ≈118 ppm no significant increase in head loss was observed in the 1100 Al test until the temperature was decreased to 100°F. This increase appeared to be induced by Al hydroxide precipitation, not by intermetallic particles. Once the head loss began to increase, a rapid increase in head loss was observed, even though the temperature was increased from 100 to 120°F.

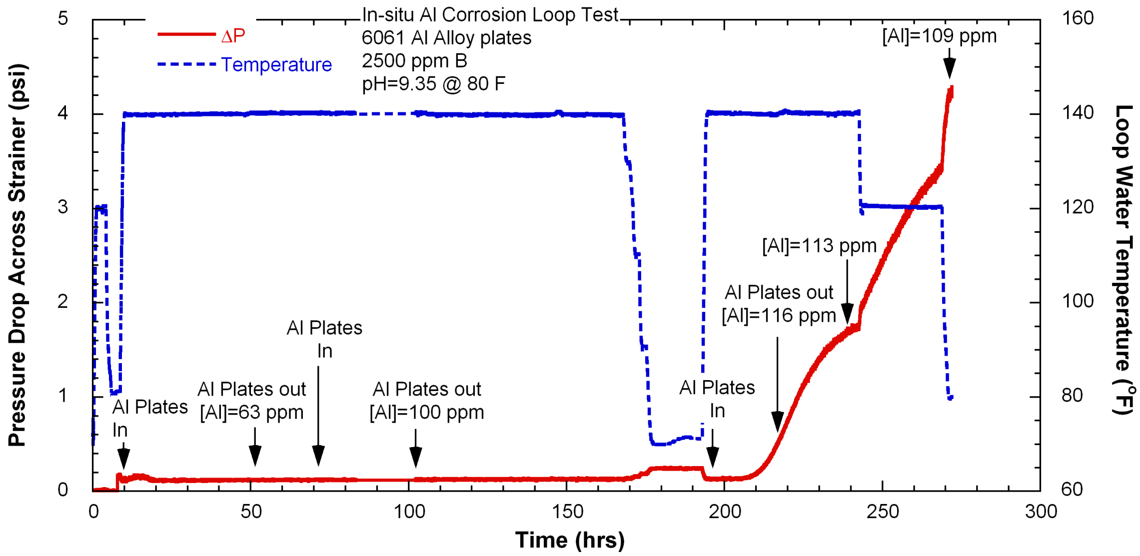


Figure 5.9-22. Pressure Drop and Loop Water Temperature vs. Time in a Loop Test using 6061 Al Plates with 2500 ppm B, Initial pH=9.35 Solution, and Temperature of 80°F (Bahn et al., 2008c).

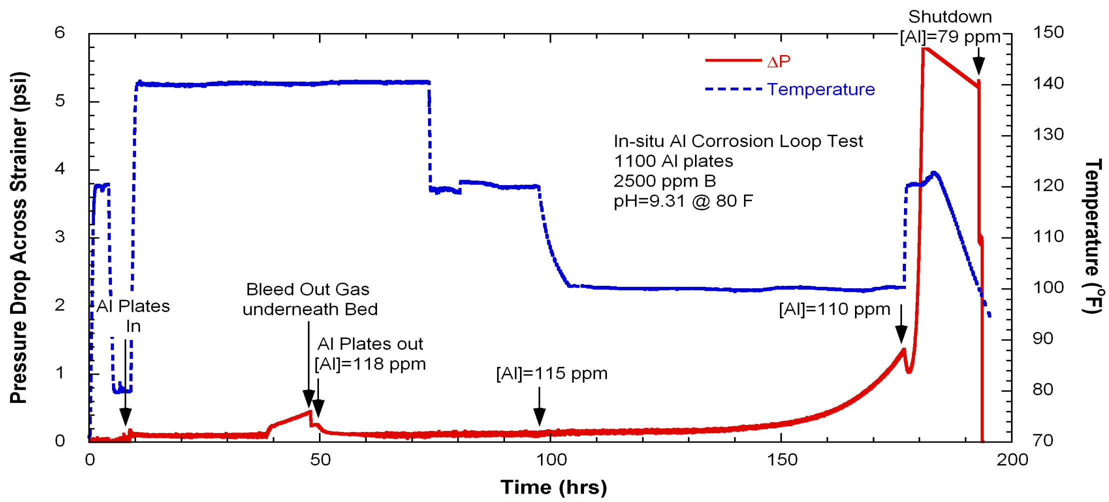


Figure 5.9-23. Pressure Drop across the Strainer and Temperature vs. Time in 1100-Al Loop Test (Bahn et al., 2008c).

The vertical-loop head loss tests for Al corrosion with 6061 and 1100 Al plates seem to suggest somewhat lower solubility than the chemical Al tests. This difference may be due to heterogeneous nucleation of Al hydroxide on intermetallic particles and/or on the surfaces of preexisting Al hydroxide precipitates. This Al solubility issue is further discussed in a later section. The test results suggest that the potential for corrosion of an Al alloy to result in increased head loss may depend on its microstructure (i.e., the size distribution and number density of intermetallic particles), as well as its Al release rate.

The increase in head loss due to in situ precipitation of Al(OH)3 observed in these tests seems reasonably consistent with that expected from the addition of corresponding amounts of the WCAP-16530-NP surrogate. Per unit mass of Al removed from solution, the WCAP-16530-NP surrogate appears somewhat more effective in increasing head loss than the $Al(OH)_3$

precipitates formed in situ by corrosion or chemical addition of Al, and thus it gives conservative estimates of the head loss due to the precipitation of a given amount of Al from solution. However, in choosing the amount of surrogate that should be used, consideration should be given to the potential for additional head losses due to intermetallic particles and the apparent reduction in the effective solubility of Al(OH)3 when intermetallic particles are present.

5.9.7.10 Long-Term Al Solubility Test

Long-term $Al(OH)_3$ solubility tests were conducted in solutions containing 2500 ppm B, and 40-98 ppm Al, using aluminum nitrate or sodium aluminate as the Al source (Bahn et al., 2008b). The solution pH values were adjusted to achieve target pH ranging from 7.0 to 8.5. The solution temperature was cycled to obtain a temperature history more representative of ECCS temperatures during operation in the recirculation mode after a LOCA in a PWR. Figure 5.9-24 shows the temperature history used in the long-term solubility test.

Precipitates were observed to form as fine, cloudy suspensions, which showed very little tendency to settle; under certain conditions, they formed as flocculated precipitates, which appeared on the inner surface of the test flasks. Table 5.9-8 shows the indication of precipitate formation under each test condition. The flocculated precipitates had an average diameter of 4-6 µm. Based on prior ANL head loss tests with surrogates (Bahn et al., 2008a), they would be expected to cause significant increases in head loss in glass fiber beds. Very fine precipitates associated with the cloudy solutions were less effective at causing head loss in the ANL vertical loop with a fiberglass-only bed, but could cause a different head loss response given different bed conditions (e.g., in cases where pore sizes are smaller than in fiberglass-only beds). The flocculation tendency of the precipitates can be qualitatively explained in terms of ionic strength or solution pH based on a colloidal stability theory referred as the Derjaguin, Landau, Verwey and Overbeek (DLVO) theory. The effect of solution pH is related to the zeta potential change on the particle surface according to this theory, and the effect of the total Al concentration is related to the resulting increased particle concentration, which tends to increase flocculation.

The Westinghouse report WCAP-16785-NP (Reid et al., 2007) also provides 30-day solubility data at 140 and 200°F for $Al(OH)_3$. The WCAP-16785-NP estimated that Al hydroxide solubility at 140 and 200°F is 40 and 98 ppm, respectively, for pH of 8.0. The Westinghouse tests considered limited temperature perturbations, but based on the results in this report from tests with increased thermal cycling, these limits still appear to be reasonable. WCAP-16785-NP also states that perturbations in pH down to 7.0 did not affect these results. However, those tests in which the pH was decreased to 7.0 appear to be short term and were only performed at 200°F with 40 ppm Al. The results in this report suggest that the solubility limit at pH=7.0 is less than 40 ppm, even at 200°F.

The thermal cycling intermittently introduced during the long-term solubility testing did not induce rapid precipitation. Thermal cycling did not cause either instantaneous Al hydroxide precipitation from clear solution or additional precipitation from already precipitated solution. A typical thermal cycling time of 30 min might not be sufficient for incubation of Al hydroxide precipitate in the temperature range (60-27°C) of interest. However, this result does not necessarily exclude the possibility that precipitation would be enhanced by the thermal cycling at a heat exchanger because one ANL loop head loss test showed that the head loss decreased but rapidly increased again after the temperature increase from 100 to 120°F. More systematic experiments are needed to evaluate this issue.

Table 5.9-8. Indication of Precipitate Formation as either a Cloudy Suspension or a Flocculate in Test Solutions on Cooling from 200 to 80°F (Bahn et al., 2008b).

Total Al Concentration (ppm)	Initial Solution pH at Room Temperature Before Adding Al Solution			
	7.0	7.5	8.0	8.5
98	●a	●	△[b]	ND[c]
70	●	●	ND	ND
55	●	△	ND	ND
40	ND	△	△	△[d]

[a] Solid symbols indicate precipitates were flocculated.
[b] Open symbols indicate precipitate was a cloudy suspension and not flocculated.
[c] ND indicates no test data are available.
[d] Solution became cloudy after cooling down from 100 to 80°F.

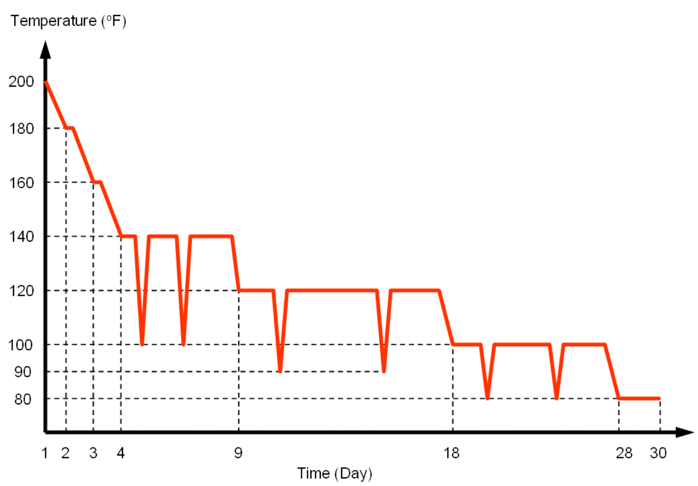


Figure 5.9-24. Typical Solution Temperature History for the 30-day Al Solubility Tests (Bahn et al., 2008b).

5.9.7.11 Aluminum Solubility Curve

A degree of supersaturation Π_j of aluminate with respect to aluminum hydroxide having crystallographic phase, j, in alkaline environment is given by the equation (Van Straten et al. 1984)

$$\Pi_j = \frac{a_{Al(OH)_4^-} \cdot a_{H^+}}{K_{sp,j}}$$

where a_i and $K_{sp,j}$ denote the activity of ionic species i and solubility product of aluminum hydroxide having crystallographic phase j, respectively. There are several crystalline forms for aluminum hydroxide, for example, , pseudoboehmite, boehmite, bayerite, gibbsite and an amorphous form. Taking log to the base 10 of the above expression leads to

$$\log \Pi_j = \log a_{Al(OH)_4^-} + \log a_{H^+} - \log K_{sp,j}$$
$$pH + p[Al]_T = p\Pi_j + pK_{sp,j}$$

In these expressions, p[Al]T denotes the negative log to the base 10 of the activity of aluminate ion. The reaction shows that Π_j increases with a decrease in pH + p[Al]T; if the solution pH increases at a constant aluminum concentration, Π_j decreases, and if aluminate ion concentration increases at a constant pH, Π_j increases. By using the parameter pH + p[Al]T, all the test results reported in the ANL long-term solubility tests can be combined in a pH + p[Al]T vs. temperature domain (see Figure 5.9-25). In this figure, p[Al]T denotes the negative log to the base 10 of the total aluminum content in solution either as dissolved or precipitated form in units of mol/kg. At relatively lower concentration, replacing activity with molal concentration does not induce a large error. Three distinct regions are revealed: no precipitation, non-flocculated precipitation, and flocculated precipitation. Since precipitation/non-precipitation was determined by visual observation, extremely fine precipitates (<100 nm) might be present in the non-precipitation region. It appears that the boundary of the flocculated precipitation region is almost independent of temperature while the boundary between the non-flocculated precipitation and no-precipitation regions shows a dependency on temperature.

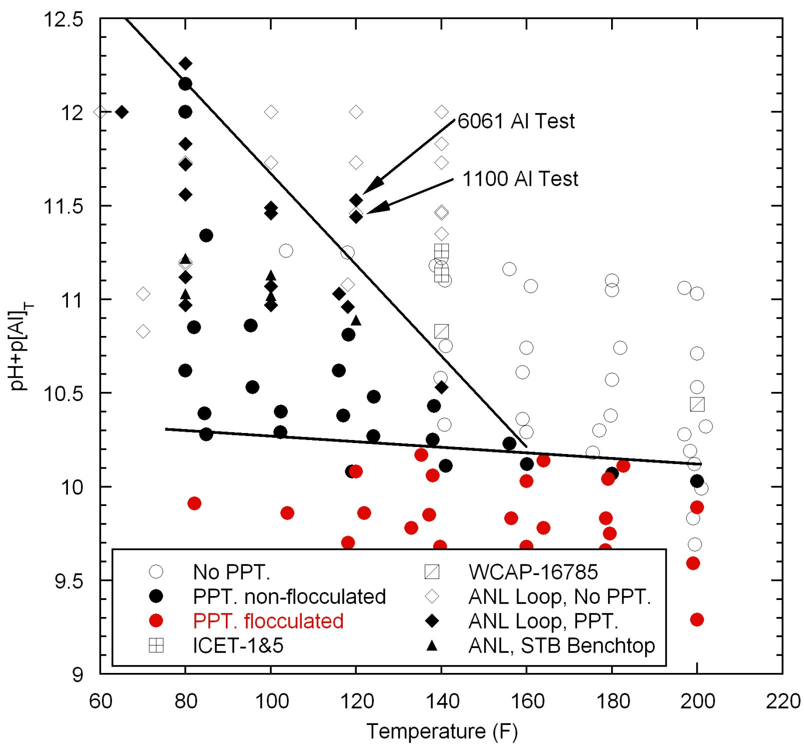


Figure 5.9-25. Al Stability Map in the pH + p[Al]T vs. Temperature Domain for Solutions Containing Boron. Filled and open symbols mean the occurrence of Al hydroxide precipitation and no precipitation, respectively; pH and p[Al]T are the solution pH at temperature and the negative log to the base 10 of the total aluminum content as dissolved or precipitated in units of mol/kg (Bahn et al., 2008d).

Since using pH + p[Al]T is a convenient way to display and compare solubility test results obtained under various test conditions, previous ANL test results and literature data were combined with current long-term solubility test results in Figure 5.9-25. In this figure, the filled symbol indicates Al hydroxide precipitation was observed at that test condition, and an open symbol indicates Al hydroxide precipitation was not observed. The circle symbols represent the ANL long-term solubility test data (Bahn et al., 2008b), including some room-temperature data points from the previous ANL report (NUREG/CR-6913). In cases where the precipitates were flocculated, a filled square symbol was used. The saturated Al concentrations observed in the ICET-1 and -5 (NUREG/CR-6914) are plotted along with the solubility test data at 140 and

200°F reported in WCAP-16785-NP (Reid et al., 2007) and the ANL bench-top test data in STB solution (Bahn et al., 2007). The previous ANL head loss test data associated with Al hydroxide precipitates (NUREG/CR-6913 and Bahn et al., 2008a) including the two Al alloy plate tests (Bahn et al., 2008c) are designated by diamond symbols. The boundary between precipitation and non-precipitation area appears to be well represented by a straight line that depends on solution temperature up to 71°C (160°F). Above 71°C, the dependence of the boundary between precipitation and non-precipitation on solution temperature is weaker. The data from the loop tests appear to indicate less solubility than bench-scale test data. The loop tests using chemical Al sources such as aluminum nitrate are relatively close to the proposed boundary shown in Figure 5.9-26. However, two data points obtained from the Al corrosion loop tests at 49°C are located above the proposed boundary line.

Based on the solubility data summarized in Figure 5.9-25, bounding estimates of aluminum solubility in alkaline environments containing boron were obtained. The Al solubility was estimated with and without inclusion of data from the Al corrosion loop tests. The bounding curves were drawn based on engineering judgment.

Because we are interested in alkaline solutions, the chemical form of the dissolved Al is $Al(OH)_4^-$, and p[Al]T can be replaced by $-\log[Al(OH)_4^-]$, where $\log[Al(OH)_4^-]$ is log to the base 10 of the molal concentration of $Al(OH)_4^-$. One mole of $Al(OH)_4^-$ has one mole of Al, which is equivalent to 26.98 g.

The upper line in Figure 5.9-25 bounds all data except for the two data points from the Al corrosion loop tests and one other data point from another loop test based on chemical additions and is given by

$$\log\left[Al(OH)_4^-\right] = pH - 14.1 + 0.0243T \qquad (T \leq 162\ ^\circ F)$$

$$\log\left[Al(OH)_4^-\right] = pH - 10.41 + 0.00148T \qquad (T > 162\ ^\circ F)$$

where T is the temperature in degrees Fahrenheit. Therefore, the solubility of Al in units of ppm can be expressed as:

$$\left[Al(ppm)\right] = 26980 \times 10^{pH-14.1+0.0243T} \qquad (T \leq 162^\circ F)$$

$$\left[Al(ppm)\right] = 26980 \times 10^{pH-10.41+0.00148T} \qquad (T > 162^\circ F)$$

Estimates of Al solubility as a function of pH and solution temperature based on the above expression are shown in Figure 5.9-26. The data in this figure show that the predicted Al solubility values form a lower bound on the available solubility data in alkaline solutions containing boron, except for the Al corrosion loop tests.

Shifting the solubility estimate upward to bound the two data points from the Al corrosion loop tests gives

$$\log\left[Al(OH)_4^-\right] = pH - 14.4 + 0.0243T \qquad (T \leq 175\ ^\circ F)$$

$$\log\left[Al(OH)_4^-\right] = pH - 10.41 + 0.00148T \qquad (T > 175\ ^\circ F)$$

The corresponding solubility of Al in units of ppm can be expressed as:

$$[\text{Al(ppm)}] = 26980 \times 10^{\text{pH} - 14.4 + 0.0243T} \quad (T \le 175^{\circ}\text{F})$$
$$[\text{Al(ppm)}] = 26980 \times 10^{\text{pH} - 10.41 + 0.00148T} \quad (T > 175^{\circ}\text{F})$$

The solubility values based on the above expression are more conservative, i.e., they predict a lower value for the amount of Al that can be present before precipitation occurs, shown in Figure 5.9-27. The data in this figure give a lower bound on all the available solubility data (including loop tests) in alkaline solutions.

Most of the available high temperature (>140°F) data come from long-term Al solubility tests at ANL. The test solution was alkaline or near neutral and composed of boric acid and sodium hydroxide. Aluminum was added as sodium aluminate. The temperature history was to be representative of the temperature of the reactor coolant as it passes through the core, a heat exchanger, and the sump after a LOCA. The test durations at higher temperatures (>140°F) are short, no more than one day at each temperature. The relatively short test times and the presence of boric acid in the test solution should be kept in mind when applying the proposed Al solubility curves at relatively high temperatures (>140°F) or in boron-free environments. In a boron-free environment the Al solubility may decrease significantly.

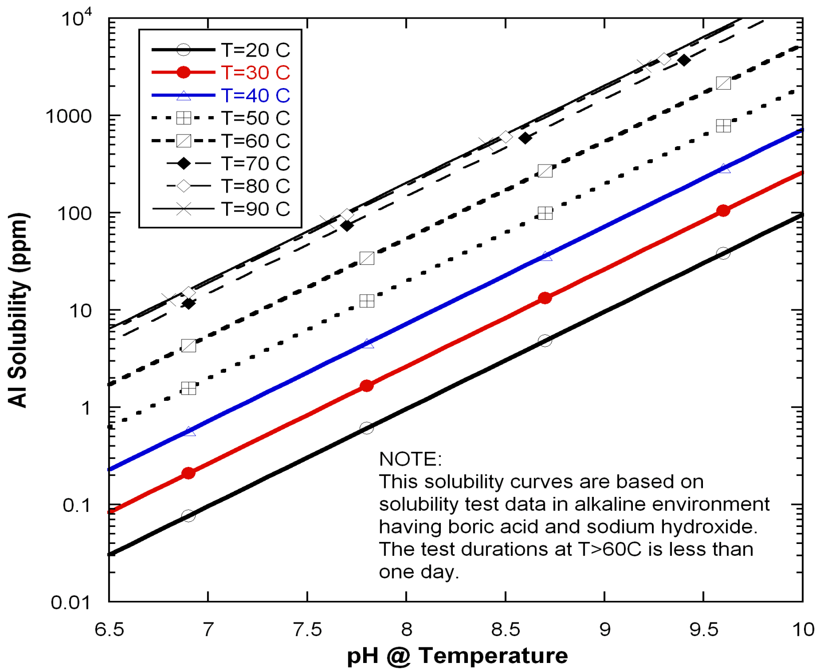


Figure 5.9-26. Al Solubility Curves as Functions of pH and Temperature without Considering Test Data from Al Corrosion Loop Tests (Bahn et al., 2008d).

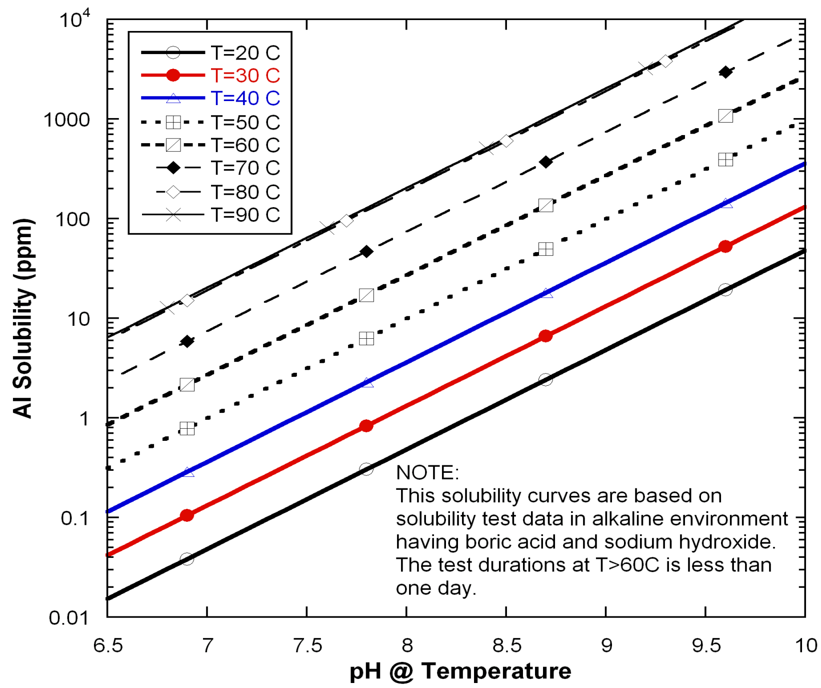


Figure 5.9-27. Al Solubility Curves as a Function of pH and Temperature with Consideration of Test Data from Al Corrosion Loop Tests (Bahn et al., 2008d).

5.9.7.12 Alternative Buffers

Description of Tests and Procedures

The two most common buffering agents in PWRs are NaOH and TSP. Sodium tetraborate (STB) is used in ice condenser plants, although several plants with large dry containments have recently switched to STB due to calculated reductions in post-LOCA precipitates with this buffer. Both NaOH and TSP can be easily employed as pH control agents for the post-LOCA environment. Both form precipitation products in this environment, which can lead to clogging of containment sump strainers. The Westinghouse report WCAP-16596-NP (Reid et al., 2006) examined the feasibility of using other buffering agents that would not have the deleterious effects of strainer clogging.

The buffering agents that were compared during this testing regime were TSP, sodium metaborate (SMB), STB, sodium gluconate (SG), and sodium tripolyphosphate (STPP). The stated objectives of the test program were to evaluate selected candidate buffers against the following criteria:

- Quantity of material required to adjust pH to target value
- Dissolution rate of the material in water at post-LOCA sump temperatures
- Affordability and ready availability
- Absence of demonstrated deleterious effects, e.g., corrosion to key containment structural materials

Other factors evaluated included

- Does not adversely affect the solubility of boric acid or lead to an increase in boric acid precipitation on structures.

- Is resistant to degradation from radiation, elevated temperatures, and humidity, i.e., long storage life in the containment environment.
- Is non-hazardous material, i.e., does not create habitability concerns during storage or handling.
- Will not cause significant release of metal oxide deposits from the fuel or primary coolant system surfaces.

These objectives were tested using seven steps that attempted to ascertain the properties of the buffering agents under a variety of conditions in the post-LOCA environment. The seven steps were the following:

1 Dissolution of the buffering agent at 150°F in demineralized water.
2 Adjustment of the pH of boric acid solutions to several different concentrations using the buffering agent.
3 Dissolution of the buffering agent at 100°F in 2500 ppm boric acid solution.
4 Assessment of calcium and aluminum effects on a solution containing 2500 ppm boron with enough of the buffering agents to bring pH to 8.5.
5 Corrosion test (2 week trial) of the effects of each of the candidate buffer solutions (2500 ppm boron adjusted to pH 8.0) on pure aluminum and A508 steel (carbon steel).
6 Long-term (30 days) test at elevated (150°F) temperature and 100% or 30% relative humidity of candidate buffer solid stability.
7 Solubility stability test with boric acid solutions at boiling by adding each of the candidate buffers.

The performance goal for Test 1 on these buffering agents was that the final simulated post-LOCA solution would have a pH above 8.0. Although the regulatory position on this issue is that the minimum acceptable pH is 7.0, Westinghouse decided to make the requirements for pH control more stringent to account for any acidic materials that may form from radiolysis of organics (such as cable wrap materials that may contain chlorides) in containment.

Summary of Important Results and Conclusions

Six buffering agents (NaOH, TSP, SMB, SG, STB, and STTP) were identified at the start of this project. The important characteristics were solution stability, pH buffering capacity, low probability of forming insoluble precipitates or gels, and cost. The overall conclusion was that STB is the best alternative to TSP for plants with appreciable calcium-containing materials. Buffer TSP is recommended for plants with very little contribution from calcium-containing materials. In addition, SMB was identified as a suitable replacement for NaOH, although the SMB would need to be in solution due to its solubility characteristics.

Sodium gluconate was eliminated as a possible buffering agent as it did not meet the Test 1 requirements for final pH. All buffering agents dissolved between two hours and 21 minutes and five hours and 20 minutes. As a comparison, the TSP dissolution took place in two hours and 20 minutes. The buffers TSP, SMB, and STB all used similar mass quantities to achieve pH values >8.0 in 2500 ppm boron solutions. Sodium hydroxide took much less, and STPP could not achieve a pH of greater than ≈7.5 regardless of mass added. The buffers STB, TSP, SMB and STPP all achieved solubility in 2500 ppm boric acid solution at temperatures of 100, 150 and 200°F, without any precipitation of boric acid.

All recommended buffers increased the solubility of boric acid. A formal calculation is provided to allow plants to accurately estimate the SMB or STB concentration required in the final volume of post-LOCA liquid to achieve an acceptable pH. The buffering agents tested are rated as excellent, good, or poor for each of the testing areas and depend upon the environmental conditions within the containment building. Table 5.9-9 gives a summary of the results.

Of all the buffering agents tested, TSP caused the least amount of combined corrosion with A508 carbon steel and aluminum coupons. Calcium addition to all solutions containing the individual buffer in 2500 ppm boron solution yielded a precipitate or suspended floc (except NaOH). Aluminum addition to all solutions containing the individual buffer in 2500-ppm boron solution yielded a precipitate or suspended floc (except for STPP). Testing at elevated pH (initial value of 8.5) and lower concentrations of calcium and aluminum showed that precipitation did not occur before threshold values of >177 ppm (STB) or 75 ppm (SMB) for aluminum, and >254 ppm for calcium (in both STB and SMB). Values of pH less than 8.0 for SMB and STB showed no evidence of precipitation with calcium (of up to 700 ppm Ca). The following recommendations were made: STB for use at plants that will have high calcium concentrations in the post-LOCA environment, TSP for plants that will have low calcium concentrations in the low post-LOCA environment, and SMB as a replacement for sodium hydroxide in any plant that currently uses sodium hydroxide.

The corrosion rates for both aluminum and carbon steel in STPP solution (at pH 7.5) were very high relative to other buffering agents. The solution from the carbon steel test was yellow from the high level of dissolved Fe ion.

Table 5.9-9. Summary of Characteristics of Candidate ECCS Buffering Agents (Reid et al., 2006)

Criterion	Buffering Agent[a]					
	NaOH	TSP	STB	SMB	STPP	SG
Precipitate Formation	P[b]	G[c]	E	G	E	No Data
Quantity required to adjust pH>8.0	E	G	G	E	P	P
Dissolution Rate	N/A[d]	G	G	G	G	G
Affordability/Availability	E	E	E	G	G	G
Corrosiveness	G	E	G	G	P	No Data
Effect on Boric Acid Solubility	G	G	G	G	G	No Data
Environmental Stability	G	G	G	G	G	No Data
Habitability Concern	G	E	G	G	E	E
Oxide/CRUD Release	G	G	G	G	P	P

[a]E=excellent, G=good, P=poor.
[b]NaOH rated P due to elevated Al production.
[c]TSP rated P under elevated calcium conditions.
[d]NaOH provided as a 50 percent solution.

Comments and Observations

Threshold values for precipitate formation from dissolved aluminum in STB (177 ppm) are significantly higher than those observed during longer term bench testing and head loss testing at ANL and ICET-5 (about 50 ppm).

The radiolytic stability of the compounds and their solutions was not tested. The two recommended buffers, SMB and STB, were not tested under conditions of a radiolytic field. In the presence of gamma radiation sodium metaborate would likely become STB or mono-borate anion, although this needs to be tested.

For Test 1 it is not clear if the dissolution testing was performed under static conditions (i.e., no mixing) that would best simulate the effect in containment. Most likely the solution was heated by using a hot plate, which would have caused convection currents. In the post-LOCA environment, the opposite effect would be occurring because sump water would be cooling down (from contact with concrete below the material), and no upward convection would occur. Actual simulation of the dissolution based on plant design should be a major consideration in the actual testing of any material. If the water is to flow over the solid buffer material, any test should also simulate this effect.

Sodium gluconate is the product of a strong base (sodium hydroxide) and a weak acid (gluconic acid). The measured pH for 10 g SG in 1 L of demineralized water was 6.93. The equilibrium constant for gluconate anion dissolved in water in equilibrium with gluconic acid is 4 x 10-11, which would yield a pH of about 8.1 in demineralized water (O'Neil, 2006). The difference in pH indicates that another factor was present in this test that was not considered.

Test 4 did not add calcium and aluminum together, but separately. Thus, no potential synergic effect of the mixture can be assessed from this data. Silica was not used in any of these tests. The positive or negative effect of silica or silicates on these test results is unknown. The results of the precipitation settling tests and coefficients of filter cake formation tests are reported as: "These results do not provide an accurate measure of the precipitate contribution to sump strainer head loss." Thus, there is no quantitative fashion in which these results can be used.

The Al solubility data in STB are contradicted by ANL work that found that concentrations of aluminum at 60-70 ppm yielded precipitate and at 80-100 ppm plugged filters in STB solution. While investigating the effects of aluminum concentration on precipitate formation in STB, WCAP-16530-NP tests (Lane et al., 2006) showed that the formation of precipitates is dependent on the temperature of the solution at the time of the addition of the metal solution. Less precipitate was formed when the same amount of dissolved aluminum was added at room temperature compared to addition at 60°C. This effect was not studied, so it is not known if this is related to precipitation kinetics.

5.9.7.13 Additional Issues on Chemical Effects

Both NRC and industry have sponsored research to provide additional information and develop some guidance for evaluating chemical effects (NUREG-1918). The NRC convened an external peer review panel to review the NRC-sponsored research and to identify and evaluate additional chemical phenomena and issues that were either unresolved or not considered in the original NRC-sponsored research.

A phenomena identification and ranking table (PIRT) exercise was conducted to support this evaluation in an attempt to fully explore the possible chemical effects that may affect ECCS performance during a hypothetical LOCA. The PIRT was not intended to provide a comprehensive set of chemical phenomena within the post-LOCA environment. Rather, these phenomena should be combined with important findings from past research and informed by ongoing research results.

The PIRT panel identified several significant chemical phenomena. These phenomena pertain to the underlying containment pool chemistry; radiological considerations; physical, chemical, and biological debris sources; solid species precipitation; solid species growth and transport; organics and coatings; and downstream effects. Several of these phenomena may be addressed using existing knowledge of chemical effects in combination with an assessment of their implications over the range of existing generic or plant-specific post-LOCA conditions. Other phenomena may require additional study to understand the chemical effects and their relevance before assessing their practical generic or plant-specific implications.

Experimental testing and other studies have been completed to determine the effect of cooling water composition, debris sources, and materials corrosion on the nature of the debris, presuming no fuel cladding failure. However, ten further topics related to chemical effects were identified that deserve additional consideration (NUREG/CR-6988).

The ten topic areas are radiation effects (particularly on material corrosion), differences in concrete carbonation between tested systems and existing containment structures, effects of alloy variability between tested and actual materials, galvanic corrosion effects, biological fouling, co-precipitation, other synergistic solids formation effects, inorganic agglomeration, crud release effects (types and quantities), retrograde solubility and solids deposition, and organic material impacts. Sufficient data or prior related studies were available to sufficiently address some of the questions raised in the 10 topic areas. However, within these ten broad areas, topics that merit additional consideration also were identified.

The topic with the greatest perceived influence on ECCS performance is the interactions of organic materials (lubricants and coatings) with inorganic solids. The effects of radiolysis on redox potential and thus metal corrosion have the next most influence. Of similar influence are the effects of biological growth in the post-LOCA system and the impacts of dried borate salts on hot fuel cladding and reactor pressure vessel materials. Of lesser, but not insignificant, influence are galvanic corrosion, inorganic agglomeration, and crud release effects on increasing and altering solids delivered to the post-LOCA coolant. Changes in concrete carbonation and differences in alloy corrosion rates were judged to have minor impacts on ECCS functionality.

The NRC staff conducted an initial evaluation of phenomena identified by the peer review panel, which are summarized in NUREG-1918, and reduced the list to those phenomena that can be potential contributors to ECCS performance degradation. The final list is consisted of 41 items and tabulated in an NRC evaluation report (NRC, 2011). The NRC staff grouped these phenomena into 10 topic areas, which were subsequently evaluated and reported in NUREG/CR-6988 by PNNL. A team of NRC staff further evaluated these phenomena using existing knowledge and the findings from the industry and NRC-sponsored research. The staff's evaluation of the outstanding issues concluded that the implications of these issues are either not generically significant or are appropriately addressed, although several issues associated with downstream in-vessel effects remain. The remaining issues are summarized below (NRC, 2011).

- The deposition of precipitates on reactor fuel and its effects on core cooling
- The effect of physical and chemical debris contained within the core on the ability of the coolant to remove heat from the core
- The effect of debris settling on the grid straps to block flow and prevent heat transfer from the fuel cladding
- The potential for particulate settling on the grid straps to block flow and prevent heat transfer from the fuel cladding

5.9.8 Summary and Completeness Assessment

Potential chemical effects on the head loss across the debris-loaded sump strainer under a post-LOCA condition, raised by ACRS, were experimentally evidenced by small-scale bench tests (NUREG-6868), integrated chemical effects tests (NUREG/CR-6914), and vertical loop head loss tests (NUREG/CR-6913). Industry's efforts to address the chemical effects were documented in WCAP-16530-NP (Lane et al., 2006). Three main precipitates were identified by WCAP-16530-NP: calcium phosphate, aluminum oxyhydroxide, and sodium aluminum silicate. The assumption that all released calcium would form precipitates is reasonable. CalSil insulation needs to be minimized especially in a plant using TSP buffer, which has already been conducted by licensees. The assumption that all released aluminum would form precipitates appears highly conservative because ICETs (NUREG/CR-6914 and NUREG/CR-6915), and other studies (Bahn et al., 2008b, 2008d, and Reid et al., 2007) suggest substantial solubility of aluminum at high temperature and inhibition of aluminum metal corrosion by silicate or phosphate. The buffer STB tends to enhance even more the solubility of aluminum (NUREG/CR-6914; Bahn et al., 2007; Reid et al., 2006, 2007). This buffer was estimated as a good candidate to replace NaOH (Reid et al., 2007).

The WCAP-16530-NP (Lane et al., 2006) is conservative in terms of not only aluminum solubility but also filterability of surrogates. The AlOOH and SAS surrogates are quite effective in increasing the head loss across the debris-loaded bed and more effective than the prototypical aluminum hydroxide precipitates generated by in-situ aluminum corrosion (Bahn et al., 2008a, 2008c). The NRC Safety Evaluation of WCAP-16530 (NRC-SER-2007b) also notes that some of the conservative assumptions in the WCAP-16530-NP methodology are the basis for accepting other chemical effects uncertainties. In the plant-specific surrogate case, aluminum hydroxide precipitates were deflocculated by dissolved silicates, which led to fine particle size (100-300 nm) and poor filterability by a glass fiber debris bed (Bahn et al. 2008a). This result suggests that preparation procedures and test conditions for the chemical surrogates different from the one proposed by WCAP-16530-NP (Lane et al., 2006) need to be carefully evaluated so that any non-conservatism can be avoided. The NRC Final Safety Evaluation Report for WCAP-16530-NP (ML073520891, 2007) notes that some of the conservative assumptions in the WCAP-16530-NP methodology are the basis for accepting other chemical effects uncertainties.

Modeling efforts to predict possible chemical precipitates formed under a post-LOCA sump water condition were documented (NUREG/CR-6873 and NUREG/CR-6912). As discussed in other peer-review report (NUREG-1861), thermodynamic modeling is limited by available thermodynamic database and cannot predict effects related to reaction kinetics, such as aluminum inhibition/passivation. Thermodynamic modeling, therefore, needs to be benchmarked by experimental results.

5.10 Downstream Effects

In accordance with Title 10 of the CFR Part 50, Subsection 50.46(b)(5), licensees of domestic nuclear power plants are required to provide long-term cooling of the reactor core "after any calculated successful initial operation of the ECCS." Furthermore, the "calculated core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core." If debris collects and clogs or wears components or pathways that support operation of the ECCS or CSS, then compliance with this regulation may be affected. In response to this requirement, the report "Pressurized Water Reactor Sump Performance Evaluation Methodology" (NEI, 2004) provided the general guidance on evaluating the impact of debris on the ECCS and CSS and their components.

5.10.1 Ex-Vessel Debris Effects

The NEI report provides licensees guidance on evaluating the flowpaths downstream of the containment sump for blockage from entrained debris. The guidance specified three issues yet to be addressed: (1) blockage of flowpaths in equipment, such as containment spray nozzles and tight-clearance valves, (2) wear and abrasion of surfaces, such as pump running surfaces, and heat exchanger tubes and orifices, and (3) blockage of flow clearances through fuel assemblies. This report identified the starting point for the evaluation to be the flow clearance through the sump screen and stated that the flow clearance through the sump screen determines the maximum size of particulate debris for downstream analysis. It also stated that wear and abrasion of surfaces in the ECCS and CSS should be evaluated based on flow rates to which the surfaces will be subjected and the abrasiveness of the ingested debris. The NEI report also stated that abrasiveness of debris is plant-specific and therefore should be evaluated on a plant-specific basis.

The safety evaluation (SE) of this NEI report by NRC staff (NRC-SER-2004) found that the guidance statements did not fully address the potential safety impact of LOCA-generated debris on components downstream of the containment sump. In its SE, the NRC staff stated that the evaluation of GSI-191 should include a review of the effects of debris on pumps and rotating equipment, piping, valves, and heat exchangers downstream of the containment sump related to the ECCS and CSS. In particular, any throttle valves installed in the ECCS for flow balancing (e.g., HPSI throttle valves) should be evaluated for blockage potential.

The NRC stipulated that the downstream review should first define both long- and short-term system-operating lineups, conditions of operation, and mission times. Where more than one ECCS or CS configuration is used during long- and short-term operation, each lineup should be evaluated with respect to downstream effects.

Evaluations of systems and components are to be based on the flow rates to which the wetted surfaces will be subjected and the abrasiveness of the ingested debris. The abrasiveness of the debris is plant specific and depends on the site-specific materials that may become latent or break-jet-generated debris.

Specific to pumps and rotating equipment, an evaluation should be performed to assess the condition and operability of the component during and after its required mission times. Consideration should be given to wear and abrasion of surfaces (e.g., pumps running surfaces, bushings, and wear rings). Tight clearance components or components where process water is used either to lubricate or cool should be identified and evaluated.

Changes in component rotor dynamics and long-term effects on vibrations caused by potential wear should be evaluated in the context of pump and rotating equipment operability and reliability. The evaluation should include the potential impact on pump internal loads to address such concerns as rotor and shaft cracking.

The downstream effects evaluation should also consider system piping, containment spray nozzles, and instrumentation tubing. Settling of dust and fines in low-flow/low fluid velocity areas may impact system operating characteristics and should be evaluated. The evaluation should include such tubing connections as provided for differential pressure from flow orifices, elbow taps, and venturi and reactor vessel/RCS leg connections for reactor vessel level.

Valve and heat exchanger wetted materials should be evaluated for susceptibility to wear, surface abrasion, and plugging. Wear may alter the system flow distribution by increasing flow down a path (decreased resistance caused by wear), thus starving another critical path. Conversely, increased resistance from plugging of a valve opening, orifice, or heat exchanger tube may cause wear to occur in another path that experiences increased flow or some flow paths to be blocked completely.

Decreased heat exchanger performance resulting from plugging, blocking, plating of slurry materials, or tube degradation should be evaluated with respect to hydraulic and heat removal capability required by the overall system.

An overall ECCS and CSS 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 through external leakage. Internal leakage of pumps may be through inter-stage supply and discharge wear rings, shaft support, and volute bushings. Piping systems design bypass flow may increase as bypass valve openings increase or as flow through a heat exchanger is diverted because of plugging or wear. External leakage may occur as a result of leakage through pump seal leak-off lines, from the failure of shaft sealing or bearing components, from the failure of valve packing, or through leaks from instrument connections and any other potential fluid paths leading to fluid inventory loss. Leakage past seals and rings caused by wear from debris fines to areas outside containment should be evaluated with respect to fluid inventory, overall accident scenario design, and licensing bases environmental and dose consequences.

In response to the NRC guidance, Westinghouse Electric issued WCAP-16406-P, "Evaluation of Downstream Sump Debris Effects in Support of GSI-191," in May 2006.[10] The report is intended to address the above comments and provide detailed guidance and a consistent approach for licensees to evaluate the downstream impact of sump debris on the performance of their ECCS and CSS following a LOCA. The report was developed to address the issues identified in both the NEI report and the associated NRC SE.

In December 2007, NRC staff finalized the Safety Evaluation for WCAP-16406-P and determined that this report was acceptable for referencing in licensing applications for Westinghouse, Combustion Engineering, and Babcock and Wilcox designed PWRs to the extent specified and under the limitations delineated in the technical report and the final SE of the report (a non-proprietary version of the topical report does not exist).

5.10.2 In-Vessel Debris Effects

The NRC Safety Evaluation on WCAP-16793, Rev. 2 accepted a fibrous debris limit of 15 grams per fuel assembly for operating PWRs. Testing demonstrated that in the absence of fibrous debris, other types of debris small enough to pass through the ECCS sump strainer did not cause a significant head loss. Testing also demonstrated that at some fiber load above 15 grams, head loss can increase significantly when chemical precipitates are present. For

[10] The report is proprietary to Westinghouse Electric.

example, some tests with 20 grams of fiber resulted in relatively high head losses. The NRC concluded that at some fiber load above 15 grams that head loss can increase significantly.

Testing was accomplished using a single, partial height fuel assembly with the core support plate modeled in the test rig. The test fuel assemblies consisted of a prototypical inlet nozzle, fuel protective filter, and spacer grids (usually 4 or 5 grids), and prototypically sized fuel rods and instrument tubes. The assemblies were about one-third full height. Testing was generally conducted with room temperature tap water, but some tests were run at about 130°F. Tests were run at various flow rates. It was determined that the maximum flow rate resulted in the limiting head loss.

Tests to simulate the fuel response to hot-leg and cold-leg breaks were conducted because each condition has different flow conditions and available driving head. The cold-leg break condition has a much lower flow rate, but also has less driving head to force coolant into the core. It was determined that if a plant meets the hot-leg break fiber limit of 15 grams then the cold-leg break will also be acceptable.

Tests showed that small fibers can become trapped in the spacer grids or fuel filters. These fibers are effective at filtering particulate debris and chemical precipitates. If enough fiber becomes trapped within a limited volume in the fuel assembly it can capture other debris and cause significant head loss. It was observed that the greatest head losses occurred when all or most of the debris was trapped at a single elevation within the assembly.

Fuel assembly testing included Nukon® fiberglass as the fibrous debris and silicon carbide as the particulate. The particulate had a nominal diameter of 10 microns. The fiber size distribution was based on samples of fibers collected downstream of prototypical strainers during testing. Some tests also included microporous type insulation. In these fuel assembly tests, microporous insulation behaved similarly to silicon carbide. Aluminum oxyhydroxide chemical precipitates (prepared in accordance with WCAP-16530) were added after all particulate and fiber debris was added. Tests showed that a relatively small amount of chemical surrogate could result in a significant head loss with further additions having little effect. It was discovered that the head loss depended on the amount of particulate that was included in the test. The particulate to fiber ratio (p/f) was varied. For high flow rate (hot-leg break) cases it was determined that a low p/f ratio resulted in the limiting head loss when chemicals were added. For lower flow rates (cold-leg break response) a higher p/f ratio resulted in the limiting head loss after chemicals were added. Without chemical surrogates added, the p/f ratio that results in the highest head loss is different.

The 15 gram fiber limit, which is applicable to all plants, was determined using the most conservative inputs in all areas that were varied during the testing. It is unlikely that the most limiting conditions would occur following a LOCA. However, because review of the test program identified many uncertainties regarding fuel blockage behavior and a theoretical model for blockage behavior has not been developed, the NRC concluded that the limit is appropriate. The NRC will review additional information as it becomes available to determine if the limit can be increased under plant specific conditions or if the limit should be changed based on updated analyses.

The NRC safety evaluation on WCAP-16793, Rev. 2 contains a number of limitations and conditions in Section 4.0 of the document (NRC-SER-2013).

5.11 Vendor Head Loss Test Programs

Although the BWR test program occurred prior to the PWR test program, the PWR program is discussed first because the PWR tests were more rigorous and the testing included chemical effects and particulate insulation materials, such as calcium silicate, thereby providing a more complete understanding of the complexities of head loss testing at the onset. Note that the PWR program did not depend upon the result of the BWR program.

5.11.1 Strainer Debris Head Loss Testing by PWR Vendors

There were five vendors that supplied large passive replacement strainer to the 69 U.S. PWRs for the resolution of GSI-191. These vendors included: (1) Atomic Energy of Canada Limited (AECL), (2) General Electric (GE), (3) Performance Contracting Incorporated (PCI), (4) Enercon Services, Inc., and (5) Control Component Inc. (CCI). AECL manufactured, tested, and installed their strainers. GE conducted head loss testing at Continuum Dynamics Inc. AREVA conducted head loss testing for the PCI-manufactured strainers at Alden Research Laboratories (ARL). ALION Science and Technology conducted head loss testing on the Enercon-manufactured strainers. CCI conducted the testing on the their strainers with the exception of the CCI strainers installed at Arkansas Nuclear One, Units 1 and 2, which were tested by Fauske and Associates, LLC. Duke conducted testing for the Enercon strainers installed at some of their plants at Wyle Labs.

The features of the head loss testing that all the strainer vendors have in common include the testing of a prototype strainer in a reduced-scale test tank or flume that uses a pump to recirculate water through the strainer and tank. The thermal and hydraulic conditions within the tank are intended to approach conditions prototypical of the licensee's sump. The scaling of the test strainers is based on maintaining the average screen approach velocity for the test strainer module the same as that calculated for the plant strainer. That is, the ratio of test strainer area to plant strainer area is used to establish the test pump flow rate to obtain the calculated plant approach velocity, and to maintain the same debris amount per unit area between the test and the plant. The test strainer prototypes consist of sections, or modules, that are similar to the plant strainer designs, but smaller. These reduced scale test strainers maintain key design parameters (gap widths, disk dimensions, etc.) of the plant strainer.

The vendors' head loss testing programs have commonalities but also substantial differences in their respective approaches. All replacement strainers are large passive designs. The vendor test procedures evolved during the resolution of GSI-191 as new issues were identified and resolved through interactions with the NRC staff.

Typical of all vendors, the test debris quantities are scaled from the plant's bounding estimates of debris predicted to transport to the replacement strainers as determined by the debris generation and transport analyses. The scaling from the plant debris loads to the test loads is based on the ratio of the effective screen area for the test strainer divided by that of the plant replacement strainer. The total replacement strainer screen area is reduced by an area referred to as a "sacrificial area," which accounts for the potential for miscellaneous debris (e.g., tape, labels, etc.) to block a portion of the strainer. Sacrificial area is based on an estimation for the generation and transport of such debris. The sacrificial are is subtracted from the total strainer area resulting in an effective screen area for the accumulation of fibrous and particulate debris. During early testing, the preparation of fibrous debris was based on the vendor's generic debris preparation protocol rather than an attempt to match the analytically determined size distributions of debris predicted to reach the strainer. Some vendors created finer debris than others. The NRC staff became concerned that some vendors were using non-prototypical fibrous debris size distributions in their tests. Staff guidance on fibrous debris size distributions for testing was provided to the industry The size distributions for the particulate debris were generally based on either the SE-accepted recommendations in the guidance report or plant specific data.

The PWR vendor specific strainer designs and head loss testing procedures are summarized as follows

AECL Strainer Design and Testing

The passive AECL Finned Strainers™ consist of perforated corrugated sheets of stainless steel welded together to form hollow core fins connected to a common header (NRC, 2006b; NRC, 2007c; NRC, 2007b). The diameter of the perforation holes is typically 1/16 in. and the corrugated plate bend angle was 60°. The basic design was modified to create plant-specific strainer designs to fit into the individual plant sump. Some fins were shortened to accommodate surrounding sump area structures. The water enters the perforated plate surface of each strainer "fin" and is collected by a common header for each strainer module. The strainer design incorporates orifices designed to force uniformity in the rates of flow across the various fins, i.e., the same flow rate through each fin. AECL supplied plant specific designed strainers to seven U.S. units.

Tests of prototypical head loss and vortex formation susceptibility were performed with a reduced-scale head loss testing apparatus and large-scale prototypical strainer. Tests with the reduced-scale head loss loop were performed to determine the thin bed thickness and optimize the total surface area and fin pitch for normal debris. In addition, the reduced-scale test loop was used to perform chemical-effects and bypass tests. The large-scale test loop was used to test strainer prototypes. The reduced-scale test facility consisted of a 90-in.-diameter, open plastic tank with a maximum fill height of 56 in. The test strainer was positioned on the floor of the tank and was attached to a piping system leading to a pump below the tank. The pump was capable of producing a flow rate from 1 to 100 gpm. The large-scale head loss test loop consisted of an open lined tank that was 64 in. deep, 8 ft wide, and 19 ft long, and had an external piping system connected to a pump; the strainer test module was positioned on the floor of the tank.

The large test loop accommodated a test strainer module that was approximately 1/16 scale, based on the screen surface area, with a representative array of full-scale sized fins. The large-scale test loop was capable of producing a flow rates from 5 to 3000 gpm. A photograph of an AECL large-scale test module is shown in Figure 5.11-1. Plant strainers used the same base fin design, but the fin and plenum structures were tailored to the specific plant. Based on the test results from the reduced-scale head loss loop, the final strainer module design was tested using the large-scale head loss facility to investigate thin-bed and full-debris load head losses. The head loss tests were conducted at water temperatures controlled at about 104°F.

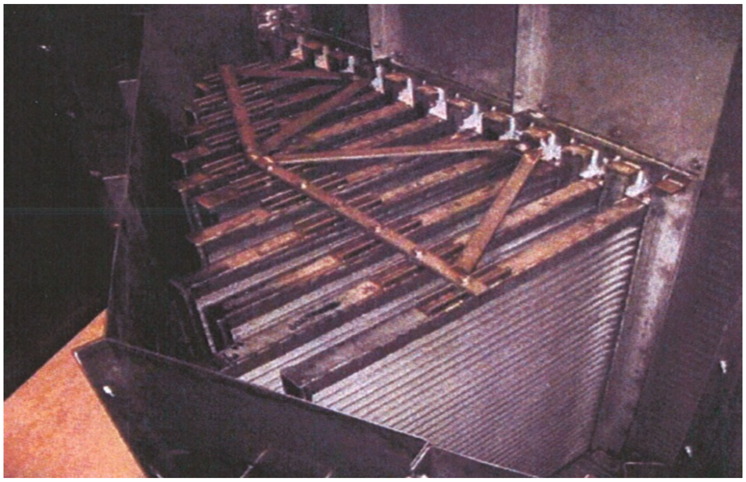


Figure 5.11-1. Photo of AECL Large Scale Test Module (NRC, 2008g, page 39/77)

The AECL testing focused on determining the peak thin-bed head losses by introducing small batches of fiber, with the particulate introduced first and then fibrous debris batches added until full load objectives were achieved. The test pump was started prior to introducing the particulate debris.

AECL used walnut shell flour to simulate coatings and latent particulates based on the rationale that the flour's density of 81 lb/ft3 was close to the typical target coatings density of 94 lb/ft3, which would result in a conservative transport to the strainer in the tests. The NRC staff accepted the use of walnut shell flour as a surrogate for particulates, even though its particles do not phsically represent either coatings particulate or the latent dirt. Walnut shell flour particles, which look like little platelets under a microscope, do not well resemble the hardened particles of coatings particulates, which look like little rocks. The basis for accepting a non-representative material was that walnut shell flour caused head losses that were either on par or conservative relative to the head losses that would be caused by the spherical 10-μm particles recommended in the guidance report. In retrospect, walnut shell flour may have been a poor surrogate for the coatings particulate because it may cause unrealistically high head losses in thin bed formations due to compaction not representative of coatings or latent particles. While the measured head losses may have been conservative, the high head losses could cause a strainer to unrealistically fail its qualification test. The NRC staff audit report of the suction strainer design for Millstone Unit 2 contains a more detailed analysis of the acceptablility of walnut shell flour as a coating debris surrogate (NRC, 2007b).

AECL prepared its fibrous debris by first passing the insulation material through a leaf shredder and then using a water jet from a pressure washer to further separate the fibers. This process generated debris substantially finer than the shredded debris, but only a portion of the generated debris truly represented the fines that would prototypically remain suspended in the plant sump pool. The adequacy of this debris preparation process can only be gauged by comparing the quantity of the debris settling in the test tank to the debris accumulation on the strainer. For the audited testing, a majority of such debris introduced into the test tank accumulated on the test strainer module. Particulate insulation materials were crushed into powder. The test debris was all wetted prior to introduction into the tests.

AECL introduced the debris into their test tank upstream of the strainer in batches consistent with determining a peak thin-bed head loss. Mechanical agitation was used near the location of the debris introduction to minimize debris settling, and near-field debris settling was reduced to acceptable quantities, even though significant fibrous debris settling occurred within the test tank as indicated by the post-test collection of the debris. The settling within the tank could have been a concern in situations where the fiber sources were limited and transport of the majority of fibers would be needed to attain the bounding head loss. Since the maximum head losses for these tests was attained for thin beds, and there was excess fiber available, the settling did not adversely affect the results of the tests. The settling of debris such that adequate debris is not available to result in the plant's peak head loss is a potential concern with each of the vendor testing programs.

The AECL stability criterion for head loss used to terminate a test was a change of less than 5% or 0.1 psi, whichever is greater, and no general steadily increasing trend in pressure within 1.5 hr. Typically, the minimum number of tank turnovers within 1.5 hours was about 4.5, but the testing typically occurred over several days such that the water was visually clearing of particulate at termination. Clearing of the water is a good indicator that the tests were conducted for an adequately long time before termination. Test head losses were scaled to the plant conditions based on the temperature-dependent viscosity.

Once the non-chemical debris beds in the multi-loop test rig had reached a suitably stable head loss value, AECL proceeded to introduce chemical debris in batches over an extended period of time (ADAMS #ML090410618, 2008). The total duration of the multi-loop rig tests was roughly three months. Based on the test results, the licensee recognized that reducing the aluminum inventory in containment would be necessary to ensure the conservatism of the limiting aluminum concentration assumed for the post-LOCA sump pool. Therefore, aluminum ladders were removed from the containment. Since aluminum is an important contributor to chemical effects, the NRC staff was interested in comparing the predicted plant-specific aluminum release between the AECL method and the WCAP-16530-NP spreadsheet. The licensee provided a comparison of aluminum release for the two different methods as a function of pH. For a pH of 8.5, which was used to calculate the aluminum release, the AECL method predicted a slightly higher aluminum release than the WCAP method.

General Electric Strainer Design and Testing

The GE strainers consist of modules of stacked disks connected via a common header or plenum (NRC, 2008a). The disks are constructed of perforated plates. The dimensions and number of disks vary with the plant application. The modules can be connected in trains to fit plant-specific sumps. The typical perforations in the strainer plate consist of 3/32 in. diameter holes. The GE strainer design also incorporates a coarse wire mesh over the strainer surface. After water passes through the perforated plates, it flows into the common plenum to the recirculation pump suction flowpath. Plant specific strainers were constructed of these disks, oriented either vertically or horizontally, and arranged in a manner to fit the plant sump. GE supplied plant-specific designed strainers to 11 U.S. units. An example of GE plant strainer is shown in Figure 5.11-2.

GE conducted head loss testing with strainer module prototypes in a tank equipped with a recirculating pump loop (NRC, 2008a; General Electric, 2007a). Instrumentation included a loop flow sensor to monitor the strainer flow rate, a thermocouple to monitor water temperature, a differential pressure transducer to measure strainer head loss, and equipment to record these measurements. The test tank was sufficiently small with respect to the strainer module that the debris settling within the tank was minimized. Debris settling could be reduced with agitation. Full debris loads, including those capable of circumscribing the strainer, were tested with the prototype strainers. GE testing also included reduced fibrous and particulate loads in varied combinations to determine strainer behavior under different debris loads. Figure 5.11-3 shows a photograph of a GE prototype strainer undergoing testing.

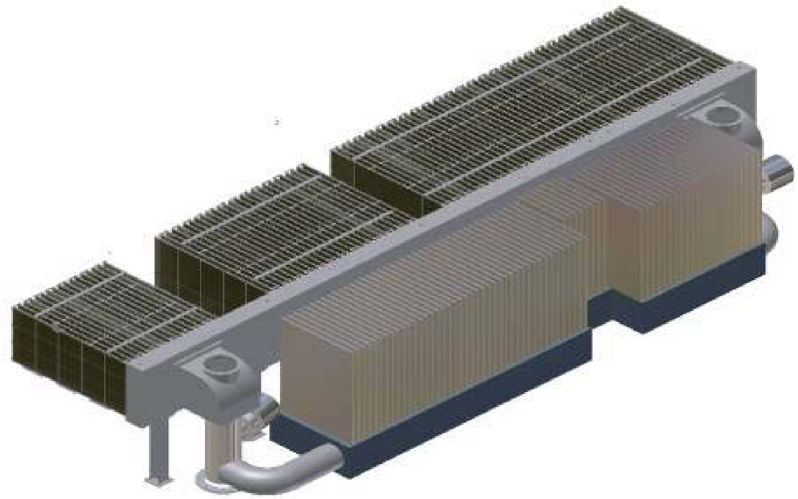


Figure 5.11-2. Example Plant GE Strainer Design (General Electric, 2007a)

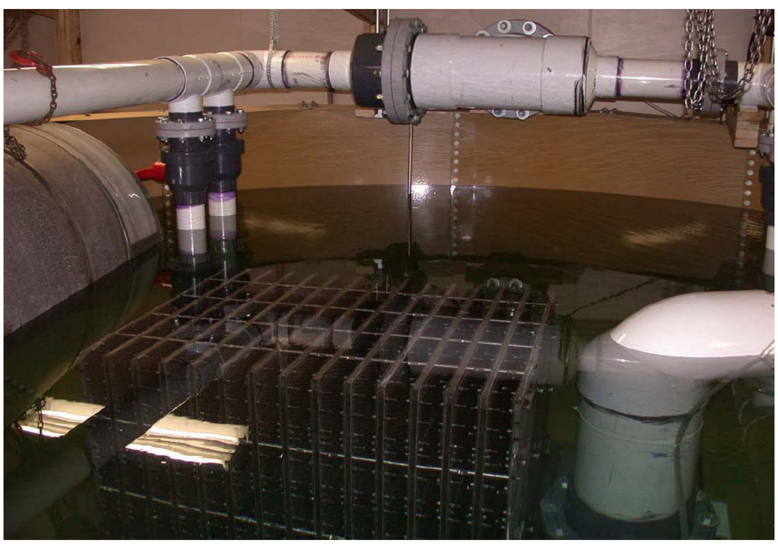


Figure 5.11-3. Photograph of GE Prototype Test Module (General Electric, 2007a)

In addition, GE conducted small-scale tests in a test loop consisting of a 1250-gal tank that was approximately 82 in. diameter and 4.5 ft deep, referred to as “sector tests” because the test strainer consisted of a replication of one strainer gap between two disk surfaces, oriented horizontally (NRC, 2008a). The bottom of the strainer was located six inches above the tank floor. The sector tests were run in two basic modes. Completely stirred tests used agitation to maintain the debris in suspension in an attempt to move all debris onto the test strainer. Partially stirred tests did not use agitation and, therefore, allowed settling of debris to occur. Two variable-speed agitators were used to help prevent settling in the test tank for completely stirred tests and to help suspend debris uniformly prior to starting the test strainer flow for partially stirred tests. For all tests, a tee in the return line with a valve allowed bypass samples to be taken. GE used the sector testing to test debris loads that are insufficient to form a circumscribed bed, including thin bed tests.

The GE procedure for preparing fibrous debris evolved from simple shredding toward generation of the finer shreds of debris shown in Figure 5.11-4. The improved multiple-pass process created debris that was much finer than the single-pass shredder debris, but still not as fine as true prototypical individual fibers. Particulate insulation debris was mechanically pulverized into fines for testing.

Figure 5.11-4. Photograph of GE Prepared Fibrous Debris (OPPD 2008)

GE selected suitable test surrogates for plant-specific prototype debris. GE either used the specific plant insulations or insulation materials with like properties, such as Transco fibrous insulation for NUKON fibrous insulation. GE used Carbo-Zinc to represent the IOZ coating debris and ElectroCarb® Black Silicon Carbide as a suffogate for the other types of coating debris and for latent particulate; both debris types had a size distribution conservative with respect to the guidance report recommendation and SE-accepted value of 10 µm particles. The use of Carbo-Zinc for the IOZ coatings debris is acceptable because the source particulate of the Carbo-Zinc was actually the base ingredient for the manufacturing of the IOZ paint. The silicon carbide density of 94 lb/ft^3 would cause the near-field debris settling behavior of the surrogate particulate to be prototypical of non-IOZ particulate coating debris because they have similar density. The debris samples were weighed, mixed with water in buckets, and poured into the test pool. Powders were wetted before introduction.

Prior to the addition of debris to the test loop, the recirculation pump was started, and clean head loss was measured. In earlier testing, the recirculation pump was then stopped until the debris was added to the test tank (NRC, 2008a). The fiber and particulate debris was added into the test loop and kept suspended by agitation until the recirculation pump was started. After the recirculation pump was started, head loss data were collected. In addition, bypass samples were taken for determination of strainer debris bypass. After it was determined that the test head loss termination criteria had been reached, the recirculation pump was stopped, and the tank was drained to allow observations of the test article. The NRC staff recommended that the pumps be started prior to introducing the debris, and that the particulate be introduced prior to the fibrous debris. The circulation of the pumps was intended to uniformly mix the particulate in the tank and loop water prior to the accumulation of fibers on the strainer. In later GE testing, the fibers were introduced slowly in a multiple batch process after the start of the pumps.

In some earlier testing, GE introduced debris into their test tank relatively close to the strainer, such that the fibrous debris may not have had enough opportunity to disperse before being drawn onto the strainer. This practice raised the concern that the location of introduction could skew the debris accumulation away from prototypical uniformity. GE subsequently responded to staff concerns by introducing the debris in a highly agitated zone away from the strainer so that the debris had to transport several feet to reach the strainer.

GE also conducted thin bed testing in a small-scale sector test apparatus and concluded that a thin bed had not occurred in their tests. Test results presented during an NRC audit showed that sudden drops in the head loss occurred during fully stirred sector testing. Although the actual phenomena occurring during the sector head loss tests cannot be known with certainty, the NRC staff inferred from test data, showing sudden large head loss reductions, that the accumulation of shreds within the sector gap may have caused a blockage to form and then give way. If this phenomenon occurred, once the shreds entered the gap and were no longer influenced by the turbulence from pool stirring, they would settle onto the lower gap strainer surface close to the outer perimeter of the disk, creating a location for debris to collect, essentially a dam. Once the dam had built up in the gap at the outer edges of the disk sufficiently to cause a substantial head loss across the dam, the debris would be pushed inward, partially clearing a portion of the strainer surface. The clearing resulted in a sudden decrease in measured head loss across the strainer. Individual fibers are not susceptible to gravitational settling and would not have preferentially settled to the lower surface, nor created an entrance dam. The NRC staff had observed a thin bed formation in prior prototype testing of a GE strainer (NRC, 2006) and also observed thin-bed behavior in later tests. Therefore, the staff concluded that a thin bed may form on a GE strainer.

The GE test termination criterion for defining a steady state was that the measured head loss increase became less than 1% over a period of 30 min or five turnovers, whichever was greater, but the criterion does not apply until all fiber debris has been added to the tank as scheduled. However, at this rate of increase the head loss could potentially increase at a rate of 48% in 24 hr, assuming the rate remained linear. A minimum of five turnovers is adequate to filter the fibrous debris that is likely to accumulate on the strainer with a filtration efficiency of nearly 100%. However, five turnovers is not sufficient for the subsequent filtration of particulates, especially the finer particulate where the effective filtration efficiency may be quite low, based information documented in the NRC head loss test guidance report (NRC, 2008d). The staff recognized these issues and reviewed the test results to ensure that they were conducted for adequate lengths of time or that appropriate post-test data extrapolation accounted for potential head loss increases.

PCI Strainer Design and Testing

The PCI strainers consist of modules of stacked disks connected via a common header or plenum (NRC, 2007e). The disks are constructed of stainless steel perforated plates, where the dimensions and number of disks vary with the plant application. The perforated sheets are riveted together along the outside edge and shop welded to a core tube along the inner edges. The tube of each module is constructed of stainless steel pipe, and the modules are connected together by means of a coupling sleeve fitted over the core tubes and secured by a latch. The core tube has holes cut in the pipe wall to admit flow of strained water from the inside of the perforated sheets. The holes along the core tube length are sized to maintain a uniform rate of flow from disk to disk. The modules can be connected in trains or stacks to fit plant-specific sumps. The perforations in the strainer plate consist of holes with a licensee-specified diameter. After water passes through the perforated plates, it flows to the common plenum to the recirculation pump suction. Plant-specific strainers were constructed of these disks, oriented either vertically or horizontally, and arranged in a manner to fit the plant sump. PCI supplied plant specific designed strainers to 17 U.S. units.

PCI conducted head loss testing with strainer module prototypes in a tank equipped with a recirculating pump loop (NRC 2007e; Scott, 2006; Smith, 2008a, 2008b; Hiser, 2008). Earlier PCI testing, conducted by AREVA at ARL, was conducted in a test flume approximately 27 in. wide, 39 in. high, and about 21 ft long. Later testing was conducted in a larger steel-reinforced test flume that was 10 ft wide by 45 ft long, and 6 ft high, and that had an optional 6-ft-deep pit at one end. For the larger flume a flow channel was constructed inside the flume to achieve prototypical flow approach velocities needed to simulate near-field debris settling. Some tests conducted in the larger facility were agitated to prevent settling of debris. Instrumentation included a loop flow sensor to monitor the strainer flow rate, a thermocouple to monitor water temperature, a differential pressure transducer to measure strainer head loss, and equipment to record these measurements.

In the larger flume, the test module can be either floor-mounted or recessed in a pit-mounted configuration. Testing in the PCI flume can be conducted at temperatures up to 120°F. The specification of the temperature is an option of the licensee. The testing observed by the staff was conducted at about 120°F. Prototypical rising water levels associated with filling the sump pool can be simulated. The flow is controlled either by variable-frequency motor controllers or flow control valves. The instrumentation includes orifice plate flow meters, pressure taps, and temperature probes with the data fed to data acquisition computers. A plant-specific internal flume flow channel is constructed of lumber and installed within the outer steel test flume. The shape of the flow channel is designed to model the flow velocities that are prototypical of average plant strainer approach velocities. The purpose of the internal flow channel is to simulate the plant flow conditions so that debris settling within the test flume prototypical of the plant can be credited. This settling has been referred to as “near-field debris settling” or the “near field effect.” The design of the flow channel associated with the tests observed by the staff was based on CFD modeling of the plant sump. The analytical approach to designing the shape of the test flume may have resulted in test flow velocities that adequately represented the plant flow conditions. However, the staff raised several issues regarding the modeling of the plant flow and continues to interact with the test vendor to ensure that the testing is representative of conservative with respect to the plant conditions. Whether or not the debris settling seen in the tests is prototypical of the plant also depends significantly on whether or not the surrogate debris used in the tests was prototypical of the plant debris. In the observed testing, most of the heavier debris, including NUKON shreds settled within the flume before the flow reached the test strainer modules. In some tests with higher velocities the majority of the small fibrous debris transported to the strainer. The vendor has developed a debris preparation and introduction methodology that improves these aspects of testing. The test module in the testing is composed of full sized disks, and plant specific disk spacing and core tube geometry. In one observed test, for example, two vertical strainer module towers were installed in the pit below floor level, with the tops of the strainer positioned several inches above the flume floor level (Hiser 2008). Each tower had 40 horizontally mounted square strainer disks.

The preparation of the fibrous debris is an issue of importance to the PCI test protocol. PCI prepares fibrous debris in the three categories designated as “fines,” “small pieces,” and “large pieces,” and then matches the quantities of each category to the licensee’s specific analytically determined size distributions Smith, 2010). The small pieces are prepared by passing the fibrous insulation through a commercially available wood chipper. This process produces small shreds of fibrous debris that also include a certain intermixed amount of essentially individual fiber. The fine fibrous debris is prepared with a second shredder that produces substantially finer debris than the common wood chipper. This fine debris is intended to represent the very fine fibrous debris that would typically transport as suspended fibers in the plant sump pool (i.e., essentially individual fibers). However, a majority of this fine debris still tended to settle in the test flume during some tests. The vendor continued to refine the test methodology for testing that allowed near-field settling and has developed a method for debris introduction. PCI conducted tests with plant-specific foreign debris surrogates such as tape, tags, stickers, and label materials transporting in the flume to achieve a prototypical accumulation of such materials in the strainer or show that certain types of debis would not transport.

The PCI test procedures evolved to starting the pumps prior to debris introduction (their earlier testing varied with the pump starting before and after debris introduction). The PCI test termination criteria include 1) less than 1% increase in head loss in 30 min unless otherwise directed by the test engineer and 2) a minimum of 15 pool turnovers after all debris has been introduced.

Enercon Strainer Design and Testing

The Enercon replacement strainers consist of several individual “top hat” units connected to a manifold (NRC, 2008e). Each top hat unit typically consisted of two concentric hollow cylinders (some top hats were designed with a single cylinder) that allow flow through the inner and outer surfaces of each cylinder through perforations in the circular plates. Each cylinder annulus typically (but not all) contains a bypass prevention material that is similar to steel wool, which limits the amount of debris that will pass through the strainer to downstream components. The top hat dimensions as installed at Indian Point, for example, included the outer diameter of the outer cylinders as either 12 or 12.5 in.; the inner diameter of these cylinders as either 10 or 10.5 in.; the outer and inner diameters of the inner cylinders as 7 or 7.5 in. and 5 or 5.5 in. respectively; and the lengths as 15.5 to 43.5 in. The top hats can be oriented either vertically or horizontally. Strainer modules can be interconnected as needed for each plant-specific application. Water passes through the perforations, through the steel wool, and into the common manifolds. Enercon supplied plant-specific designed strainers to 14 U.S. units. An example Enercon plant strainer is shown in Figure 5.11-5.

ALION Science and Technology typically conducted the head loss testing on the Enercon manufactured strainers (one strainer test for multiple units was conducted at Wyle Labs). An isometric view of the ALION test tank with an Enercon prototype strainer installed is shown in Figure 5.11-6. In this configuration, the prototype strainer, consisting of a 3 x 3 array of top hat units connected to a common plenum, was enclosed with four plywood walls to control the approach of the incoming debris-laden flow. The plywood baffles were also used to ensure that the test array was geometrically and volumetrically configured to simulate a section of the plant strainer. ALION scaled the test flow rate based on the ratio between the net testing module surface area and the actual strainer net surface areas to maintain the plant strainer screen approach velocity in the test prototype. The test tank was approximately 6.0 ft high, 6.0 ft wide, and 10.0 ft long. Pressure transmitters, a flow meter, and thermocouples were installed to measure the head loss, total flow rate, and the water temperature.

Figure 5.11-5. H. B. Robinson Strainer (NRC, 2008b)

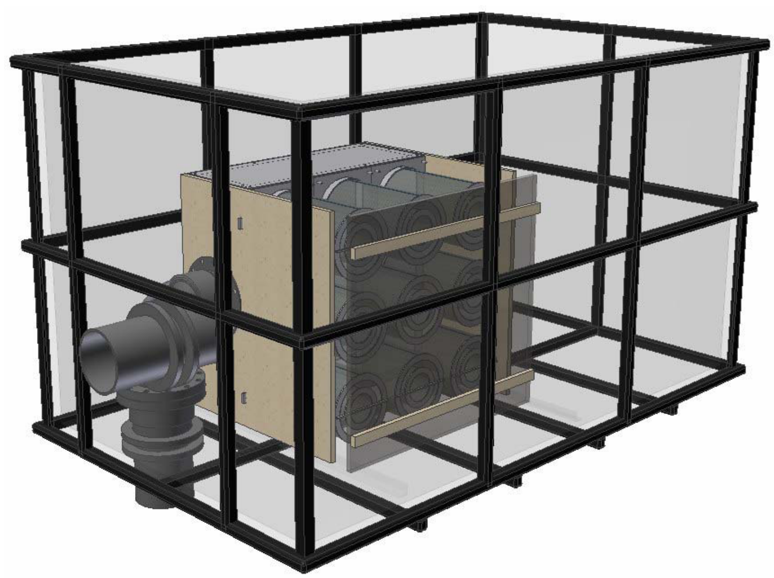


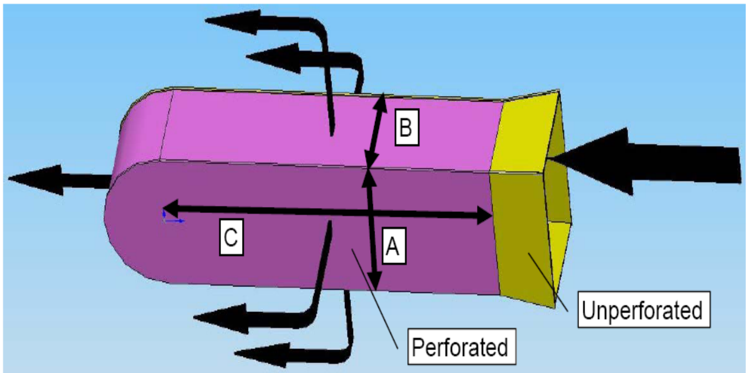
Figure 5.11-6. Isometric View of Alion Test Tank with Prototype Strainer (NRC, 2008e)

ALION used the actual plant insulation materials, where practical, or suitable surrogates as sources of debris for the testing. NUKON® was used to simulate the latent fibers. NUKON® has been accepted as a valid latent fiber surrogate. The latent particulate is simulated with silica sand with a size distribution sized according to the recommendation in NUREG/CR-6877. The size distribution of the surrogate fibrous debris was based on the vendor's generic debris preparation protocol, rather than attempting to match the plant's analytically determined size distributions. For the prototype tests, the fibrous debris was prepared by processing the fibrous insulation through a commonly available leaf shredder and then further refining the wetted shredded debris using a paint stirrer. The NRC staff was concerned that the shredded fibrous debris in the test did not adequately represent the suspended fibers that were predicted to reach the strainer by the transport analysis. Only very fine suspended debris would accumulate on the typical licensee strainer due to the very slow approach velocities associated with a large replacement strainer. ALION revised their debris preparation procedure so that the resulting fibrous debris met staff expectations. The particulate materials were generally obtained in a powder form so that no additional preparation was required other than wetting. The method of introducing the debris depended upon the plant-specific requirements. The stabilization or test termination criteria for the prototype tests were 1% change in head loss in a 1-hr period and a minimum of five pool turnovers having occurred but also subject to the judgment of the test coordinator who could extend the test.

ALION also sponsored chemical-effects head loss testing conducted by VÚEZ in a small tank designed to represent the containment conditions with respect to pool liquid volume, pool chemistry, temperature, materials, and impact on debris head loss (NRC, 2008e). The experiment was designed to replicate the corrosive interactions of the spray and pool fluid chemistry with those materials and debris sources in containment and resident on the sump screen over a 30-day mission time. The experiment attempted to prototypically simulate head loss parameters of debris bed thickness and composition and the flow velocity. The debris test screen in these small-scale tests was a horizontally mounted flat plate screen with an area of 0.135 ft^2. Instrumentation measured the pump flow rate, the water temperature, the head loss across the debris bed, and the fluid pH level. The water level was monitored. The water temperature was regulated to simulate the postulated time-dependent plant sump temperature. The pump flow rate was specified to simulate the plant strainer approach velocity. The scaling from the plant debris loads to the test loads was based on the ratio of the effective test area for the test strainer divided by that of the plant replacement strainer. The prepared fibrous debris was combined with the particulate debris to form a slurry. After the tank chemistry, temperature, and pump flow conditions were established, the debris slurry was poured directly onto the horizontal test screen to form the debris bed with the intent of having all of the debris actually accumulate on the screen. However, this method of forming a debris bed was not prototypical of the plant since in the plant, the debris would accumulate slowly as the flow carried the debris onto the strainer surfaces basically one fiber at a time, which would allow the flow-driven debris to slowly patch weak areas of the bed. Forming the debris bed by pouring the debris, rather than allowing the flow to form the bed results in beds that form less tightly compacted than would be prototypical. The staff observations noted the formation of non-uniform beds and inadequate debris preparation. Bulkier and non-uniformly formed debris beds could preclude the formation of an effective thin-bed and lead to an incorrect thin-bed conclusion. Since the chemical-effects head loss tests are run for the 30-day mission time, there was no need to specify any termination criteria associated with head loss increases or the number of pool turnovers. The termination criterion was 30 days. The staff ultimatedly did not accept the results of this the tests conducted at VUEZ.

CCI Strainer Design and Testing

The CCI strainers modules consist of a large array of strainer pockets connected via a common header or plenum (NRC, 2007d; NRC, 2008f). Each pocket is typically 4.29 in. high, 2.76 in. wide, and about 12 in. deep (although these dimensions could be varied). The rear surface of each pocket is curved. The total screen area depends upon the number of pockets incorporated into each strainer module and the number of modules in the plant strainer. The typical diameter of a perforation hole was 2.1 mm (0.082 in.). CCI supplied plant-specific designed strainers to 20 U.S. units. Schematics of an individual pocket and a small test strainer module are shown in Figure 5.11-7. A photograph of an example installed plant strainer is shown in Figure 5.11-8.



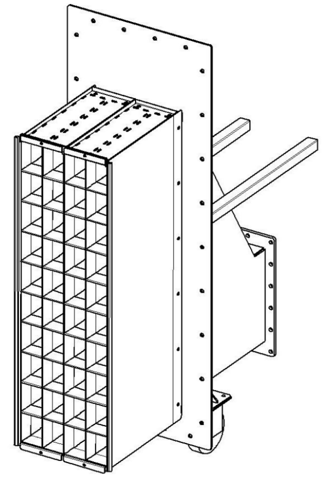


Figure 5.11-7. Schematic of Individual Pocket and Small Test Strainer Module (Blumer, 2007)

Figure 5.11-8. Photograph of Installed Plant Strainer (NRC, 2007d)

CCI typically conducted strainer prototype testing to determine potential head loss from debris, with and without chemical effects, using their test flume with three separate rigs: a testing module consisting of an array strainer pockets (e.g. 90 pockets), a small test flume with a test module consisting of a simulation of six pockets, and a medium-scale multifunctional test loop usually consisting of 40 pockets (NRC, 2008f). The choice of test rigs and the size of the modular test array depended upon the licensee test objectives and plant strainer design.

The schematics illustrating the multifunctional test rig are shown in Figures 5.11-9 and 5.11-10. The multifunctional test loop at CCI consisted of a closed recirculation loop with recirculation flow returning at the opposite end of the fume from where the test strainer was used to draw flow from the flume. The test tank consisted of a Plexiglas channel about 1.3 ft wide and 4.6 ft high and the test strainer was 10 pockets high by four pockets wide. A centrifugal pump circulated the water through the loop with the flow regulated using a pump rpm controller and/or an upstream valve. Instrumentation included a loop flow sensor to monitor the strainer flow rate, a thermocouple to monitor water temperature, differential pressure transducer to measure strainer head loss, and equipment to record these measurements. The large flume apparatus, approximately 8.5 ft wide, 9.8 ft high, and about 14.4 ft long, accommodated a larger strainer prototype, for example, the 120 pockets strainer used in the Oconee testing (NRC, 2007d).

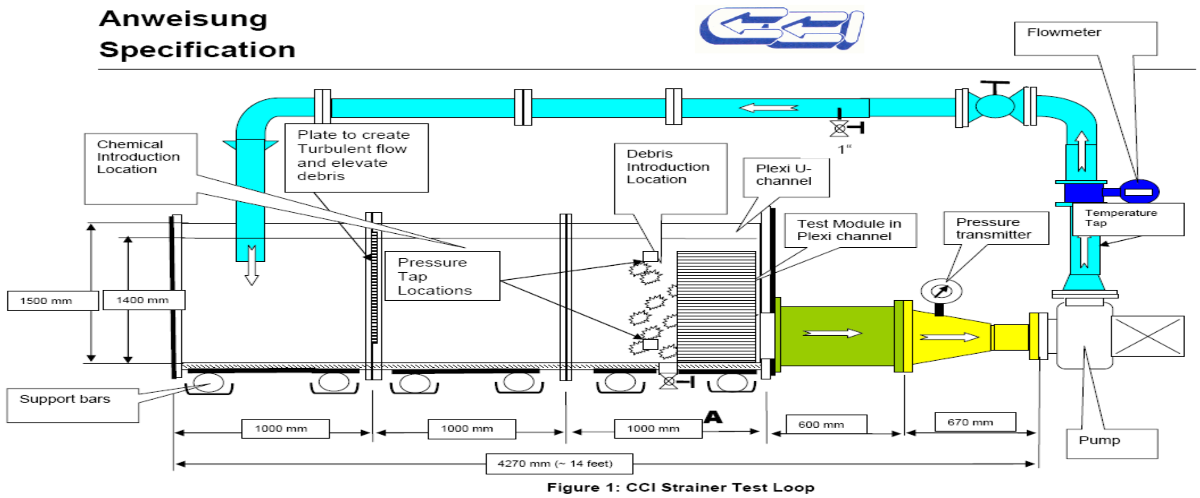


Figure 5.11-9. Illustration of the Multifunctional Head Loss Test Rig (Blumer 2007)

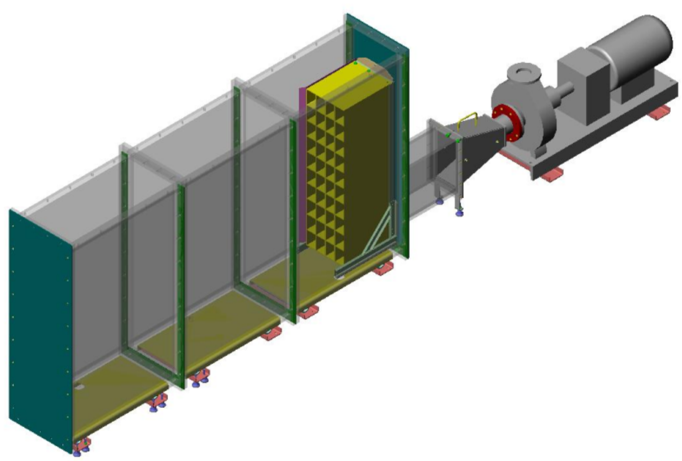


Figure 5.11-10. Illustration of the Multifunctional Head Loss Test Rig
(NRC 2008f)

The scaling from the plant debris loads to the test loads was based on the ratio of the effective screen area for the test strainer divided by that of the plant replacement strainer. To determine the strainer effective screen area, the total replacement strainer screen area was reduced by an area referred to as a "sacrificial area" that would, in theory, account for the miscellaneous debris (e.g., tape, labels, etc.) that could accumulate on the strainer. This practice was used by most strainer vendors.

CCI used actual plant insulation materials, where practical, or suitable surrogates as sources of debris for the testing. NUKON® was used to simulate the latent fibers. CCI used stone flour to simulate coatings and latent particulate.

The CCI preparation of the fibrous debris included baking the insulation at 300°C for 24 hours, cutting the insulation into pieces, soaking in water, and then using a high pressure water jet to decompose the insulation pieces into pieces smaller than 10 mm (⅜ in.). This process seemed to create debris considerably smaller than a single pass through a typical shredder, but the debris was still substantially larger than fiber that would remain suspended given typical sump pool flow and turbulence conditions. Although the settling behavior may have been corrected in later testing, CCI testing reviewed during NRC staff audits showed a fraction of the fibrous debris settling to the floor in front of the strainer rather than transporting as the prototypically fine fibers most capable of forming an effective thin-bed. The typical thin-bed accumulation of fibrous debris on the large PWR replacement strainers is due to suspended fibers primarily, which were not well represented by the CCI preparation. The CCI test conclusion, based on testing prior to adjusting their debris preparation procedure, that either a thin bed cannot form or its head loss would be substantially less than the fully loaded case was likely due to the non-prototypical debris preparation. CCI mechanically crushed the particulate insulations used in testing into a powder. The chemical precipitates were either allowed to form in the test loop to simulate precipitates under containment sump conditions, or were prepared per the WCAP test guidance, depending on the customer. The staff did not completely accept the in-situ method, but noted that it did produce significant head losses in some cases. The debris samples were weighed, mixed into a wetted homogeneous mixture in buckets, and poured into the test pool.

In the CCI test protocol, the pumps were started and the recirculation flows were established prior to introducing debris into the test flume. The early procedure used in the CCI multifunctional testing was to introduce the debris in close proximity to the test strainer to reduce debris settling within the tank. The wetted debris was slowly poured into the test loop within about 1 ft of the strainer entrance. The test strainer perimeter approach velocities of the test strainer at this location would be approximately prototypical of the corresponding plant strainer velocities. While this approach reduced near field settling, it did not eliminate it. Post-test photographs clearly showed varying amounts of both fibrous and particulate debris on the tank floor.

The early CCI approach of introducing the debris in close proximity to the strainer allowed larger debris to accumulate in the pockets than would accumulate under plant prototypical conditions where only suspended fines would reach the plant strainer. Larger pieces of debris were pulled into a pocket as the debris descended in front of the pocket, but once the larger piece was inside the pocket, it readily settled to the pocket floor, resulting in a non-uniform accumulation with respect to the other pocket surface orientations. Suspended fines would accumulate relatively uniformly on all surface orientations. Hence, introducing debris directly in front of the test strainer caused non-prototypical debris accumulation that disrupted the formation of a prototypical thin bed and thereby compromised the thin bed testing. Later testing prepared the fibrous debris more finely and added the debris further from the strainer so that it would transport more realistically to the strainer. Figure 5.7-7 shows a relatively uniform accumulation on a CCI test strainer, which was the result when debris was introduced far enough away from the strainer to allow the heavier debris to settle so that only the suspended fines reached the strainer.

The CCI test termination criteria included a 3% or less percentage change in head loss increase in 10 min for the thin bed test and 1% in 30 minutes for the full load tests when the head loss was less than 1 ft. For a head loss greater than or equal to one foot, the criteria were set at 1% in 30 minutes for both thin bed and full load tests. The procedure did not specify a minimum number of tank volume turnovers following the final addition of debris. However, the CCI tests generally ran for significant lengths of time prior to termination.

Comparison of Vendor Head Loss Testing for PWRs

The trend in replacement strainer design has been the implementation of large passive strainers withsurface areas up to several thousand square feet. These large strainers distribute the debris over a larger area. This philosophy has resulted in thinner debris beds and reduced water flow velocities, which in turn, reduce the head loss across the debris. The vendor designs vary primarily on how larger screen areas are incorporated into relatively small volumes that can be tailored to fit into a specific licensee's recirculation sump. The qualification testing of these strainers involves the replication of the plant post-LOCA strainer environment that would surround the strainer. The parameters that need to be prototypically replicated, or conservatively treated, include water flow velocities, pool turbulence, temperature, and water depth.

There are limitations to prototypically reproducing the sump pool environment in small-scale testing. All vendors conducted prototype tests at reduced temperatures that ranged from room temperature to 120°F with the exception of some long term tests where the test attempted to replicate the prototypical plant sump temperature profiles as closely as possible.

The flow approaching the perimeter of these large PWR replacement strainers is typically moving slower than 0.1 ft/sec on average. The average velocity of flow through the screen surfaces is typically less than 0.01 ft/sec. At these velocities, in the absence of turbulence caused by falling water, nearly all debris that would readily settle in the sump pool would have settled so that the debris approaching the strainer would consist mainly of suspended fines. The suspended fines consisted of the very fine particulate and individual fibers or very small fiber shreds. The chief characteristic of the fines was that this debris takes substantial time to settle, even in still water, so in the sump pool it would effectively remain in suspension and would be relatively uniformly distributed in the water. This condition leads to relatively uniform debris accumulations on all active strainer screen surfaces. When holistically considering the potential threat to blocking a large plant strainer, a thin bed debris accumulation likely has the greater potential to cause significant blockage. Note that some plant may have higher approach velocities due to their particular configuration.

If the licensee transport evaluation conservatively predicted larger pieces reaching the strainer in addition to adequately accounting for the suspended fines, this prediction would conservatively increase the bounding debris estimate. If the larger pieces of debris were to be added to an head loss test flume where the pieces could prototypically settle, these pieces should then have no significant effect on the test head loss. However, if these pieces were somehow forced to accumulate on the strainer in a non-prototypical manner, their presence on the strainer could preclude the formation of a thin-bed and lead to a non-prototypically low head loss result. NRC guidance, which has been followed by the test vendors during their latest rounds of tests, is designed to minimize the effects of non-prototypical transport of larger debris by adding all of the finest debris before moving to larger sizes. The use of staff guidance for fibrous debris preparation is another important factor in obtaining realistic thin bed head loss values.

All vendors based their test debris loads on the bounding quantities of debris as determined by plant-specific debris generation/transport analyses. The vendors have, in general, made reasonable selections for their surrogate debris. In early testing each vendor prepared their fibrous debris using a generic method that did not ensure that the debris added to the head loss test matched up with the debris predicted by the debris generation and transport analyses to arrive at the strainer. AECL and CCI prepared their surrogate fibrous debris using a high-pressure jet to separate the fibers after first reducing the insulation to small pieces. This process creates debris finer than a single pass through a leaf shredder but potentially not prototypical of suspended fibers. Only a portion of this debris may transport as prototypical suspended fines. GE, PCI, and ALION all first shredded their debris but then applied different secondary processes. GE in a later protocol passed their debris through the shredder a minimum of five times until the debris passed their qualification test. PCI created three sizes of shredded debris, for which they match the sizes to the licensee size categories, but the PCI fines were not sufficiently fine to represent the licensee's suspended fines. This was potentially complicated by the fact that some PCI testing credited near-field settling and some of the debris may have settled non-prototypically because it was larger than true fines. After shredding, ALION further processed the shreds with a paint stirrer in the prototypes tests, and used a cake mixer in the 30-day chemical effects tests.

The typical vendor fiber preparation methods create debris that contains a portion of individual fibers that will transport prototypically as suspended debris. Because none of the vendors experimentally ascertained the percentage of the prepared debris that was prototypical of suspended fiber they could not verify that the plant specific transport estimates were represented in the testing. As an example where this consideration could be critical, consider an all-RMI plant where the only fibers that can reach the strainer are latent fibers. Latent fibers are assumed to be individual fibers that completely transport to the strainers. Here, the debris generation evaluation estimates a given quantity of latent fibers that is assumed to completely transport and accumulate on the strainer. The vendor debris preparation methods created debris so that some fraction of the debris could settle so that an insufficient quantity might accumulate on the strainer. Ensuring the prototypicality of the fibrous debris is very important in ensuring valid head loss testing results. For particulate debris, the vendors generally acquired particulate in powder form. Microporous insulations were either crushed into a powder or purchased in powder form. With the exception of a few specific cases, the treatment of particulate debris has not been problematic for head loss testing.

Issues associated with debris introduction to the test involve the method, the timing and the location of debris introduction. Debris introduction must consider the test objectives, which are typically based on either a thin bed test or a full load test. The vendor debris introduction procedures evolved during the GSI-191 resolution. Later vendor protocols made improvements to start the pumps to establish the hydraulic conditions prior to introducing the debris; the debris was wetted prior to slowing pouring it into the test tank or flume to preclude non-prototypical agglomeration of the debris. The debris was typically introduced in batches, with the head loss being allowed to stabilize prior to introducing the next batch.

One difference among the vendor approaches was the location that the debris was introduced with respect to the location of the prototype test strainer. With the exception of PCI, the vendor approaches were generally designed to minimize debris settling within the test tank or flume. Later PCI testing used a flume shaped so that the approaching flow velocities would be prototypical of the plant sump. The flume shape was based on CFD analyses of the plant sump. Later evaluation showed that in some cases the turbulence predicted for the flume was significantly lower than the turbulence predicted for the plant. Had the turbulence levels been comparable, the debris settling in the PCI flume should be similar to that in the plant sump pool provided the test debris is also prototypical. Further, PCI was the only vendor that chose to test the transport and accumulation of the miscellaneous foreign debris such as tapes and labels rather than simply including a penalty for miscellaneous debris in the scaling for the test. The other vendors introduced debris closer to the test strainer to reduce potential for the debris to settle. These vendors also used pool turbulence to reduce the debris settling or actually introduced the debris directly in front of the strainer. Later tests suspended the practice of introducing debris too close to the strainer and evaluated added turbulence to ensure that it did not affect debris bed formation non-conservatively.

The adequacy of the debris introduction location with respect to the fibrous debris is directly related to the debris size distribution. If fine fibrous debris is prepared prototypically so that it essentially remains suspended under sump pool conditions its introduction location is not critical as long as it is not too close to the strainer. However, when a substantial portion of the prepared debris readily settles in the test tank, its introduction location when considered in conjunction with the quantities introduced is very important. Staff guidance is (1) that the suspendable debris be adequately represented, and (2) that larger debris is not to be forced to accumulate when that debris would not prototypically accumulate in the plant sump. The PCI flume protocol allowed the heavier debris to settle without reaching the sump. Therefore, the issue with the PCI methodology is ensuring that the individual fibers are prototypically represented in the mix of prepared debris. In the early CCI protocol, the fibrous debris was introduced directly in front of the strainer to minimize debris settling, but this protocol essentially forced larger debris that would not prototypically reach the strainer pockets to accumulate on the pockets floors. This behavior could preclude the formation of a thin bed. A similar situation occurred in the GE Waterford head loss testing, where mechanical stirring in the sector testing kept shreds in motion until the shreds accumulated in the sector gaps. This type of accumulation effectively formed debris dams at the entrance to the gap that subsequently shifted inward and cleared a portion of the screen area, which also precluded the formation of a thin bed. Vendors have taken actions to reduce the effects of non-prototypical debris accumulation on the strainers during testing.

During the auditing process, the NRC staff encountered a range of vendor attitudes regarding thin bed testing. Thin bed testing seems to be a cornerstone of the AECL protocol, where AECL consistently tested for thin bed head losses and found situations where the thin bed losses exceeded the full load head losses. By contrast, GE, PCI, ALION, and CCI all seem to have concluded that thin beds could not form on their respective strainers. The staff had observed thin beds on GE and PCI strainers and evidence of potential thin bed accumulations on CCI and ALION strainers. The reason that thin beds consistently formed on AECL strainers and not on other strainer designs was likely associated with test practices including the concerns described in this section.

The staff identified issues in small- scale testing conducted by ALION and AECL. These vendors conducted smaller scale tests over long periods in an attempt to allow chemical precipitates to form on a debris bed under conditions similar to those that would occur in a plant. The vendors conducted these tests because they believed that the chemical precipitates that were added to larger tests resulted in very conservative head loss values. Upon review of the test results the staff identified, for some tests, that for a similar debris load, the small-scale tests had a significantly lower head loss value than similar larger scale tests before chemical debris was allowed to accumulate on the debris bed. Because the small-scale test pre-chemical values were lower than the larger scale test values with similar debris loads the staff was concerned that the effects of chemicals were not adequately represented in the small-scale tests. In some cases the test results were not accepted. In some cases the tests were repeated assuring that pre-chemical head loss values were on par with previous larger scale test results prior to chemical effects.

Test Termination and Post Test Data Scaling

The test termination criteria and subsequent data extrapolation vary considerably from one vendor to another. Test data may be extrapolated from the test temperature to the plant sump pool temperatures. Results may be extrapolated from test termination to the mission time, and also extrapolated to alternative conditions, such as an alternative debris load, to account for deviations between the test module and the final replacement strainer design.

The primary termination criterion of the vendors has been that the rate of head loss increase be less than a certain percentage within a specified period of time. This criterion varies from 1% increase within 10 minutes to 1% within 60 minutes. The NRC staff observed head loss tests that were terminated when the head loss was increasing. One method for adjusting the measured head loss at test termination to account for the head loss increases that could occur is to extrapolate the head loss to the scenario mission time. Only GE and PCI included mission time extrapolations in their respective protocols. However, the staff acceptance review of design basis strainer head losses ensured that potential time based increases were accounted for. GE, PCI, and ALION methods have a criterion for the minimum number of pool turnovers between final debris introduction and test termination to allow debris filtration to occur. It was analytically shown that it takes about five pool turnovers to ensure the accumulation of the suspended fibers. However, for particulates it can take a substantially longer time to complete filtration because the filtration efficiency is much lower for particulates than for fibers. The staff recommended at least 15 turnovers between the completion of the debris introduction and test termination {NRC 2008d).

All of the vendors extrapolated head loss test data from the colder test temperatures to the warmer plant sump pool temperatures to obtain lower head losses more prototypical of the plant. The staff is concerned that certain head loss results may not scale with viscosity when pressure-driven bed degradation processes, such as bore holes, are present in the bed. Staff guidance is that tests should include flow sweeps to validate whether flow through the debris bed is laminar prior to extrapolating test results to higher temperatures.

The ALION protocol included an analytical method for combining chemical effects data from the 30-day VÚEZ tests with the prototype head loss test results based on applying a bump-up factor, determined from the chemical-effects testing, to the prototype head losses. Further, ALION used the NUREG/CR-6224 correlation to extrapolate to alternative conditions. The staff did not accept the use of the chemical bump-up factor and some of the extrapolations based on the 6224 correlation.

5.11.2 Strainer Debris Head Loss Testing by BWR Vendors

Four strainer vendors supplied replacement strainers to the 35 operating U.S. BWR units. These vendors were: (1) GE, who supplied strainers to 12 units, (2) PCI, who supplied strainers to 15 units, (3) Enercon, who supplied strainers to 3 units, and (4) ABB Combustion Engineering (ABB), who supplied strainers to 4 units (LA-UR-01-1595). All of the replacement strainers were large-capacity passive designs. With the exception of the Enercon strainer, the strainer designs incorporated cavities, troughs, or traps to collect debris so that relatively large screen areas could be fit into relatively small volumes. The Enercon strainer made use of the large available space within the Mark III suppression pool to increase the screen areas without the use of internal entrapments. The large screen areas reduced the velocity of flow through the debris bed and simultaneously reduced the thickness of the postulated bed of debris.

The BWROG conducted prototype head loss testing to gather data on alternative ECCS suction strainer designs as a possible resolution to the strainer-clogging problem. The strainer head loss tests were conducted at the EPRI non-destructive evaluation (NDE) center in Charlotte, North Carolina. Supplemental tests to determine the effects of individual debris components on head loss and combinations of debris components were conducted at Continuum Dynamics, Inc. (CDI) in Princeton, New Jersey. These tests are documented in the URG (NEDO-32686, Volume I).

The overall objective of the full-scale test program was to develop and test strainer concepts that could be used to resolve the strainer clogging issue. Three specific concepts were evaluated: high-capacity passive strainers, strainer backflushing, and an active self-cleaning strainer. Testing was also conducted on a truncated cone strainer, similar to those installed at typical BWRs, to provide a baseline for comparison. For the passive strainers, the primary objective was to determine the capacity of each strainer to accumulate debris without clogging.

Seven passive strainers and one active self-cleaning strainer were tested to obtain pressure loss and performance data as a function of debris type, debris quantity, flow rate, and time. The tested strainers were 1) the truncated cone design, 2) the 20-point star design, 3) the 60-point star design, 4) two-thirds of the 60-point star design (i.e., sheet metal covered one-third of 60-point star, 5) prototype #1 of the stacked-disk design, 6) prototype #2 of the stacked-disk design, and 7) the stacked disk section of the self-cleaning strainer design (in passive mode).

For passive strainers, tests were conducted to evaluate the maximum fiber and corrosion product capacity, the feasibility of backflushing, and the effect of RMI on head loss. Tested debris included prototypical fibrous insulation, RMI, simulated corrosion products, and miscellaneous debris. The active strainer was tested to evaluate its ability to maintain a clean strainer surface area under various debris loadings at design flow rates and the resistance of the rotating assembly to start-up after a period at a minimum flow condition.

Two centrifugal pumps connected in parallel with a combined capacity of 10,000 gpm pumped water from a 50,000-gal tank and subsequently returned the flow to the tank. The test strainer was attached to the pump suction piping. Strainers could be mounted either vertically or horizontally. Backflushing was performed by aligning one pump to pull water from the tank through alternative suction piping and then discharging the water back through the test strainer. The primary measurements taken during these tests were 1) strainer head loss, 2) system flow rate, 3) the masses of insulation debris, corrosion products and other debris introduced into the vessel, and 4) plow/brush rotation rate and strainer torque on the self-cleaning strainer.

The BWROG concluded that (1) corrosion products, when mixed with fibrous insulation, greatly increased the head loss over that of fibrous insulation alone, (2) lower approach velocities produced lower head losses although the relationship was non-linear over the range of flow rates and strainer sizes tested, (3) miscellaneous debris can also create significant increases in head loss, (4) thin debris bed tests indicated a fibrous bed thickness slightly greater than 1/8 in. was sufficient to cause high head loss on the truncated cone but not the alternative strainer designs, (5) the measured amount of fibrous NUKON™ insulation that passed through the truncated cone strainer was 0.4% of the total fiber in the tank for a specific flow rate and strainer head loss, and (6) passive strainers can collect significant amounts of fibrous insulation and corrosion products with acceptable head loss at the flow rates of interest for BWR ECCS. The BWROG also found that a minimum approach velocity is required to keep RMI debris on the strainer, and that an RMI debris bed causes less significant head loss than a fibrous/particulate debris bed. Backflushing did not always remove accumulated fibrous/particulate debris on the complex strainer designs. The active front portion of the self-cleaning strainer was kept clean for all debris types and loadings tested at the design flow rate of 5,000 gpm; however, the torque generated by the turbine (rotating cleaning blades) was higher than expected.

The NRC staff reviewed the BWROG testing and found that, while the URG contained valuable and useful data for predicting strainer head loss, there were several concerns regarding the quality and applicability of these data. One important NRC staff concern regarding the BWROG tests was that reasonable steady-state head loss measurements were not achieved in a significant number of the tests. This concern is important because the amount of debris on the strainer was deduced from known quantities of debris introduced into the water tank by assuming that essentially all of the debris was deposited onto the strainer when the test head loss was measured. Therefore, the debris bed composition was relatively unknown during transient conditions. Direct application of the head loss data obtained for the prototype strainers to the plant strainers was not justified because the test modules were not actual prototypes of the plant-specific design. In some cases, the debris loads used in the test programs did not cover the entire range of debris loads in the plants. This resulted in potential inaccuracies in the estimation of strainer head loss. In spite of these reservations, NRC found that use of the data obtained from the test programs in plant-specific calculations was reasonable, provided the vendor or the licensee used the data within the original range of testing or established a theoretical basis for extrapolating the data to other strainer designs or debris loads.

Subsequent prototype testing by the vendors generally followed the BWROG testing procedures which initiated the recirculation pump prior to introducing the debris, used the return flow to keep most of the debris in suspension, and terminated the test when the head loss increases slowed to an acceptable rate. In general, the test procedures assumed that the head loss would always increase with the debris quantities accumulated on the strainer (i.e. the greater the debris load, the greater the head loss). While the BWROG concluded that thin beds could not form on the alternative strainer designs, the PWR testing demonstrated that thin debris beds can readily form on complex strainers and can cause significant head losses, often greater than head losses obtained with greater debris loads. Discussions of the limited information available for vendor-specific head losses testing follow.

GE Strainer Design and Testing

The GE stacked-disk BWR ECCS suction strainer uses disks whose internal radius and thickness vary over the height of the strainer. The patented GE stacked-disk suction strainer for the ECCS pump was designed to have minimum head loss while accumulating a maximum quantity of debris within a given volume. The strainer has a central core of varying radius such that the flow through the entire central region is maintained at constant velocity. A number of perforated disks of varying internal diameters and whose thickness varied with radius surround the central core. The spacing between the disks is maintained constant at 1.75 in. The outer diameter of the disks is typically constant, but can be varied and still maintain the constant velocity core. Figure 5.11-11 is an isometric view of a typical GE stacked-disk strainer with a quarter segment removed to illustrate the internal design. GE tested their stacked-disk strainer design at the EPRI NDE Center (NEDO-32721-A,).

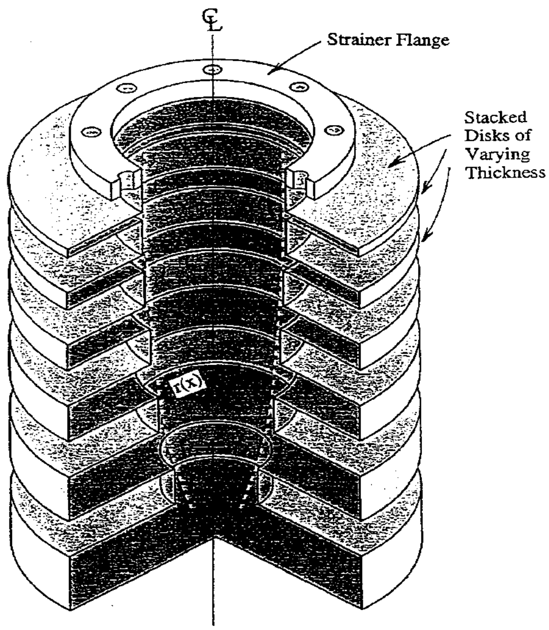


Figure 5.11-11. Isometric View of a Typical GE BWR Replacement Strainer (NEDO-32721-A).

The methodology used for hydraulic design of the GE stacked-disk suction strainer includes the calculation of the head loss with a clean strainer, the head loss due to fiber and corrosion product laden debris, and the use of bump-up factors to account for miscellaneous types of debris. GE conducted hydraulic testing on a GE prototype strainer to determine both clean-strainer and debris-laden head losses. GE used data from their prototype testing and from the BWROG head loss testing (NEDO-32686) to develop a design correlation for the GE strainers. This correlation consisted of a dimensionless head loss coefficient that was essentially a linear function of the flow velocity, water viscosity, and debris bed thickness divided by the square of an inter-fiber distance.

The prototype test strainer was mounted horizontally to a 24-in. tee in a 50,000 gal vessel. Two centrifugal pumps capable of producing a total flow of 10,000 gpm were used to provide system flow which was controlled by valves on the pump outlets. The flow returned to the vessel through a venturi and then through a pipe whose exit was centered in the vessel and directed down toward the floor. This pipe orientation prevented material from settling on the vessel floor. Instrumentation included a differential pressure transmitter to measure head loss across the strainer, differential pressure across the venturi in the return leg of the piping to measure the flow rate, and a thermometer to measure the temperature. A schematic of the test facility is shown in Figure 5.11-12.

The GE test procedures essentially duplicated the BWROG test procedures. The pumps were started and the flow rate established prior to introducing the debris. The flow rate was maintained at a nearly constant value determined by the test matrix, unless the strainer maximum pressure drop was reached or the pump performance was degraded. After the strainer head loss became approximately steady state, the flow rate could be adjusted down and up (a flow sweep) to obtain head loss at different flow rates. A run was terminated when the strainer head loss became relatively stable or a pre-determined value of head loss was achieved (after conducting any required flow sweeps).

GE provided proprietary design details of the strainer and the hydraulic performance characteristics of their strainer to the NRC for review (NEDO-32721P). In addition, the NRC staff performed an onsite audit of the Duane Arnold plant, which is a single BWR/4 unit with a Mark I containment. Duane Arnold was the reference plant used in the NUREG/CR-6224 study that formed the basis for the resolution of the BWR strainer blockage issue.

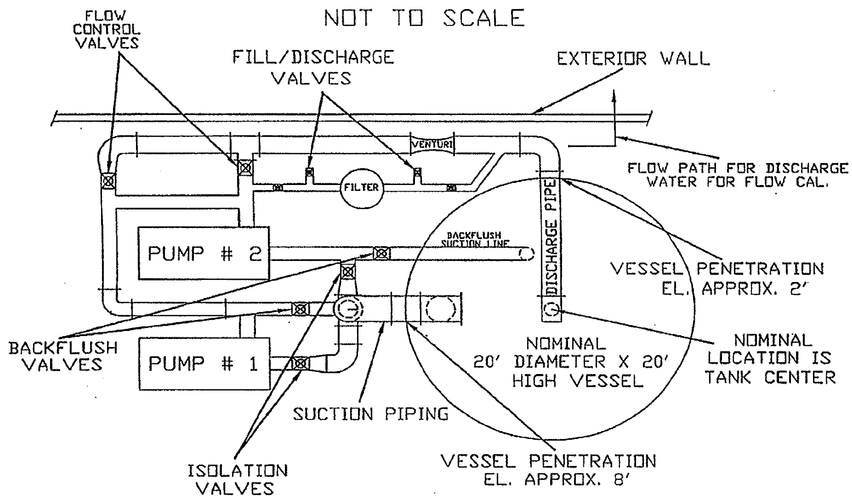


Figure 5.11-12. Schematic of the GE Test Facility (NEDO-32721-A).

These reviews formed the basis for the NRC acceptance of the GE replacement strainers. Based on the NRC review, the staff concluded that the test program used by GE for verifying the hydraulic performance of the prototype strainer and validating GE's head loss correlation was acceptable; however, the staff expressed concerns regarding the validity and use of this correlation. GE adopted an empirical means for correlating the head loss test data for the fiber/sludge debris bed. The GE head loss correlation is based on test data generated over a narrow range of test parameters, and the GE correlation does not account for the geometric effects systematically. After further review, the staff concluded that GE introduced sufficient margin to compensate for any deficiencies in the correlation. The staff concluded that extending the test results over a narrow parametric range outside the test range is reasonable.

PCI Strainer Design and Testing

PCI supplied advanced passive stacked-disk strainers to the nuclear industry under the trademark Sure-Flow™ strainer. The strainers consist of stacks of coaxial perforated metal plate disks that are welded to a common perforated internal core tube. The design maximizes the surface area of the perforated plate while keeping the circumscribed area to a minimum. The internal core tube is designed to provide structural support and to ensure uniform approach flow velocity to all disks. The design of a specific PCI strainer was tailored to fit each plant application. Figure 5.11-13 is a photograph of one installed BWR PCI strainer, and Figure 5.11-14 shows a typical strainer core tube (Rao et al., 2001).

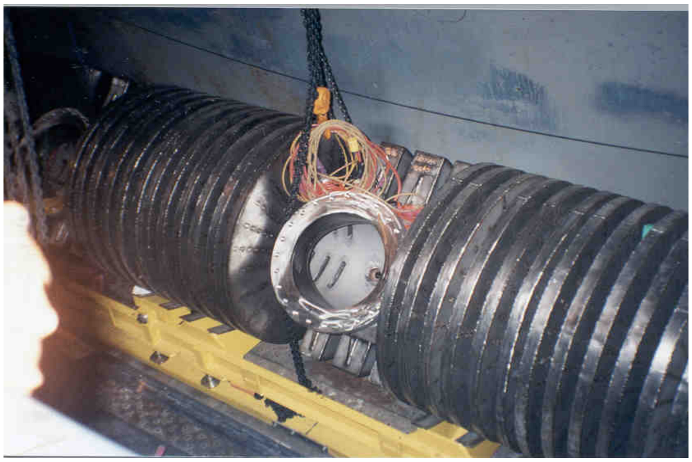


Figure 5.11-13. PCI Stacked Disk Strainer Being Installed at Pilgrim Nuclear Power Plant (Rao et al., 2001).

Figure 5.11-14. Core Tube Used in the PCI Stacked Disk Strainers (Rao et al., 2001).

PCI conducted prototype testing and used the NUREG/CR-6224 head loss correlation, as implemented in an industry proprietary computer code named HLOSS developed by Innovative Technology Solutions (ITS) Corp to predict strainer head loss. The overall technical approach was to use the prototype test data to validate the head loss correlation and then use the correlation to make strainer-specific head loss predictions.

PCI developed two prototype Sure-Flow stacked-disk strainers and tested them at the EPRI NDE Center. The test data were published in the BWROG URG (NEDO-32686). One prototype, referred to as “Stacked-Disk #1” in the URG, was a 40%-scale prototype with six disks, five troughs between the disks, a 13-in. core tube, a 30-in. outside diameter, and a length of 2.5 ft. A larger prototype, referred to as “Stacked-Disk #2,” was 4-ft long with a core tube diameter of 26 in. and a stack outer diameter of 40 in. Both the BWROG and PCI tested the head loss performance of these strainers.

The tests were conducted by first starting the pumps and establishing the flow rate. Then, the debris was introduced. The tests were instrumented to measure strainer head loss, flow rate, and water temperature. Return flow was discharged downward at the center of the tank 12 inches above the tank floor to reduce debris settling. When the pressure drop across the strainer reached a pre-determined limit or approximate steady state, the value was recorded, and if needed, the flow rate was adjusted down and up (a flow sweep) to obtain head loss at different flow rates.

The NRC staff reviewed the PCI strainer design, performance characteristics, head loss data, and the adequacy of the head loss models. The test data were obtained primarily for debris beds consisting of NUKON™ fibrous debris with and without sludge, and for RMI debris. As part of this review, the staff explored the adaptation of the NUREG/CR-6224 correlation developed for uniform flat screen debris beds to stacked-disk strainers so that the correlation could be used by the staff to evaluate the performance of strainers installed at the various operating BWR plants. The adaptation of the correlation to a stacked-disk strainer involved the implementation of the concept of a variable effective strainer area, where the initial actual strainer screen area progressively decreased due to debris accumulation in the disk gaps until the debris accumulation area became the strainer circumscribed area (Rao et al., 2001). The shape of this effective area curve versus debris accumulation was to be deduced from applicable strainer head loss data.

Enercon Strainer Design and Testing

Enercon Services designed and manufactured large capacity passive suction strainers specifically for the BWR Mark III containment toroidal suppression pool. Figure 5.11-15 shows an individual Enercon module of the Mark III strainer installed at the Grand Gulf Nuclear Station (GGNS). These strainer modules were joined together to form a large plant strainer located on the floor of the suppression pool, as illustrated in the Figure 5.11-16. The resulting strainers have surface areas in excess of 6000 ft2. Enercon tested these strainers at a quarter-scale testing facility.

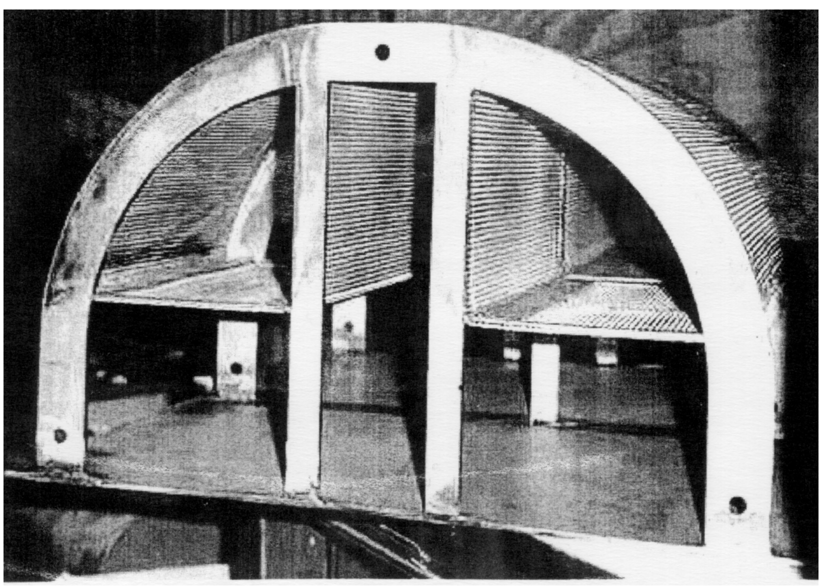


Figure 5.11-15. Individual Enercon Mark III Strainer Module (Rao et al., 2001).

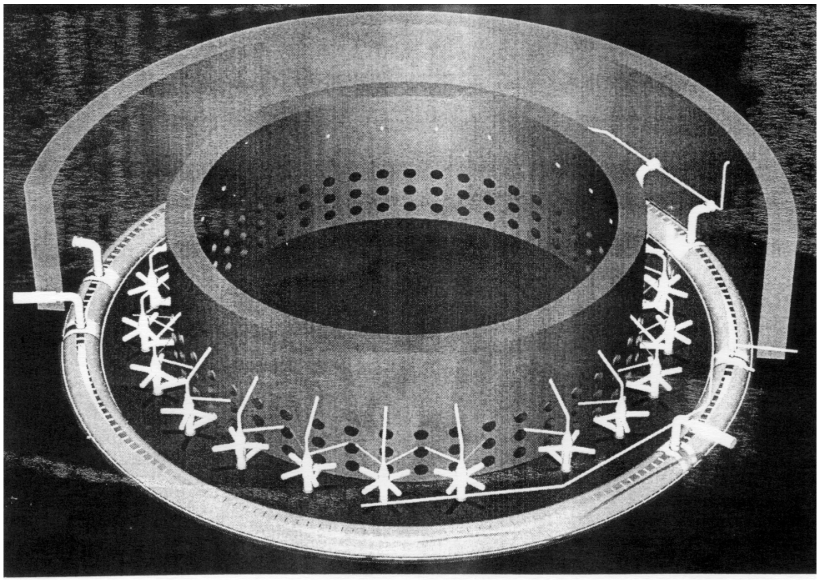


Figure 5.11-16. Illustration of Installed Enercon Mark III Strainer (Rao et al., 2001).

Prototype replacement strainer testing was conducted at a specially constructed test facility, where quarter-scale strainer prototypes were installed. The quarter-scale prototype test strainer module differed in construction from the actual plant modules with respect to specifics such as the number of ribs and the plate thickness, which affected the scalability of the clean-strainer head loss but not the scalability of the screen surface area. Plant hydraulic conditions and debris loads were scaled to the prototype strainer size. Specifically the approach velocities were maintained the same and the debris loadings per unit area were equal to or greater than those expected in the plant.

The NRC staff audited the GGNS strainer clogging resolution and reviewed the Grand Gulf head loss testing. The GGNS replacement strainer has a screen area of 6253 ft^2 and serves as a common header for all six ECCS pumps so that any combination of operating systems can draw recirculation water through the same large screen area. All of the prototype tests were conducted at 75°F. The data repeatability was acceptable. Head loss variations of 2-ft water or less were measured during repeatability tests, and the plant had sufficient NPSH margin to account for these uncertainties. The head loss test data indicated that some of the tests might not have reached steady state before termination. The licensee accounted for this apparent shortcoming by extrapolating to a steady value for the mission time (Rao et al., 2001).

Grand Gulf uses predominantly Mirror™-brand RMI cassettes to insulate reactor system piping, but substantial inventories of Kaowool, calcium-silicate, and fiberglass insulations are also present in the containment. Due to the low strainer approach velocities of approximately 0.016 ft/sec, RMI debris did not accumulate or remain attached to the strainer. Therefore, the head loss concern at Grand Gulf came from the combined effects of fibrous debris (Kaowool and fiberglass) and particulate debris (calcium silicate). The combination of these types of debris resulted in high head losses even though the approach velocity was relatively low. These results represented a significant finding because such data had previously not been available.

ABB Strainer Design and Testing

The large-capacity passive replacement strainers designed by ABB are constructed of a strainer plate shaped into longitudinal pleats to extend the plate area and thus reduce the approach velocity at the plate. The strainer plates, have 5/8-in. perforations with an overlaying 1/16-in.

wire mesh. ABB conducted prototype testing of their design at the EPRI facility.   The debris loads for the Limerick testing consisted primarily of NUKON and iron oxide corrosion products. The design report for the ABB strainer is proprietary. The strainer is described as a strainer with pleated surfaces. A correlation algorithm and a scaling factor were developed, based on the test data, which the staff found accpetable.

6 BWR INDUSTRY RESPONSE

The NRC staff first addressed ECCS clogging issues in detail during its review of Unresolved Safety Issue (USI) A-43, “Containment Emergency Sump Performance.” The resolution of USI A-43 is documented in GL-85-22, “Potential for Loss of Post-LOCA Recirculation Capability due to Insulation Debris Blockage,” dated December 3, 1985. The staff concluded at that time that no new requirements would be imposed on licensees. During the 1990s, however, new information arose which challenged the adequacy of the NRC’s conclusion that no new requirements were needed to prevent clogging of ECCS strainers in BWRs. In July 1992, a Barsebäck event demonstrated the potential for a pipe break to generate and transport a sufficient amount of debris to the suppression pool to clog the ECCS strainers.

Similarly, in 1993, two events involving the clogging of ECCS strainers occurred at the Perry Nuclear Power Plant, a domestic BWR. Both Perry events involved clogging of the RHR pump suction strainers by debris in the suppression pool. The debris consisted of glass fibers and corrosion products (or “sludge”) that had been filtered from the pool by the glass fibers that had accumulated on the strainer. The Perry events demonstrated the deleterious effects on strainer pressure drop caused by the filtration of particulates by fibrous materials adhering to the strainer surface, a previously unrecognized effect.

The Barsebäck and Perry events led to the development of NRC Bulletin 96-03, the draft for which was released for a 60-day public comment on July 31, 1995 (Office of Federal Register, 1995). During the public comment period, NRC staff resources were diverted from NRC Bulletin 96-03 to the development of NRC Bulletin 95-02 due to an event at Limerick Generating Station, Unit 1. On September 11, 1995, Limerick Unit 1 was operating at 100 percent power when a reactor safety relief valve (SRV) spuriously opened. Operators were unable to close the SRV, and a manual reactor scram was initiated. During the event, two loops of suppression pool cooling were operated to remove heat being released into the pool. During the event, the operators observed fluctuating motor current and flow on the “A” loop of suppression pool cooling. Cavitation was the apparent cause, and the loop was secured. The “A” pump was checked and successfully restarted with no further problems observed. Following the event, a diver inspected the condition/cleanliness of the strainers and suppression pool. The diver found both “A” loop strainers almost entirely covered with a thin mat of debris, consisting mostly of fibers and sludge. The “B” loop strainers had a similar covering, but less of it. Analysis showed that the mat primarily consisted of iron oxides and polymeric fibers. The fiber source was not identified, but the licensee determined that they did not originate within the suppression pool and contained no trace of either fiberglass or asbestos. This event demonstrated the importance of FME practices to ensure adequate suppression-pool cleanliness. In addition, it re-emphasized that materials other than fibrous insulation could clog strainers.

NRC Bulletin 96-03 was issued on May 6, 1996. It requested BWR licensees to implement appropriate procedural measures and plant modifications to minimize the potential for clogging of ECCS suction strainers by debris generated during a LOCA. Also issued was RG 1.82, Revision 2, “Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident,” which presents guidance on plant-specific analyses to evaluate the ability of the ECCS to provide long-term cooling consistent with the requirements of 10 CFR 50.46.

6.1 NRC Bulletin 1995-02

On October 17, 1995, NRC issued NRC Bulletin 95-02 to all holders of BWR operating licenses or construction permits. It was issued because the staff was concerned that BWR licensees had inadequately maintained suppression pool cleanliness. The concern arose out of the Limerick event described above. Limerick had never cleaned the Unit 1 suppression pool. Some of the debris that clogged their strainers had apparently been left in the pool during plant construction. Clearly, debris in the suppression pool threatened the ability of the pumps that draw suction from the suppression pool to adequately perform their safety functions. This bulletin was issued to:

1 Alert addressees to complications experienced during the Limerick event.
2 Request addressees to assess the operability of their ECCS and other pumps that draw suction from the suppression pool on the basis of suppression pool/suction strainer cleanliness, and the effectiveness of the addressee's FME practices. In addition, addressees were requested to implement appropriate procedural modifications and other actions (e.g., suppression pool cleaning), as necessary, to minimize foreign material in the suppression pool and containment. Addressees were requested to verify their operability evaluation through appropriate testing and inspection.
3 Require that addressees report to the NRC whether and to what extent they complied with the requested actions. A second report was required upon completion of confirmatory test(s) and inspection(s) to provide the results, verify that addressees had complied with the requested actions, or indicate completion of any proposed alternative actions.

Figure 6.1-1 shows that BWR licensees had, in fact, cleaned their suppression pools. Figure 6.1-1 does not include Big Rock Point because its design does not have a suppression pool, and Browns Ferry, Unit 1, which was in an extended shutdown at the time of the response. Tennessee Valley Authority, the licensee for Browns Ferry, stated in their response that they would address the bulletin issues for Unit 1 before restarting the plant.

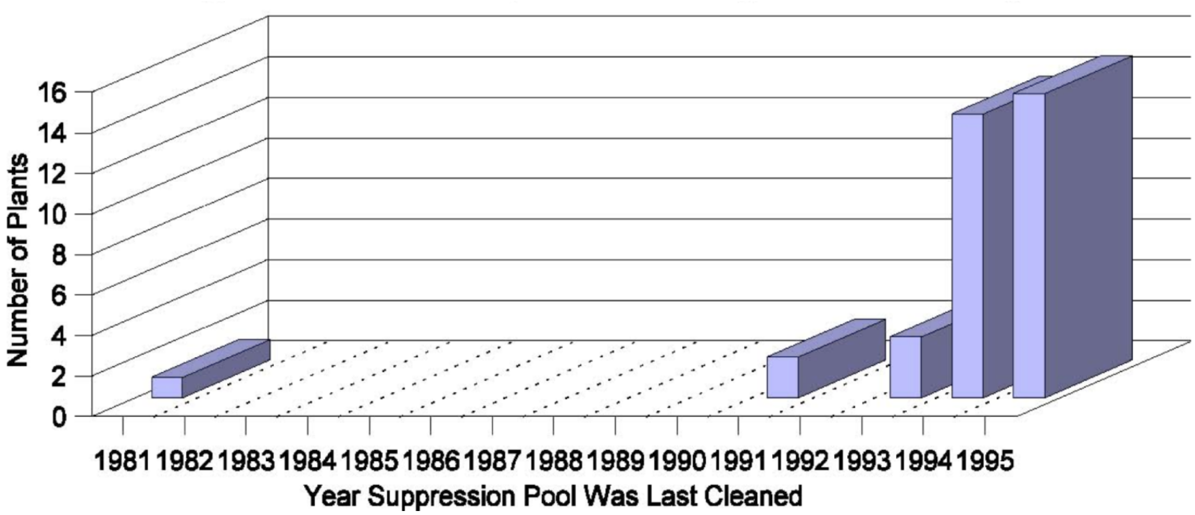


Figure 6.1-1. NRC Bulletin 95-02 Responses on Last Suppression Pool Cleaning

The Containment Systems and Severe Accident Branch of NRC performed detailed reviews of 11 plants and wrote safety evaluations on those responses. Since no safety issues were identified in either the preliminary or the detailed reviews, and it was learned that utilities had been cleaning their suppression pools, NRC redirected its resources to the completion of NRC Bulletin 96-03. The NRC also completed reviews on addional plants.

NRC concluded that it was appropriate to close this multi plant action (MPA) without further review for the following reasons:

1 Over 85% of the BWRs had been reviewed in detail with no safety concerns identified.
2 Of the five remaining plants, an inspection visit to two (Perry and Grand Gulf) showed suppression pools to be extremely clean.
3 As part of the review of NRC Bulletin 96-03, a detailed audit of Grand Gulf Nuclear Station (GGNS) was performed including FME procedures. The audit team concluded that GGNS had implemented an appropriate inspection program to ensure the operability of the ECCS (relative to strainer and suppression pool cleanliness). The team also implemented appropriate foreign material control procedures to limit the potential for clogging the ECCS with materials brought into the drywell or wetwell during outage operations.
4 The NRC issued "Temporary Instruction (TI) 2515/125—Foreign Material Exclusion Controls" on August 25, 1994 to determine whether licensees had implemented effective procedures to prevent foreign material from inadvertently entering safety systems during maintenance activities, outages, and routine operations. After reviewing the FME controls at Fitzpatrick and Hatch in response to TI 2515/125, resident inspectors for both plants concluded that the FME controls of the licensees were adequate.

In general, NRC review found that concerns raised by the events at Barsebäck and Perry, as well as the NRC's focus on strainer issues, had increased awareness of foreign material issues among BWR licensees. This heightened awareness resulted in increased attention being given to suppression-pool cleanliness even before the issuance of the NRC Bulletin 95-02. This is evidenced by the fact that most of the plants had cleaned their suppression pools within the three years prior to the bulletin. Limerick had cleaned the Unit 2 suppression pool prior to the Unit 1 event, and Unit 1 was scheduled for cleaning at the next refueling outage at the time of the event. Only NMP-1 had not recently cleaned their suppression pool, and in response to the bulletin, they committed to do so at the next outage of sufficient duration. It should not be construed that NMP-1 had any less sensitivity to the issue than the other BWR licensees. Their analysis of the plant led them to conclude that they did not need to clean their pool again. In 1981, they had drained and cleaned the entire torus. Since then, they have minimized any potential to introduce debris into the torus. Divers retrieved items that were inadvertently dropped into the torus pool by workers. Because NMP-1 uses mostly RMI, NMP-1 staff concluded that they were not likely to introduce fibrous material into the torus during outages. On this basis, they had concluded that there was no need to clean the torus again. However, as noted above, they committed to do so in response to NRC Bulletin 95-02.

6.2 NRC Bulletin 1996-03

NRC Bulletin 96-03 was issued to request licensees to implement appropriate procedural measures and plant modifications to minimize the potential for clogging of suction strainers in the suppression pool by debris generated during a LOCA. The bulletin identified three resolution options. These options were to install one of the following: a large-capacity passive strainer, a self-cleaning strainer, or a backflush system.

Table 6.2-1 summarizes the actions taken by each licensee. All licensees elected to use option 1, installation of large-capacity passive strainers. Four different vendor designs were used: the GE stacked disk strainer, the PCI "Sure-Flow" stacked disk strainer, the Enercon toroidal strainer, and ABB strainer. The total installed strainer surface areas per plant are also shown in Table 6.2-1.

At the time of the issuance of the bulletin, the BWROG was developing topical report NEDO-32686, "Utility Resolution Guidance for ECCS Suction Strainer Blockage." The purpose of the URG is to provide utilities with (1) guidance on evaluation of the ECCS potential strainer clogging issue for their plant, (2) a standard industry approach to resolution of the issue that is technically sound, and (3) guidance that is consistent with the requested actions in the bulletin for demonstrating compliance with 10 CFR 50.46. The URG included guidance on a calculational methodology for performing plant-specific evaluations of potential strainer blockage. After reviewing responses to NRC Bulletin 96-03, NRC concluded that all affected BWR licensees had designed their new large-capacity passive strainers consistent with the criteria in the URG which had been reviewed and approved by the NRC staff.

During the development of NRC Bulletin 96-03, NRC decided not to perform detailed reviews of every plant. As a result, the reporting requirements for the bulletin do not contain detailed descriptions of proposed resolutions by the licensees. Instead, the staff developed a strategy for reviewing the implementation of this bulletin which consisted of conducted a review of the URG combined with a sampling of plants. Specifically, the staff first reviewed and issued a safety evaluation on the URG. The URG provided a baseline evaluation process for determining how much strainer area was needed for each plant. The second component of the staff's review included detailed audits of four sites to ensure that the application of the URG guidelines was consistent with the staff's basis for approval of the URG.

The NRC staff conducted audits (Rao et al., 2001) of four sites: Limerick Generating Station, Units 1 and 2; Dresden Nuclear Power Station, Units 2 and 3; Duane Arnold Energy Center; and Grand Gulf Nuclear Station. The results of these audits showed that these licensees had adequately designed their ECCS strainers to withstand the debris loads anticipated during a LOCA. No safety concerns were identified at any of the plants. On the basis of the audit findings and results of the staff's review of the URG, NRC did not consider it necessary to perform any additional detailed reviews of licensee resolutions. In addition to the review work cited above, the staff performed a number of additional reviews related to the strainer clogging resolution. This work included several test programs, both by the NRC and the industry. The work was conducted at LANL and reported in Report LA-UR-01-1595 (Rao et al., 2001), which summarizes the efforts of the NRC, the NRC's contractors, and industry to resolve the BWR ECCS strainer clogging issue.

Table 6.2-1. Summary of Strainer Modifications Made in Response to NRC Bulletin 96-03

Plant Name, Plant Type and Containment Type	Stacked Disk Strainer Designs			Other Strainer Design	Type of Review Performed by NRC	Approximate Total Strainer Area (ft2) per Plant	Strainer Vendor
	Bolt-on	Supplemental Supports	Ring Girder Mounted				
Browns Ferry 2 & 3 BWR/4, Mark I	X				1,2,5	1192	GE
Brunswick 1 & 2 BWR/4, Mark I	X	X			1,4	1575	PCI
Clinton BWR/6, Mark III				Toroidal	1	6057	Enercon
Cooper BWR/4, Mark I	X				1,7	2164	GE
Dresden 2 & 3 BWR/3, Mark I	X				1,6	475	PCI
Duane Arnold BWR/4, Mark I	X				1,6	1359	GE
Fitzpatrick BWR/4, Mark I			X		1,2	2928	PCI
Fermi 2 BWR/4, Mark I	X				1	2322	GE
Grand Gulf BWR/6, Mark III				Toroidal	1,2,6	6253	Enercon
Hatch 1 & 2 BWR/4, Mark I	X				1,3	1110	GE
Hope Creek BWR/4, Mark I			X		1,3	3788	PCI
LaSalle 1 & 2 BWR/5, Mark II	X				1,2	500	PCI
Limerick 1 & 2 BWR/4, Mark I				X	1,6	2715	ABB
Monticello BWR/3, Mark I			X		1,7	1224	PCI
NMP-1 BWR/2, Mark I			X		1	1286	PCI
NMP-2 BWR/4, Mark II	X				1	1412	GE
Oyster Creek BWR/2, Mark I	X				1,3	1425	GE
Peach Bottom 2 & 3 BWR/4, Mark I				X	1,2,3	3550	ABB
Perry BWR/6, Mark III				Toroidal	1,2,7	5326	Enercon
Pilgrim BWR/3, Mark I			X		1,2,5,7	1340	PCI
Quad Cities 1 & 2 BWR/3, Mark I	X				1,2,5	832	PCI
River Bend BWR/6, Mark III	X	X			1,2	2424	GE
Susquehanna 1 & 2 BWR/4, Mark II	X				1	1340	GE
Vermont Yankee BWR/4, Mark I			X		1,2	2488	PCI
WNP-2 BWR/5, Mark II	X				1	825	PCI

1) Review of licensee response to NRC Bulletin 96-03 only.
2) Meeting with licensee to discuss licensee's proposed resolution and strainer sizing criteria.
3) Review of strainer sizing criteria, including performance of confirmatory calculations of estimated debris loadings.
4) Review of strainer sizing criteria and strainer performance characteristics (i.e., head loss), including performance of confirmatory calculations.
5) Review of strainer sizing criteria and strainer performance characteristics, including performance of confirmatory calculations in support of license amendment for containment pressure credit in NPSH calculations.
6) Detailed audit of plant resolution of the strainer blockage issue.
7) Site visit.

7 PWR INDUSTRY RESPONSE

7.1 NRC BULLETIN 2003-01

7.1.1 Introduction

On June 9, 2003 NRC issued NRC Bulletin 2003-01 (03-01), "Potential Impact of Debris Blockage on Emergency Sump Recirculation at Pressurized-Water Reactors." This bulletin was addressed to all holders of operating licenses for PWRs and was issued to:

1 Inform addressees of the results of NRC-sponsored research identifying the potential susceptibility of pressurized-water reactor (PWR) recirculation sump strainers to debris blockage in the event of a high-energy line break (HELB) requiring recirculation operation of the emergency core cooling system (ECCS) or containment spray system (CSS).
2 Inform addressees of the potential for additional adverse effects due to debris blockage of flowpaths necessary for ECCS and CSS recirculation and containment drainage.
3 Request that, in light of these potentially adverse effects, addressees confirm their compliance with 10 CFR 50.46(b)(5) and other existing applicable regulatory requirements, or describe any compensatory measures implemented to reduce the potential risk due to post-accident debris blockage as evaluations to determine compliance proceed.
4 Require addressees to provide the NRC a written response in accordance with 10 CFR 50.54(f).

The bulletin described the history of the occurrences of sump strainer blockage, the corresponding regulatory basis, and the research conducted by NRC on the issue to date. In response to the issues associated with the potential post-accident debris blockage concerns identified in the bulletin, the NRC requested that individual PWR licensees submit information on an expedited basis to document that they had either (1) analyzed the ECCS and CSS recirculation functions with respect to the identified post-accident debris blockage effects, taking into account the recent research findings, and determined that compliance exists with all applicable regulatory requirements, or (2) implemented appropriate interim compensatory measures to reduce the risk associated with potentially degraded or nonconforming ECCS and CSS recirculation functions while evaluations to determine compliance proceed.

Conditions at specific PWRs were expected to vary with respect to susceptibility to post-accident debris blockage, and various options were anticipated to be available to addressees for preventing or mitigating the effects of debris blockage. For these reasons, addressees that were unable to confirm compliance with all existing regulatory requirements within 60 days in light of the potential debris blockage effects identified in the bulletin were requested to consider a range of possible interim compensatory measures (ICM) and to implement those which they deemed appropriate, based upon the specific conditions associated with their plants. The risk benefit of certain interim compensatory measures was demonstrated by the NRC-sponsored technical report LA-UR-02-7562 (Kern and Thomas, 2003). Possible ICMs proposed in NRC Bulletin 03-01 are listed in Table 7.1-1.

In addition to the measures listed, addressees were also requested to consider implementing unique or plant-specific compensatory measures, as applicable. Commensurate with the potential risk-significance of post-accident debris blockage effects, addressees electing to implement ICMs in response to the NRC Bulletin 03-01 were requested to ensure that the interim measures were implemented as soon as practical.

Table 7.1-1. Interim Compensatory Measures (ICM) and Their Categories

Category	Description
ICM 1	Providing operator training on indications of and responses to sump clogging
ICM 2	Making procedural modifications that would delay the switchover to containment sump recirculation
ICM 3	Ensuring alternative water sources to refill the RWST or to otherwise provide inventory to inject into the reactor core and spray into the containment atmosphere
ICM 4	Undertaking more aggressive containment cleaning and increased foreign material controls
ICM 5	Ensuring containment drainage paths are unblocked
ICM 6	Ensuring sump strainers are free of adverse gaps and breaches

Responding to the NRC Bulletin 03-01, all plants stated that they had chosen option 2 and listed the ICMs they either implemented or were planning to implement. The plant responses also provided the basis for any measures they rejected.

In response to NRC Bulletin 03-01, the Westinghouse Owners Group prepared a report, WCAP-16204 (Westinghouse Electric, 2004). The report provided a list of candidate operator actions (COA) recommended for consideration and implementation by the Westinghouse and Combustion Engineering designed plants. The possible actions that were proposed by WCAP-16204 are listed in Table 7.1-2.

Table 7.1-2. Candidate Operator Actions and Their Categories

Category	Description
A1a	Implement operator action to secure one spray pump
A1b	Implement operator action to secure both spray pumps
A2	Manually establish one train of containment sump recirculation before automatic actuation
A3	Terminate one train of safety injection (HPSI/high-head injection) after recirculation alignment
A4	Implement early termination of one LPSI/RHR pump before recirculation alignment
A5	Refill of refueling water storage tank
A6	Inject more than one RWST volume by drawing from a refilled RWST or by bypassing the RWST
A7	Provide more aggressive cooldown and depressurization following a SBLOCA
A8	Provide guidance on symptoms and identification of containment sump blockage
A9	Develop contingency actions in response to containment sump blockage, loss of suction, and cavitation
A10	Implement early termination of one train of HPSI/high-head injection before recirculation alignment
A11	Prevent or delay containment spray for SBLOCAs (<1.0 in. dia) in ice condenser plants

Since the WCAP-16204 report was issued after the requested response date for NRC Bulletin 03-01, NRC requested all Westinghouse- and Combustion Engineering-designed plants to provide the discussion of candidate operator actions through requests for additional information (RAIs). A response similar to the ICMs, listed in NRC Bulletin 03-01, was requested. That is, the plants were to either list the particular actions they had implemented or planned to implement, or provide the basis for rejecting specific actions. In addition, a few Babcock & Wilcox plants also provided their discussion of the COAs.

7.1.2 NRC Bulletin 2003-01 Database

Argonne National Laboratory (ANL) was tasked by NRC with creating an NRC Bulletin 03-01 database. The database collected every action, in both ICM and COA categories, discussed by each plant in the responses to NRC Bulletin 03-01 and subsequent RAIs from NRC. The actions have been categorized for the database in the following types:

- Accepted: meaning that the particular action has either been already implemented by a plant or implemented as a result of NRC Bulletin 03-01 response.

- Planned: meaning that in its NRC Bulletin 03-01 response, a plant proposed to implement the action in the near future, often by a specified date or at coming refueling outage. Although it is expected that the planned actions were later implemented, those actions are still distinguished in the database from the accepted actions.

- Rejected: meaning that this particular action or measure was not implemented by a plant. For those actions, a basis for the rejection is recorded in the database.

- Not applicable: meaning that action could not be applied to a plant. Examples include responses of a dry atmospheric containment plant to the actions specifically designed for ice condenser containments.

- Not considered: meaning that a plant did not consider a particular action. Usually, this type refers to unique or plant-specific actions requested by NRC Bulletin 03-01, in cases when the response specifically stated that a plant did not consider any actions (if a plant considered some action, but decided not to implement those, such actions would be listed as “rejected” in the database).

The NRC Bulletin 03-01 database was developed using Microsoft Access software. As stated above, each record of the database refers to a particular action or compensatory measure discussed by a plant. For each action, the information is recorded for the following fields:

Plant Name	There are two special cases – Arkansas Nuclear One and Millstone – which have different plant designs for different units. To have a one-to-one relationship between the plant name and its design, it was decided in the NRC Bulletin 03-01 database to treat Arkansas Nuclear One Units 1 and 2 and Millstone Units 2 and 3 as separate plants. They are referenced as, for example, Arkansas Nuclear One 1 in the database.
Unit	This field either states that the action is common for all units of the plant or otherwise specifies the unit number the action is applied to.
ICM/COA	This field specifies if the action belongs to either ICMs or COAs.
Category	Specifies a category of ICM (numbered "1" to "6" according to Table 7.1-1, plus a "plant specific" option) or COA (according to Table 7.1-2, numbered "A1a" to "A11").
Action type	"Accepted", "Planned", "Rejected", "Not considered", or "Not applicable", as described above.
Action Description	A brief, up to few sentences, description of the action. Additional information there may include, for example, a specific procedure reference for procedure modification actions, or a basis for rejection for "Rejected" actions.
ML Number	Specifies the ADAMS accession number of the document on which the database entry is based, such as licensee response or NRC closure letter.

Based on the above information, a table of actions is generated in the NRC Bulletin 03-01 database. This table is automatically integrated in the database with a table specifying characteristics of each plant, such as NRC region, reactor supplier, and containment type. As a result of such integration, each action is associated with the reactor characteristics. This provides an opportunity, for example, to select actions for Westinghouse-designed plants only.

A total number of 1,084 actions (database records) have been collected for the NRC Bulletin 03-01 database. The distribution of these records by various fields – such as by reactor, by action type, by ICM/COA category – is analyzed in the Database Results section below. These types of statistics, displayed in various table forms, is one of the two major database's capabilities. The other is the detailed report for records that satisfy user-selected criteria, as described in the Appendix A, Section A.1.

7.1.3 NRC Bulletin 2003-01 Database Results

The detailed results from NRC Bulletin 03-01 database are presented in Appendix A, Section A.1. Figure 7.1-1 shows a summary of the database results in the form of the distribution of the actions from all plants by ICM/COA categories and type. Figure 7.1-1 demonstrates that majority of the ICMs from NRC Bulletin 03-01 have been implemented or were planned for implementation. The noticeable exception is ICM 2 (procedural modifications that would delay the switchover to containment sump recirculation), where the plants rejected a significant portion of such actions. For COAs, the majority of A1a-A4 candidate actions were rejected, while most A5-A9 actions were either implemented or planned. Most of the actions in COA A10 category were either rejected or not applicable. None of the A11 actions was implemented or planned. This inference is similar for all reactor types (although COA categories were not developed for Babcock & Wilcox plants – see Appendix A for details).

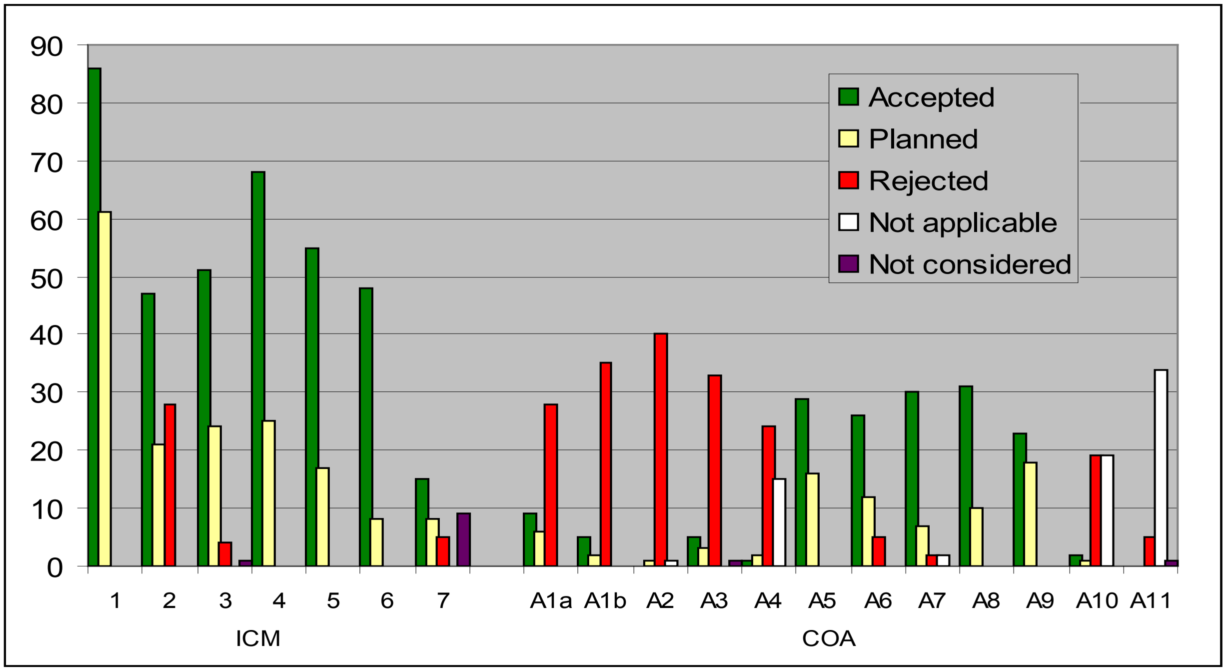


Figure 7.1-1. Action Type by ICM/COA Categories

7.2 NRC Generic Letter 2004-02

7.2.1 Introduction

In Section 4.5 of this report, the contents of the NRC-issued Generic Letter 2004-02 (GL-04-02) were presented. In particular, NRC issued this Generic Letter to:

1 Request that addressees perform an evaluation of the ECCS and CSS recirculation functions in light of the information provided in the letter and, if appropriate, take additional actions to ensure system function. Additionally, addressees were requested to submit the information specified in the letter to the NRC. The request was based on the identified potential susceptibility of PWR recirculation sump strainers to debris blockage during design basis accidents requiring recirculation operation of ECCS or CSS and on the potential for additional adverse effects due to debris blockage of flowpaths necessary for ECCS and CSS recirculation and containment drainage.

2 Require addressees to provide the NRC a written response in accordance with 10 CFR 50.54(f).

To assist in determining, on a plant-specific basis, the impact on sump strainer performance and other related effects of extended post-accident operation with debris-laden fluids, addressees were permitted to use the guidance in RG 1.82, Revision 3, "Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident," dated November 2003. Revision 3 enhanced the debris blockage evaluation guidance for PWRs provided in Revision 1 to better model sump-strainer debris blockage and related effects. Revision 1 replaced the 50% blockage assumption in Revision 0 with a comprehensive, mechanistic assessment of plant-specific debris blockage potential for future modifications related to sump performance, such as thermal insulation changeouts. This revision was made in response to the findings of USI A-43. The staff issued Revision 2 of RG 1.82 after evaluating blockage events such as the Barsebäck Unit 2 event mentioned above but for BWRs only. The NRC staff determined after the issuance of Revision 2 that research for PWRs indicated that the guidance in that revision was not comprehensive enough to ensure adequate evaluation of a PWR plant's susceptibility to the detrimental effects of debris accumulation on debris interceptors (e.g., trash racks and sump strainers). This led to the issuance of Revision 3 to address the PWRs.

In order to better understand the concerns identified in the generic letter, both the NRC and industry have conducted extensive research programs in the areas of debris generation, debris transport, protective coatings, head loss tests, chemical effects and downstream effects. One result from these research prgrams is that the NRC staff concluded that the NUREG/CR-6224 correlation for suction strainer qualification developed for the BWRs in response to Bulletin 1995-02 was not accurate enough to use with PWR strainers. Every licensee needed to conduct plant specific head loss tests with plant specific prototypical debris.

Each PWR liscensee has conducted site specific tests as mentioned above and has provided the NRC staff a response to the generic letter which summarizes the analyses completed and test results which demonstrate qualification of their suction strainers. The remainder of this chapter describes the database developed from the generic letter responses.

7.2.2 Generic Letter 2004-02 Database

To address the sump blockage issues, this knowledge base report collected the initial responses of the licensees to GL-04-02, RAIs, and any further correspondence between NRC and the licensees up through April 28, 2011 (the date of the latest document incorporated in the database). The information was organized in a form of a database. For the database creation, the licensee responses were collected in several areas that included:

- Strainer
  - Previous screen area per strainer and number of strainers per plant
  - New screen area with number per plant
  - Strainer hole size
  - Strainer type and vendor,
  - Whether the strainer is vented or not
  - Number of trains[11] per plant

- Plant modifications in response to GL-04-02, including
  - Physical modifications (such as an installation of new strainer)
  - Administrative modifications (such as procedure changes)
  - Downstream modifications (separately)

- Information on head loss testing, including
  - Strainer approach velocity
  - Test facility location
  - Clean strainer head loss
  - Head loss with non-chemical debris
  - Full debris head loss
  - Thin bed thickness

- Net Positive Suction Head (NPSH)
  - NPSH required and available along with NPSH margin for each pump
  - Minimum strainer submergence in accidents
  - Submergence at switch over to sump circulation and final submergence

- Debris generation, such as
  - Amount and composition of latent debris
  - Strainer sacrificial area (for tags, etc.)
  - Strainer scaling factor for testing,
  - Amount of the debris generated and transported to the strainer
  - Surrogate debris types and amounts used for testing
  - Debris zone of influence
  - Chemical buffer

- Downstream effects

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[11] The number of safety trains and strainers per plant varies by plant design. Some plants have separate suction strainers for the safety injection and containment spray systems that are in the same train, others have a combined strainer. While even others have separate strainers in different parts of the containment building, such a one for vapor containment and one for internal recirculation. For the purposes of the GL-04-02 database, the definition of "train" is the same as in the licensee responses.

- Model used for ex-vessel and in-vessel analyses
- Amount of debris that bypasses the strainer
- Fuel type
- Core head loss

For each value or entry from the above list, the source of the information was recorded in the database in the form of ML number of the document and the page number. Another field indicates whether the information comes from a proprietary document.[12] In addition to that, a comment field was created in the database for the user to record any related information for each entry.

The exact structure of database entries is different for the different types of the information collected. However, in general, each database entry has the following format:

- Plant name
- Unit[13] (if a record is applied to all units, 0 is entered in this field)
- Pump or strainer to which the record is applied
- Case (such as SBLOCA)
- The value (such as screen size)
- ML number for the source document
- Page number in that document[14]
- Proprietary information checkmark
- Comments

A group of the database fields is often referred to as just "field" in this report. For example, the report may refer to New Screen Area field, which actually means a group of the database fields, including the actual value for the screen area, ML number, page number, comments, etc.

The detailed description of each field along with the specifics of the information collected for the database is presented in Appendix A (Section A.2.3).

The compilation is linked to a database that includes the NRC region, NSSS supplier, and containment type for each plant (the same table that was used for the NRC Bulletin 03-01 database). That linkage enables the sorting and/or selections of the GL-04-02 database records by NSS supplier, for example.

The GL-04-02 database was developed in the Microsoft Access environment. The user interface for the GL-04-02 database is described in Appendix A, Section A.2.1.

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[12]The database capability to distinguish proprietary records has not been used for this report. All the information collected in the GL 04-02 databse to date and used in this report come from public sources.

[13]Unit is a required field for the GL-04-02 database. For single-unit plants, such as Ginna, "1" is entered in the unit field. Thus, in the results presented further in this section, that and other similar plants would be shown as "Ginna-1."

[14]Page number in the PDF ML document is recorded in the database (as opposed to the page number in the original submission). For example, several submissions and/or appendixes can be combined into one ML document, each with its own page numbering. Using page number for the entire document avoids any possible confusion to what part of the document this page number is applied.

At the time of this report preparation, the interactions between NRC and the plants regarding the GL-04-02 are still in progress. Some of the plants are still submitting RAI responses to NRC. For these reasons, the GL-04-02 database, as it is presented in this report, cannot be viewed as “finished”; it is expected that new information may be available for the database in the future. In addition to the potential for new data to be added, some of the data currently in the database may become outdated due to ongoing evaluations. At the time this knowledge base was completed the NRC was reviewing the industry guidance for in-vessel resolution so the issue had not been completed at most plants. Additionally, some plants had not provided adequate information to the staff regarding strainer performance. Therefore, plant changes or additional evaluations may be required to address these issues.

The detailed description of the database field and the information entered into each field in the GL-04-02 database are presented in the Section A.2.3 of Appendix A.

7.2.3 Generic Letter 2004-02 Database Results

The results obtained with the GL-04-02 database are presented in Appendix A, Section A.2.3. Appendix A also provides the detailed describtion of each field in the database along with the assumptions made during the database compilation.

As an example of the GL-04-02 database results, Fig. 7.2-1 compares the new and previous strainer screen area for all plants (the exact meaning of the data plotted in Fig. 7.2-1 is provided in Appendix A). Overall, Fig. 7.2-1 demonstrates significant increases in strainer screen areas in response to GL-04-02. It also shows the significant difference in newly installed screen size among the plants (and sometimes among the units of the same plant).

Similar variation between the plants was observed for almost all of the parameters recorded in the GL-04-02 database (see Appendix A). For the fields for which no graphs can be plotted (for example, for the list of the plant modification), the information is displayed in Appendix A in a table form.

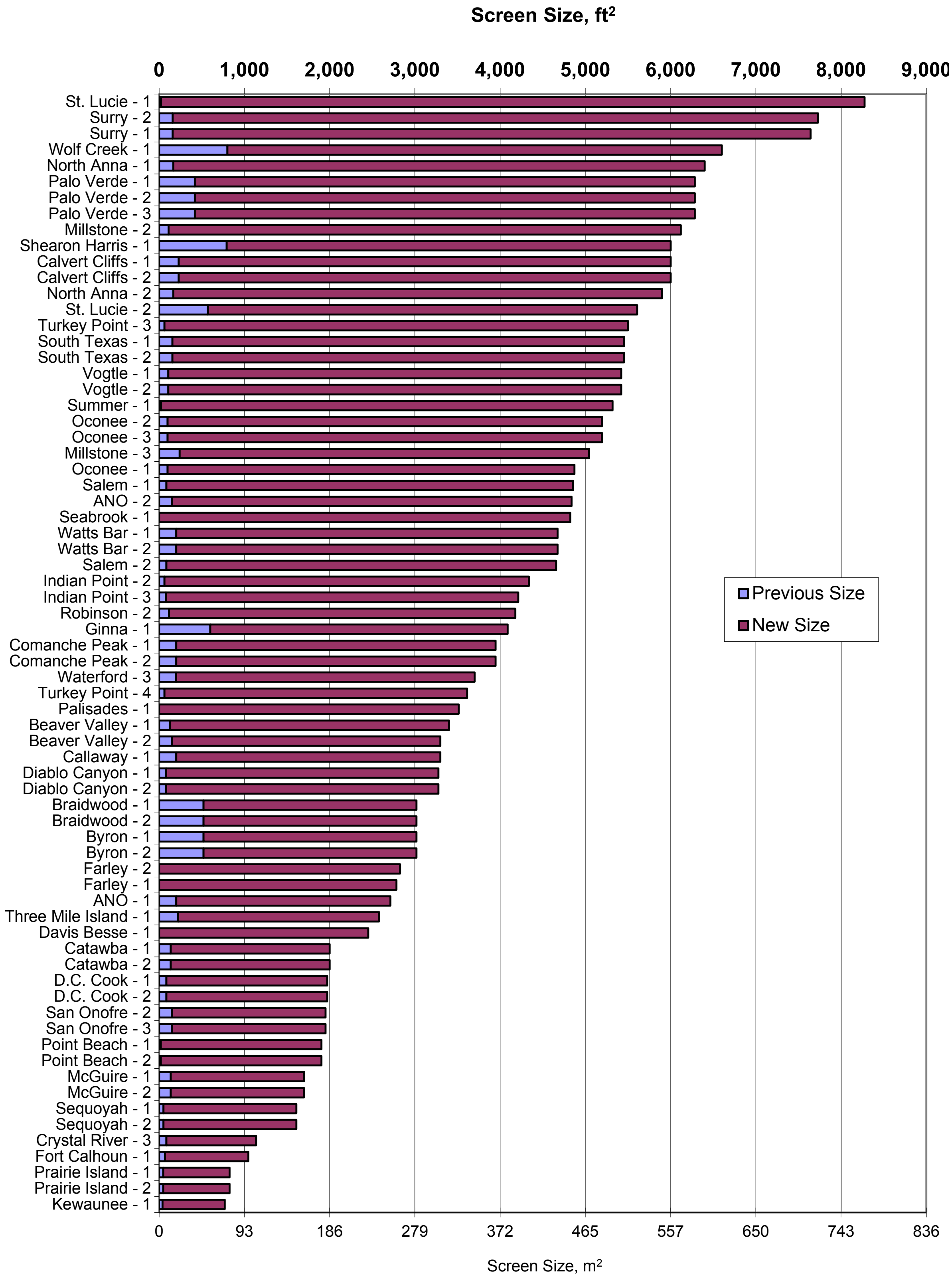

Figure 7.2-1. Total Strainer Screen Area

8 SUMMARY

The containment sumps in PWRs (also known as the emergency or recirculation sump) and suppression pools in BWRs, and ECCS and recirculation strainers are integral parts of a safety systems required to ensure the safety of commercial nuclear reactors. Every nuclear power plant in the United States is required by the Code of Federal Regulations (10 CFR 50.46) to have an ECCS that is capable of mitigating a design basis accident.

In PWRs, the containment sump collects reactor coolant and chemically reactive spray solutions after a LOCA. The sump serves as the water source to support long-term recirculation for residual heat removal, emergency core cooling, containment cooling and pressure control, and containment atmosphere cleanup. In BWRs the suppression pool provides the water source. This water source, the related pump inlets, and the piping between the source and inlets are important safety components. In the event of a LOCA within the containment of a light water reactor (LWR), piping thermal insulation and other materials in the vicinity of the break will be dislodged by the pipe break and steam/water-jet impingement. A fraction of this fragmented and dislodged insulation and other materials, such as paint chips, paint particulates, and concrete dust, will be transported to the containment floor by the steam/water flows induced by the break and by the containment sprays. Some of this debris eventually will be transported to and accumulated on the recirculation-sump suction strainers in PWR containments or on the pump-suction strainer in BWR containments. Debris accumulation on the sump strainers could challenge the plant's capability to provide an adequate water supply to the ECCS and the CSS pumps.

The current state of knowledge has evolved significantly due to the work on PWRs, conducted by the NRC and the nuclear industry. The Generic Safety Issue (GSI)-191 study, "Assessment of Debris Accumulation on PWR Sump Performance," was established by the NRC to determine if the transport and accumulation of debris in a containment following a LOCA could impede the operation of the ECCS in operating PWRs. Assessing the likelihood of the ECCS and CSS pumps in domestic PWRs experiencing a debris-induced loss of NPSH margin during sump recirculation was the primary objective of the NRC's technical assessment of GSI-191. The technical assessment culminated in a parametric study that mechanistically treated phenomena associated with debris blockage using analytical models of domestic PWRs generated with a combination of generic and plant-specific data.

This report describes the current status of the knowledge base on emergency core cooling sump performance in operating LWRs. The report discusses the substantial knowledge that has been developed as a result of the research on issues related to debris clogging of BWR suction strainers and PWR sump strainers. The report provides brief background information (Sections 1 through 4) regarding these issues. This background information includes a historical overview of the resolution of the BWR issue with a lead into the PWR issue, a description of the safety concern relative to PWR reactors, the criteria for evaluating sump failure, descriptions of postulated accidents, descriptions of relevant plant features that influence accident progression, and a discussion of the regulatory considerations.

Section 5 of the report presents the current state-of-the-art resolution methodology for understanding the strainer blockage phenomena and processes that have evolved over the years. This section incorporates our current understanding of many of the actions/processes that can have an impact on the available NPSH margin in ECCS and CSS. The section presents details on pipe break characterization, debris generation and zone of influence, debris transport, coatings and coating debris, latent debris, debris accumulation and head loss, debris head loss correlations, chemical effects on head loss, and downstream effects. The section also includes a description of the test programs conducted by several vendors in support of BWRs and PWRs.

Section 6 is a summary of industry response by BWR licensees and the closure of NRC Bulletin 96-03, based on the URG for ECCS suction strainer blockage. Since no safety concerns were identified at any of four audited plants and NRC accepted the URG methodology, NRC did not consider it necessary to perform any additional detailed reviews of licensee resolutions. In addition to the review work cited above, the staff performed a number of additional plant reviews related to strainer clogging, including several test programs conducted both by the NRC and the nuclear industry. The work is reported in LA-UR-01-1595 (Rao et al., 2001), which summarizes the efforts of the NRC, the NRC's contractors, and industry to resolve the BWR ECCS strainer clogging issue.

Section 7 and Apendix A discuss in detail the plant-by-plant PWR licensee responses to NRC Bulletin 03-01 and GL-04-02. The licensee responses to the initial generic letter and the responses to the requests for information were collected for several areas and put into a database. Information regarding strainer characteristics, physical and administrative plant modifications, head loss test information, chemical effects, NPSH required and available, debris characteristics, and downstream effects are included in the database. The collected information has been incorporated in user-friendly databases based on Microsoft Access with capabilities to select various criteria to filter the information, carry out search/sort of the data, and assess phenomenon-specific or plant-specific information.

To organize the information related to the NRC Bulletin 2003-01, a database was developed, and information was input on the interim compensatory measures (ICMs) proposed in the bulletin with regard to which measures were implemented, planned, or rejected by each plant. In addition to ICMs, the database also contains, in a similar manner, the plant responses to the candidate operator actions (COAs) proposed by the Westinghouse Owners Group to address Bulletin 03-01 issues. Each Bulletin 03-01 database record refers to a single action discussed by a plant. A record includes the plant name, unit, ICM/COA category, action type (such as "accepted"), a brief description of the action, and the ML number reference for this record.

The Bulletin 03-01 responses in the database were combined with a table defining design features of each plant, such as NSS supplier and containment type. That expanded database allows the selection of the Bulletin 03-01 responses by various parameters and their combination, such as accepted actions for a given containment type. A user interface was developed for the Bulletin 03-01 database to facilitate such selection in an interactive manner. The results of a search of the database that satisfy the selected criteria can be displayed in a table or in graphical form. In addition to this criteria selection capability, the database also provides the statistics covering all the information stored in the database. For example, a total number of accepted, planned, or rejected actions can be displayed for each ICM/COA category.

Based on the Bulletin 2003-01 database results, the following observations were made. A majority of ICM measures were either implemented or were planned for implementation by the response time. Among the ICM categories (see Table 7.1-1), ICM category 2 displayed the largest number of rejected actions. Also, several plant-specific measures were implemented. For COA categories (see Table 7.1-2), the majority of COAs for A1-A4 and A10-A11 were either rejected or not applicable to a specific plant. In contrast, most of the A5-A9 actions were implemented or planned for implementation. This inference is similar for all reactor types (although COA categories were not developed for Babcock & Wilcox plants).

Similar to the Bulletin 03-01 database, the responses to the GL-04-02, “Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized-Water Reactors,” were collected to create a GL-04-02 database. The GL-04-02 database includes 28 tables in six areas. Each table contains the information on a particular field, such as new screen area, for each plant. The structure of each table changes depending on the specifics of the information in that table, but in general the structure of the database records is similar to that of the Bulletin 03-01 database. Each record at least contains the plant name, unit, the recorded value (such as the screen area), the ML number and page number for the source of the information, and a Comments field. In some cases, more than one value is stored in the database records. For example, the Debris-Amount table contains information on the amount of debris both generated at a break and used in testing.

A user interface, similar to that of the Bulletin 03-01 database, was developed for the GL-04-02 database. The interface provides the user with the capability to select various criteria to filter the information, carry out search/sort of the information, and select the particular database table for which the results are displayed. The results are presented in a table form and can be transferred to Microsoft Excel for plotting. The GL-04-02 database also incorporates a table defining the specifics of each plant such that the database records can be filtered, based on selected design features.

Based on the information in the GL-04-02 database, the plots of various parameters were prepared to compare the results for all the PWR plants in the U.S. For example, the new screen size plot shows a significant increase in the screen area for the strainers installed in response to GL-04-02. It also shows, however, a significant variation in the size of these new strainers among the plants. Similar variations between the plants were observed for almost all of the parameters recorded in the GL-04-02 database. For the fields for which no graphs can be plotted (for example, the list of the plant modifications), the information is displayed in a table form. At the time of this report’s preparation, the work on the resolution of issues associated with GL-04-02 was in progress so some information in the database may change.

In August 2010, NRC issued a document (SECY-10-0113) on closure options for GSI-191. On December 23, 2010, NRC issued a memorandum (Vietti-Cook, 2010) stating that two major outstanding issues (namely, the size of the zone of influence and quantity of fiber that could cause a blockage in the reactor core which could affect long term core cooling) need to be resolved jointly by the NRC and industry to achieve closure of the ECCS issue in U.S. PWRs. These documents were updated in 2012 by SECY-12-0093 and its related SRM. The 2012 update proposed a risk-informed approach for GSI-191 resolution, which the Commission approved in December 2012. At the time of this NUREG publication a pilot plant submittal is under review by NRR staff.

9 REFERENCES

9.1 NRC Documents Cited

ADAMS Accession No. ML043090005, Response to Advisory Committee on Reactor Safeguards on Safety Evaluation of the Industry Guidelines Related to Pressurized Water Reactor Sump Performance, November 26, 2004.

ADAMS Accession No ML090410618, North Anna Power Station Audit Report, Corrective Actions for Generic Letter 2004-02: Chemical Effects, 2008.

Bulletin 03-01 “Potential Impact of Debris Blockage on Emergency Sump Recirculation at Pressurized-Water Reactors,” June 9, 2003.

Bulletin 93-02, “Debris Plugging of Emergency Core Cooling Suction Strainers,” May 11, 1993.

Bulletin 95-02, “Unexpected Clogging of a Residual Heat Removal (RHR) Pump Strainer While Operating in Suppression Pool Cooling Mode,” October 17, 1995.

Bulletin 96-03, “Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling-Water Reactors,” May 6, 1996.

DG-1107, “Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident,” Draft Regulatory Guide, February 2003. ADAMS Accession No. ML043090005

Evaluation of NEI Guidance on PWR Sump Performance, GSI-191 SER, Rev. 0, U.S. Nuclear Regulatory Commission, December 2004. ADAMS Accession No. ML043280007

GL-04-02, “Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized-Water Reactors,” September 2004.

GL-85-22, “Potential for Loss of Post-LOCA Recirculation Capability Due to Insulation Debris Blockage,” December 3, 1985.

GL-97-04, “Assurance of Sufficient Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal Pumps,” October 7, 1997.

GL-98-04, “Potential for Degradation of the Emergency Core Cooling System and the Containment Spray System after Loss-of-Coolant Accident Because of Construction and Protective Coating Deficiencies and Foreign Material in Containment,” July 14, 1998.

IN-88-28, “Potential for Loss of Post-LOCA Recirculation Capability Due to Insulation Debris Blockage,” NRC Information Notice, May 19, 1988.

IN-89-77, “Debris in Containment Emergency Sumps and Incorrect Screen Configurations,” NRC Information Notice, November 21, 1989.

IN-89-77, Supplement 1, “Debris in Containment Emergency Sumps and Incorrect Screen,” NRC Information Notice, December 3, 1993.

IN-92-71, “Partial Blockage of Suppression Pool Strainers at a Foreign BWR,” NRC Information Notice, September 30, 1992.

IN-92-85, “Potential Failures of Emergency Core Cooling Systems Caused by Foreign Material Blockage,” NRC Information Notice, December 23, 1992.

IN-93-02, Bulletin 93-02, Supplement 1, “Debris Plugging of Emergency Core Cooling Suction Strainers,” NRC Bulletin to Licensees, February 18, 1994.

IN-93-34, “Potential for Loss of Emergency Cooling Function due to a Combination of Operational and Post-LOCA Debris in Containment,” NRC Information Notice, April 26, 1993.

IN-94-57, “Debris in Containment and the Residual Heat Removal System,” NRC Information Notice, August 12, 1994.

IN-95-06, “Potential Blockage of Safety-Related Strainers by Material Brought inside Containment,” NRC Information Notice, January 25, 1995.

IN-95-47, “Debris in Containment and the Residual Heat Removal System,” NRC Information Notice, August 12, 1994.

IN-96-10, “Potential Blockage by Debris of Safety System Piping Which Is Not Used during Normal Operation or Tested During Surveillances,” NRC Information Notice, February 13, 1996.

IN-96-59, “Potential Degradation of Post Loss-of-Coolant Recirculation Capability as a Result of Debris,” NRC Information Notice, October 30, 1996.

IN-97-13, “Deficient Conditions Associated with Protective Coatings at Nuclear Power Plants,” NRC Information Notice, March 24, 1997.

LER 50-266/97-006, “Potential Refueling Cavity Drain Failure Could Affect Accident Mitigation,” Point Beach Unit 1, February 19, 1997.

LER 50-269/97-010, “Inadequate Analysis of ECCS Sump Inventory due to Inadequate Design Analysis,” Oconee Unit 1, January 8, 1998

LER 50-315/98-017, “Debris Recovered from Ice Condenser Represents Unanalyzed Condition,” D.C. Cook Unit 1, July 1, 1998

LER 50-346/02-005-01, “Potential Clogging of the Emergency Sump due to Debris in Containment,” Davis-Besse Unit 1, December 11, 2002.

LER 50-346/03-002-00, “Potential Degradation of High Pressure Injection Pumps due to Debris in Emergency Sump Fluid Post Accident,” Davis-Besse Unit 1, May 5, 2003.

LER 50-369/90-012, “Loose Material Was Located in Upper Containment during Unit Operation Because of an Inappropriate Action,” McGuire Unit 1, August 30, 1990.

LER 50-440/93-011, “Excessive Strainer Differential Pressure across the RHR (Residual Heat Removal) Suction Strainer Could Have Compromised Long Term Cooling during Post-LOCA Operation,” May 19, 1993.

LER 50-455/97-001, “Unit 2 Containment Drain System Clogged due to Debris,” Byron Unit 2, April 17, 1997.

NEA/CSNI/R (95) 11, “Knowledge Base for Emergency Core Cooling System Recirculation Reliability,” Prepared by U.S. Nuclear Regulatory Commission for the Principal Working Group 1, International Task Group, Committee on the Safety of Nuclear Installations, Organization for Economic Cooperation and Development Nuclear Energy, February 1996.

NEDO-32686, “Utility Resolution Guidance for ECCS Suction Strainer Blockage,” Boiling Water Reactor Owners Group, Rev. 0, November 1996. ADAMS Accession No ML092530500.

NEDO-32721-A, T. A. Green et al., "Application Methodology for the General Electric Stacked Disk ECCS Suction Strainer," Licensing Topical Report, Revision 2, Non-Proprietary Version, March 2003. ADAMS Accession No. ML031010388.

NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Coatings Evaluation, U.S. Nuclear Regulatory Commission, March 2008. ADAMS Accession No ML080230462.

NRC-ENR, 2001, Event Notification Report for October 22, 2001, Event No. 38408, (located at http://www.nrc.gov/reading-rm/doc-collections/event-status/event/2001/20011022en.html.)

NRC-ONS, 2004, Oconee Nuclear Station-Integrated Inspection Report 05000269/2004002, 05000270/2004002, and 05000287/2004002, April 26, 2004.

NRC-SECY-99-127, Weekly Information Report-Week Ending April 30, 1999, US Nuclear Regulatory Commission, May 5, 1999.

NRC-SER-1998, “Safety Evaluation by the Office of Nuclear Reactor Regulation Related to NRC Bulletin 96-03 Boiling Water Reactor Owners Group Topical Report NEDO-32686, Utility Resolution Guidance for ECCS Suction Strainer Blockage,” Docket No. PROJ0691, August 20, 1998. ADAMS Accession No ML092530482.

NRC-SER-2007, “Final Safety Evaluation for Pressurized Water Reactor Owners Group Topical Report WCAP-16406-P, Evaluation of Downstream Sump Debris Effects in Support of GSI 191, Revision 1,” December 2007, ADAMS Accession No. ML073520295.

NRC-SER-2007b, Final Safety Evaluation by the Office of Nuclear Reactor Regulation Topical Report WCAP-16530-NP, “Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191,” for Pressurized Water Reactor Owners Group Project No. 694, December 2007 . ADAMS Accession No. ML073520891.

NRC-SER-2013, Final Safety Evaluation by the Office of Nuclear Reactor Regulation Topical Report WCAP-16793-NP, Revision 2, “Evaluation of long-term cooling considering particulate, fibrous and chemical debris in the recirculating fluid,” Pressurized Water Reactor Owners Group, ADAMS, Accession Number ML13084A154.

NUREG-0510, “Identification of Unresolved Safety Issues Relating to Nuclear Power Plants,” January 1979.

NUREG-0869, A. W. Serkiz. “USI A-43 Regulatory Analysis,” October 1985.

NUREG-0897, A. W. Serkiz, “Containment Emergency Sump Performance,” Rev. 1, October 1985.

NUREG-1861, P. A. Torres, “Peer Review of GSI-191 Chemical Effects Research Program,” December 2006.

NUREG-1862, W. J. Krotiuk, “Development of a Pressure Drop Calculation Method for Debris-Covered Sump Strainers in Support of Generic Safety Issue 191,” February 2007.

NUREG-1918, R. T. Tregoning, J. A. Apps, W. Chen, C. H. Delegard, R. Litman, and D. D. MacDonald, “Phenomena Identification and Ranking Table Evaluation of Chemical Effects Associated with Generic Safety Issue 191,” February 2009.

NUREG/CR-2791, J. J. Wysocki, and R. Kolbe, "Methodology for Evaluation of Insulation Debris Effects," September 1982.

NUREG/CR-2913, G. G. Weigand, et al., "Two-Phase Jet Loads," January 1983.

NUREG/CR-2982, D. N. Brocard, “Buoyancy, Transport, and Head Loss of Fibrous Reactor Insulation,” Rev. 1, July 1983.

NUREG/CR-3170, W. W. Durgin and J. Noreika, "The Susceptibility of Fibrous Insulation Pillows to Debris Formation under Exposure to Energetic Jet Flows," March 1983.

NUREG/CR-3394, J. J. Wysocki, "Probabilistic Assessment of Recirculation Sump Blockage due to Loss of Coolant Accidents," July 1983.

NUREG/CR-3616, D. N. Brocard, “Transport and Screen Blockage Characteristics of Reflective Metal Insulation Materials,” SAND83-7471, January 1984.

NUREG/CR-5640, P. Lobner, C. Donahoe, and C. Vavallin, “Overview and Comparison of U.S. Commercial Nuclear Power Plants,” SAIC-89/1541, September 1990.

NUREG/CR-6224, G. Zigler, J. Brideau, D. V. Rao, C. Shaffer, F. Souto, and W. Thomas, "Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris," Final Report, SEA-93-554-06-A:1, October 1995.

NUREG/CR-6368, F. J. Souto and D. V. Rao, “Experimental Investigation of Sedimentation of LOCA-Generated Fibrous Debris and Sludge in BWR Suppression Pools,” SEA-95-554-06-A:9, December 1, 1995.

NUREG/CR-6369, Vol. 1, D. V. Rao, C. Shaffer, and E. Haskin, “Drywell Debris Transport Study,” SEA97-3501-A:14, September 30, 1999.

NUREG/CR-6369, Vol. 2, D. V. Rao, C. Shaffer, B. Carpenter, D. Cremer, J. Brideau, G. Hecker, M. Padmanabhan, and P. Stacey, “Drywell Debris Transport Study: Experimental Work,” SEA97-3501-A:15, September 1999.

NUREG/CR-6370, D. V. Rao, W. Bernahl, J. Brideau, C. Shaffer and F. Souto, "BLOCKAGE 2.5 User’s Manual," SEA96-3104-A:3, December 1996.

NUREG/CR-6371, C. Shaffer, W. Bernahl, J. Brideau, and D. V. Rao, "BLOCKAGE 2.5 Reference Manual," SEA96-3104-A:4, December 1996.

NUREG/CR-6762, Vol. 1, D. V. Rao, B. Letellier, C. Shaffer, S. Ashbaugh, and L. Bartlein, “GSI-191 Technical Assessment: Parametric Evaluation for Pressurized Water Reactor Recirculation Sump Performance,” LA-UR-01-4083, 2002.

NUREG/CR-6762, Vol. 2, D. V. Rao, B. Letellier, K. W. Ross, L. Bartlein, and M. T. Leonard, “GSI-191 Technical Assessment: Summary and Analysis of U.S. Pressurized Water Reactor Industry Survey Responses and Responses to GL 97-04,” LA-UR-01-1800, 2002.

NUREG/CR-6762, Vol. 3, C. J. Shaffer, D. V. Rao, and S. G. Ashbaugh, “GSI-191 Technical Assessment: Development of Debris-Generation Quantities in Support of the Parametric Evaluation,” LA-UR-01-6640 (2002).

NUREG/CR-6762, Vol. 4, S. G. Ashbaugh and D. V. Rao, “GSI-191 Technical Assessment: Development of Debris Transport Fractions in Support of the Parametric Evaluation,” LA-UR-01-5965 (2002).

NUREG/CR-6770, D. V. Rao, K. W. Ross, and S. G. Ashbaugh, “GSI-191: Thermal-Hydraulic Response of PWR Reactor Coolant System and Containments to Selected Accident Sequences,” August 2002.

NUREG/CR-6772, D. V. Rao, B. C. Letellier, A. K. Maji, and B. Marshall, “GSI-191: Separate-Effects Characterization of Debris Transport in Water,” August 2002.

NUREG/CR-6773, D. V. Rao, C. Shaffer, B. C. Letellier, A. K. Maji, and L. Bartlein, “GSI-191: Integrated Debris-Transport Tests in Water Using Simulated Containment Floor Geometries,” December 2002.

NUREG/CR-6808, C. J. Shaffer, D. V. Rao, M. T. Leonard, and K. W. Ross, “Knowledge Base for the Effect of Debris on Pressurized Water Reactor Emergency Core Cooling Sump Performance,” LA-UR-03-0880, February 2003.

NUREG/CR-6868, R. C. Johns, B. C. Letellier, K. J. Howe, and A. K. Ghosh, “Small-Scale Experiments: Effects of Chemical Reactions on Debris-Bed Head Loss,” LA-UR-03-6415, March 2003.

NUREG/CR-6873, V. Jain, X. He, and Y.-M. Pan, “Corrosion Rate Measurements and Chemical Speciation of Corrosion Products Using Thermodynamic Modeling of Debris Components to Support GSI-191,” 2005.

NUREG/CR-6874, C. J. Shaffer, M. T. Leonard, B. C. Letellier, D. V. Rao, A. K. Maji, K. Howe, A. Gosh, J. Garcia, W. A. Roesch, and J. D. Madrid, “GSI-191: Experimental Studies of Loss-of-Coolant-Accident-Generated Debris Accumulation and Head Loss with Emphasis on the Effects of Calcium Silicate Insulation,” May 2005.

NUREG/CR-6877, B. C. Letellier et al., “Characterization and Head-Loss Testing of Latent Debris from Pressurized-Water-Reactor Containment Buildings,” July 2005.

NUREG/CR-6912, J. McMurry, V. Jain, X. He, V. D. Pickett, R. Pabalan, and Y-M. Pan, “GSI-191 PWR Sump Strainer Blockage Chemical Effects Tests: Thermodynamic Simulations,” December 2006.

NUREG/CR-6913, J. H. Park, K. Kasza, B. Fisher, J. Oras, K. Natesan, and W. J. Shack, “Chemical Effects Head-Loss Research in Support of Generic Safety Issue 191,” December 2006.

NUREG/CR-6914, Volume 1, J. Dallman, B. Letellier, J. Garcia, J. Madrid, W. Roesch, D. Chen, K. Howe, L. Archuleta, and F. Sciacca, “Integrated Chemical Effects Test Project: Consolidated Data Report,” LA-UR-06-3673, December 2006.

NUREG/CR-6914, Volume 1: Appendix C, T. S. Andreychek, “Test Plan: Characterization of Chemical and Corrosion Effects Potentially Occurring Inside a PWR Containment Following a LOCA,” Westinghouse Electric Company, July 2005.

NUREG/CR-6915, M. Klasky, J. Zhang, M. Ding, B. Letellier, D. Chen, and K. Howe, “Aluminum Chemistry in a Prototypical Post-Loss-of-a-Coolant-Accident, Pressurized-Water-Reactor Containment Environment,” December 2006.

NUREG/CR-6916, A. Fullerton, T. Fu, D. Walker, and J. Carneal, “Hydraulic Transport of Coating Debris,” Naval Surface Warfare Center, Bethesda, MD, December 2006.

NUREG/CR-6917, C. W. Enderlin, B. E. Wells, M. White, F. Nigl, D. R. Rector, T. J. Peters, and A. D. Guzman, “Experimental Measurements of Pressure Drop Across Sump Strainer Debris Beds in Support of Generic Safety Issue 191,” PNNL-16313, February 2007.

NUREG/CR-6988, C.H. Delegard, M.R. Elmore, K.J. Geelhood, M.A. Lilga, W.G. Luscher, G.T. MacLean, J.K. Magnuson, R.T. Pagh, S.G. Pitman, and R.S. Wittman, “Final Report- Evaluation of Chemical Effects Phenomena in Post-LOCA Coolant,” March 2009.

NUREG/CR-7011, J. M. Cuta, B. E. Wells, C. H. Delegard, and B. F. Saffell, “Evaluation of Treatment of Effects of Debris in Coolant on ECCS and CSS Performance in Pressurized Water Reactors and Boiling Water Reactors,” May 2010.

RG 1.1, “Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal System Pumps,” Regulatory Guide, 1997.

RG 1.54, “Quality Assurance Requirements for Protective Coatings Applied to Water-Cooled Nuclear Power Plants,” Regulatory Guide, Rev. 1, July 2000.

RG 1.82, “Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident,” Regulatory Guide, Revision 0, 1974, Revision 1, November 1985, Revision 2, May 1996, Revision 3, November 3003, Revision 4, September 2005.

SE NEI-04-07, Safety Evaluation by the Office of Nuclear Reactor Regulation Related to NRC Generic Letter 2004-02, Nuclear Energy Institute Guidance Report (NEI 04-07) “Pressurized Water Reactor Sump Performance Evaluation Methodology,” December 2004, ADAMS Accession No. ML043280007.

SECY-10-0113, R. W. Borchardt, “Closure Options for Generic Safety Issue-191, Assessment of Debris Accumulation on Pressurized Water Reactor Sump Performance,” August 26, 2010.

SECY-12-0093, R. W. Borchardt, “Closure Options for Generic Safety Issue - 191, Assessment of Debris Accumulation on Pressurized-Water Reactor Sump Performance,” July 9, 2012.

SECY-85-349, “Resolution of Unresolved Safety Issue A-43, ‘Containment Emergency Sump Performance’,” October 31, 1985.

Trip Report, Staff Observations of Testing for Generic Safety Issue 191 During February 12 and February 13 Trip to the Alden Test Facility for PCI Strainer Tests, , April 30, 2008, ADAMS Accession No. ML080920398.

USI A-43, “Containment Emergency Sump Performance,” Rev. 1, 1979 (see NUREG-0933).

9.2 Other Documents Cited

ANSI, 1972, “Protective Coatings (Paints) for Light Water Nuclear Reactor Containment Facilities,” American National Standards Institute, ANSI N101.2-1972.

ANSI, 1988, “Design Basis for Protection of Light Water Nuclear Power Plants against the Effects of Postulated Pipe Rupture,” American National Standards Institute, ANSI/ANS-58.2-1988.

ASTM, 1994, “Standard Guide for Developing a Training Program for Coating Work Inspectors in Nuclear Facilities,” American Society for Testing and Materials, ASTM D 5498-94.

ASTM, 1995a, “Standard Practice for Qualification of Coating Applicators for Application of Coatings to Concrete Surfaces,” American Society for Testing and Materials, ASTM D 4227-95.

ASTM, 1995b, “Standard Practice for Qualification of Coating Applicators for Application of Coatings to Steel Surfaces,” American Society for Testing and Materials, ASTM D 4228-95.

ASTM, 1995c, “Standard Terminology Relating to Protective Coating and Lining Work for Power Generation Facilities,” American Society for Testing and Materials, ASTM D 4538-95.

ASTM, 1995d, “Standard Test Method for Effects of Gamma Radiation on Coatings for Use in Light-Water Nuclear Power Plants,” American Society for Testing and Materials, ASTM D 4082-95.3.

ASTM, 1995e, “Standard Test Methods for Measuring Adhesion by Tape Test,” American Society for Testing and Materials, ASTM D 3359-95, Revision A.

ASTM, 1995f, “Standard Test Method for Chemical Resistance of Coatings Used in Light-Water Nuclear Power Plants,” ASTM D 3912-95.

ASTM, 1995g, “Standard Test Method for Evaluating Coatings Used in Light-Water Nuclear Power Plants at Simulated Design Basis Accident (DBA) Conditions,” ASTM D3911-95.

ASTM, 1996a, “Standard Guide for Establishing Procedures To Qualify and Certify Inspection Personnel for Coating Work in Nuclear Facilities,” American Society for Testing and Materials, ASTM D 4537-91 (re-approved 1996).

ASTM, 1996b, “Standard Guide for Establishing Procedures To Monitor the Performance of Safety Related Coatings in an Operating Nuclear Power Plant,” American Society for Testing and Materials, ASTM D 5163-96.

ASTM, 1996c, “Standard Guide for Maintaining Unqualified Coatings (Paints) within Level Areas of a Nuclear Power Facility,” American Society for Testing and Materials, ASTM D 5962-96.

ASTM, 1996d, “Standard Practice for Determining Coating Contractor Qualifications for Nuclear Powered Electric Generation Facilities,” American Society for Testing and Materials, ASTM D 4286-90 (re-approved 1996).

ASTM, 1996e, “Standard Specification for Sample Preparation for Qualification Testing of Coatings To Be Used in Nuclear Power Plants,” American Society for Testing and Materials, ASTM D 5139-90 (reapproved 1996).

ASTM, 2000a, “Standard Guide for Use of Protective Coating Standards in Nuclear Power Plants,” American Society for Testing and Materials, ASTM D 5144-00.

ASTM, 2000b, “Standard Practices for Measurement of Dry Film Thickness of Protective Coating Systems by Destructive, Cross-Sectioning Means,” American Society for Testing and Materials, ASTM D4138-00.

ASTM, 2001a, “Standard Practices for Measurement of Dry Film Thickness of Protective Coating Systems by Destructive, Cross-Sectioning Means,” American Society for Testing and Materials, ASTM D4138-01.

ASTM, 2001b, “Standard Test Method for Evaluating Adhesion by Knife,” American Society for Testing and Materials, ASTM D6677-01.

ASTM, 2002, “Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers,” American Society for Testing and Materials, ASTM D4541-02.

ASTM, 2004, “Standard Test Method for Nondestructive Measurement of Dry Film Thickness of Applied Organic Coatings Using an Ultrasonic Gage,” American Society for Testing and Materials, ASTM D6232-04.

ASTM, 2005, “Standard Test Method for Evaluating Adhesion by Knife,” American Society for Testing and Materials, ASTM D6677-05.

ASTM, 2008, “Standard Test Method for Evaluating Coatings Used in Light-Water Nuclear Power Plants at Simulated Design Basis Accident (DBA) Conditions,” American Society for Testing and Materials, ASTM D3911-08.

Bahn, C. B., K. E. Kasza, and W. J. Shack, 2007, “Follow-on Studies in Chemical Effects Head-Loss Research: Studies on WCAP Surrogates and Sodium Tetraborate Solutions,” NRC Technical Letter Report, ADAMS Accession No. ML070580086.

Bahn, C. B., K. E. Kasza, W. J. Shack, and K. Natesan, 2008a, “Evaluation of Chemical Effects: Studies on Precipitates Used in Strainer Head Loss Testing,” NRC Technical Letter Report, ADAMS Accession No. ML080600180.

Bahn, C. B., K. E. Kasza, W. J. Shack, and K. Natesan, 2008b, "Evaluation of Long-term Aluminum Solubility in Borated Water Following a LOCA," NRC Technical Letter Report, ADAMS Accession No. ML081550043.

Bahn, C. B., K. E. Kasza, W. J. Shack, and K. Natesan, 2008c, "Evaluation of Head Loss by Products of Aluminum Alloy Corrosion," NRC Technical Letter Report, ADAMS Accession No. ML082330153.

Bahn, C. B., K. E. Kasza, W. J. Shack, and K. Natesan, 2008d, "Aluminum Solubility in Boron Containing Solutions as a Function of pH and Temperature," NRC Technical Letter Report, ADAMS Accession No. ML091610696.

Bahn, C. B., K. E. Kasza, W. J. Shack, and K. Natesan, 2009a, "Evaluation of WCAP Aluminum Hydroxide Surrogate Stability at Elevated pH," NRC Technical Letter Report, ADAMS Accession No. ML090480294.

Berg, Van der A. C., 2008, "Blast Charts for Explosive Evaporation of SupeRHReated Liquids," Process Safety Progress, 27(3), 219-224.

Blumer, U., 2007, "CCI Chemical Testing Status of Strainer Testing," Presentation to Nuclear Regulatory Commission, August 23, 2007. ADAMS Accession No.ML072420572.

Boiling Water Reactor Owners Group, 1994, "Interim Report of the BWROG, ECCS Suction Strainer Committee." ADAMS Accession No.ML9412233048.

Bonaca, M. V., 2004, "Safety Evaluation of the Industry Guidelines Related to Pressurized Water Reactor Sump Performance," Letter to N. J. Diaz, Advisory Committee on Reactor Safeguards, October 18, 2004, ADAMS Accession No.ML042960409.

Bostelman, J., G. Zigler, and G. Ashley, 1998, "Failed Coating Debris Characterization," Prepared for BWROG Containment Coating Committee, July 21, 1998, ADAMS Accession No.ML082970197.

BWR-PIRT, Gary E. Wilson, et. al., "BWR Drywell Debris Transport Phenomena Identification and Ranking Tables (PIRTs)," INEEL/EXT-97-00894, September 1997.

CFR, 1997, "Domestic Licensing of Production and Utilization Facilities," 10 CFR Part 50, Code of Federal Regulations, January 1, 1997.

Dupont, M.E., N. C. Iyer, P. S. Lam, R. L. Sindelar, T. E. Skidmore, F. R. Utsch, and P. E. Zapp, 2000a, "Degradation and Failure Characteristics of NPP Containment Protective Coating Systems," Westinghouse Savannah River Co., WSCR-TR-2000-00079. ADAMS Accession No. ML003703890.

Dupont, M.E., N. C. Iyer, P. S. Lam, R. L. Sindelar, T. E. Skidmore, F. R. Utsch, and P. E. Zapp, 2000b, "Degradation and Failure Characteristics of NPP Containment Protective Coating Systems," Westinghouse Savannah River Co., WSCR-TR-2000-00340. ADAMS Accession No. ML003772811.

Dupont, M.E., N. C. Iyer, P. S. Lam, R. L. Sindelar, T. E. Skidmore, F. R. Utsch, and P. E. Zapp, 2001a, "Degradation and Failure Characteristics of NPP Containment Protective Coating Systems, Interim Report No. 3," Westinghouse Savannah River Co., WSCR-TR-2001-00067. ADAMS Accession No. ML010600462.

Dupont, M.E., N. C. Iyer, P. S. Lam, R. L. Sindelar, T. E. Skidmore, F. R. Utsch, and P. E. Zapp, 2001b, "Degradation and Failure Characteristics of NPP Containment Protective Coating Systems, Preliminary Evaluation of Plant Coating Specimens," Westinghouse Savannah River Co., WSCR-TR-2001-00163. ADAMS Accession No. ML011130094.

Elliot, R. B., 2001, “Completion of Staff Reviews of NRC Bulletin 96-03 and NRC Bulletin 95-02 (TAC Number MA0704),” Letter to Gary M. Holahan, Director of Division of Systems Safety and Analysis, October 18, 2001. ADAMS Accession No. ML012970229.

EPRI, 2007a, “Plant Support Engineering: Adhesion Testing of Nuclear Coating Service Level I Coatings,” Electric Power Research Institute, Palo Alto, CA, EPRI 1014883.

EPRI, 2006, Plant Support Engineering: Aging and Degradation Survey for Nuclear Service Level I Coatings. EPRI, Palo Alto, CA,. EPRI 1013465.

EPRI, 2007b, Plant Support Engineering: Degradation Research for Nuclear Service Level I Coatings. EPRI, Palo Alto, CA, EPRI 1014884.

General Electric, 2007a, Slide Presentation at NRC Public Meeting with Nuclear Energy Institute, Pressurized Water Reactor Owners Group, Licensees, and Sump Strainer Vendors to Discuss the Resolution of Generic Safety Issue-191, August 23-24, 2007. ADAMS Accession No. ML072420567.

Hiser, A. L., 2008, “Staff Observations from January 2008 Trip to the PCI/Alden Test Facility to Observe Head Loss Testing for Wolf Creek and Callaway Plants,” Letter to M. L. Scott, Safety Issues Resolution Branch, ADAMS Accession No. ML081830645.

Information Systems Laboratories, 2005, “Development and Implementation of an Algorithm for Void Fraction Calculation in the ‘6224 Correlation’ Software Package,” ISL-NSAD-TR-05-01, ADAMS Accession No ML051590366.

Kern, K. T. and W. R. Thomas, 2003, “The Impact of Recovery From Debris-Induced Loss of ECCS Recirculation on PWR Core Damage Frequency,” LA-UR-02-7562, ADAMSAccession No. ML030610174.

Lane, A. E., T. S. Andreychek, W. A. Byers, R. J. Jacko, E. J. Lahoda, and R. D. Reid, 2006, “Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191,” Westinghouse Electric Company, WCAP-16530-NP ADAMS Accession No. ML060890509.

Lane, A. E., T. S. Andreychek, W. A. Byers, R. J. Jacko, E. J. Lahoda, E. J. Lahoda, and R. D. Reid, 2008, “Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191,” Westinghouse Electric Company, WCAP-16530-NP-A, ADAMS Accession No. ML081830645.

Langmuir, D., 1996, Aqueous Environmental Chemistry, Prentice Hall, New York.

McMurry, J. and X. He, 2006, “Supplementary Leaching Tests of Insulation and Concrete for GSI-191 Chemical Effects Program,”, Center for Nuclear Waste Regulatory Analyses, San Antonio, TX. ADAMS Accession No. ML063330573.

Moody, F. and T. Green, 1996, “Evaluation for Existence of Blast Waves Following Licensing Basis Double-Ended Guillotine Pipe Breaks (DRAFT),” GE Nuclear Energy, DRF A74-00003, ADAMS Accession No.ML092530507.

NEI, 2004, “Pressurized Water Reactor Sump Performance Evaluation Methodology,” Nuclear Energy Institute PWR Sump Performance Task Force, Rev. 0, NEI 04-07, ADAMS Accession No. ML050550138.

NRC, 2006, “Fort Calhoun Station Pilot Plant Audit Report Analyses Required for the Response to GL 2004-02 and GSI-191 Resolution,” Audit Report, Appendix II. ADAMS Accession No. ML060240026

NRC 2006b, “Foreign Travel Trip Report—NRC Staff visit to Chalk River Laboratories to observe sump strainer head loss testing performed by Atomic Energy of Canada, Limited,” ADAMS Accession No. ML062020596.

NRC, 2007a, “Watts Bar Unit 1 Nuclear Power Plant Corrective Actions for GL 2004-02,” Audit Report, ADAMS Accession No. ML062120469.

NRC, 2007b, “Millstone Unit No. 2 Corrective Actions for GL 2004-02,” ADAMS Accession No. ML072290454.

NRC, 2007c, “North Anna Power Station Corrective Actions for GL 2004-02,” ADAMS Accession No. ML072770236.

NRC, 2007d, “Oconee Nuclear Station Corrective Actions for Generic Letter 2004-02,” ADAMS Accession No. ML071790169.

NRC, 2007e, “Prairie Island Nuclear Generating Plant Corrective Actions for GL 2004-02,” ADAMS Accession No. ML070750065.

NRC, 2008a, “Waterford Corrective Actions for GL 2004-02,” ADAMS Accession No. ML080140315.

NRC, 2008b, “Supplemental Response to NRC Generic Letter 2004-02, ‘Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized-Water Reactors’,” H. B. Robinson Steam Electric Plant, Unit No. 2, Docket No. 50-261/License No. DPR-23. ADAMS Accession No.ML080730290.

NRC, 2008c, “Knowledge Base Review of Chemical Effects,” Appendix B in “NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Plant-Specific Chemical Effect Evaluations.” ADAMS Accession No. ML080380214.

NRC, 2008d, “NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Strainer Head Loss and Vortexing.” ADAMS Accession No. ML080230038.

NRC, 2008e, “Indian Point Energy Center Corrective Actions for Generic Letter 2004-02,” ADAMS Accession No.ML082050433.

NRC, 2008f, “Salem Units 1-2 GSI-191 Generic Letter 2004-02 Corrective Actions,” ADAMS Accession No.ML082170506.

NRC, 2008g, “GSI-191 Resolution Submittal for Virgil C. Summer Nuclear Station,” Docket No. 50/395, February 29, 2008. ADAMS Accession No. ML080640545.

NRC, 2011, “Evaluation of Chemical Effects Phenomena Identification and Ranking Table Results,” ADAMS Accession No. ML102280592.

OPG, 2001, “Jet Impact Tests—Preliminary Results and Their Applications,” Ontario Power Generation, N-REP-34320-10000-R00, April 2001. ADAMS Accession No.ML020290085.

OPPD, 2008, Letter from Omaha Public Power District (OPPD) to the US NRC “Supplemental Response to Generic Letter 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized-Water Reactors" February 29, 2008, ADAMS Accession No. ML080650369.

PWR-PIRT, B.E. Boyack, et. al., “Pressurized Water Reator Debris Transport in Dry Ambient Containments – Phenomena Identification and Ranking Tables (PIRTs),” LA-UR-99-3371, Rev. 2, December 14, 1999, ADAMS Accession No.ML003698506.

Ransom, V. H., 2004, “Comments on GSI-191 Models for Debris Generation,” ADAMS Accession No. ML050830341, September 14, 2004.

Rao, D. V., C. J. Shaffer, and R. Elliot, 2001, “BWR ECCS Strainer Blockage Issue: Summary of Research and Resolution Actions,” Los Alamos National Laboratory, LA-UR-01-1595, ADAMS Accession No. ML012970246.

Reid, R. D., K. R. Crytzer, A. E. Lane, and T. S. Andreychek, 2006, “Evaluation of Alternative Emergency Core Cooling System Buffering Agents,” Westinghouse Electric Company, WCAP-16596-NP Revision 0, ADAMS Accession No ML062570173.

Reid, R. D., K. R. Crytzer, A. E. Lane, 2007, “Evaluation of Additional Inputs to the WCAP-16530-NP Chemical Model,” Westinghouse Electric Company, WCAP-16785-NP, Revision 0, ADAMS Accession No. ML072010381.

Scott, M. L., 2006, “Staff Observations Regarding Flume Testing of a Prototype Portion of the Proposed Replacement Suction Screen Design for the Comanche Peak Steam Electric Station,” Letter to Jared S. Wermiel, Division of Safety Systems, Docket Nos. 50-445 and 50-446, ADAMS Accession No..ML061280580.

Scott, P., et al., “Review of GE Nuclear Energy/BWR Owners Group Report on the Evaluation for Existence of Blast Waves Following Licensing Basis Double-Ended Guillotine Pipe Breaks,” Battelle Columbus, Inc., April 11, 1996, ADAMS Accession No.ML9605140096.

Shack, W. J., 2007, “Technical Letter Report on WACP-16530-NP, Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191,” NRC Technical Letter Report, ADAMS Accession No..ML080650350.

Smith, S. J., 2008a, “Staff Observations of Testing for Generic Safety Issue 191 during February 12 and February 13 Trip to the Alden Test Facility for PCI Strainer Tests,” Letter to M. L. Scott, Safety Issues Resolution Branch, ADAMS Accession No. ML080920398.

Smith, S. J., 2008b, “Staff Observations of Testing for Generic Safety Issue 191 during July 29 to July 31, 2008 Trip to the Alden Test Facility for PCI Strainer Tests,” Letter to M. L. Scott, Safety Issues Resolution Branch, ADAMS Accession No. ML083470317.

Smith, S. J., 2010, “Staff Observations of Testing for Generic Safety Issue 191 during July 12 to July 14, 2010 Trip to the Alden Test Facility for PCI Strainer Tests,” Letter to M. L. Scott, Safety Issues Resolution Branch, ADAMS Accession No. ML102160226.

Städtke, H., 2006, Gasdynamic Aspects of Two-Phase Flow, Wiley-VCH, Federal Republic of Germany.

Van Straten, H. V., B. T. W. Holtkamp, and P. L. de Bruyn, 1984, “Precipitation from Super-saturated Aluminate Solutions: I. Nucleation and Growth of Solid Phases at Room Temperature,” J. Colloid Interface Sci. 98, 342-362.

Vietti-Cook, A. L., “Staff Requirements – SECY-10-0113 – Closure Options for Generic Safety Issue-191, Assessment of Debris Accumulation on Pressurized Water Reactor Sump Performance,” Memorandum to R. W. Borchardt, December 23, 2010, ADAMS Accession No. ML072550227.

Wallis, G., 2004, “The ANSI/ANS Standard 58.2-1988: Two-Phase Jet Model,” ADAMS Accession No. ML050830344.

Westinghouse Electric, 2004, “Evaluation of Potential ERG and EPG Changes to Address NRC Bulletin 2003-01 Recommendations (PA-SEE-0085),”, WCAP-16204 Rev. 1.

Westinghouse Electric, 2006, Submittal of “Evaluation of Downstream Sump Debris Effects in Support of GSI 191,” Rev. 1, WCAP-16406-P ADAMS Accession No. ML072550227.

Appendix A. NRC BULLETIN 2003-01 AND GENERIC LETTER 2004-02 DATABASES

This appendix contains a discussion and summary tables of two Microsoft Access databases developed to tabulate PWR liscensees' responses to NRC Bulletin 2003-01 and Generic Letter 2004-02. The complete databases are archived in ADAMS at Ascession Nos. ML13170A449 and ML13170A455, respectively. (When opening these database files from the ADAMS system, the user my receive a message "The file does not exist, or you do not have read access to the file". If you see this message just click ok and save the file to your desktop.)

A.1 NRC BULLETIN 2003-01 DATABASE

The description of the Bulletin 2003-01(03-01) Database is provided in Chapter 7.1 of this report. Here, only the user interface and detailed results from the database are presented.

A.1.1 Bulletin 03-01 Database User Interface

A total number of 1,084 actions (database records) have been collected for the NRC Bulletin 03-01 database. The distribution of these records by various fields – such as by reactor, by action type, by Interim Compensatory Measure/Candidate Operator Action (ICM/COA) category – is analyzed in the Database Results section below. This type of statistics, displayed in various table forms, is one of the two major database's capabilities. The other is the detailed report for records that satisfy user-selected criteria, as described below. A choice between these two capabilities is presented to the user of the database in the main database window, as shown in Fig. A.1-1.

In the Database-wide Statistics section, a user can select which particular result is to be displayed (Fig. A.1-2). Again, those results are presented in the Result section below.

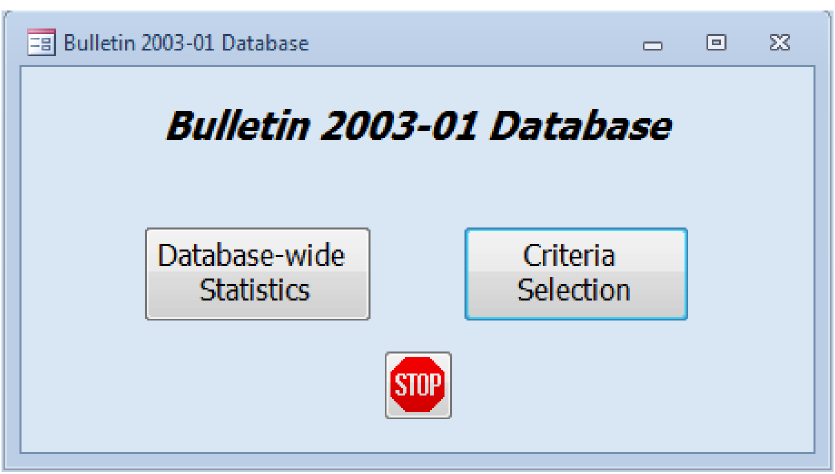

Figure A.1-1. Bulletin 03-01 Database Main Window

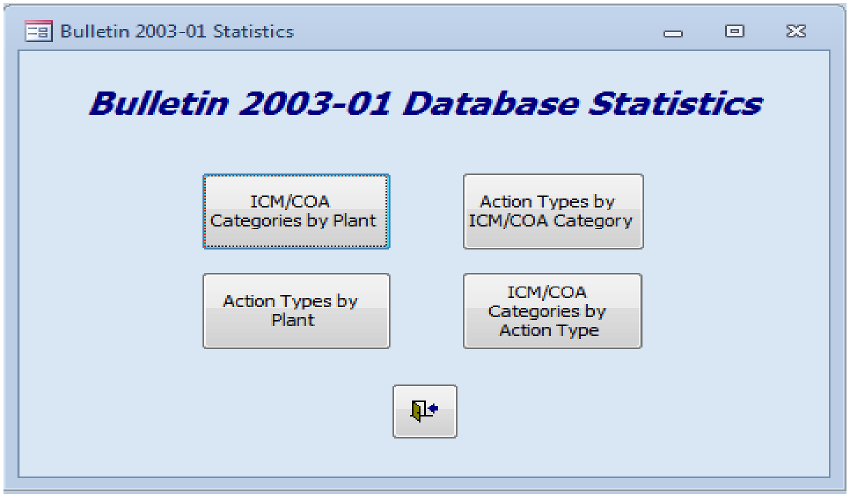

Figure A.1-2. Bulletin 03-01 Database Database-wide Statistics Selection Form

In the Criteria Selection section, a form is opened to assist a user in criteria selection. The Criteria Selection form (Fig. A.1-3) allows for interactive selection of a particular criterion for the filtering and a combination of various criteria. It also provides word-searching capabilities. The ICM, COA, and Action Type sections of the Criteria Selection form provide a possibility to choose any records based on these criteria. The ICM and COA sections of the database can be turned off completely by clicking on the option button in the corresponding section title bar. "Select All" and "Unselect All" buttons are provided in the ICM, COA, and Action Type sections to quickly turn on or clear all checkmarks in the corresponding section. The options in these sections are independent meaning that any combination of the criteria in these sections can be applied to the database records. The help ("?") buttons in the ICM and COA sections provide the description of ICM and COA categories (similar to Tables A.1-1 and A.1-2), respectively.

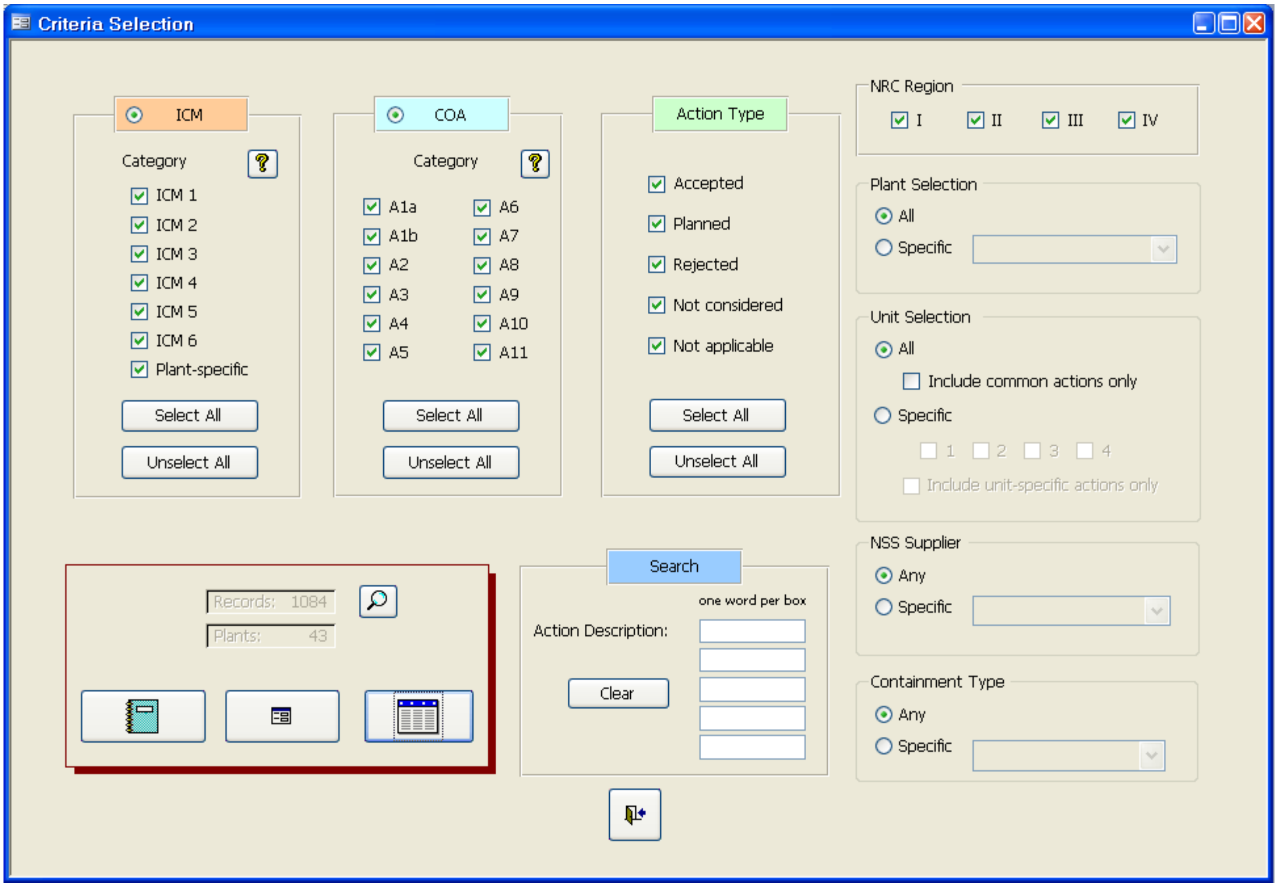

Figure A.1-3. Criteria Selection Form of NRC Bulletin 03-01 Database

On the right-hand side of the form, a selection regarding the plants and units can be made. On top, the NRC regions of interest can be specified. Plant Selection allows choosing either all plants or selecting a specific plant. The Unit Selection group can filter records based on the plant unit the actions are applied to. “All” means to display all actions (no filter). The option “Include common actions only”, if turned on, will filter out the actions for specific units such that only actions described as those applicable to all plant units will be selected. “Specific” option means that the actions applicable to the selected plant units are displayed. Unless the “Include unit-specific actions only” option is selected, actions applicable to all units will also be displayed. The NSS Supplier and Containment Type sections allow filtering the database records by the reactor supplier (B&W, CE, or WEST), and containment type (DRYAMB (large dry), DRYSUB (subatmospheric), or ICECND (ice condenser)), respectively. Either all types or a specific value can be selected from the drop down box. In general, the selection options in the right-hand side of the form are inter-dependent. For example, if a specific NRC region is selected, then the list in the drop down box for the reactor plant would only have the reactor names from this region. Similarly, if a specific reactor plant is selected, then the NSS Supplier and the Containment Type would already be defined by the reactor selection. Thus, if a specific plant is selected, these two sections will be deactivated on the form. If a specific NSS Supplier is selected, then the list options in the containment type will be limited to this supplier. Only the Unit Selection section is independent from other selections; any selection can be made regardless the other options.

The Search section of the Criteria Selection form provides an opportunity to look for specific words in the Action Description field of the database. Up to five words can be entered in this section; only records which have an exact match for non-empty search boxes, in any order, will be displayed. For example, to find the records dealing with procedure modifications regarding RWST, words “RWST” and “procedure” can be entered in separate boxes of the Search section. The search is not case-sensitive.

When any action is taken in the Criteria Selection form, the database automatically recalculates the number of records and number of plants that satisfy the selected criteria. Those two numbers are displayed in the corresponding boxes in the lower left-hand side of the Criteria Selection form. The statistics of the distribution of the selected records by ICM/COA categories and action types can be displayed by clicking on the magnifying glass button next to the record count. This is one of the report forms available from the Criteria Selection form. The other three types of the report can be displayed by clicking on a corresponding button below the plant count. These reports will show the complete database information (i.e., content of all fields) for the records that satisfy the selected criteria. The information displayed by these reports is the same; only the form of the reports is different. The Report button opens a report when all records are displayed in a printer-ready table. (An example of such report is shown in Table A.1-6 in the Results section below.) The selected criteria are repeated on top of this report. The Form report displays the information on record-by-record basis. The Table report shows the information in a table form. The results of the statistical and printer-ready reports can be transferred to MS Word or MS Excel for further analysis (with an exception of the selected criteria header).

A.1.2 NRC Bulletin 03-01 Database Results

This section presents the results obtained from NRC Bulletin 03-01 database. The results presented here are statistical results only in that they usually do not show the details of each particular tasks but rather the overall distribution of the tasks either by plants, categories, or types. Detailed reports can be generated by the database; they are not presented here due to space limitations.

It is also noted that the results presented here represent a historical snapshot in time and may not be valid in future times, unless updated with new information. For example, the actions characterized as “planned” for this report are those that were planned for implementation by a plant at a time when Bulletin 03-01 response was prepared. It was not verified as part of this report whether those commintments were indeed carried out. Similarly, the information presented below does not guarantee that the actions described as “completed” would not be reversed in future, for example, as a result of design modifications.

Responding to the NRC Bulletin 03-01, all plants stated that they had chosen option 2 and listed the ICMs (Table A.1-1) they either implemented or were planning to implement. The plant responses also provided the basis for any measures they rejected.

Table A.1-1. Interim Compensatory Measures (ICM) and Their Categories

Category	Description
ICM 1	Providing operator training on indications of and responses to sump clogging
ICM 2	Making procedural modifications that would delay the switchover to containment sump recirculation
ICM 3	Ensuring alternative water sources to refill the RWST or to otherwise provide inventory to inject into the reactor core and spray into the containment atmosphere
ICM 4	Undertaking more aggressive containment cleaning and increased foreign material controls
ICM 5	Ensuring containment drainage paths are unblocked
ICM 6	Ensuring sump strainers are free of adverse gaps and breaches

In response to NRC Bulletin 03-01, the Westinghouse Owners Group prepared a report, WCAP-16204 (Westinghouse Electric, 2004). The report provided a list of candidate operator actions (COA) recommended for consideration and implementation by the Westinghouse and Combustion Engineering designed plants. The possible actions that were proposed by WCAP-16204 are listed in Table A.1-2.

Table A.1-2. Candidate Operator Actions and Their Categories

Category	Description
A1a	Implement operator action to secure one spray pump
A1b	Implement operator action to secure both spray pumps
A2	Manually establish one train of containment sump recirculation before automatic actuation
A3	Terminate one train of safety injection (HPSI/high-head injection) after recirculation alignment
A4	Implement early termination of one LPSI/RHR pump before recirculation alignment
A5	Refill of refueling water storage tank
A6	Inject more than one RWST volume by drawing from a refilled RWST or by bypassing the RWST
A7	Provide more aggressive cooldown and depressurization following a SBLOCA
A8	Provide guidance on symptoms and identification of containment sump blockage
A9	Develop contingency actions in response to containment sump blockage, loss of suction, and cavitation
A10	Implement early termination of one train of HPSI/high-head injection before recirculation alignment
A11	Prevent or delay containment spray for SBLOCAs (<1.0 in. dia) in ice condenser plants

Table A.1-3 shows the distribution of actions by ICM/COA categories for each plant. The plants are grouped by NRC region. The total number of actions for each plant is also shown in Table A.1-3. Table A.1-4 shows how the same actions are distributed between the action types for each plant.

Table A.1-5 and Fig. A.1-4 show the distribution of the actions from all plants by ICM/COA categories and type. Figure A.1-2 demonstrates that majority of the ICMs from NRC Bulletin 03-01 have been implemented or were planned for implementation. The noticeable exception is ICM 2 (procedural modifications that would delay the switchover to containment sump recirculation), where the plants rejected a significant portion of such actions. For COAs, the majority of A1a-A4 candidate actions were rejected, while most A5-A9 actions were either implemented or planned. Most of the actions in COA A10 category were either rejected or not applicable. None of the A11 actions was implemented or planned.

Table A.1-3. Action Categories by Plant

Plant	Total	ICM 1	2	3	4	5	6	7	COA A1a	A1b	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11
NRC Region 1																				
Beaver Valley	22	2	2	3	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1
Calvert Cliffs	19	2	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1
Ginna	27	6	2	1	3	1	2		2		1	1	1	1	1	1	1	1	1	1
Indian Point	24	6	1	1	2	1	1		1	2	1	1	1	1	1	1	1	1	1	
Millstone 2	24	6	1	1	1	2	1		1	1	1	1	1	1	1	1	1	1	1	1
Millstone 3	33	9	2	5	1	1	2		1	1	1	1	1	2	1	1	1	1	1	1
Salem	59	8	7	2	12	3	2	1	2	2	2	2	2	2	2	2	2	2	2	2
Seabrook	24	2	4	1	1	2	2		1	1	1	1	1	1	1	1	1	1	1	1
Three Mile Island	21	3	2	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1
NRC Region 2																				
Catawba	25	4	3	2	2	1	1		1	1	1	1	1	1	1	1	1	1	1	1
Crystal River	17	3	3	3	3	2	2	1												
Farley	18	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1
McGuire	25	4	3	2	2	1	1		1	1	1	1	1	1	1	1	1	1	1	1
North Anna	27	4	3	2	2	2	1		1	1	1	1	1	2	1	1	1	1	1	1
Oconee	21	4	8	2	2	3	1	1												
Robinson	22	3	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sequoyah	20	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Shearon Harris	33	3	2	2	5	6	2	1	1	1	1	1	1	1	1	1	1	1	1	1
St. Lucie	33	7	3	1	1	2	1	1	2	2	2	2	2	1	1	1	1	1	1	1
Summer	22	2	2	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Surry	21	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Turkey Point	30	3	1	3	4	3	3	1	1	1	1	1	1	1	1	1	1	1	1	1
Vogtle	19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Watts Bar	27	4	1	1	3	2	1	3	1	1	1	1	1	1	1	1	1	1	1	1
NRC Region 3																				
Braidwood	23	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Byron	23	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Davis Besse	13	1	1	2	2	4	2	1												

DC Cook	32	2	1	1	1	4	2	5	1	1	1	1	1	3	3	1	1	1	1	1
Kewaunee	26	2	3	2	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Palisades	22	1	3	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Point Beach	22	2	2	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Prairie Island	25	2	4	2	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
NRC Region 4																				
Arkansas Nuclear One 1	22	1	2	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Arkansas Nuclear One 2	22	1	2	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Callaway	23	2	1	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Comanche Peak	25	3	2	2	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Diablo Canyon	23	3	1	2	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Fort Calhoun	35	7	7	1	1	1	1	5	1	1	1	1	1	1	1	1	1	1	1	1
Palo Verde	28	2	1	3	3	2	4	1	1	1	1	1	1	1	1	1	1	1	1	1
San Onofre	25	4	1	2	4	1	1		1	1	1	1	1	1	1	1	1	1	1	1
South Texas	28	6	2	5	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1
Waterford	28	7	1	2	3	2	1		1	1	1	1	1	1	1	1	1	1	1	1
Wolf Creek	26	6	2	2	2	1	1		1	1	1	1	1	1	1	1	1	1	1	1

Table A.1-4. Action Types by Plant

Plant	Total of Record	Accepted	Planned	Rejected	Not Applicable	Not Considered
NRC Region 1						
Beaver Valley	22	10	3	7	2	
Calvert Cliffs	19	10	2	6	1	
Ginna	27	16	8	1	2	
Indian Point	24	16	4	4		
Millstone 2	24	16		6	1	1
Millstone 3	33	21	5	4	3	
Salem	59	39	7	11	2	
Seabrook	24	12	4	5	3	
Three Mile Island	21	9	6	4		2

NRC Region 2						
Catawba	25	17	1	5	2	
Crystal River	17	3	12	2		
Farley	18	10	2	3	3	
McGuire	25	17	1	5	2	
North Anna	27	17	2	6	2	
Oconee	21	10	10	1		
Robinson	22	13		6	2	1
Sequoyah	20	8	3	8	1	
Shearon Harris	33	15	8	7	2	1
St. Lucie	33	15	11	6	1	
Summer	22	9	5	7	1	
Surry	21	11	2	6	2	
Turkey Point	30	15	8	3	3	1
Vogtle	19	9	1	5	3	1
Watts Bar	27	16	2	8	1	
NRC Region 3						
Braidwood	23	2	11	6	3	1
Byron	23	2	11	6	3	1
Davis Besse	13	6	7			
DC Cook	32	20	3	7	2	
Kewaunee	26	10	9	4	3	
Palisades	22	3	14	4	1	
Point Beach	22	9	8	3	2	
Prairie Island	25	12	9	3	1	
NRC Region 4						
Arkansas Nuclear One 1	22	11	3	6	1	1
Arkansas Nuclear One 2	22	9	3	8	1	1
Callaway	23	5	10	6	2	
Comanche Peak	25	9	8	5	3	
Diablo Canyon	23	9	4	5	4	1
Fort Calhoun	35	10	15	9	1	

Palo Verde	28	12	9	6	1	
San Onofre	25	18		6	1	
South Texas	28	22		5	1	
Waterford	28	15	5	7	1	
Wolf Creek	26	13	6	6	1	

Table A.1-5. Action Types by ICM/COA Category

			Action Type				
ICM/COA	Category	Total	Accepted	Planned	Rejected	Not Applicable	Not Considered
ICM	1	147	86	61			
	2	96	47	21	28		
	3	80	51	24	4		1
	4	93	68	25			
	5	72	55	17			
	6	56	48	8			
	7	37	15	8	5		9
COA	A1a	43	9	6	28		
	A1b	42	5	2	35		
	A2	42		1	40	1	
	A3	42	5	3	33		1
	A4	42	1	2	24	15	
	A5	45	29	16			
	A6	43	26	12	5		
	A7	41	30	7	2	2	
	A8	41	31	10			
	A9	41	23	18			
	A10	41	2	1	19	19	
	A11	40			5	34	1

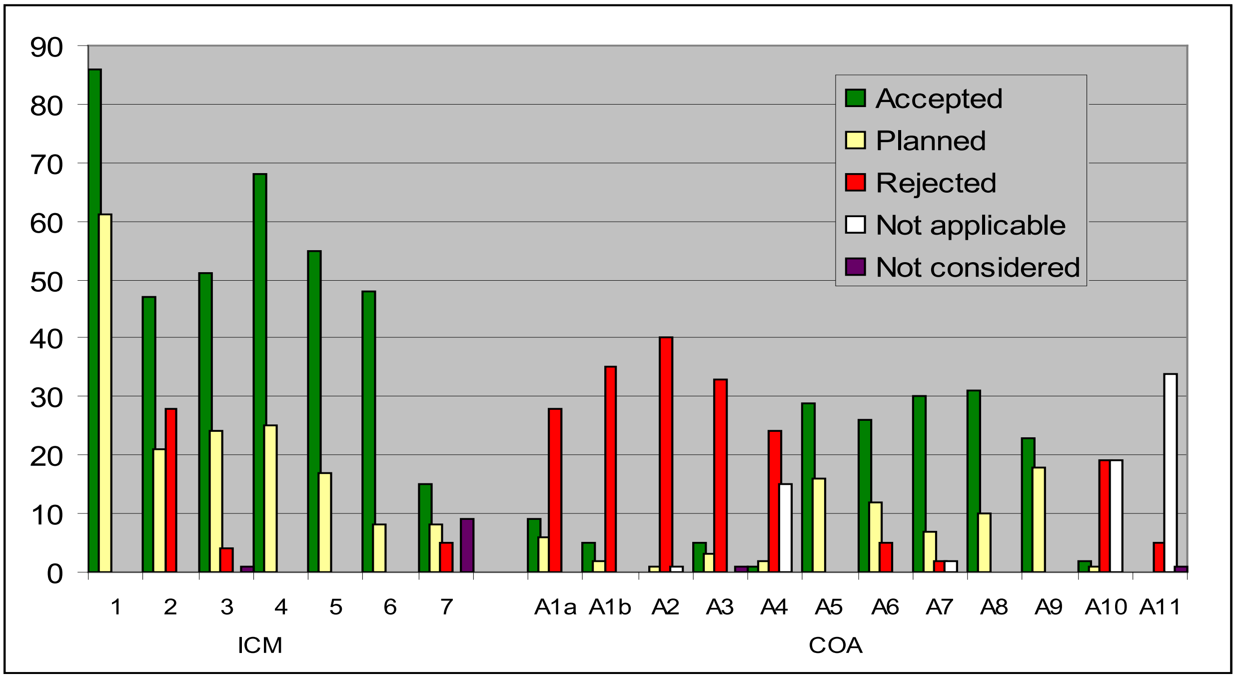

Figure A.1-4. Action Type by ICM/COA Categories

The results in previous tables and figure are generated based on the data from the entire database. Below are database results obtained from subsets of the data based on some selection criteria. These results utilize the selection criteria capability of the NRC Bulletin 03-01 database described above. Note that the results presented below show only a fraction of data available from the database; an almost unlimited set of results can be generated using various combinations of criteria selection and/or search filters.

Figure A.1-5 compares the distribution of the actions by the ICM/COA categories and type for three reactor suppliers. Note that the COA proposed by WCAP-16204 (Westinghouse Electric, 2004) generally do not apply to Babcock & Wilcox plants, but two B&W plants, Arkansas Nuclear One 1 and Three Mile Island still provided a discussion of those actions. That information is easily available from the NRC Bulletin 03-01 database report with corresponding selection criteria, as demonstrated in Table A.1-6.

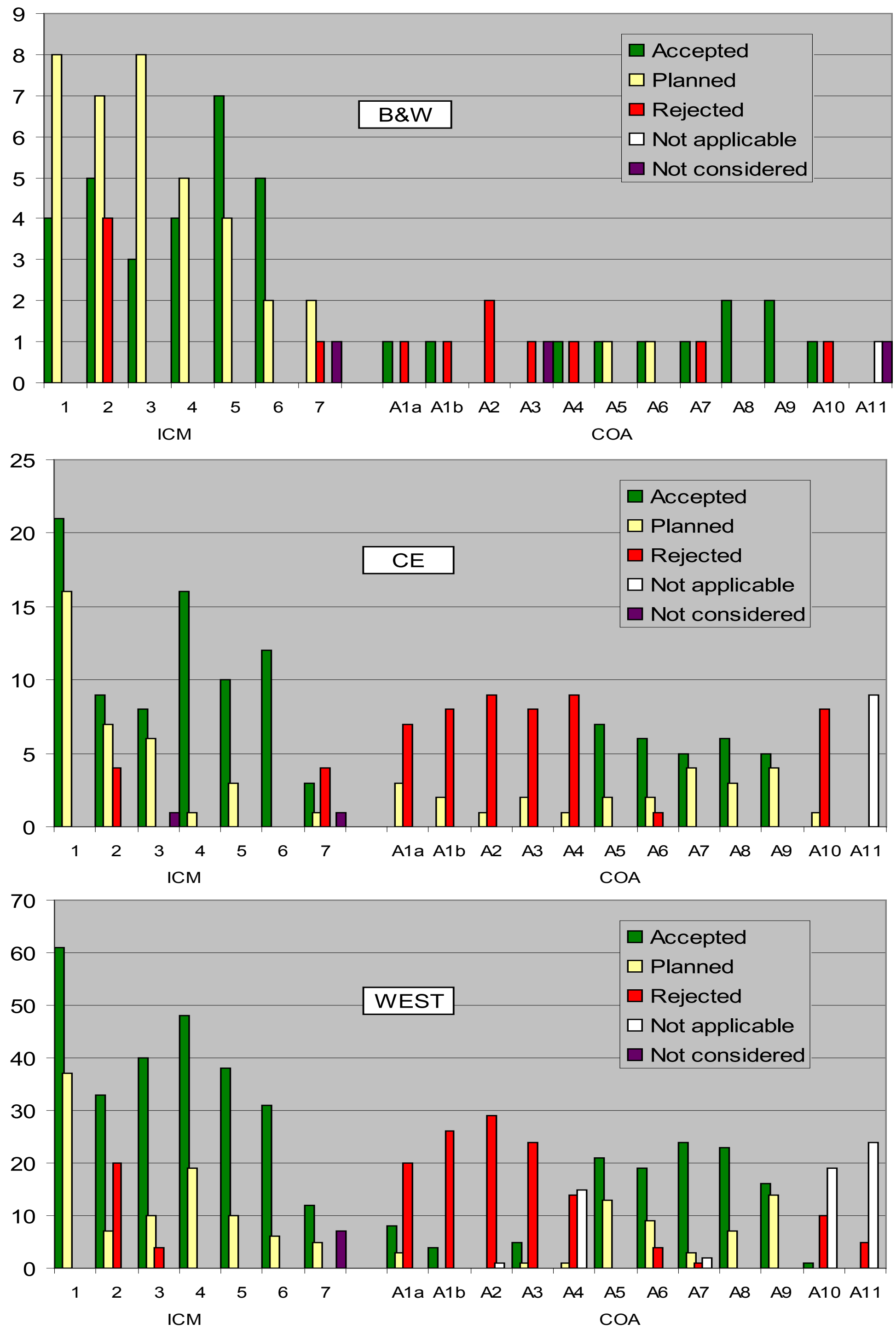

Figure A.1-5. NRC Bulletin 03-01 Database Results by Supplier

Table A.1-6. NRC Bulletin 03-01 Database Report - COA for B&W Plants

Selected Criteria:

ICM -	COA -		Action type -	NRC Region(s):	1 2 3 4
	A1a	A6	Accepted	Plant(s):	All
	A1b	A7	Planned	Unit(s):	All
	A2	A8	Rejected		
	A3	A9	Not considered	NSS Supplier:	B&W
	A4	A10	Not applicable		
	A5	A11		Containment:	Any
Action Description Search:			<None>		

Conditions Satisfied for
24 Records 2 Plants

Plant	NSS Supplier	Containment	Unit (s)	ICM/ COA	Category	Action Type	Action Description	ML Number
Arkansas Nuclear One 1	B&W	DRYAMB						
			1	COA	A1a	Accepted	This step is already in current EOPs. However, ANO-1 does not secure either reactor building spray pump prior to sump recirculation, and in response to sump blockage, one spray pump is secured if there is indication of a containment breach or two spray pumps are secured if there is no indication of containment breach.	ML052560232 ML053480199
			1	COA	A1b	Accepted	This step is already in current EOPs. However, ANO-1 does not secure either reactor building spray pump prior to sump recirculation, and in response to sump blockage, one spray pump is secured if there is indication of a	ML052560232 ML053480199

							containment breach or two spray pumps are secured if there is no indication of containment breach.	
			1	COA	A2	Rejected	Automatic actuation of sump recirculation is not applicable, and transfer of one train of sump recirculation early was unacceptable due to net positive suction head requirements, BWST drawdown rate, and valve stroke times	ML052560 232 ML053480 199
			1	COA	A3	Rejected	Licensee is maintaining the same vendor HPSI termination criteria (which are applicable both before and after sump recirculation) as have been in effect, i.e., “ECCS flows shall not be throttled while the core outlet is not sub-cooled other than that required for pump protection” (actual sump blockage indication).	ML052560 232 ML053480 199
			1	COA	A4	Rejected	Licensee is maintaining the same vendor HPSI termination criteria (which are applicable both before and after sump recirculation) as have been in effect, i.e., “ECCS flows shall not be throttled while the core outlet is not sub-cooled other than that required for pump protection” (actual sump blockage indication).	ML052560 232 ML053480 199
			1	COA	A5	Accepted	Implemented in current operating procedures. (see also ICM category #3).	ML052560 232 ML053480 199
			1	COA	A6	Accepted	Covered under current procedures. Additional borated water sources can be made available for injection into the RCS and they include but are not limited to any remaining or refilled BWST inventory, clean waste receiver tanks via	ML052560 232 ML053480 199

							BWST, batch boric acid additions via BWST, delivered offsite sources, unborated water via the spent fuel pool. As a last resort, pure unborated water can be provided to the BWST for injection by the LPI pumps. A proceduralized method of adding inventory to the RCS, bypassing the BWST, is via normal makeup from the makeup tank. (see also ICM category #3).	
			1	COA	A7	Accepted	Current EOPs expedite cooldown during a LOCA, but cooldown limits do not apply when the core exit thermo-couples are not sub-cooled. Forced Flow Cooldown Procedure is written for a plant cooldown under LOCA conditions where sub-cooling margin is adequate, so normal cooldown limits apply. The term “rapid cooldown” has a specific procedure-based meaning (a rate faster than technical specification limits), but operators are trained to perform all other cooldowns as quickly as possible within technical specification limits. (see also ICM category #2).	ML052560 232 ML053480 199
			1	COA	A8	Accepted	This guidance is in the currently approved EOPs, which provide detailed symptoms of sump blockage as well as indications to monitor. These symptoms are lowering sump level and fluctuation in the ECCS pump performance, including erratic indication of suction and discharge pressure, flow, and amperage (see also ICM category #1).	ML052560 232 ML053480 199
			1	COA	A9	Accepted	Owners Group interim guidance states	ML052560

							that whenever ECCS is placed on reactor building sump recirculation and there are symptoms of sump degradation, operator should verify suction lineups, throttle LPI to minimum flow rate, if both RBS trains are operating then stop one RBS train, if no evidence of containment breach then stop all RBS pumps, and refer to station management. If the sump were to clog, procedures would direct the staff to consider such actions as injecting additional coolant into the RCS. (see also ICM category #1).	232 ML053480 199
			1	COA	A10	Rejected	Not implemented. Licensee is maintaining the same vendor HPSI termination criteria (which are applicable both before and after sump recirculation) as have been in effect, i.e., "ECCS flows shall not be throttled while the core outlet is not sub-cooled other than that required for pump protection" (actual sump blockage indication).	ML052560 232 ML053480 199
			1	COA	A11	Not applicabl e	Applies only to ice condenser plants.	ML052560 232 ML053480 199
Three Mile Island	B&W	DRYAMB						
			All	COA	A1a	Rejected	Not implemented, since minimal benefit relative to an existing long duration time to switchover (BWST drawdown of approximately 28 min in the most limiting LOCA events) relative to core cooling needs; operator burden early in an	ML052710 116

							event; resultant reduction of dose mitigation capability; and the ability to eventually throttle the LPSI pumps while then securing one or both core spray pumps (depending on potential dose consequences) should sump clogging indications arise.	
			All	COA	A1b	Rejected	Not implemented, since minimal benefit relative to an existing long duration time to switchover (BWST drawdown of approximately 28 min in the most limiting LOCA events) relative to core cooling needs; operator burden early in an event; resultant reduction of dose mitigation capability; and the ability to eventually throttle the LPSI pumps while then securing one or both core spray pumps (depending on potential dose consequences) should sump clogging indications arise.	ML052710 116
			All	COA	A2	Rejected	Not implemented, since the relatively long BWST drawdown time allows for substantial core cooling prior to switchover to ECCS recirculation.	ML052710 116
			All	COA	A3	Not considere d	Not considered probably because TMI is B&W design.	
			All	COA	A4	Accepted	Considered the post-switchover LPSI pump throttling procedures to be reasonably similar in effect to COA A4 (ICM #1)	ML052710 116
			All	COA	A5	Planned	Revise the site emergency operating procedures to incorporate interim measures to include initiating BWST refill after switchover to recirculation by September 15, 2005. TMI-1 has existing	ML052710 116

							procedures for refilling the BWST from the spent fuel pool and the condensate storage tanks, and the technical support center guidance procedure currently being developed will recommend an alternate injection path using a normal makeup/RCS fill capability to have other transfer pumps draw from one of the reactor coolant bleed tanks and pump through the makeup system to the RCS. (ICM #3)	
			All	COA	A6	Planned	Develop guidance for injecting more than one BWST volume from a refilled BWST or for injecting from alternate water sources September 30, 2005. (ICM #3)	ML052710116
			All	COA	A7	Rejected	Not implemented, since the relatively long BWST drawdown time allows for substantial core cooling prior to switchover to ECCS recirculation.	ML052710116
			All	COA	A8	Accepted	Enhanced the emergency procedures to provide the guidance in regard to ECCS operation after switchover to ECCS sump suction. All the necessary indications are readily available to the operators, including high vibration alarms on the LPSI pumps. (ICM #1)	ML041940373
			All	COA	A9	Accepted	Enhanced the emergency procedures to provide the guidance in regard to ECCS operation after switchover to ECCS sump suction. (ICM #1)	ML041940373
			All	COA	A10	Accepted	Already implemented through existing procedures to shut down HPSI pumps as soon as RCS pressure allows (ICM #2)	ML052710116
			All	COA	A11	Not considered	Not considered probably because TMI is B&W design.	

Figure A.1-6 shows a comparison of the distribution of the actions between different containment types, such as dry ambient pressure, dry sub-atmospheric, and wet ice condenser.

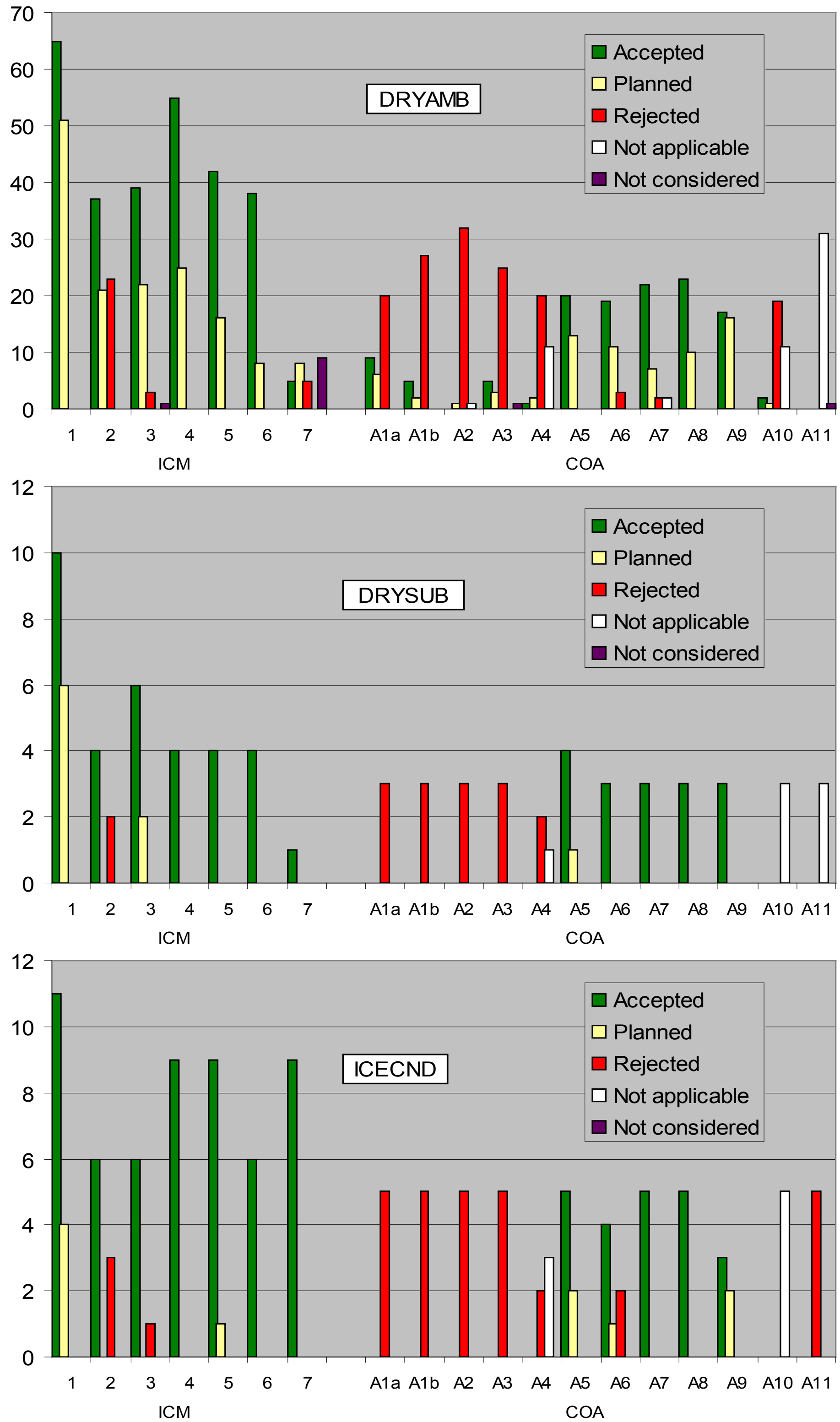

Figure A.1-6. Results from NRC Bulletin 03-01 Database by Containment Type

A.2 NRC Generic Letter 2004-02

General description of the GL-04-02 Database is provided in Chapter 7.2 of this report. Here, only the user interface and detailed results from the database are presented.

A.2.1 Generic Letter 2004-02 Database Interface

The GL-2004-02 database was developed in the Microsoft Access environment. A user interface was created to simplify the navigation and use of the database. The main database form, which first opens when the database is loaded, is shown in Fig. A.2-1. From there, the user can select either to work with the results of the database or to view and modify each database record.

The main database form (Fig. A.2-1) also lists the current date of the database. This capability is added to the database since by the time of this report preparation the GL-04-02 was not closed and plants continued to provide the information related to the GL-04-02. The current date reflects the date of the most recent document used for the database entries.

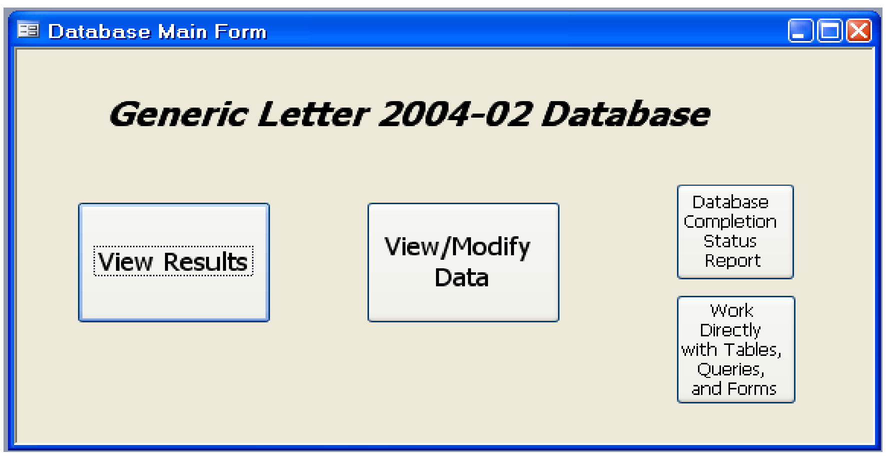

Figure A.2-1. Main Form for GL-04-02 Database

In addition, two other options are available from the database main form (defined by smaller buttons on the right-hand side of the form). One is to see the database completion report (described in Section A.2.2.2). The other is to work with the tables, queries, and forms. This option is provided for further database development.

The data modification mode is initiated by clicking on the View/Modify Data button on the main database form. In this mode, all database entries can be modified or deleted. A warning message is displayed when this mode is selected. Also in this mode, new entries can be added to the database. A data modification form, such as one shown in Fig. A.2-2, is opened. The desired database area (such as Strainer) can be selected on the right side of the form. A particular field of the database (such as New Size) is selected from the tabs at the top of the form, which are updated when new area is selected. In this form, all fields are open and can be modified and saved in the database (no dedicated “save” action is needed; the modified data are stored in the database instantaneously). The navigation through the records is done by clicking on the buttons on the lower side of the form. Built-in capabilities, such as searching, filtering, and sorting (available from either Access menu or toolbars) can be used to find the specific records.

The Exit button is used to return to the main database form.

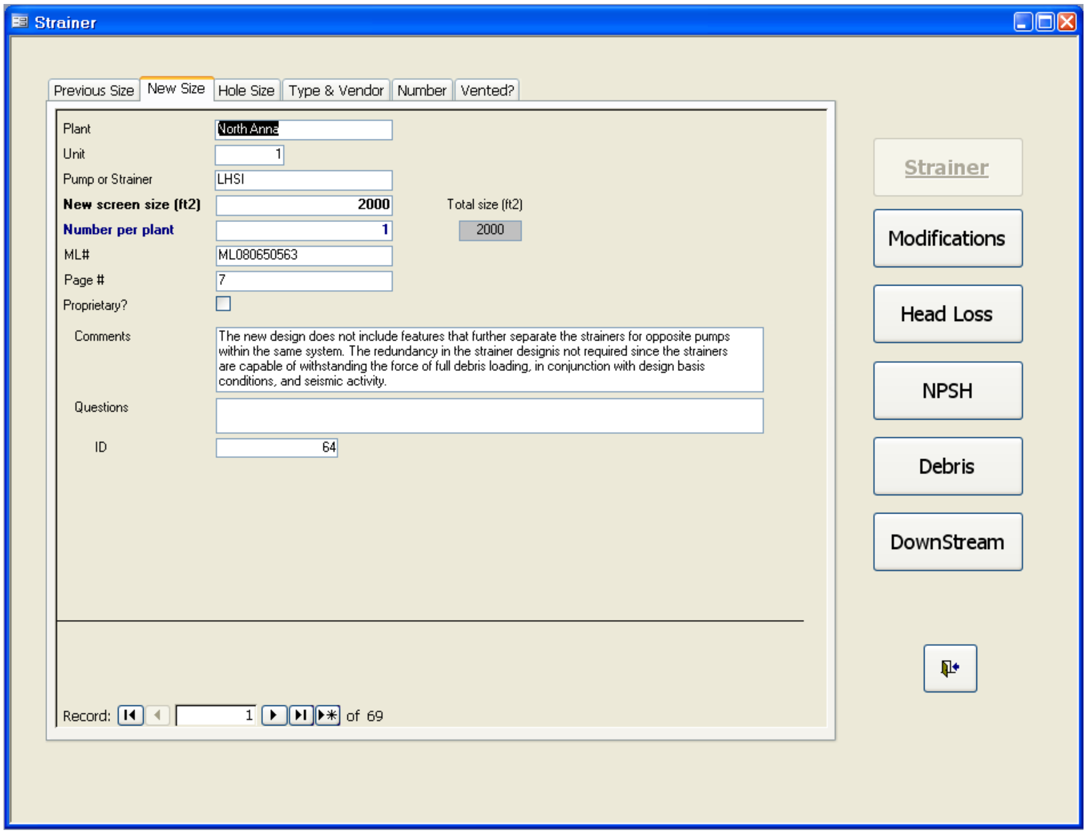

Figure A.2-2. Data View/Modification Form

In the View Results part of the database interface, two forms are opened (left and top forms in Figure A.2-3). The first form, Criteria Selection, allows selecting various parameters and their combination for filtering the database records. For example, only records for the plant, which belong to NRC Region 4, with NSSS supplied by CE and applicable to units 1 and 2 can be chosen to display in the Results form. This form is interactive in a way that each selection defines the choices available from other areas. For example, if any selection is made for the NRC region, the plant list (available after selecting “Specific” in the Plant area) will display only plants that satisfy the region selections. Similarly, if a specific NSSS supplier is selected, only containment types available with that selection will be displayed.

The total number of plants, which satisfy the selected criteria, is shown below for the containment type selection on this form. Clicking on the magnifying glass icon next to that number will open a window with the list of those plants. This form also allows selection of units (English or SI) for the result forms. The Apply button will reload any open result form to reflect any changes made to the selection criteria. The Reset button clears any previously made selection such that all database records will be displayed.

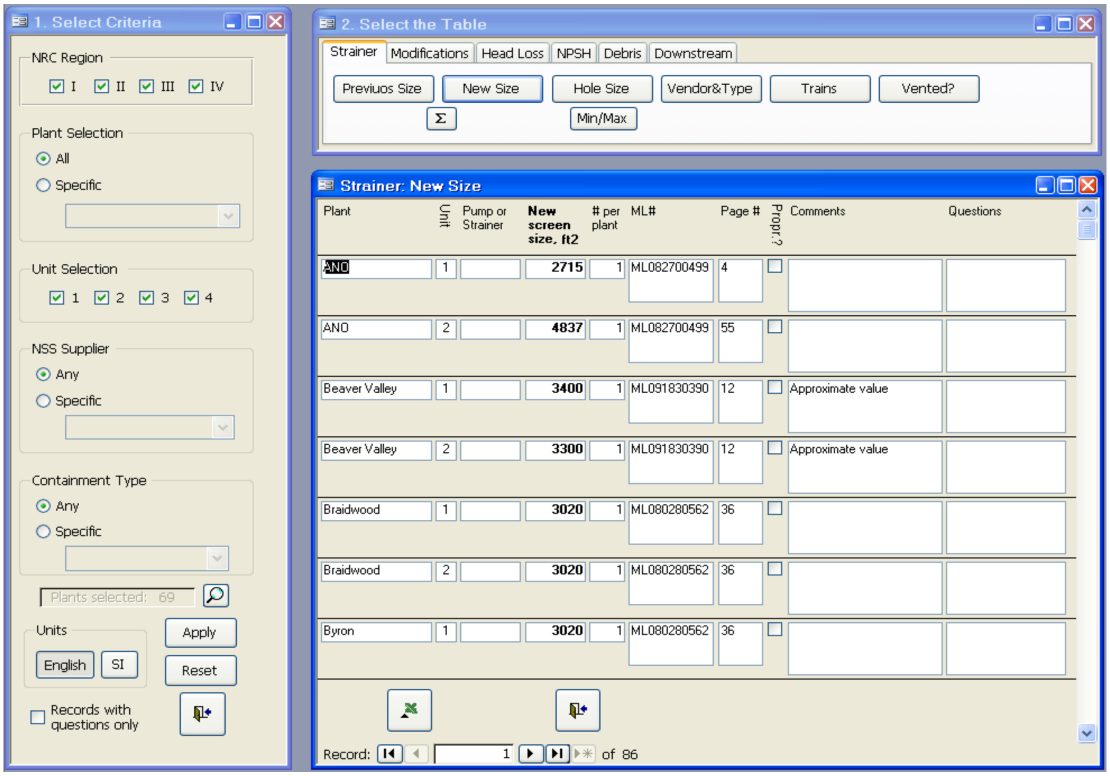

Figure A.2-3. Database Interface: Result View

The second (top) form in the Results view allows choosing the particular part (or table) of the database. The database area can be selected by clicking on the corresponding tab at the top of this form. In each tab, the buttons showing the available database fields (such as New Size) are displayed. In addition, in some cases, combined (modified) results can be viewed, such as minimum and maximum or total values of the specific field for each plant.

Clicking on any of the buttons in the Table selection form opens the Result form below it (an example of Strainer New Size is shown in Figure A.2-3). The Results form shows the database records in a table form. Only the records that satisfy the criteria from the Criteria Selection form are displayed. In addition to that, the Access built-in tool for searching, sorting, and filtering can be applied to any field in the Results form. The data from the form (with conservation of any applied filters) can be transferred to Microsoft Excel by clicking on the Excel button at the bottom of the form (the results presented in Section A.2.3 were obtained by using this capability).

The data in the Results form can only be viewed, searched, and filtered. They cannot be modified. Any modifications to the Results form (such as sorting) only affect the way the data are displayed in this form. Such modifications do not affect the data stored in the database. (The View/Modify Data section available from the main database form should be used for data modifications.)

A.2.2 Generic Letter 04-02 Database Status

At present, the interactions between NRC and the plants regarding the GL-04-02 are still in progress. Some of the plants are still submitting RAI responses to NRC. For these reasons, the GL-04-02 database, as it is presented in this report, cannot be viewed as "finished"; it is expected that new or updated information may be available for the database in the future.

The detailed description of the database field and the information entered into each field in the GL-04-02 database are presented in the next section.

A.2.3 Generic Letter 2004-02 Database Results

This section presents the compilation of the information stored in the GL-04-02 database. The information is presented for each field and covers all database records for that field. Where possible, the information is presented in a graphical form; otherwise, it is shown as a table. The results are preceded by a description of the specifics of the information collected for the database along with any assumptions made for a particular database field.

Even though the information for some fields may be available from other sources, for this database the information was collected exclusively (with the exception of the fuel type) from the licensees' responses to the GL-04-02. For example, the previous screen size refers to the strainer screen area installed before GL-04-02 was issued and might be recorded in earlier NRC documents. However, for consistency with other fields of the GL-04-02 database, only information reported by the plants in the GL-04-02 responses is entered into the database. A similar approach was adopted for all other fields.

Strainer: Previous Size

In this field, the strainer screen area installed prior to GL-04-02 issuance is recorded. The screen area is usually provided in square feet (ft2). For the plants that have more than one strainer, the screen area is recorded for one strainer and the number of strainers per plant is also recorded. If multiple strainers were installed in a plant, then a separate database record is created for each strainer indicated by "Pump or Strainer" field. The total strainer area for a plant unit (Figure A.2-4) is calculated by the database and the results are presented together with the new strainer area described below.

Strainer: New Size

This field contains the information on the strainer screen area installed in response to the GL-04-02. The same approach to the multiple strainers, as for the previous size, is adopted for this field. In case when physically one strainer is installed in a plant, but there is a solid plate divided (such as for different trains), the strainer is considered to consist of two independent strainers, each with 50% area (unless otherwise split is stated). If the divider plate has perforations in it, the strainers are not treated as independent. For these situations the strainer is considered to be one strainer with the full screen area alotted to the strainer.

Similarly to the previous size field, the total area per plant unit is calculated by the database. Figure A.2-4 compares the new and previous strainer screen area for all plants. In some cases, the previous screen size was not stated in the GL-04-02 responses and it is not included in Fig. A.2-4. The light bars show the previous screen size; the dark bars shown the new size. The light bars are shown atop of the dark bars to save the space; the dark bars should be considered starting from zero (not from where the light bars end). For example, for the Wolf Creek-1 plant (fourth line from the top in Fig. A.2-4), the previous screen size is 800 ft2 as indicated by the light bar. The new size is 6,600 ft2 and is shown by the location of the end of the dark bar. The same approach with overlapping bars is used for all the figures presented further in this section, unless otherwise stated.

Overall, Fig. A.2-4 demonstrates a significant increase in strainer screen area in response to GL-04-02. It also shows the significant difference in newly installed screen sizes among the plants (and sometimes among the units of the same plant).

Strainer: Hole Size

The hole (perforation) size for the newly installed strainers is shown in Fig. A.2-5. The database includes the hole size for all strainers reported in GL-04-02 responses. The database was built with a capability to display maximum and minimum hole size. However, for all the plants, maximum and minimum hole sizes, if reported, are always the same. Therefore, Fig. A.2-5 displays only one strainer hole size per plant unit.

Strainer: Strainer Type and Vendor

The strainer vendor was recorded for each plant in the GL-04-02 database. A separate table was created in the database to indicate the type of the strainer for each vendor (so far, a one-to-one relationship between the vendors and types exists). That table is automatically linked to the vendor field in the GL-04-02 database such that the strainer type is displayed for each plant in every database form where the vendor is displayed, although the strainer type is not stored specifically for each plant.

Table A.2-1 shows the strainer type and the plants where this strainer was installed for each strainer vendor. Three plants, listed at the bottom of Table A.2-1, did not report the strainer type or vendor in GL-04-02 responses.

Strainer: Vented

This field records if the strainer is vented or not. In most cases, the strainers are not vented. If it it not specifically stated in the response whether the strainer is vented or not, that field was left blank in the datatabse. Table A.2-2 lists the plant units for which the strainers were identified as vented in GL-04-02 responses.

Strainer: Number of Trains per Plant

The number of safety trains and the number of strainers per plant varies by plant design. Some plants have separate suction strainers for the safety injection and containment spray systems that are in the same train, others have a combined strainer. While even others have separate strainers in different parts of the containment building, such as one for vapor containment and one for internal recirculation. For the purposes of the GL-04-02 database, the definition of “train” is the same as in the licensee responses. It is possible, for example, that a plant can have a common strainer for all its safety trains. In most cases, there are two safety trains per plant. Only one plant, South Texas units 1 and 2, reported three safety trains.

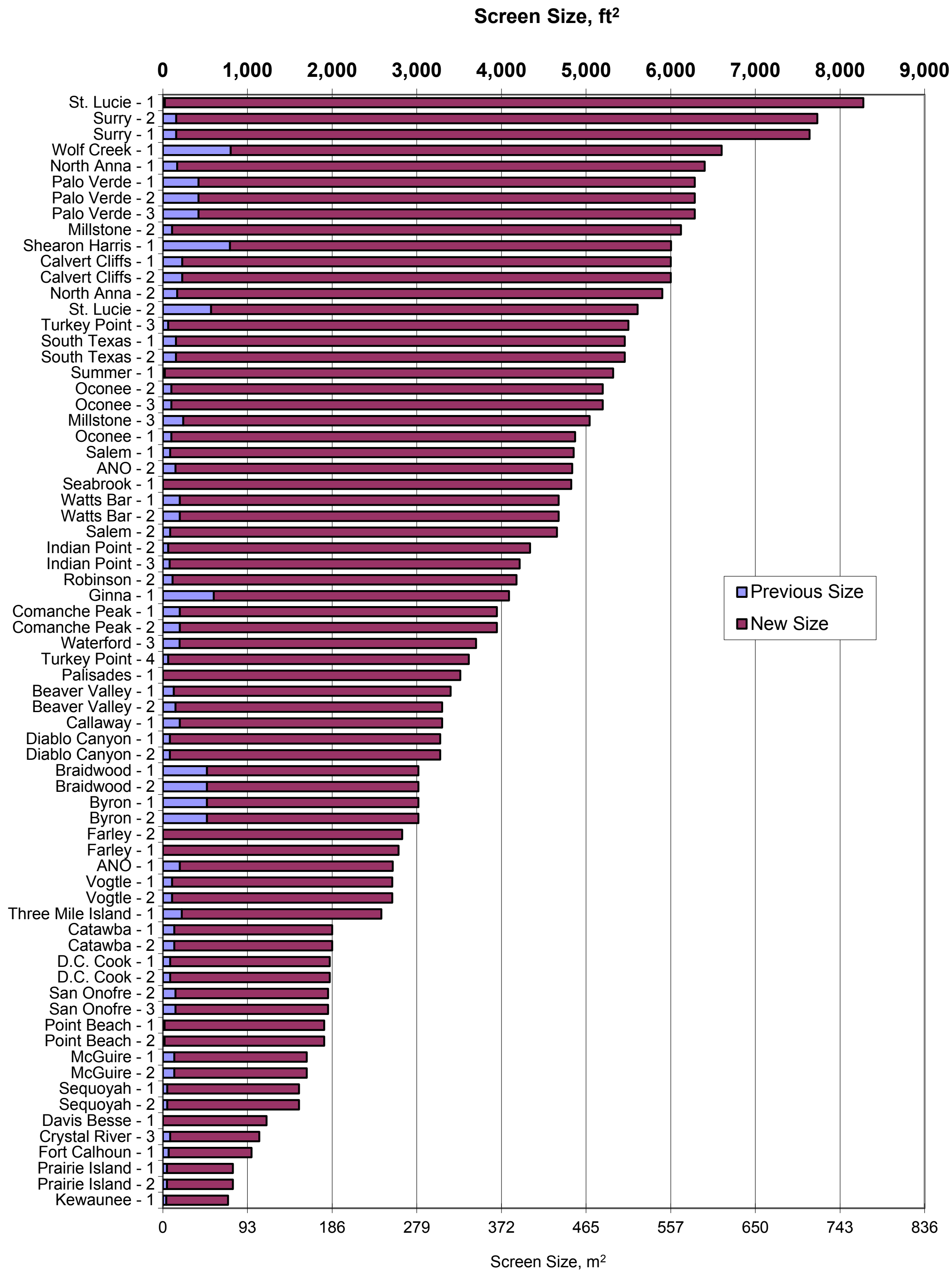

Figure A.2-4. Total Strainer Screen Area

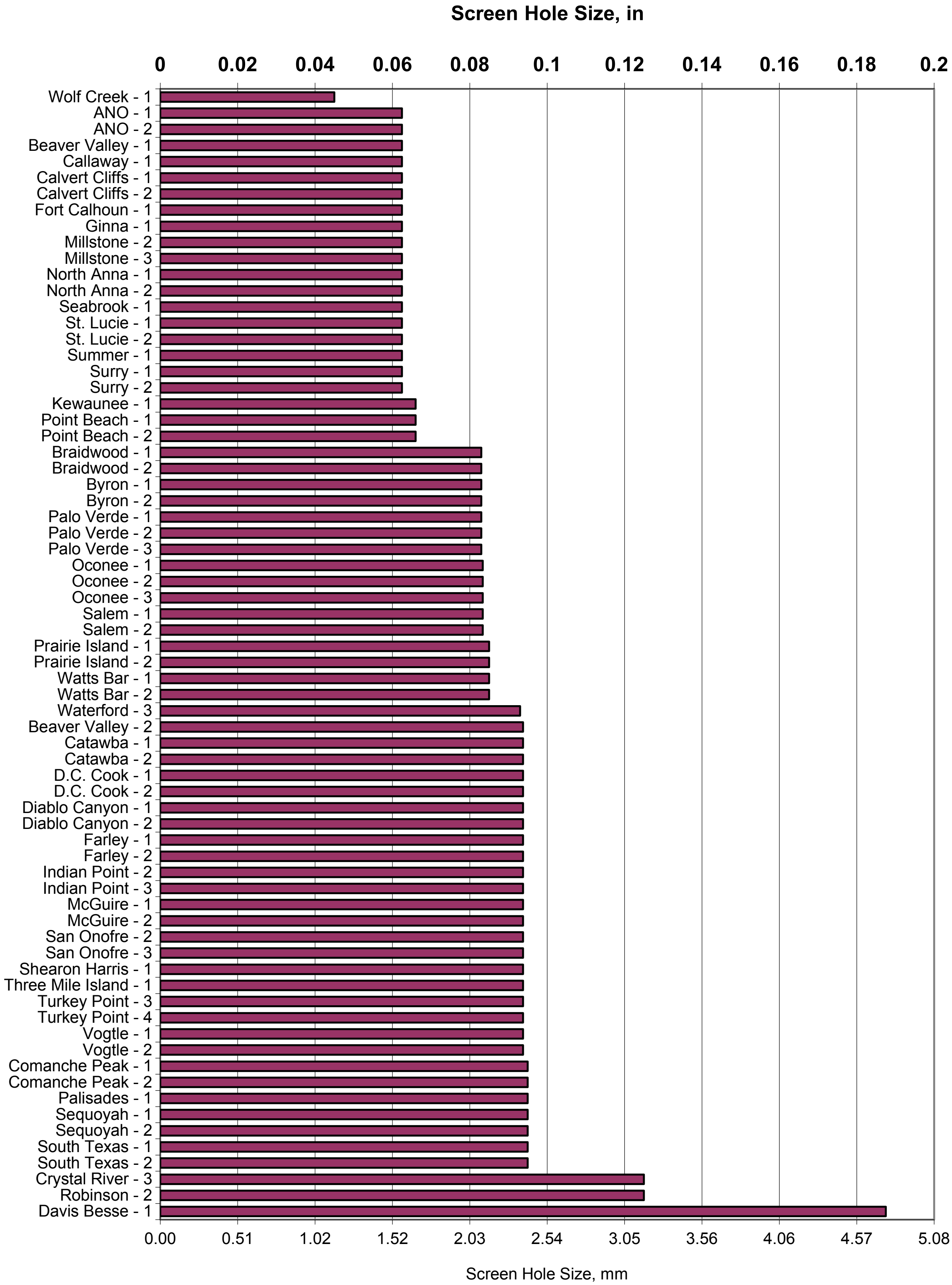

Figure A.2-5. New Strainer Hole Size

Table A.2-1. Strainer Vendors and Types.

Vendor	Type	Plant Name	Unit			
			1	2	3	4
AECL	Finned strainer with corrugated, perforated stainless steel fins	Millstone		■	■	
		North Anna	■	■		
		Summer	■			
		Surry	■	■		
CCI	Pocket Cassette design	ANO	■	■		
		Beaver Valley	■			
		Braidwood	■	■		
		Byron	■	■		
		Calvert Cliffs	■	■		
		D.C. Cook	■	■		
		Ginna	■			
		Oconee	■	■	■	
		Palo Verde	■	■	■	
		Salem	■	■		
Enercon	Top hat style	Beaver Valley		■		
		Catawba	■	■		
		Crystal River			■	
		Davis Besse	■			
		Indian Point		■	■	
		McGuire	■	■		
		Robinson		■		
		San Onofre		■	■	
		Shearon Harris	■			
		Three Mile Island	■			
GE	Stacked disk	Diablo Canyon	■	■		
		Farley	■	■		
		Fort Calhoun	■			
		Seabrook	■			
		St. Lucie	■			
		Turkey Point			■	
		Vogtle	■	■		
		Waterford			■	
PCI	Stacked disk	Callaway	■			
		Comanche Peak	■	■		
		Kewaunee	■			
		Palisades	■			
		Point Beach	■	■		
		Prairie Island	■	■		
		Sequoyah	■	■		
		South Texas	■	■		
		St. Lucie		■		
		Turkey Point				■
		Watts Bar	■	■		
		Wolf Creek	■			

Table A.2-2. Vented Strainers

Plant Name	Unit
ANO	2
Comanche Peak	1
Comanche Peak	2
D.C. Cook	1
D.C. Cook	2
Palisades	1

Plant Modifications: Physical

This field collects the physical plant modifications listed in the GL-04-02 responses. Only actions implemented, as a direct response to the GL-04-02, are collected for the database, i.e., no prior actions are included.

For each action, a separate field is provided where it is stated if the action was credited in the evaluations for GL-04-02. If it was not clear from the response whether the action was credited or not, that field was left blank in the database.

The entries in this and the following two fields reflect the information provided by the plant in the GL-04-02 responses. Similar to Bulletin 03-01 database, no verification was carried out to ensure that the commitments listed here were actually fulfilled.

Table A.2-3 lists all physical plant modifications in the GL-04-02 database.

Plant Modifications: Administrative

In addition to the physical actions, administrative actions were also recorded in the GL-04-02 database. Those actions include procedure modifications, training, tagging, etc. Similarly to the physical modifications, the database records include a Yes/No field for credited actions. Table A.2-4 lists all administrative modifications collected in the database.

Plant Modifications: Downstream

The plant modifications for the components located downstream of the strainer are recorded separately in the GL-04-02 database (the physical plant modifications filed excluded downstream actions). The database records for the downstream modification also includes Yes/No field for such actions. If a plant response explicitly states that no downstream actions were needed, then "no" is recorded in that field, and no actions are listed. Table A.2-5 shows downstream plant modifications for those plants that provided the list of such actions. Plants with an indication that no downstream actions are needed are listed separately in Table A.2-6.

Table A.2-3. Physical Plant Modifications

Plant	Plant Modifications (Physical)	Credited?
ANO-1	Insulation replacements and modifications to reduce potential debris.	Yes
	Original concrete curb surrounding the sump was removed.	Yes

ANO-2	Insulation replacements and modifications to reduce potential debris.	Yes
	Modifications to refueling canal drain cover.	Yes
	Several pieces of equipment relocated to accommodate new strainer.	Yes
Beaver Valley-1	Bell-mouth flanges were added in the sump trench at the pump suction inlets for the outside RSS pumps and the low head safety injection pumps to reduce the suction head loss.	Yes
	Borated Temp-Mat TM insulation encapsulated in RMI on the reactor vessel closure head has been replaced with RMI to reduce debris loading on the sump strainer.	Yes
	Iodine filters, containing a significant amount of thin aluminum that would have been submerged, were removed from the containments.	Yes
	Mitigation of the additional fibrous insulation will be accomplished through removal, replacement, analysis or design modification prior to startup from the next refueling outage (1 R20, Fall 2010).	Yes
	New RMI was installed on the replacement steam generators and associated piping in the vicinity of the SGs, resulting in a reduced quantity of insulation that could contribute to debris loading on the sump strainer.	Yes
	Quench spray loop seals were modified.	Yes
	Reactor cavity drain cross bars that have the potential to collect debris and block water flow to the containment sump were removed.	Yes
	Recirculation spray pump test dike was modified.	Yes
	Replacement of high-pressure safety injection cold leg throttle valves to increase the throttle valve gap and thereby reduce flow restrictions.	Yes
	Support columns for the existing sump screens' frame were deleted or relocated.	Yes
	Temperature sensors, used to provide containment water temperature post LOCA, were relocated.	Yes
	Temp-Mat fibrous insulation or calcium-silicate on select piping was replaced with RMI.	Yes
	Temp-Mat insulation encapsulated in metal jacketing on the reactor coolant loop piping was replaced with RMI.	Yes
	The start signal for the RSS pumps has been changed from a fixed time delay to an Engineered Safety Features Actuation System signal based on a refueling water storage tank level low coincident with a containment pressure high-high signal to allow sufficient pool depth to cover the sump strainer before initiating recirculation flow.	Yes
	Plant modifications planned to be completed for BVPS-1 associated with Cal-Sil insulation removal that ensures that the requirements of FENOC's revised methodology of assuming 100 percent destruction of Cal-Sil to fines is met prior to startup from the next refueling outage (1 R20,	Yes

Beaver Valley-2	Bell-mouth flanges were added in the sump trench at the pump suction inlets for the outside RSS pumps to reduce the suction head loss. Grating is attached to these flanges for vortex suppression.	Yes
	Borated Temp-Mat insulation encapsulated in RMI on the Reactor Vessel Closure Head flange has been replaced with RMI, and Min-K insulation encapsulated in RMI on portions of the Reactor Coolant System piping has been replaced with Thermal Wrap insulation encapsulated RMI.	Yes
	Conduits to containment sump level instruments were modified.	Yes
	Conduits to containment sump level switches were modified.	Yes
	Containment sump level transmitters and containment sump level switches were relocated locally within the sump.	Yes
	Insulation modifications were to be implemented prior to startup following the fall 2009 refueling outage (2R14).	Yes
	Iodine filters, containing a significant amount of thin aluminum that would have been submerged, were removed from the containments.	Yes
	Modification of high-pressure safety injection cold leg throttle valves to increase the throttle valve gap and thereby reduce flow restrictions.	Yes
	Modifications to the RSS test return lines and supports were implemented	Yes
	Modifications were performed to shorten a QS line and to relocate a QS support.	Yes
	Reactor cavity drain cross bars that have the potential to collect debris and block water flow to the containment sump were removed.	Yes
	The sodium hydroxide buffer was scheduled for replacement in the fall 2009 refueling outage with sodium tetraborate.	Yes
	The start signal for the RSS pumps has been changed from a fixed time delay to an Engineered Safety Features Actuation System signal based on a refueling water storage tank level low coincident with a containment pressure high-high signal to allow sufficient pool depth to cover the sump strainer before initiating recirculation flow.	Yes
	FENOC plans to repair and/or replace the insulation on the 3-inch and 6-inch PORV supply piping with appropriately applied stainless steel jacketing and sure-hold bands. Plant modifications, repairing and/or replacing NUKONO insulation will be completed on the 3-inch and 6-inch BVPS-2 PORV supply piping with appropriately applied stainless steel jacketing and sure-hold bands, prior to startup from the next refueling outage (2R15, Spring 2011).	Yes
Braidwood-1	A short (nominal 2 in.) curb was installed around the perimeter of the modified trash rack.	Yes
	Stainless steel grating ("trash rack") 4 ft high with 1-7/8 in. x 7/8 in. openings installed to enclose openings for both sumps, along with debris retainers approx. 14 in. long by 5 in. high.	Yes

Braidwood-2	A short (nominal 2 in.) curb was installed around the perimeter of the modified trash rack to ensure online leakage in containment will reach the leakage detection sumps rather than enter the ECCS sumps.	Yes
	Single level switch assembly inside each sump removed and associated cables removed and/or abandoned in place.	Yes
	Stainless steel grating ("trash rack") 4 ft high with 1-7/8 in. x 7/8 in. openings installed to enclose openings for both sumps, along with debris retainers approximately 14 in. long by 5 in. high.	Yes
Byron-1	A short (nominal 2 in.) curb was installed around the perimeter of the modified trash rack to ensure online leakage in containment will reach the leakage detection sumps rather than enter the ECCS sumps.	Yes
	Single level switch assembly inside each sump removed and associated cables removed and/or abandoned in place.	Yes
	Stainless steel grating ("trash rack") 4 ft high with 1-7/8 in. x 7/8 in. openings installed to enclose openings for both sumps, along with debris retainers approximately 14 in. long by 5 in. high.	Yes
Byron-2	A short (nominal 2 in.) curb was installed around the perimeter of the modified trash rack to ensure online leakage in containment will reach the leakage detection sumps rather than enter the ECCS sumps.	Yes
	Single level switch assembly inside each sump removed and associated cables removed and/or abandoned in place.	Yes
	Stainless steel grating ("trash rack") 4 ft high with 1-7/8 in. x 7/8 in. openings installed to enclose openings for both sumps, along with debris retainers approximately 14 in. long by 5 in. high.	Yes
Callaway-1	Debris barriers installed in all openings through secondary shield wall near emergency recirculation sumps.	Yes
	Recirculation sump level indication relocated and modified.	Yes
	Trisodium phosphate dodecahydrate baskets relocated in containment.	Yes
Calvert Cliffs-1	Calvert Cliffs installed debris interceptors in Unit 1 during the spring 2008 refueling outage to shield a portion of the strainer surface area from debris. No credit is taken in evaluations for these debris interceptors. The debris interceptor in Unit 1 is planned for removal in the 2010 refueling outage.	No
	The aluminum scaffolding was removed from Unit 1 in 2008 and Unit 2 in 2009.	Yes
	Two pipes in Unit 1 will have insulation removed during the 2010 RFO. The pipes are the shutdown cooling line insulated with mineral wool insulation and the pressurizer relief valve line outside of the pressurizer compartment insulated with generic fiberglass insulation.	Yes
	By July 2014, replace appropriate mineral wool insulation with reflective metal insulation or banded Nukon/Thermal Wrap insulation.	Yes

	By July 2014, remove telescoping aluminum ladder from the Polar Crane in Containment.	Yes
	By July 2014, enlarge the reactor refueling cavity drains to reduce post-loss-of-coolant accident water holdup and increase strainer submergence.	Yes
	By July 2014, ensure Operations has a means of assessing containment sump pool temperature.	Yes
	By July 2016, replace selected reactor coolant piping and reactor coolant pump insulation with reflective metal insulation.	Yes
	By July 2014, replace appropriate generic fiberglass insulation with reflective metal insulation, banded Nukon/Thermal Wrap insulation, Foamglas insulation or coatings.	Yes
	By July 2016, add Sure-Hold Bands to appropriate piping sections containing existing Nukon insulation, or replace existing Nukon insulation on appropriate piping sections with reflective metal insulation.	Yes
Calvert Cliffs-2	The aluminum scaffolding was removed from Unit 1 in 2008 and from Unit 2 in 2009.	Yes
	By July 2014, replace appropriate mineral wool insulation with reflective metal insulation or banded Nukon/Thermal Wrap insulation.	Yes
	By July 2014, remove telescoping aluminum ladder from the Polar Crane in Containment.	Yes
	By July 2014, enlarge the reactor refueling cavity drains to reduce post-loss-of-coolant accident water holdup and increase strainer submergence.	Yes
	By July 2014, ensure Operations has a means of assessing containment sump pool temperature.	Yes
	By July 2016, replace selected reactor coolant piping and reactor coolant pump insulation with reflective metal insulation.	Yes
	By July 2014, replace appropriate generic fiberglass insulation with reflective metal insulation, banded Nukon/Thermal Wrap insulation, Foamglas insulation or coatings.	Yes
	By July 2016, add Sure-Hold Bands to appropriate piping sections containing existing Nukon insulation, or replace existing Nukon insulation on appropriate piping sections with reflective metal insulation.	Yes
Catawba-1	Replacement of the existing orifice plates with smaller diameter orifice plates to allow the ECCS throttle valves to be opened greater than currently allowed for flow balancing.	
	Replacement of the fiberglass blankets (NUKON) insulation on the bottom bowls of the Unit 1 steam generators with reflective metal insulation RMI.	Yes
	Replacement of the Microtherm® insulation, previously installed on portions of the reactor vessel heads, with RMI.	Yes
	Catawba has replaced a significant amount of low-density fiberglass (LDFG) insulation in specific areas of lower containment with reflective metal insulation (RMI) via Fiber Insulation Replacement Projects (FIRP).	

Catawba-2	Replacement of the existing orifice plates with smaller diameter orifice plates to allow the ECCS throttle valves to be opened greater than currently allowed for flow balancing.	
	Replacement of the Microtherm® insulation, previously installed on portions of the reactor vessel heads, with RMI.	Yes
	Catawba has replaced a significant amount of low-density fiberglass (LDFG) insulation in specific areas of lower containment with reflective metal insulation (RMI) via Fiber Insulation Replacement Projects (FIRP).	
Comanche Peak-1	Drains holes added to the reactor vessel head stand shield wall.	Yes
	Installation of debris interceptors.	Yes
	Installation of debris screens and strainers for drains in the refueling cavity.	Yes
	Installation of water control features to optimize sump performance.	Yes
	Modifications to minimize water holdup on floors and miscellaneous items.	Yes
	Revised RWST switchover setpoints and motor operated valve modification.	Yes
Comanche Peak-2	Drains holes added to the reactor vessel head stand shield wall.	Yes
	Installation of debris interceptors.	Yes
	Installation of debris screens and strainers for drains in the refueling cavity.	Yes
	Installation of water control features to optimize sump performance.	Yes
	Modifications to minimize water holdup on floors and miscellaneous items.	Yes
	Revised RWST switchover setpoints and motor operated valve modification.	Yes
Crystal River-3	A 15-in. high stainless steel debris interceptor was installed.	
	A flow distributor was added to minimize localized flow streaming and to reduce bulk recirculation flow turbulence.	
	CR3 intended to replace all of the encapsulated mineral wool insulation in the LOCA zone of influence within the D-rings (HELB zones) with RMI.	
	CR3 reduced the amount of NUKON fiber in the RB by 40 ft3 by replacing the Pressurizer Head insulation with Reflective Metal Insulation (RMI). The amount of mineral wool fiber was also reduced, by removing the majority of insulation on the steam generator blowdown lines.	Yes
	Over 800 lb of aluminum was removed from containment by replacing storage box covers with stainless steel.	
	Perforated plate (3/16 in. holes) screens were installed in the RB floor drains to limit the transport of debris from remote areas of containment to the sump area.	
	RB sump level instrumentation was enhanced, by installing a dP cell.	

	Refueling cavity drain trash rack was installed.	
	Stainless steel plate bored with 3/16 in. perforations was added to the four scuppers.	
	The containment sump trash rack was increased in size from approximately 55 ft2 of horizontal surface area to approximately 100 ft2 of horizontal and 15 ft2 (25 lineal feet) of vertical surface areas.	
	The new steam generators will be provided without the high heat aluminum paint that exists on the current steam generators, that is Unqualified High Heat Aluminum Paint (from 1485 ft2 to 479 ft2 of 10 µm particulate loading).	Yes
	The original ¼ in. square mesh sump screen (86 ft2 of flat plane screened area) was replaced with a complex geometry sump strainer that has an effective surface area of 1139 ft2.	Yes
	The remaining 10 ft3 of NUKON insulation will also be replaced with RMI (although head loss analyses and testing assume that the 10 ft3 of NUKON will remain).	
D.C. Cook-1	Blank plate installed in crossover pipe connecting recirculation sump with adjacent lower containment sump.	Yes
	CalSil insulation removed from pressurizer relief tank (PRT) and pressurizer safety and relief valve discharge line.	Yes
	Debris interceptors installed on loop compartment side of flood-up overflow wall.	Yes
	Debris interceptors installed over the drains from hydrogen skimmer/containment pressure equalization (CEQ) fan rooms.	Yes
	Five existing 10-in.-dia openings in flood-up overflow wall modified to reduce head loss.	Yes
	Low-density fiberglass on a non-RCS systems relief valve discharge line to PRT removed.	Yes
	New level instruments installed inside recirculation sump enclosures.	Yes
	Radiation shields on annulus side of openings in flood-up overflow wall modified.	Yes
	Recirculation sump vent configuration modified.	Yes
D.C. Cook-2	Blank plate installed in crossover pipe connecting recirculation sump with adjacent lower containment sump.	Yes
	CalSil insulation on PRT drain line removed.	Yes
	CalSil insulation removed from PRT and pressurizer safety and relief valve discharge line.	Yes
	Debris interceptors installed on loop compartment side of flood-up overflow wall.	Yes
	Debris interceptors installed the drains from hydrogen skimmer/CEQ fan rooms.	Yes
	Five existing 10-in.-dia openings in flood-up overflow wall modified to reduce head loss.	Yes
	New level instruments installed inside recirculation sump enclosures.	Yes
	Opening installed on lower containment sump and internals from check valves in the West CEQ fan room drain lines were removed.	Yes

	Radiation shields on annulus side of openings in flood-up overflow wall modified.	Yes
	Recirculation sump vent configuration modified.	Yes
	Several hundred tags, labels, and other materials that presented a potentially significant debris source term were removed.	Yes
Davis Besse-1	Cleaned all floor drains and associated drain piping in containment to assure no volume holdup.	Yes
	Installed a jet deflector as part of the emergency sump modification	Yes
	Installed refuel canal drain line debris screen.	Yes
	Installed trash racks at points around containment.	No
	Modification /installation of cyclone separators for the HPI, Low Pressure Injection (LPI), and CS pumps.	Yes
	Opened a hole through the sump wall to permit lower strainer feed.	Yes
	Relocated the sump access ladder and the emergency sump water level equipment to remove interferences with strainer assembly	Yes
	Removed/replaced equipment tags, signs and labels with qualified materials.	Yes
	Replaced nearly all the fibrous insulation in containment with RMI and completely stripped and recoated containment dome.	Yes
Diablo Canyon-1	Addition of three 18-in.-high perforated plate debris interceptors.	
	Installation of multiple banding on CalSil piping insulation inside the pipe break ZOIs.	
	Installation of RMI and stainless steel jacketed Temp-Mat on the replacement SGs.	
	Installation of stainless steel jacketed Temp-Mat insulation on the inlet to pressurizer safety valves.	
	Installation of stainless steel jacketing on Temp-Mat piping insulation inside the pipe break ZOIs.	
	Installation of tray covers to protect the pressurizer heater cable insulation in cable trays below the pressurizer.	
	Modification of the reactor cavity door.	
	Removal of cable tray fire stops inside the crane wall.	
Diablo Canyon-2	Addition of three 18-in-high perforated plate debris interceptors.	
	Installation of multiple banding on CalSil piping insulation inside the pipe break ZOIs.	
	Installation of RMI and stainless steel jacketed Temp-Mat on the replacement SGs.	
	Installation of stainless steel jacketed Temp-Mat insulation on the inlet to pressurizer safety valves.	
	Installation of stainless steel jacketing on Temp-Mat piping insulation inside the pipe break ZOIs.	
	Modification of the reactor cavity door.	
	Removal of cable tray fire stops inside the crane wall.	

Farley-1	Debris interceptors are installed inside containment for both Unit 1 and 2.	No
	FNP installed the largest sized strainers practicable for the space available within containment for each unit.	Yes
	To prevent the potential for plugging and creating a hold-up volume, the refueling cavity drain covers are removed during modes requiring ECCS operability.	
Farley-2	Debris interceptors were installed inside containment for both Unit 1 and 2.	No
	FNP installed the largest sized strainers practicable for the space available within containment for each unit.	Yes
	To prevent the potential for plugging and creating a hold-up volume, the refueling cavity drain covers are removed during modes requiring ECCS operability.	
Fort Calhoun-1	A no-spray configuration, which significantly reduces debris transport and lowers flow rates through the sump strainer screens, was to be implemented during the 2008 RFO.	
	During the 2006 RFO, a significant amount of fibrous insulation was replaced with RMI during the SG, pressurizer, and RPV head replacement projects.	
	Trisodium phosphate, the previous containment sump buffer, was replaced with sodium tetraborate to reduce formation of chemical precipitates.	
Ginna-1	The existing Johnson screen, which runs the entire width of the "B" sump, will be removed to allow for structural modifications to the sump in support of adding modules to the sump cover. If left in place, the Johnson screen would operate in series with the new strainer modules; however, it is a much coarser mesh than the 1/16 in. perforated holes in the strainer modules and would therefore offer no additional removal of debris from the water passing through the strainer.	No
	The Ginna containment sump strainer system was to be installed during Ginna's April 2008 RFO.	Yes
	The reactor cavity drain line isolation valve to the reactor coolant drain tank (RCDT) may require manipulation when the sump is required to be operable. Therefore, a reach rod was to be used to penetrate the sump cover, allowing valve operation without entering the sump.	No
	The RCDT vent line, with its manual isolation valve, was to be routed up through the sump cover to allow operators to vent the tank without entering the sump.	No
Indian Point-2	Installation of a trash rack over the refueling canal drain.	Yes
	Installation of flow channeling barriers.	Yes
	Installation of passive strainer assemblies in the internal recirculation and vapor containment sumps.	Yes
	Replacement of the TSP PH buffers with sodium tetraborate.	Yes
Indian Point-3	Installation of a trash rack over the refueling canal drain.	Yes
	Installation of flow channeling barriers.	Yes
	Installation of passive strainer assemblies in the internal recirculation and vapor containment sumps.	Yes

	Removal of Kaowool from inside the crane wall.	Yes
	Replacement of the sodium hydroxide PH buffers with sodium tetraborate.	Yes
Kewaunee-1	Four beams in upper pressurizer vault covered with stainless steel jacketing.	Yes
	Jacketed calcium silicate insulation in submergence zone repaired.	Yes
	Jacketed fiberglass pipe insulation replaced.	Yes
	Nonessential equipment labels removed from containment.	Yes
	Wooden reactor vessel O-ring storage container removed from containment.	Yes
	The containment refueling cavity drain standpipe will be modified to remove the 1 in. x 1 in. grid/grating recessed into the top of the standpipe to eliminate the potential for debris to be captured on the drain opening.	Yes
	The JM Thermobestos insulation (calcium silicate insulation with asbestos fibers) in the "A" steam generator vault will be secured with stainless steel banding, similar to that performed in the "B" steam generator vault (opposite train) to enable use of a ZOI size equal to 5.45D.	Yes
	Fibrous insulation on the Service Water piping that passes through the top of the "B" reactor coolant pump vault will be removed.	Yes
	Fibrous insulation (Temp-Mat) on the pressurizer surge line pipe whip restraints will be removed and replaced with a non-fibrous material.	Yes
McGuire-1	Replacement of the Microtherm® insulation, previously installed on portions of the reactor vessel heads, with RMI.	Yes
	McGuire is replacing a significant amount of low-density fiberglass (LDFG) insulation in specific areas of lower containment with reflective metal insulation (RMI) via Fiber Insulation Replacement Projects (FIRP).	
McGuire-2	Replacement of the Microtherm® insulation, previously installed on portions of the reactor vessel heads, with RMI.	Yes
	McGuire is replacing a significant amount of low-density fiberglass (LDFG) insulation in specific areas of lower containment with reflective metal insulation (RMI) via Fiber Insulation Replacement Projects (FIRP).	
Millstone-2	Calcium silicate insulation was removed from piping and equipment in containment such that no calcium silicate insulation could be part of the ECCS strainer debris bed for any break that would require recirculation. All remaining calcium silicate insulation in containment is jacketed with stainless steel and is not susceptible to being dislodged by any break that would require ECCS recirculation.	Yes
North Anna-1	A drain was installed in the primary shield wall to the incore sump room (ISR) in Units 1 and 2 to reduce the water holdup volume and to increase the total volume of water available for recirculation.	Yes

	CalSil insulation located within the SG cubicles and pressurizer room has been replaced with Paroc and TempMat insulation in Units 1 and 2.	Yes
	Engineered safety features (ESF) circuitry was added to start the RS pumps on a CDA signal coincident with a RWST level-low signal.	Yes
	The containment sump level transmitters were modified to protect them from clogging due to debris. - Level transmitters located within the sump have been modified by drilling holes through stilling wells at various places to prevent the element from clogging, and - Level transmitters located above the containment floor have been provided with debris shields to protect them from containment spray generated debris.	Yes
	The RWST level instrumentation was modified to change the safety injection Recirculation Mode Transfer (RMT) setpoint from 19.4% to 16.0% RWST wide range level. This allows more energy to be removed from the containment and lowers the sump temperature prior to the LHSI pump suction switching from the RWST to the containment sump. This change also provides a higher water level in the containment sump prior to the LHSI pump suction switching to the containment sump. The combination of lower sump temperature and higher water level provides more NPSH to the LHSI pumps, and provides the required volume of water to maintain the strainers submerged.	Yes
	Two new containment sump strainers (with corrugated, perforated stainless steel fins) were installed with a total surface area of approximately 4400 ft2 for the RS pumps in both units, approximately 2000 ft2 for the Unit 1 LHSI pumps and approximately 1900 ft2 for the Unit 2 LHSI pumps. These strainers replaced the previous containment sump screens, which had a surface area of approximately 168 ft2.	Yes
North Anna-2	A drain was installed in the primary shield wall to the ISR in Units 1 and 2 to reduce the water holdup volume and to increase the total volume of water available for recirculation.	Yes
	CalSil insulation located within the SG cubicles and pressurizer room has been replaced with Paroc and TempMat insulation in both Units 1 and 2.	Yes
	Engineered Safety Features (ESF) circuitry was added to start the RS pumps on a Containment Depressurization Actuation (CDA) signal coincident with a Refueling Water Storage Tank (RWST) Level-Low signal. The Outside RS (ORS) pumps start immediately once the coincidence logic is satisfied. The Inside RS (IRS) pumps start following a time delay of 120 sec once the coincidence logic is satisfied. These changes ensure sufficient water is available to meet the RS strainer submergence and RS pump net positive suction head (NPSH) requirements.	Yes

	Microtherm insulation has been removed from Unit 2 containment. (No Microtherm insulation was installed in the Unit 1 containment.)	Yes
	The containment sump level transmitters were modified to protect them from clogging due to debris. - Level transmitters located within the sump have been modified by drilling holes through stilling wells at various places to prevent the element from clogging, and - Level transmitters located above the containment floor have been provided with debris shields to protect them from containment spray generated debris.	Yes
	The RWST level instrumentation was modified to change the safety injection Recirculation Mode Transfer (RMT) setpoint from 19.4% to 16.0% RWST wide range level. This allows more energy to be removed from the containment and lowers the sump temperature prior to the LHSI pump suction switching from the RWST to the containment sump. This change also provides a higher water level in the containment sump prior to the LHSI pump suction switching to the containment sump. The combination of lower sump temperature and higher water level provides more NPSH to the LHSI pumps, and provides the required volume of water to maintain the strainers submerged.	Yes
	Two new containment sump strainers (with corrugated, perforated stainless steel fins) were installed with a total surface area of approximately 4400 ft2 for the RS pumps in both units, approximately 2000 ft2 for the Unit 1 LHSI pumps and approximately 1900 ft2 for the Unit 2 LHSI pumps. These strainers replaced the previous containment sump screens, which had a surface area of approximately 168 ft2.	Yes
Oconee-1	Removal of fibrous insulation from areas in containment where it would be potentially affected by a pipe break jet (ZOI).	Yes
	Replacement of reactor building emergency sump (RBES) screens and trash racks with larger strainers.	Yes
	Replacement of seal flush orifices and cyclone separators on the LPI pumps, HPI pumps, and building spray (BS) pumps.	Yes
Oconee-2	Removal of fibrous insulation from areas in containment where it would be potentially affected by a pipe break jet (ZOI).	Yes
	Replacement of RBES screens and trash racks with larger strainers.	Yes
	Replacement of seal flush orifices and cyclone separators on the LPI pumps, HPI pumps, and building spray (BS) pumps.	Yes
Oconee-3	Removal of fibrous insulation from areas in containment where it would be potentially affected by a pipe break jet (ZOI).	Yes
	Replacement of RBES screens and trash racks with larger strainers.	Yes
	Replacement of seal flush orifices and cyclone separators on the LPI pumps, HPI pumps, and BS pumps.	Yes
Palisades-1	Containment sump buffer changed from trisodium phosphate to sodium tetraborate.	Yes

	Modifications of containment base slab configuration to eliminate choke points.	Yes
Palo Verde-1	Fiberfrax was removed from the containment. The piping penetrations in the containment bioshield walls were originally sealed with Fiberfrax.	
	NUKON insulation has been removed around letdown delay coils.	
	The existing sump temperature element was relocated to facilitate the installation of the replacement sump strainers.	
	The Microtherm (Units 1 and 2) and Min-K (Unit 3) insulation was scheduled to be removed from the reactor head in the fall 2009 RFO for Unit 2, in the spring 2010 RFO for Unit 1, and in the fall 2010 RFO for Unit 3.	
Palo Verde-2	Fiberfrax was removed from the containment. The piping penetrations in the containment bioshield walls were originally sealed with Fiberfrax.	
	NUKON insulation has been removed around letdown delay coils.	
	The existing sump temperature element was relocated to facilitate the installation of the replacement sump strainers.	
	The Microtherm (Units 1 and 2) and Min-K (Unit 3) insulation were scheduled for removal from the reactor head in the fall 2009 RFO for Unit 2, in the spring 2010 RFO for Unit 1, and in the fall 2010 RFO for Unit 3 refueling outage.	
Palo Verde-3	Fiberfrax was removed from the containment. The piping penetrations in the containment bioshield walls were originally sealed with Fiberfrax.	
	NUKON insulation has been removed around letdown delay coils.	
	The existing sump temperature element was relocated to facilitate the installation of the replacement sump strainers.	
	The Microtherm (Units 1 and 2) and Min-K (Unit 3) insulation was scheduled to be removed from the reactor head in the fall 2009 RFO for Unit 2, in the spring 2010 RFO for Unit 1, and in the fall 2010 RFO for Unit 3 refueling outage.	
Point Beach-1	Reactor cavity drain to be extended away from the strainers, or an impingement device to be installed between the strainers and the drain to prevent air ingestion.	Yes
	Structural modifications to reinforce limiting components to carry end thrust loads on strainer assemblies.	Yes
Point Beach-2	Reactor cavity drain to be extended away from the strainers, or an impingement device to be installed between the strainers and the drain to prevent air ingestion.	Yes
	Structural modifications to reinforce limiting components to carry end thrust loads on strainer assemblies.	Yes
Prairie Island-1	Capping of abandoned waste liquid disposal pipes located in sump.	Yes
	Existing components such as cable tray supports were relocated and/or reconfigured to clear space for new strainers.	Yes
	Trash rack over sump removed.	Yes

Prairie Island-2	Capping of abandoned waste liquid disposal pipes located in sump.	Yes
	Existing components such as cable tray supports were relocated and/or reconfigured to clear space for new strainers.	Yes
	Trash rack over sump removed.	Yes
Robinson-2	Installation involved removal of the original sump screens at the sump, removal of the coarse screens at the reactor coolant pump bay drain openings, installation of a jet impingement shield near the letdown line, and relocation of some interfering equipment adjacent to the new strainer.	Yes
Salem-1	PSEG installed a debris interceptor in front of the new strainer modules.	Yes
	PSEG installed new level switches installed for both units.	
	PSEG replaced all the calcium silicate insulation within the ZOI replaced at Unit 1 and 2 with Transco RMI. Min-K insulation also was replaced with Transco RMI wherever possible.	
	PSEG replaced the original strainers.	Yes
Salem-2	PSEG installed a debris interceptor in front of the new strainer modules.	Yes
	PSEG installed new level switches installed for both units.	
	PSEG replaced all the calcium silicate insulation within the ZOI replaced at Unit 1 and 2 with Transco RMI. Min-K insulation also was replaced with Transco RMI wherever possible.	
	Original strainers replaced.	Yes
	Unit 2 steam generators were replaced. The new steam generators are insulated with Transco RMI.	Yes
San Onofre-2	Bioshield gate modifications.	
	Microtherm-to-RMI insulation change-out was performed.	
	New sump screen installation.	Yes
	The completed analysis and testing work take credit for the reduced quantity of mineral wool insulation on the replacement steam generators.	Yes
San Onofre-3	Bioshield gate modifications.	
	Microtherm-to-RMI insulation change-out was performed.	
	New sump screen installation.	Yes
	The completed analysis and testing work take credit for the reduced quantity of mineral wool insulation on the replacement steam generators.	Yes
Seabrook-1	Additional debris interceptors have been installed on the scuppers in the bioshield wall to further reduce the debris that can be transported to the sump strainers from a postulated LOCA.	
	Cable tray adhesive labels have been removed to reduce the miscellaneous debris that could be generated by labels that fail due to a postulated LOCA.	
Sequoyah-1	The original containment sump intake structures were replaced with advanced designed strainers during the Unit 1, outage in the fall of 2007.	Yes

Sequoyah-2	The original containment sump intake structures were replaced with advanced designed strainers during the Unit 2, Cycle 14 RFO in the fall of 2006.	Yes
Shearon Harris-1	Installation of a trash rack in the refueling canal drain. During RFO14 (fall of 2007), HNP installed a trash rack in the refueling canal drain. This trash rack is removable such that it can be removed prior to refueling operations and reinstalled following completion of refueling operations. This trash rack is fabricated of austenitic stainless steel.	Yes
	Reinforcement of insulation cassettes containing Min-K. HNP had previously told the NRC in the September 01, 2005, submittal that it planned to remove the insulation cassettes from containment and replace them with a different type of insulation. All of these cassettes are on safety-relief valve (SRV) loop seals and power-operated valve (PORV) water seals in the pressurizer cubicle. HNP did not remove the Min-K from containment; instead, HNP reinforced the cassettes with stainless steel banding such that a break in one of the SRV lines would not affect all of the Min-K insulation in the pressurizer cubicle.	Yes
	Removal of aluminum fire extinguishers from containment. In 2003, HNP discovered that the fire extinguishers in containment were made of aluminum. These fire extinguishers were subsequently removed from containment during power operations; this action was completed in RFO14	Yes
	HNP has opted to-replace the Min-K insulation on the Pressurizer power operated relief valve (PORV) and safety relief valve (SRV) loop seal piping with a low-density fibrous insulation material that is less problematic from a sump strainer head loss standpoint. The Min-K insulation, that will be replaced, represents all Min-K insulation that could be damaged by a LOCA.	Yes
St. Lucie-1	The calcium-silicate insulation (cal-sil) on selected piping in the containment has been reinforced with a banding system. The banding system consists of 1½-in. wide stainless steel bands spaced approximately 3 in. on center.	Yes
Summer-1	Debris interceptors removed.	Yes
	Gate placed across stairwell entrance adjacent to A train sump.	Yes
	Two vertical trash rack gates in reactor building annulus.	Yes
Surry-1	Air ejectors re-installed in LHSI pump cans.	Yes
	Containment sump level transmitters modified to protect them from clogging due to debris.	Yes
	Drain drilled in primary shield wall of ISR to reduce the water holdup volume.	Yes
	Engineered safeguards features circuitry added to start the RS pumps.	Yes
	Insulation inside containment was found to be damaged, degraded or covered with an unqualified coating system and was removed or jacketed.	Yes

Surry-2	Insulation inside containment was found to be damaged, degraded or covered with an unqualified coating system and was removed or jacketed.Air ejectors re-installed in LHSI pump cans.	Yes
	Air ejectors re-installed in LHSI pump cans.	Yes
	Containment sump level transmitters modified to protect them from clogging due to debris.	Yes
	Drain drilled in primary shield wall of ISR to reduce the water holdup volume.	Yes
	Engineered safeguards features circuitry added to start the RS pumps.	Yes
	Insulation inside containment was found to be damaged, degraded or covered with an unqualified coating system and was removed or jacketed.	Yes
Three Mile Island-1	A new trash rack was installed.	
	An access ladder was modified to make room for the trash rack.	
	Configuration changes were made to address upstream flow concerns: Replacement of the door to the entrance of the D-rings and Installation of fuel transfer canal drain strainer.	
	Normal drain lines were redirected to the new normal sumps.	
	Piping interferences with the new sump trash rack were modified.	
	Radiation monitor RM-G-21 was elevated above RB flood level to make room for the strainer and trash rack.	
	The “box” strainer assembly was replaced with an array of “top hat” strainer modules.	Yes
	23 empty TSP baskets were installed in the RB basement prior to or during T1R17. The TSP was added to the baskets and the NaOH tank was isolated after Technical Specification Amendment no. 263 was approved.	
	The RB sump level instruments were modified.	
	The sump was divided into a normal “wet” sump and an ECCS “dry” sump.	
Turkey Point-3	CalSil insulation and jacketing on pressurizer relief tank replaced with post-LOCA qualified coating..	Yes
	Cylindrical core bore beneath refueling cavity to provide pathway for piping that connects the strainer assemblies to the south ECCS sump suction inlet.	Yes
	Filled existing ECCS sump suction inlet pits with reinforced concrete.	Yes
	Four sections of pressurizer surge line containing Cal-Sil and one section containing NUKON replaced with RMI.	Yes
	Reactor coolant pump insulation replaced with RMI.	Yes
Turkey Point-4	Cylindrical core bore beneath refueling cavity to provide pathway for piping that connects the strainer assemblies to the south ECCS sump suction inlet.	Yes
	Debris interceptors installed at the exit points at the bioshield wall.	Yes

Vogtle-1	Removal of cage assembly vortex suppressors in sumps.	Yes
	Replacement of Min-K insulation with NUKON.	Yes
	Temperature elements for RHR sumps replaced and relocated.	Yes
Vogtle-2	Removal of cage assembly vortex suppressors in sumps.	Yes
	Replacement of Min-K insulation with NUKON.	Yes
	Temperature elements for RHR sumps replaced and relocated.	Yes
	Three electrical interferences for new Unit 2 CS Sump Train A Screen relocated/rerouted.	Yes
	Two conduit interferences at Unit 2 RHR Sump Train A screen rerouted.	Yes
Waterford-3	Nineteen TSP baskets were relocated to allow easier installation of the new plenum and strainers, or to eliminate interferences with the baskets.	Yes
	The housing for the low level switch inside the SI sump was relocated to mount on top of the new screen plenum.	Yes
	The original box-like SI sump screen that surrounded the sump itself was removed and replaced with GE modularized, stacked disk strainers.	Yes
	The sump partition that separates the two trains of the SI inlets was replaced with stainless steel grating.	
	The tubing for two level transmitters inside the SI sump was rerouted to penetrate through the plenum in a designed location in order to prevent debris from passing through the penetration opening.	Yes
	Waterford 3 will replace the fibrous insulation on the current steam generators with Reflective Metal Insulation.	Yes
Watts Bar-1	Minor rerouting of electrical conduit during installation of new strainers.	Yes
	Several large pieces of min-K fiber insulation replaced with RMI and others banded.	Yes
Wolf Creek-1	Debris barrier plates have been installed in openings through the secondary shield wall that are near the emergency recirculation sumps.	

Table A.2-4. Administrative Plant Modifications

Plant	Plant Modifications (Administrative)	Credited?
ANO-1	Licensee committed to the measurement of latent debris quantities every third refueling outage to confirm that latent debris quantities used in strainer testing and downstream effects analysis remain bounding. This frequency may be relaxes after the first measurements, provided the results indicated that an adequate level of cleanliness was maintained.	Yes
	The coatings program has been upgraded in response to the GL-04-02 by expanding the focus beyond the liner plate to include periodic walkdown inspections of all readily accessible coatings in containment to assess damage or degradation.	Yes
	In December 2007, a design modification was implemented to reduce the concentration of the sodium hydroxide (NaOH) chemical buffer.	Yes
ANO-2	Licensee committed to the measurement of latent debris quantities every third refueling outage to confirm that latent debris quantities used in strainer testing and downstream effects analysis remain bounding. This frequency may be relaxes after the first measurements, provided the results indicated that an adequate level of cleanliness was maintained.	Yes
	The coatings program has been upgraded in response to the GL-04-02 by expanding the focus beyond the liner plate to include periodic walkdown inspections of all readily accessible coatings in containment to assess damage or degradation.	Yes
	Chemical buffer change from trisodium phosphate to sodium tetraborate to support chemical effects analysis.	Yes
Beaver Valley-1	A containment coatings inspection and assessment program and a containment-cleaning program became effective for both units in April of 2008.	Yes
	LOCADM analyses were conducted for both units in accordance with WCAP-16793-NP, Revision 1.	Yes
	WCAP-16793-NP, Rev. 1, and WCAP-17057-P, Rev. 0, which describe the Westinghouse fuel nozzle tests, were reviewed. Both units were shown to be enveloped, by testing described within those reports.	Yes
	Emergency operating procedures for Unit 1 was to be revised to enhance the steps that shut down two RSS pumps prior to the transfer to recirculation. These procedure changes were to be implemented by December 31, 2009.	Yes
Beaver Valley-2	The sodium hydroxide buffer was scheduled to be replaced with sodium tetraborate in the fall 2009 RFO.	Yes
	A containment coatings inspection and assessment program and a containment-cleaning program became effective for both units in April 2008.	Yes
	LOCADM analyses were conducted for both units in accordance with WCAP-16793-NP, Revision 1.	Yes
	WCAP-16793-NP, Rev. 1, and WCAP-17057-P, Rev. 0, which describe the Westinghouse fuel nozzle tests, were reviewed. Both	Yes

Plant	Plant Modifications (Administrative)	Credited?
	units were shown to be enveloped by testing described within those reports.	
	Emergency operating procedures will be revised to shut down one of the RSS pumps supplying the spray header when the containment pressure is reduced below a predetermined value. The change will be implemented prior to startup from the fall 2009 refueling outage.	Yes
Callaway-1	Administrative controls have been added to the plant modification process to require a specific response to the following design issues (1) added or changed materials that could become post-accident debris, (2) addition or removal of aluminum or zinc from the containment building, (3) introduction of unqualified coatings or impact on qualified coatings, (4) significantly change amounts of exposed surface area of containment structures or equipment, (5) change post-accident recirculation water flow paths through containment, and (6) changing flood levels or creating new submergence levels.	Yes
	Changes were made to the containment entry procedure to enhance requirements during plant operational modes 1 through 4 for control of materials during work activities conducted in the containment.	Yes
	Changes to the scaffold construction and use procedure to enhance requirements for control of scaffold tags and materials used during work activities conducted in the containment during plant operational modes 1 through 4.	Yes
	Licensee has implemented a containment latent debris assessment program, which utilizes swipe sampling to determine the amount of latent debris in the containment building. Housekeeping and foreign materials exclusion procedures have been revised to target containment building cleaning based on the results of the swipe sampling survey.	Yes
	Applicant has implemented a containment coatings assessment program for monitoring and assessing the containment building coatings, including administrative controls on conducting coating examinations, including deficiency reporting criteria and documentation requirements.	Yes
	Licensee has implemented a containment latent debris assessment program, which utilizes swipe sampling to determine the amount of latent debris in the containment building. Housekeeping and foreign materials exclusion procedures have been revised to target containment building cleaning based on the results of the swipe sampling survey.	Yes
Calvert Cliffs-1	Valve equipment tags are now made of materials that would sink in water and not transport to the containment sump.	Yes
Calvert Cliffs-2	Valve equipment tags are now made of materials that would sink in water and not transport to the containment sump.	Yes
Catawba-1	The modification process and the plant labeling process have been enhanced relative to GL-04-02 controls.	
	Submitted license amendments to the NRC for ECCS Water	

Plant	Plant Modifications (Administrative)	Credited?
	Management modifications, which include revisions to post-accident response that reduce recirculation flowrates through the ECCS Sump Strainer and decrease the predicted volume of transported sump pool debris. The license amendment has been approved.	
Catawba-2	The modification process and the plant labeling process have been enhanced relative to GL-04-02 controls.	
	Submitted license amendments to the NRC for ECCS Water Management modifications, which include revisions to post-accident response that reduce recirculation flowrates through the ECCS Sump Strainer and decrease the predicted volume of transported sump pool debris. The license amendment has been approved.	
Comanche Peak-1	Compensatory actions and modifications to the locked high radiation doors in response to NRC Bulletin 03-01 have been implemented as permanent changes in procedures.	Yes
	A reassessment of containment building protective coatings was conducted in support of the response to GL-04-02.	Yes
	The plant-labeling program is being evaluated to determine suitable material and program changes.	Yes
	An upstream effects evaluation was completed, and the refueling cavity drains were identified as a potential plugging point.	Yes
	An event characterization to evaluate the licensing and design basis to establish the design basis events that require emergency sump recirculation was completed.	Yes
	Bounding debris generation, transport, and loading analyses are being performed for both units in support of analysis for the new design.	Yes
	The ECCS and CSS were to be evaluated for blockage and wear concerns.	Yes
Comanche Peak-2	Compensatory actions and modifications to the locked high radiation doors in response to NRC Bulletin 03-01 have been implemented as permanent changes in procedures.	Yes
	A reassessment of containment building protective coatings was conducted in support of the response to GL-04-02.	Yes
	The plant labeling program is being evaluated to determine suitable material and program changes.	Yes
	An upstream effects evaluation was completed, and the refueling cavity drains were identified as a potential plugging point.	Yes
	An event characterization to evaluate the licensing and design basis to establish the design basis events that require emergency sump recirculation was completed.	Yes
	Bounding debris generation, transport, and loading analyses are being performed for both units in support of analysis for the new design.	Yes
	The ECCS and CSS were to be evaluated for blockage and wear concerns.	Yes
Crystal River-3	Licensed Operator training has been conducted on indications available for recognition of containment sump screen blockage and	

Plant	Plant Modifications (Administrative)	Credited?
	appropriate response measures.	
	Multiple and diverse sources to refill the BWST and inventory to inject into the RCS have been established.	
	Aggressive containment cleaning and increased foreign material controls have been established.	
	Training has been provided to the Maintenance organization on the importance of RB cleanliness towards the minimization of latent debris that could affect sump recirculation, and thus post-accident core cooling capabilities including enforcement of the use of mats and/or tarps for work activities occurring over open floor grating to minimize the spread of foreign material to lower building elevations. In addition, a checklist item to discuss housekeeping requirements for work inside the RB has been added to Administrative Instruction, AI-607, "Pre-job and Post-job Briefings."	
	The integrity of the RB sump was verified on a refueling outage interval of 24 months with the performance of Surveillance Procedure SP-175A, "Reactor Building Emergency Sump Inspection and Cleaning."	
	Engineering Change screening criteria includes questions that require the engineer to determine if the change will create or alter the potential sources of debris which could interfere with ECCS suction from the RB sump, and if the change will result in the addition of materials in containment that could affect post-accident chemical precipitation.	
	To address the possibility of high sump screen differential pressure and sump screen blockage, diverse contingency actions including backflush of sump screens were written into EM-225E, "Guidelines for Long Term Cooling."	
D.C. Cook-1	Extensive testing and analysis were conducted to determine break locations, identify and quantify debris sources, quantify debris transport, determine upstream and downstream effects, and confirm the recirculation function.	Yes
	Alternate evaluation methodology used as described in Chapter 6 of the GR and SER.	Yes
	Changes to the licensing basis, including technical specifications, made to reflect the plant modifications, and the change to a mechanistic sump strainer blockage evaluation.	Yes
	Extensive changes to plant programs, processes, and procedures made to limit the introduction of materials into containment that could adversely impact the recirculation function.	Yes
	Monitoring programs established to ensure containment conditions will continue to support the recirculation function.	Yes
	Conservative measures applied to assure adequate margins throughout the actions taken to address the GL-2004-02 concerns.	Yes
D.C. Cook-2	Extensive testing and analysis were completed to determine break locations, identify and quantify debris sources, quantify debris transport, determine upstream and downstream effects, and confirm the recirculation function.	Yes
	Alternate evaluation methodology used as described in Chapter 6	Yes

Plant	Plant Modifications (Administrative)	Credited?
	of the GR and SER.	
	Changes to the licensing basis, including technical specifications, made to reflect the plant modifications, and the change to a mechanistic sump strainer blockage evaluation	Yes
	Extensive changes made to plant programs, processes, and procedures to limit the introduction of materials into containment that could adversely impact the recirculation function.	Yes
	Monitoring programs established to ensure containment conditions will continue to support the recirculation function.	Yes
	Conservative measures made to assure adequate margins throughout the actions taken to address the GL-2004-02 concerns.	Yes
Davis Besse-1	Controls on coatings, insulation, and signage have been established.	Yes
	Procedures have been instituted that require verification of strainer integrity and containment cleanliness prior to entering a mode of operation that requires ECCS operability.	Yes
Diablo Canyon-1	Material exclusion procedures exist to verify that no loose debris is left following any activity performed in containment once containment integrity has been established.	
	An aggressive containment-cleaning program has been developed and implemented.	
	PG&E has inspection procedures to assure the containment sump screens are free of adverse gaps and breaches.	
	Classroom and simulator training on indications of, and responses to, sump clogging have been included in operator initial and requalification training.	
	Training has been provided to engineering personnel to raise their awareness of the more aggressive containment cleanliness requirements, the potential for sump blockage, and actions being taken to address sump blockage concerns.	
	Training has been conducted for Emergency Response Organization decision makers and evaluators in the Technical Support Center on indications of sump blockage and compensatory actions.	
	To ensure that alternative water sources are available to refill the RWST, Emergency Operating Procedure (EOP) ECA-I.1, "Loss of Emergency Core Cooling," provides two methods to refill the RWST: (1) refill from the boric acid blender, and (2) refill from the spent fuel pool (SFP) via the SFP pumps.	
	The following EOP changes have been implemented: EOP E-1.3, "Transfer to Cold-leg Recirculation" and EOP E-1, "Loss of Reactor or Secondary Coolant."	
	New EOP ECA-1.3, "Sump Blockage Guideline," was developed to provide specific guidance to operators when sump blockage was diagnosed to have occurred.	
Diablo Canyon-2	Material exclusion procedures exist to verify that no loose debris is left following any activity performed in containment once containment integrity has been established.	
	An aggressive containment-cleaning program has been developed	

Plant	Plant Modifications (Administrative)	Credited?
	and implemented.	
	PG&E has inspection procedures to assure the containment sump screens are free of adverse gaps and breaches.	
	Classroom and simulator training on indications of, and responses to, sump clogging have been included in operator initial and requalification training.	
	Training has been provided to engineering personnel to raise their awareness of the more aggressive containment cleanliness requirements, the potential for sump blockage, and actions being taken to address sump blockage concerns.	
	Training has been conducted for Emergency Response Organization decision makers and evaluators in the Technical Support Center on indications of sump blockage and compensatory actions.	
	To ensure that alternative water sources are available to refill the RWST, Emergency Operating Procedure (EOP) ECA-I.1, "Loss of Emergency Core Cooling," provides two methods to refill the RWST: (1) refill from the boric acid blender, and (2) refill from the spent fuel pool (SFP) via the SFP pumps.	
	The following EOP changes have been implemented: EOP E-1.3, "Transfer to Cold-leg Recirculation" and EOP E-1, "Loss of Reactor or Secondary Coolant."	
	New EOP ECA-1.3, "Sump Blockage Guideline," was developed to provide specific guidance to operators when sump blockage was diagnosed to have occurred.	
Farley-1	Procedural and program controls are in place to ensure materials used in the containments will not result in an increase of the debris loading beyond the analyzed values. This includes controls for containment coatings, labels and insulation.	
	Procedural changes have been made to ensure that the post-LOCA ECCS sump levels are maximized.	
Farley-2	Procedural and program controls are in place to ensure materials used in the containments will not result in an increase of the debris loading beyond the analyzed values. This includes controls for containment coatings, labels and insulation.	
	Procedural changes have been made to ensure that the post-LOCA ECCS sump levels are maximized.	
Fort Calhoun-1	Plant procedures, programs, and design requirements were reviewed to determine those that could impact the analyzed containment or recirculation function configuration. These reviews resulted in the identification of those documents that required revision or development of new documents to ensure maintenance of the inputs and assumptions into the future.	
Indian Point-2	Licensing basis change regarding passive failure analyses.	Yes
	Licensing basis change regarding emergency core cooling system valve surveillance requirements.	Yes
	The procedure EN-MA-118, "Foreign Material Exclusion," has been revised to identify the recirculation and containment sumps as FME Level 1 areas, the highest level of cleanliness control.	Yes

Plant	Plant Modifications (Administrative)	Credited?
	ENN-EE-S-010-1P2 "Electrical Separation Design Criteria" standard has been revised to phase out the use of vinyl cable tray tags, to exclude the use of new marinate and/or transite, to eliminate the use of new cable wrap for separation, and to require an Engineering evaluation should a deviation be necessary.	Yes
	ENN-EE-S-008-IP, "Electrical Installation Standard" has been revised to eliminate unqualified material such as vinyl tags, tape, and blankets in new installations.	Yes
	A sampling program was initiated to ensure containment dust, dirt, and latent debris do not exceed the analyzed quantities evaluated.	Yes
	The procedure EN-DC-115, "Engineering Change Development" has been revised to screen design changes for impact on GL 2004-02 compliance. Examples of specific screen items include any changes to: insulation, coatings, aluminum, and other metallic/non metallic debris sources.	Yes
	Several enhancements to the existing Entergy Nuclear Northeast fleet procedure, ENN-DC-150, "Condition Monitoring of Maintenance Rule Structures", were made. These enhancements include a detailed inspection checklist for coatings. A preventative maintenance (PM) to visually inspect coating in the Indian Point Unit 2 and 3 Vapor Containment Buildings during all future refueling outages was created for GSI-191, employing guidance from ENN-DC-150. These changes have been incorporated in fleet procedure EN-DC-150, Rev. 0. The frequency of the PM inspection for GSI-191 is every two (2) years, or every cycle during the refueling outage. The process requires any degraded coatings be evaluated as acceptable, or repaired prior to exiting the outage.	Yes
	Licensing basis change regarding the containment sump pH-buffering agent.	Yes
Indian Point-3	Licensing basis change regarding passive failure analyses.	Yes
	The procedure EN-MA-118, "Foreign Material Exclusion," has been revised to identify the recirculation and containment sumps as FME Level 1 areas, the highest level of cleanliness control.	Yes
	The standard ENN-EE-S-010-1P2, "Electrical Separation Design Criteria" standard has been revised to phase out the use of vinyl cable tray tags, to exclude the use of new marinate and/or transite, to eliminate the use of new cable wrap for separation.	Yes
	The standard ENN-EE-S-008-IP, "Electrical Installation Standard," has been revised to eliminate unqualified material such as vinyl tags, tape, and blankets in new installations.	Yes
	A sampling program was initiated to ensure containment dust, dirt, and latent debris do not exceed the analyzed quantities evaluated.	Yes
	The procedure EN-DC-115, "Engineering Change Development" has been revised to screen design changes for impact on GL-04-02 compliance. Examples of specific screen items include any changes to: insulation, coatings, aluminum, and other metallic/non metallic debris sources.	Yes
	Several enhancements to the existing Entergy Nuclear Northeast fleet procedure, ENN-DC-150, "Condition Monitoring of	Yes

Plant	Plant Modifications (Administrative)	Credited?
	Maintenance Rule Structures", were made. These enhancements include a detailed inspection checklist for coatings. A preventative maintenance (PM) to visually inspect coating in the Indian Point Unit 2 and 3 Vapor Containment Buildings during all future refueling outages was created for GSI-191 employing guidance from ENN-DC-150. These changes have been incorporated in fleet procedure EN-DC-150, Rev. 0. The frequency of the PM inspection for GSI-191 is every two (2) years, or every cycle during the refueling outage. The process requires any degraded coatings be evaluated as acceptable, or repaired prior to exiting the outage.	
	Licensing basis change regarding the containment sump pH-buffering agent.	Yes
Kewaunee-1	Fleet GSI-191 Program implemented that designates a Lead Person, and Program Owners, and delineates GSI-191 staff and management responsibilities.	Yes
	Fleet FME procedure instituted that prevents entry of foreign material into plant systems.	Yes
	Containment inspection procedure is implemented at the end of each outage to identify and remove inappropriate material and debris from containment, and to ensure portable equipment is seismically restrained or properly stored.	Yes
	During refueling, radiation protection staff routinely performs cleaning of various areas in containment.	Yes
	Controlled-area maintenance-staff clean the recirculation sump pit, as needed, during refueling outages to remove standing water and boric acid residue.	Yes
	Procedures established to perform periodic latent debris sampling in containment and to quantify the total latent debris in containment to ensure the quantity remains below the analyzed limit.	Yes
	Procedures established to apply, inspect, and quantify coatings in containment.	Yes
	Fleet guidance document issued for labeling plant equipment that includes labeling equipment in containment.	Yes
	Maintenance procedure that provides guidance for applying and replacing insulation in containment.	Yes
	Plant modification included notification to the GSI-191 responsible engineer of modifications to the screen for potential impact relative to GSI-191 issues.	Yes
	The allowable quantity of latent debris (dirt, dust) in containment will be limited to 51 lbm to prevent formation of a filtering bed of fiber on the recirculation strainer when combined with the remaining fiber in containment.	Yes
	The Dominion fleet latent debris sampling and evaluation procedure will be revised prior to the next refueling outage to require a sampling frequency of every other refueling outage for low-fiber plants that are dependent upon plant cleanliness to prevent formation of a filtering bed of fiber on the recirculation strainer. The procedure will specify the sampling frequency may be relaxed after several consecutive sample results (outages) that	Yes

Plant	Plant Modifications (Administrative)	Credited?
	identify minimal or no increasing volume of measured latent debris and ample latent debris inventory margin.	
McGuire-1	The modification process and the plant labeling process have been enhanced relative to GL-04-02 controls.	
	Submitted license amendments to the NRC for ECCS Water Management modifications, which include revisions to post-accident response that reduce recirculation flowrates through the ECCS Sump Strainer and decrease the predicted volume of transported sump pool debris. The license amendment has been approved.	
McGuire-2	The modification process and the plant labeling process have been enhanced relative to GL-04-02 controls.	
	Submitted license amendments to the NRC for ECCS Water Management modifications, which include revisions to post-accident response that reduce recirculation flowrates through the ECCS Sump Strainer and decrease the predicted volume of transported sump pool debris. The license amendment has been approved.	
Millstone-2	Containment cleanliness standards have been defined and detailed in a station housekeeping procedure.	Yes
	Design controls have been put in place to require evaluation of potential debris sources in containment created by or adversely affected by design changes.	Yes
	Insulation specification changes have been made to ensure that changes to insulation in containment can be performed only after the impact on containment strainer debris loading is considered.	Yes
Millstone-3	Containment cleanliness standards have been defined and detailed in a station housekeeping procedure.	Yes
	Design controls have been put in place to require evaluation of potential debris sources in containment created by or adversely affected by design changes.	Yes
	Insulation specification changes have been made to ensure that changes to insulation in containment can be performed only after the impact on containment strainer debris loading is considered.	Yes
North Anna-1	Revised the technical specifications for Units 1 and 2 to support the installation of the new strainers and resolution of GSI-191 and NRC GL-04-02.	Yes
	Replaced the LOCTIC containment analysis methodology for analyzing the response to postulated pipe ruptures inside containment, including a LOCA and a main steam line break (MSLB), with the NRC-approved GOTHIC evaluation methodology discussed in Dominion Topical Report DOM-NAF-3-0.0-P-A. The change to the GOTHIC code provided margin in LOCA peak containment pressure and other accident analysis results.	Yes
	Revised the LOCA Alternate Source Term (AST) analysis to include the effects from changing the RS pump start methodology and other changes identified in License Amendments 250 and 230 for NAPS Units 1 and 2, respectively, approved by the NRC on March 13, 2007 (ADAMS ML070720043).	Yes

Plant	Plant Modifications (Administrative)	Credited?
	Revised and/or created procedures and programs to ensure that future changes to the plant do not adversely affect the ability of the new containment strainers to perform their design function.	Yes
	Trained operators on the operation of the RS and LHSI systems with respect to the new containment sump strainers.	Yes
North Anna-2	Revised the technical specifications for Units 1 and 2 to support the installation of the new strainers and resolution of GSI-191 and NRC GL-04-02.	Yes
	Replaced the LOCTIC containment analysis methodology for analyzing the response to postulated pipe ruptures inside containment, including a LOCA and a main steam line break (MSLB), with the NRC-approved GOTHIC evaluation methodology discussed in Dominion Topical Report DOM-NAF-3-0.0-P-A. The change to the GOTHIC code provided margin in LOCA peak containment pressure and other accident analysis results.	Yes
	Revised the LOCA Alternate Source Term (AST) analysis to include the effects from changing the RS pump start methodology and other changes identified in License Amendments 250 and 230 for NAPS Units 1 and 2, respectively, approved by the NRC on March 13, 2007 (ADAMS ML070720043).	Yes
	Revised and/or created procedures and programs to ensure that future changes to the plant do not adversely affect the ability of the new containment strainers to perform their design function.	Yes
	Trained operators on the operation of the RS and LHSI systems with respect to the new containment sump strainers.	Yes
Oconee-1	Enhancement of plant labeling process to limit potential for tags and stickers to become post-accident debris sources.	Yes
	Enhancement of plant containment coatings program to ensure that degraded coatings identified from maintenance inspections are evaluated for potential effects on RBES evaluations.	Yes
	Enhancement of FME controls to ensure that any scaffolding remaining in containment during power operation is evaluated for potential chemical effects.	Yes
	Enhancement of plant design change process to ensure that plant modifications are evaluated for impact to RBES evaluations performed in support of GSI-191.	Yes
	Revision of technical specifications to remove reference to trash racks and screens and to add reference to strainers.	Yes
	Revision of UFSAR to update from 50% blockage criteria to debris-specific RBES evaluation criteria.	Yes
Oconee-2	Enhancement of the plant labeling process to limit potential for tags and stickers to become post-accident debris sources.	Yes
	Enhancement of plant containment coatings program to ensure that degraded coatings identified from maintenance inspections are evaluated for potential effects on RBES evaluations.	Yes
	Enhancement of FME controls to ensure that any scaffolding remaining in containment during power operation is evaluated for potential chemical effects.	Yes
	Enhancement of plant design change process to ensure that plant	Yes

Plant	Plant Modifications (Administrative)	Credited?
	modifications are evaluated for impact to RBES evaluations performed in support of GSI-191.	
	Revision of technical specifications to remove reference to trash racks and screens and to add reference to strainers.	Yes
	Revision of UFSAR to update from 50% blockage criteria to debris-specific RBES evaluation criteria.	Yes
Oconee-3	Enhancement of the plant labeling process to limit potential for tags and stickers to become post-accident debris sources.	Yes
	Enhancement of plant containment coatings program to ensure that degraded coatings identified from maintenance inspections are evaluated for potential effects on RBES evaluations.	Yes
	Enhancement of FME controls to ensure that any scaffolding remaining in containment during power operation is evaluated for potential chemical effects.	Yes
	Enhancement of plant design change process to ensure that plant modifications are evaluated for impact to RBES evaluations performed in support of GSI-191.	Yes
	Revision of technical specifications to remove reference to trash racks and screens and to add reference to strainers.	Yes
	Revision of UFSAR to update from 50% blockage criteria to debris-specific RBES evaluation criteria.	Yes
Palisades-1	Enhancements of programmatic control of LOCA debris sources in containment have been implemented.	Yes
	Administrative procedure developed to address the use of proper labeling of materials inside the containment building.	Yes
	Administrative procedure that governs general cleanliness requirements in the reactor building revised to state that general cleanliness "should be maintained by periodic cleanup efforts of the work areas."	Yes
	Administrative procedure developed that deals with failures that could adversely affect a safety-related or important-to-safety structure, system, or component.	Yes
	“Technical Specification for Painting” revised to update the requirements of coating applications inside containment in accordance with current regulatory and industry standards.	Yes
	“Technical Specification for Furnishing and Installing Conventional Type Insulation” was revised to explicitly require an engineering change process for replacing the thermal insulation material inside containment (with some exceptions).	Yes
	The “Design Input Checklist” was revised to incorporate a “Containment Sump Blockage” design checklist to determine if proposed plant modifications affect the containment sump analysis.	Yes
	“Fire Protection Surveillance Procedure” used to inspect cable tray fire stops located in containment was revised to require that a visual inspection of the integrity of fire rated assemblies and fire protection assemblies be performed every 18 months.	Yes
	“Technical Specification Surveillance Procedure” developed to require that inspected areas that are painted or coated be	Yes

Plant	Plant Modifications (Administrative)	Credited?
	examined for flaking, blistering, peeling or discoloration.	
	Technical Specification developed to verify that each containment sump inlet debris screen, containment sump passive strainer assembly, and other containment sump entrance pathways are not restricted by debris and show no evidence of structural distress or abnormal corrosion. This procedure also performs a cleanliness inspection of the containment sump, condition assessment of the sump level switches, sump drain screen, and the containment sump liner.	Yes
	General operating procedure developed to require removal of caution tags from containment and to perform inspections of containment.	Yes
	System operating procedure developed to identify senior reactor operator inspections in support of containment closeout to ensure the integrity of the containment sump envelope and containment sump screens, and to remove unauthorized material.	Yes
	Permanent maintenance procedure developed to ensure containment cleanliness throughout outage and/or online work activities in containment and provide guidelines to prepare for the final closeout inspection.	Yes
	Permanent maintenance procedure developed to provide instructions for condition assessments of protective coatings within containment and reporting of results.	Yes
	Permanent maintenance procedure developed to provide instructions for removing and installing containment sump envelope passive strainers and debris screens during operating modes 5 and 6.	Yes
	Engineering Manual Procedure defines the requirements of the program that applies to coatings on the interior surfaces of containment, exposed surfaces of equipment located in containment, and linings of tanks and piping where detachment could adversely affect the function of safety-related structures, systems or components and thereby impair safe shutdown.	Yes
	Permanent maintenance procedure developed to provide requirements for application of qualified Service Level I protective coatings to surfaces inside, or to systems, structures or components that will be installed inside containment.	Yes
	Technical Specification surveillance procedure developed to ensure a sufficient amount of sump buffering agent is installed inside containment.	Yes
Palo Verde-1	Programmatic controls are in place to verify containment cleanliness and ensure that no foreign material is present at the ECCS sump strainers prior to containment closure following refueling outages. These controls also ensure maintenance of the containment cleanliness for any entry into the containment through verification of the condition of all areas entered.	
	Procedures are also in place to control transient materials taken into or out of containment during any entry of the containment at	

Plant	Plant Modifications (Administrative)	Credited?
	power.	
	Programmatic controls are in place to perform periodic coatings assessment walkdowns to verify the condition of the containment coatings.	
Palo Verde-2	Programmatic controls are in place to verify containment cleanliness and ensure that no foreign material is present at the ECCS sump strainers prior to containment closure following refueling outages. These controls also ensure maintenance of the containment cleanliness for any entry into the containment through verification of the condition of all areas entered.	
	Procedures are also in place to control transient materials taken into or out of containment during any entry of the containment at power.	
	Programmatic controls are in place to perform periodic coatings assessment walkdowns to verify the condition of the containment coatings.	
Palo Verde-3	Programmatic controls are in place to verify containment cleanliness and ensure that no foreign material is present at the ECCS sump strainers prior to containment closure following refueling outages. These controls also ensure maintenance of the containment cleanliness for any entry into the containment through verification of the condition of all areas entered.	
	Procedures are also in place to control transient materials taken into or out of containment during any entry of the containment at power.	
	Programmatic controls are in place to perform periodic coatings assessment walkdowns to verify the condition of the containment coatings.	
Prairie Island-1	The minimum level in the refueling water storage tank was administratively increased to 90%.	Yes
	Additional measures were implemented to provide more aggressive requirements for containment closeout and foreign material controls.	Yes
	The containment closeout procedures were enhanced to include specific verifications that containment drainage paths are not blocked.	Yes
	The post-outage containment inspection procedure specifically looked at the sump strainer for evidence of structural distress or abnormal corrosion.	Yes
Prairie Island-2	The minimum level in the refueling water storage tank was administratively increased to 90%.	Yes
	Additional measures were implemented to provide more aggressive requirements for containment closeout and foreign material controls.	Yes
	The containment closeout procedures were enhanced to include specific verifications that containment drainage paths are not blocked.	Yes
	The post-outage containment inspection procedure specifically looked at the sump strainer for evidence of structural distress or	Yes

Plant	Plant Modifications (Administrative)	Credited?
	abnormal corrosion.	
Robinson-2	To limit the amount of plastic debris in containment, an inspection was conducted in RO-24 and plant labeling procedure PLP-050, "Plant Labeling, Stenciling, and Signs," was revised to prohibit the installation of new, or replacement of existing, plastic tags or labels in containment and requires stainless steel or porcelain coated stainless steel signs.	Yes
	Procedure EGR-NGGC-0005, "Engineering Change," which is used for development of plant modifications, was revised to add screening questions regarding insulation, aluminum-containing material in containment, and flow paths during the recirculation phase of an accident.	Yes
	Procedure PLP-006, "Containment Vessel Inspection/Closeout," was revised to emphasize inspection for latent debris to ensure latent debris is maintained within the inputs and assumptions that support the GSI-191 issue resolution. PLP-006 is also used for identifying additions, deletions, and locations of aluminum in containment. The strainer design analysis is based on 400 lbs of latent debris in the containment, as compared to an estimated 202.5 lbs of latent debris in containment. The latent debris in containment was estimated in accordance with the NEI 04-07 methodology.	Yes
	Specification L2-M-039, "Piping and Equipment Thermal Insulation," was revised to provide guidance to control insulation materials used in containment in order to maintain the debris source term in accordance with the analysis. Procedure MMM-003, "Maintenance Planning," was revised to include guidance for maintenance planners to use the new specification for activities inside containment involving insulation.	Yes
Salem-1	PSEG revised appropriate Administrative Procedures. As part of the newly installed containment sump strainers, PSEG revised its administrative procedures to ensure that potential sources of debris that may be introduced into containment will be assessed for adverse effects on the ECCS and CSS recirculation functions. These programmatic controls include requirements related to coatings, containment housekeeping, materiel condition, and modifications.	
Salem-2	PSEG revised appropriate Administrative Procedures. As part of the newly installed containment sump strainers, PSEG revised its administrative procedures to ensure that potential sources of debris that may be introduced into containment will be assessed for adverse effects on the ECCS and CSS recirculation functions. These programmatic controls include requirements related to coatings, containment housekeeping, materiel condition, and modifications.	
San Onofre-2	Procedural guidance and training; containment cleanliness and control of debris sources.	
San Onofre-3	Procedural guidance and training; containment cleanliness and control of debris sources.	

Plant	Plant Modifications (Administrative)	Credited?
Seabrook-1	The containment entry procedure has been updated to require that any aluminum to be taken into containment should be evaluated prior to entry.	
	The surveillance procedure that inspects the containment recirculation sumps has been extensively revised.	
Shearon Harris-1	Removal of plastic signage from containment. During RFO 14 (fall of 2007), HNP removed most of the plastic signage from containment. These signs and labels were operator aids for locating components. In some cases, the components had redundant stainless-steel tags that were left on the components. In some other cases, the plastic signs were replaced with porcelainized metal tags. In other cases, the plastic signs were replaced with stenciling.	Yes
	Revised the modification procedure. The corporate modification procedure, EGRNGGC-0005, has been revised to add screening questions regarding insulation and aluminum-containing material in containment as well as regarding flow paths that water would take during the recirculation phase of an accident.	Yes
	The site deficiency tags are paper tags and represent a potential source of debris. The site deficiency tag procedure, AP-038, was revised to specifically prohibit the use of deficiency tags in containment.	Yes
	Revised the containment closeout procedure. The site containment closeout procedure, OST-1081, was revised to provide a definition of latent debris, acceptance criteria for latent debris, and specific steps to assure that any latent debris in containment is within the acceptance criteria. Although HNP has determined that the quantity of latent debris in containment is significantly less than that assumed in the debris generation calculation, HNP elected to place a control on the latent debris that may be generated inside containment.	Yes
St. Lucie-1	A walkdown to confirm the absence of potential choke points was completed.	Yes
	Enhancements to programmatic controls have been put in place at St. Lucie Unit 1. Engineering procedures have been revised to provide guidance to the design engineer working on plant modifications to take into account the impact of the design on the "containment sump debris generation & transport analysis and/or recirculation functions."	Yes
	As an enhancement to the existing process for controlling the quantities of piping insulation within the containment, the engineering specification that controls thermal insulation was revised to provide additional guidance for maintaining containment insulation configuration.	Yes
	New controls have been instituted limiting the permissible quantity of unqualified coatings in the containment building.	Yes
St. Lucie-2	Plant walkdowns have been completed to evaluate the potential for chokepoints in the flow path from potential break locations to the containment recirculation sump, and it was concluded that there	Yes

Plant	Plant Modifications (Administrative)	Credited?
	were no chokepoints that would inhibit flow.	
	Improvements in programmatic controls have been implemented to ensure that the potential quantity of post-loss of coolant accident (LOCA) debris does not exceed the evaluation assumptions for Net Positive Suction Head (NPSH) margins on recirculation ECCS/CSS pumps, or the evaluation assumptions in downstream analysis for components and systems, or for fuel and in-vessel effects.	Yes
Summer-1	A cumulative effects program has been established for tabulating, controlling and evaluating changes to quantities of insulation inside the reactor building.	Yes
	A cumulative effects program has been established for tabulating, controlling and evaluating changes to quantities of unqualified coatings inside the reactor building.	Yes
	A Level 1 coatings program for the reactor building has been established.	Yes
	Licensee is developing an Alternate Source Term LOCA Dose Analysis that does not require the assumption of a pump seal failure in the event of a LOCA.	Yes
Surry-1	Performed an analysis of clogging for components in ECCS and RS flow streams downstream of ECCS and RS strainers.	Yes
	Completed analysis of water hold-up in containment to identify locations where water will be blocked from reaching the RS and LHSI strainers.	Yes
	Revised the SPS Units 1 and 2 Technical Specifications to increase the containment air partial pressure limits to provide analytical margin, including NPSH margin for the RS and LHSI pumps.	Yes
	Replaced the LOCTIC containment analysis methodology for analyzing the response to postulated pipe ruptures inside containment, including a LOCA and a MSLB, with the NRC-approved GOTHIC evaluation methodology discussed in Dominion Topical Report DOM-NAF-3-0.0-P-A. The change to the GOTHIC code provided margin in LOCA peak containment pressure and other accident analysis results.	Yes
	Revised the LOCA Alternate Source Term analysis to include the effects from changing the RS pump start methodology and from other modifications associated with the GSI-191 project.	Yes
	Revised and/or created procedures and programs to ensure that future changes to the plant do not have adverse affects on the ability of the new containment strainers to perform their design function.	Yes
	Trained operators on the operation of the RS and LHSI systems with respect to the new containment strainers.	Yes
Surry-2	Performed an analysis of clogging for components in ECCS and RS flow streams downstream of ECCS and RS strainers.	Yes
	Completed analysis of water hold-up in containment to identify locations where water will be blocked from reaching the RS and LHSI strainers.	Yes

Plant	Plant Modifications (Administrative)	Credited?
	Revised the SPS Units 1 and 2 Technical Specifications to increase the containment air partial pressure limits to provide analytical margin, including NPSH margin for the RS and LHSI pumps.	Yes
	Replaced the LOCTIC containment analysis methodology for analyzing the response to postulated pipe ruptures inside containment, including a LOCA and a MSLB, with the NRC-approved GOTHIC evaluation methodology discussed in Dominion Topical Report DOM-NAF-3-0.0-P-A. The change to the GOTHIC code provided margin in LOCA peak containment pressure and other accident analysis results.	Yes
	Revised the LOCA alternate source term analysis to include the effects from changing the RS pump start methodology and from the other modifications associated with the GSI-191 project.	Yes
	Revised and/or created procedures and programs to ensure that future changes to the plant do not have adverse affects on the ability of the new containment strainers to perform their design function.	Yes
	Trained operators on the operation of the RS and LHSI systems with respect to the new containment strainers.	Yes
Three Mile Island-1	Revised emergency operating procedures to throttle LPI flow, if high strainer differential pressure is observed.	
Turkey Point-3	Engineering procedures have been revised to provide guidance to design engineers working on plant modifications to take into account the impact of the design on the "containment sump debris generation & transport analysis and/or recirculation functions."	Yes
	The engineering specification that controls thermal insulation was revised to provide additional guidance for maintaining containment insulation configuration.	Yes
	New controls have been instituted limiting the permissible quantity of unqualified coatings in the containment building.	Yes
Turkey Point-4	The coating specification update ensures that strainer design basis coating debris loads will not be exceeded.	Yes
	The insulation specification has been revised to enhance configuration management controls to ensure that insulation within that could become debris does not exceed strainer design inputs.	Yes
	Procedures are in place to ensure that the single potential choke point, refueling canal drain covers, are removed prior to Mode 4 restart so that the design basis sump water supply is available.	Yes
Vogtle-1	Procedural and program controls are in place to ensure materials used in the containments will not result in an increase of the debris loading beyond the analyzed values. They include controls for containment coatings, labels and insulation.	Yes
Vogtle-2	Procedural and program controls are in place to ensure materials used in the containments will not result in an increase of the debris loading beyond the analyzed values. This includes controls for containment coatings, labels and insulation.	Yes
Waterford-3	Changes to plant programs, processes, and procedures to limit the introduction of materials into containment that could adversely	

Plant	Plant Modifications (Administrative)	Credited?
	impact the recirculation function, and establish monitoring programs to ensure containment conditions will continue to support the recirculation function.	
	Revise Emergency Operating Procedures to include contingency actions for a Low Pressure Safety Injection pump failing to trip on Recirculation Actuation Signal.	
Wolf Creek-1	Changes to the scaffold construction and use procedure to enhance requirements for control of scaffold tags and materials used during work activities conducted in the containment during plant operational modes 1 through 4.	
	Changes were implemented for design change process procedures to ensure that necessary engineering evaluations will be performed when preparing a change to the plant design that either directly or indirectly affects containment, ECCS, or CSS. Administrative controls were added to the plant modification process.	
	Changes were made to the containment entry and material control procedure to enhance requirements during plant operational modes 1 through 4 for control of materials during work activities conducted in the containment and for control of radiological postings.	
	Changes were made to the clearance order procedure to ensure that Generic Letter 2004-02 analyses and evaluations are considered prior to making future changes to existing requirements that clearance order tags are not installed on components inside the containment being removed from service (tagged out) during plant operational modes 1 through 4.	
	Changes to the work request procedure to ensure that GL-04-02 analyses and evaluations are considered prior to making future changes to existing requirements that work request tags are not installed on components inside the containment.	
	WCNOC implemented a program to assess the containment latent debris.	
	WCNOC implemented a program to assess the containment coatings.	
	WCNOC implemented changes to Technical Specifications Surveillance procedures to ensure that the installed replacement strainers would not have openings in excess of the maximum designed strainer opening.	

Table A.2-5. Downstream Plant Modifications

Plant	Plant Modifications (Downstream)
Braidwood-1	Three ECCS safety injection throttle valves modified to avoid potential blockage by incorporating a new bonnet, stem, trim assembly, manual operator, and locking device.
Braidwood-2	Three ECCS safety injection throttle valves modified to avoid potential blockage by incorporating a new bonnet, stem, trim assembly, manual operator, and locking device.

Plant	Plant Modifications (Downstream)
Byron-1	Three ECCS safety injection throttle valves modified to avoid potential blockage by incorporating a new bonnet, stem, trim assembly, manual operator, and locking device.
Byron-2	Three ECCS safety injection throttle valves modified to avoid potential blockage by incorporating a new bonnet, stem, trim assembly, manual operator, and locking device.
Calvert Cliffs-1	Replacement of all HPSI pump cyclone separators with the tested unit was completed by June 30, 2008.
Calvert Cliffs-2	Replacement of all HPSI pump cyclone separators with the tested unit was completed by June 30, 2008.
Catawba-1	Modification of the Catawba Unit 1 and 2 Charging and Safety Injection line flow orifices, along with an adjustment to the associated throttle valve clearances, was required to resolve throttle valve plugging and erosion concerns identified by the downstream debris effects evaluations.
Catawba-2	Modification of the Catawba Unit 1 and 2 Charging and Safety Injection line flow orifices, along with an adjustment to the associated throttle valve clearances, was required to resolve throttle valve plugging and erosion concerns identified by the downstream debris effects evaluations.
Crystal River-3	The cyclone separators on the DH and BS pumps have been removed and replaced with models that do not need throttled flow. The throttle valves were removed as part of the cyclone separator replacement.
	The HP auxiliary spray valve has been fully opened based on supporting hydraulic analyses.
Davis Besse-1	Modification/installation of cyclone separators for the HPI, LPI, and CS pumps.
Farley-1	ECCS branch flow throttle valves have been replaced.
Farley-2	ECCS branch flow throttle valves have been replaced.
Indian Point-3	The IR pumps were replaced during the spring 2007 refueling outage [Ref. 971 with a double inlet suction style pump. Due to the predicted increased sump screen debris load determined by GL 2004-02 related analyses, the head losses through the IR sump are also predicted to increase. Based on hydraulic and NPSH calculations, due to the increased debris loads the original pumps would not have been able to fulfill their safety functions. The replacement pumps are demonstrated to have the capability to operate without cavitation at the required flow rates assuming maximum anticipated sump screen head losses.
Kewaunee-1	The ICS pump Durametallic seal and safety bushing require additional evaluation.
Oconee-1	Replacement of HPI, RHR, and BS pump seal flush orifices and cyclone separators due to "potential for plugging."
	Replacement of HPI pump internals to soft, wear-susceptible materials.
Oconee-2	Replacement of HPI, RHR, and BS pump seal flush orifices and cyclone separators due to "potential for plugging."
	Replacement of HPI pump internals to soft, wear-susceptible materials.
Oconee-3	Replacement of HPI, RHR, and BS pump seal flush orifices and cyclone separators due to "potential for plugging."
	Replacement of HPI pump internals to soft, wear-susceptible materials.
Palisades-1	Replacement of HPSI pumps mechanical seals, cyclone separators, and CSS valves.

Plant	Plant Modifications (Downstream)
Prairie Island-1	John Crane Type 1/1B mechanical seals in RHR pumps were to be replaced with Chesterton 180 mechanical seals.
Prairie Island-2	John Crane Type 1/1B mechanical seals in RHR pumps were to be replaced with Chesterton 180 mechanical seals.
Robinson-2	The seal on the CS pump "B" was noted to have a graphite bushing. This seal was replaced with a seal using a metallic bushing.
St. Lucie-1	The High Pressure Safety Injection (HPSI) pump seals and cyclone separators have been replaced with a seal system that does not use cyclone separators or rely on the HPSI pumped water for flushing and cooling the mechanical seals. The new seal system recirculates the seal cavity water through an external heat exchanger to flush and cool the seal faces. The new seal system will prevent the potential failure of shaft seals that could be caused by the carryover of debris in the pumped water when the HPSI pumps take suction of potentially debris-laden fluid from the new containment strainer system in the recirculation mode.
St. Lucie-2	The HPSI pumps were modified by removing the cyclone separator and associated piping and by replacing the mechanical seals with a new seal design that uses a recirculated seal cavity fluid for flushing and cooling of the seal faces.
	The CSS pumps were modified by removing the cyclone separator and associated piping and by replacing the mechanical seals with a new seal design that uses a recirculated seal cavity fluid.
Summer-1	Downstream high head safety injection throttle valve replaced.
	Replacement of pump carbon/graphite disaster bushing with an acceptable alternative was being investigated.
Surry-1	Holes in stilling well increased and debris shields provided to prevent potential blockage of containment sump wide range level indicators.
Surry-2	Holes in stilling well increased and debris shields provided to prevent potential blockage of containment sump wide range level indicators.
Three Mile Island-1	One modification to DH manual throttle valves was performed during T1R17 (Fall 2007) to address a downstream effect concern.
	The stacked disk cage design used in the valves contained small openings in the disk stack that had the potential to become blocked with the small debris that could pass through the Reactor Building Sump Strainer. These valve disk stacks were therefore replaced in T1R17 (Fall 2007) with a new design with larger flow passages less susceptible to blockage by fibrous debris.
Turkey Point-4	Containment spray pump mechanical seals modified and their cyclone separators removed.
Vogtle-1	Orifices installed in intermediate and high head ECCS lines; associated throttle valves adjusted to ensure that no blockage will occur.
Vogtle-2	Orifices installed in intermediate and high head ECCS lines; associated throttle valves adjusted to ensure that no blockage will occur.
Watts Bar-2	New throttle valves were procured for installation in the CVCS and SI lines to the RCS. The valves will be installed under EDCR 54783. The new valves will be opened sufficiently to preclude downstream blockage and reduce the number of components that need to be considered for potential debris erosion.

Table A.2-6. Plants with No Downstream Modifications

Plant Name	Unit #
ANO	1
ANO	2
Comanche Peak	1
Comanche Peak	2
D.C. Cook	1
D.C. Cook	2
Diablo Canyon	1
Diablo Canyon	2
Fort Calhoun	1
Ginna	1
Indian Point	2
McGuire	1
McGuire	2
Millstone	2
Millstone	3
North Anna	1
North Anna	2
Palo Verde	1
Palo Verde	2
Palo Verde	3
Point Beach	1
Point Beach	2
Salem	1
Salem	2
San Onofre	2
San Onofre	3
Seabrook	1
Sequoyah	1
Sequoyah	2
Shearon Harris	1
South Texas	1
South Texas	2
Turkey Point	3
Waterford	3
Watts Bar	1
Wolf Creek	1

Head Loss: Strainer Approach Velocity

If the value for the strainer approach velocity is provided, it is recorded directly into the database. Otherwise, it is calculated as:

$$Approach\ Velocity = \frac{Design\ Flow}{Total\ Screen\ Area}$$

where the “Design Flow” is the flow rate as indicated in the response for each case, where applicable, and the “Total Screen Area” is calculated as in Figure A.2-4.

For this field, multiple entries were allowed for a plant for different strainers and scenarios (such as SBLOCA, LBLOCA), where applicable. Figure A.2-6 shows maximum and minimum values for the approach velocity for each plant unit.[15] In most cases, only one value is provided, such that maximum and minimum velocities are equal.

Head Loss: Test Location

Table A.2-7 shows the head loss test locations as they are recorded in the GL-04-02 database.

Head Loss: Clean Strainer Head Loss

This field collects the information on the clean (no debris) strainer head loss. If available, the head loss is recorded in the database for the entire strainer at the design conditions. In any case, the exact assumption and/or conditions used to determine the clean strainer head loss are recorded in the Comments field for each entry.

Table A.2-8 lists the clean strainer head loss data recorded in the GL-04-02 database. The table (rather than chart) form is selected in this report since the head loss is a function of many parameters (including the flow rate, for example), such that a direct comparison of these values between different plants is not meaningful. The same approach is used for other head loss fields below.

Head Loss: Non-Chemical Head Loss

Table A.2-9 lists the GL-04-02 database entries for the head loss testing in which chemical debris was not included.

Head Loss: Full Head Loss

Table A.2-10 presents the database entries for the recorded full-debris (including chemicals) head loss.

Head Loss: Thin Bed

The GL-04-02 database also collected the information, where provided, on the thin bed thickness for the head loss testing. In cases where the response indicated “insufficient fiber debris to form 1/8 in. thin bed,” 0 is entered in this database field. Figure A.2-7 summarizes the database entries for the thin bed thickness. For about half of the plants, no thin bed effect is reported.

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[15]Note that min/max values in this and the following figures refer to the range of the database entries. This range does not necessarily covers all conditions discussed in the GL 2004-02 submittals.

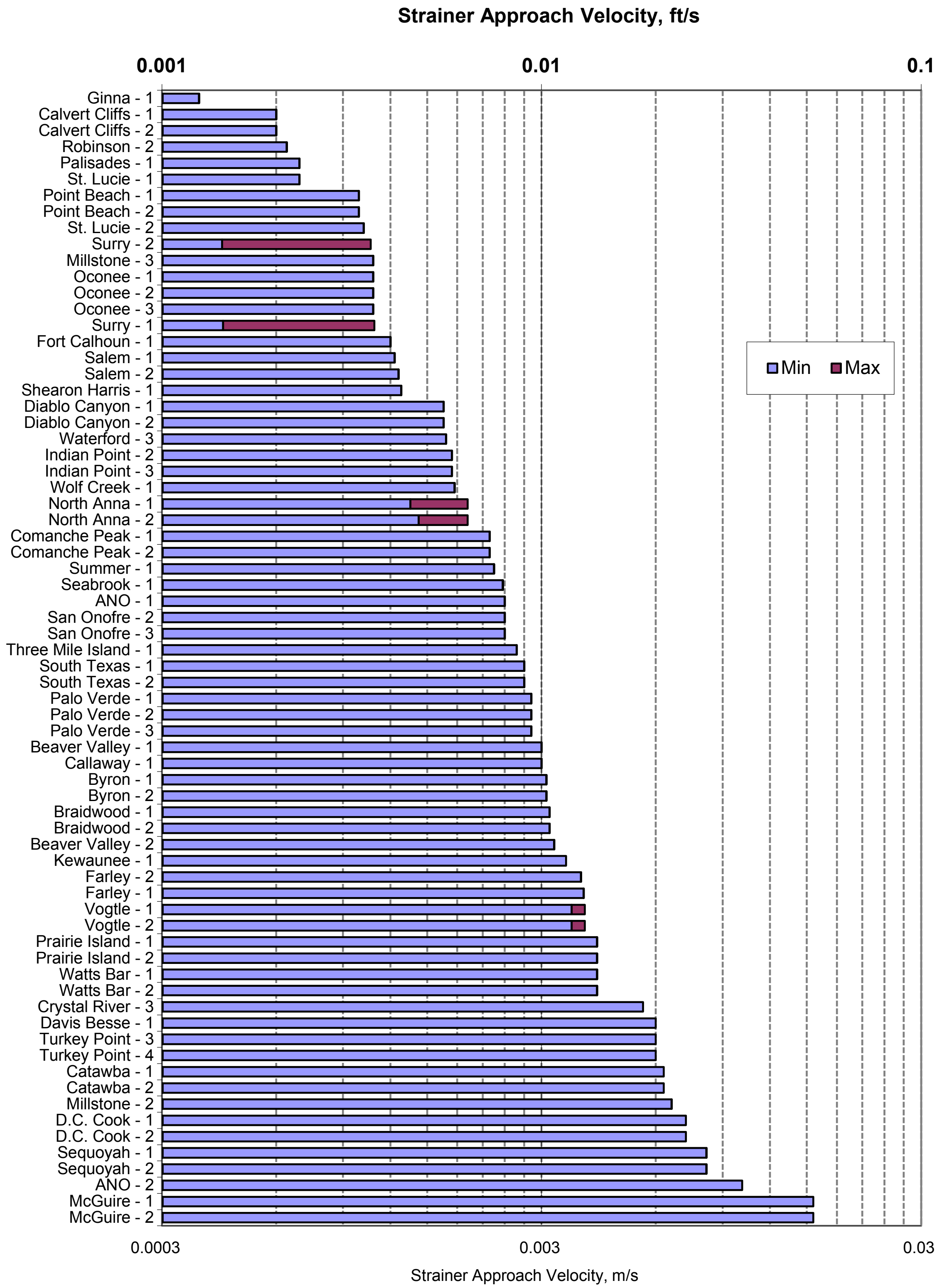

Figure A.2-6. Strainer Approach Velocity

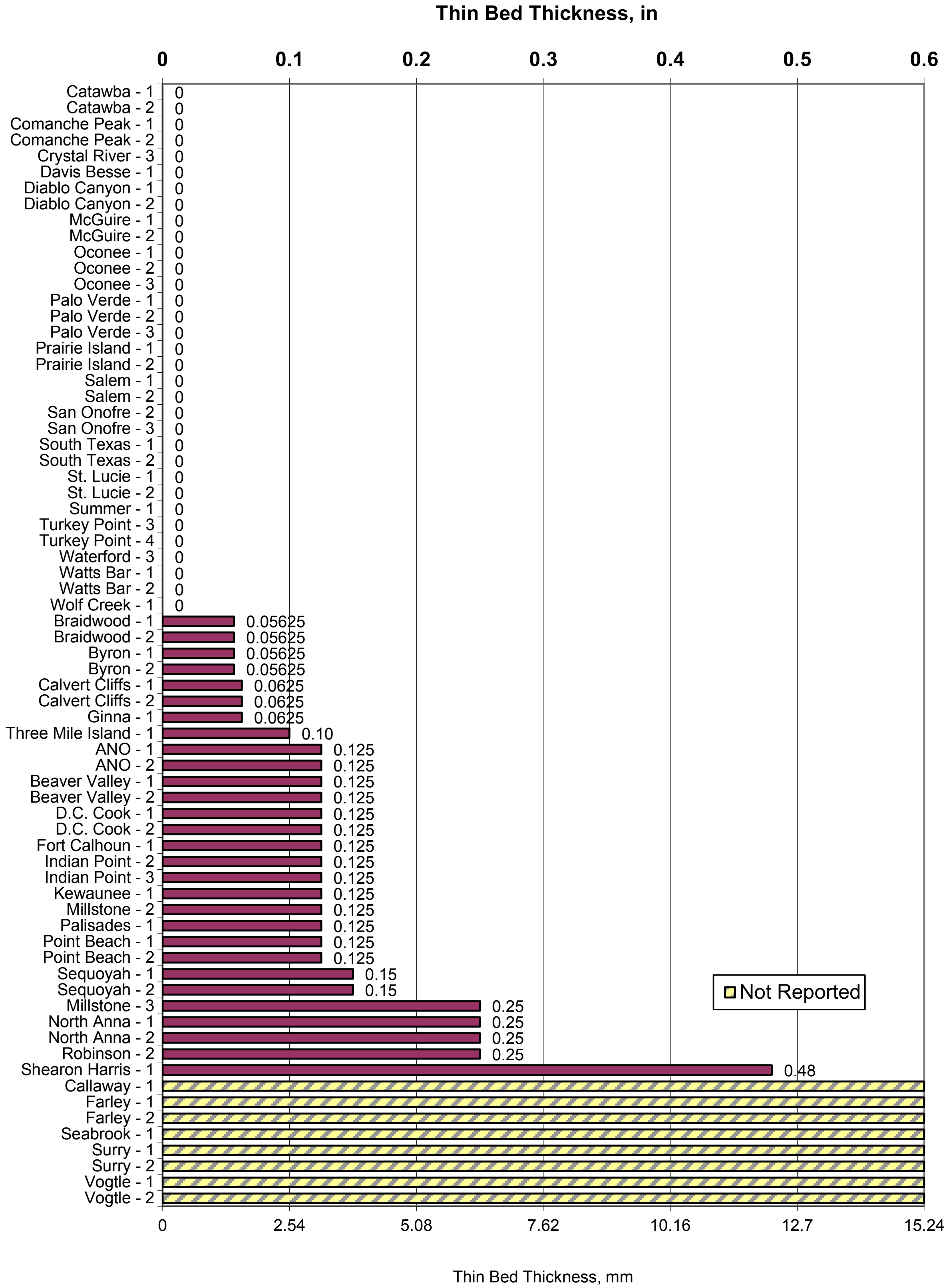

Figure A.2-7. Thin Bed Thickness

Table A.2-7. Head-Loss Test Location

Plant Name	Unit	Test Location	Comments
ANO	1	Fauske and Associates; Westinghouse	
ANO	2	Control Components, Inc.; Fauske and Associates; Westinghouse	
Beaver Valley	1	Original testing by CCI superseded by tests at Alion Science & Technology	
Beaver Valley	2	Alion Science & Technology	
Braidwood	1	Control Components, Inc., Winterthur, Switzerland	
Braidwood	2	Control Components, Inc., Winterthur, Switzerland	
Byron	1	Control Components, Inc., Winterthur, Switzerland	
Byron	2	Control Components, Inc., Winterthur, Switzerland	
Callaway	1	Alden Research Laboratory, Inc., Holden, MA	
Calvert Cliffs	1	CCI's facility in Winterthur, Switzerland	
Calvert Cliffs	2	CCI's facility in Winterthur, Switzerland	
Catawba	1	Wyle Laboratories in Huntsville, Alabama	
Catawba	2	Wyle Laboratories in Huntsville, Alabama	
Comanche Peak	1	Testing by Performance Contracting Inc. at Alden Research Laboratory, Inc., Holden, MA	
Comanche Peak	2	Testing by Performance Contracting Inc. at Alden Research Laboratory, Inc., Holden, MA	
Crystal River	3	Alion Science and Technology, Warrenville, IL	
Davis Besse	1		Head loss testing not performed. Enercon and Alion Science and Technology performed head loss calculations.
D.C. Cook	1	Control Components, Inc.; Winterthur, Switzerland and ALION, Vuez	
D.C. Cook	2	Control Components, Inc.; Winterthur, Switzerland and ALION, Vuez	
Diablo Canyon	1	Continuum Dynamics, Inc. facilities in Ewing, New Jersey	
Diablo Canyon	2	Continuum Dynamics, Inc. facilities in Ewing, New Jersey	
Farley	1	General Electric Hitachi at Continuum Dynamics Incorporated/Alion at the Vuez facility	
Farley	2	General Electric Hitachi at Continuum Dynamics Incorporated/Alion at the Vuez facility	
Fort Calhoun	1	General Electric at Continuum Dynamics Incorporated	
Ginna	1	CCI's facility in Winterthur, Switzerland	Initial head loss testing

Plant Name	Unit	Test Location	Comments
Indian Point	2	Alion Science and Technology, Warrenville, IL	Location is mentioned only with regard to bypass and chemical testing
Indian Point	3	Alion Science and Technology, Warrenville, IL	Location is mentioned only with regard to bypass and chemical testing
Kewaunee	1	Alden Research Laboratory, Inc., Holden, MA	
McGuire	1	Wyle Laboratories in Huntsville, Alabama	
McGuire	2	Wyle Laboratories in Huntsville, Alabama	
Millstone	2	AECL’s Chalk River Laboratory in Canada	
Millstone	3	AECL’s Chalk River Laboratory in Canada	
North Anna	1	AECL’s Chalk River Laboratory in Canada	
North Anna	2	AECL’s Chalk River Laboratory in Canada	
Oconee	1	CCI's manufacturing facility in Switzerland	
Oconee	2	CCI's manufacturing facility in Switzerland	
Oconee	3	CCI's manufacturing facility in Switzerland	
Palisades	1	Performance Contracting Inc. at Alden Research Laboratory, Inc., Holden, MA	
Palo Verde	1	Control Components, Inc., Winterthur, Switzerland	
Palo Verde	2	Control Components, Inc., Winterthur, Switzerland	
Palo Verde	3	Control Components, Inc., Winterthur, Switzerland	
Point Beach	1	Testing by AREVA at Alden Research Laboratory, Inc., Holden, MA	
Point Beach	2	Testing by AREVA at Alden Research Laboratory, Inc., Holden, MA	
Prairie Island	1	Testing by Performance Contracting Inc. at Alden Research Laboratory, Inc., Holden, MA	
Prairie Island	2	Testing by Performance Contracting Inc. at Alden Research Laboratory, Inc., Holden, MA	
Robinson	2		
Salem	1	Control Components, Inc., Winterthur, Switzerland	
Salem	2	Control Components, Inc., Winterthur, Switzerland	
San Onofre	2	Alion Science and Technology, Warrenville, IL	
San Onofre	3	Alion Science and Technology, Warrenville, IL	
Seabrook	1	General Electric at Continuum Dynamics Incorporated	
Sequoyah	1	Alden Research Laboratory, Holden, MA	
Sequoyah	2	Alden Research Laboratory, Holden, MA	
Shearon Harris	1	Alion Science and Technology, Warrenville, IL	
South Texas	1	Performance Contracting, Inc., Alden	

Plant Name	Unit	Test Location	Comments
		Research Laboratory at the Alden facility, Holden, MA	
South Texas	2	Performance Contracting, Inc., Alden Research Laboratory at the Alden facility, Holden, MA	
St. Lucie	1	Continuum Dynamics, Inc.	
St. Lucie	2	Performance Contracting, Inc., along with AREVA NP, Inc. and Alden Research	
Summer	1	AECL's Chalk River Laboratory in Canada	
Surry	1	AECL's Chalk River Laboratory in Canada	
Surry	2	AECL's Chalk River Laboratory in Canada	
Three Mile Island	1	Alion Science and Technology, Warrenville, IL	
Turkey Point	3	Continuum Dynamics Inc. (non-chemical head loss tests); Alion Science and Technology (chemical effects testing) at VUEZ	
Turkey Point	4	Alden Research Laboratory, Inc., Holden, MA	
Vogtle	1	Alion Science and Technology at VUEZ facility	Chemical effects testing
Vogtle	2	Alion Science and Technology at VUEZ facility	Chemical effects testing
Waterford	3	Alion Science and Technology at Vuez facility	30-day integrated test was done at Vuez facility, but it is not specified for another prototype testing with Westinghouse surrogates (probably by GE).
Watts Bar	1	Framatome ANP at Alden Research Laboratory, Inc., Holden, MA	
Watts Bar	2	Alden Research Laboratory, Inc., Holden, MA	
Wolf Creek	1	Alden Research Laboratory, Inc., Holden, MA	

Table A.2-8. Clean Strainer Head Loss

Plant Name	Unit	Clean HL, ft	Comments
ANO	1	0.2	The clean head loss without debris is less than 0.2 ft at maximum flow based on current draft calculation analysis.
ANO	2	0.33	For design flow of 7065 gpm.
Beaver Valley	1	1.800	Calculated at a flow rate and temperature of 14,500 gpm and 100°F.
Beaver Valley	2	0.756	Calculated at a flow rate of 13,636 gpm. (0.923 ft @ 12,600 gpm)
Braidwood	1	0.090	Value reported as 2.7 mbar.
Braidwood	2	0.090	Value reported as 2.7 mbar.
Byron	1	0.090	
Byron	2	0.090	

Plant Name	Unit	Clean HL, ft	Comments
Callaway	1	0.651	
Calvert Cliffs	1	0.335	10 millibar for the head losses internal to the strainer.
Calvert Cliffs	2	0.335	10 millibar for the head losses internal to the strainer.
Catawba	1	3.700	Clean strainer head loss reported for limiting Unit (Catawba 1) at 60˚F.
Catawba	2	3.700	Clean strainer head loss reported for limiting Unit (Catawba 1) at 60˚F.
Comanche Peak	1	1.270	Calculated design value at 120˚F.
Comanche Peak	2	1.270	Calculated design value at 120˚F.
Crystal River	3	0.083	Total strainer head loss, including the friction loss due to the inner walls of the top hats, the inner support members, and the exit at the bottom of the top hats. The flow rate was assumed to be 8696 gpm. The minimum fluid temperature was assumed to be 120˚F.
Davis Besse	1	0.140	Value for upper strainer reported as 0.06 psi at 11,000 gpm, as calculated by Enercon and Alion Science and Technology.
Davis Besse	1	2.330	Value reported as 1.01 psi at 11,000 gpm, as calculated by Enercon and Alion Science and Technology.
D.C. Cook	1	0.050	
D.C. Cook	2	0.050	
Diablo Canyon	1	1.700	Plenum plus entrance head losses.
Diablo Canyon	2	1.700	Plenum plus entrance head losses.
Farley	1	2.217	RHR A-Train, calculated at 120°F.
Farley	1	2.217	RHR B-Train, calculated at 120°F.
Farley	1	1.142	CSS A-Train, calculated at 120°F.
Farley	1	0.250	CSS B-Train, calculated at 120°F.
Farley	2	2.217	RHR A-Train, calculated at 120°F.
Farley	2	2.217	RHR B-Train, calculated at 120°F.
Farley	2	1.142	CSS A-Train, calculated at 120°F.
Farley	2	2.292	CSS B-Train, calculated at 120°F.
Fort Calhoun	1	0.071	SI-12A, the clean head-loss evaluation is based on a combination of strainer head loss and piping head loss.
Fort Calhoun	1	0.123	SI-12B, the clean head-loss evaluation is based on a combination of strainer head loss and piping head loss.
Ginna	1	0.131	No measurable head loss of the clean strainer surface area was recorded. The total clean strainer head loss is 3.91 mbar or 0.131 ft WC at the containment sump minimum temperature of 195°F and 2300 gpm.
Indian Point	2	0.111	IR, LBLOCA or RC-LBLOCA at 3568 gpm.
Indian Point	2	1.026	VC, 6 Inch or RC-6 Inch Break LOCA at 3221 gpm.
Indian Point	3	0.214	IR, LBLOCA or RC-LBLOCA at 4149 gpm.
Indian Point	3	0.101	VC, 6 Inch or RC-6 Inch Break LOCA at 1226 gpm.

Plant Name	Unit	Clean HL, ft	Comments
Kewaunee	1	0.365	
McGuire	1	5.71	For the maximum recirculation flow condition (four trains) at 60°F.
McGuire	1	3.79	For single train RHR/two-train CS operation at 60°F.
McGuire	2	5.99	For the maximum recirculation flow condition (four trains) at 60°F.
McGuire	2	3.91	For single train RHR/two-train CS operation at 60°F.
Millstone	2	0.094	Calculated value for a total scaled testing flow rate of 6800 gpm
Millstone	3	0.382	The maximum clean strainer head loss at 100°F.
North Anna	1	0.970	LHSI, clean strainer head loss.
North Anna	1	1.500	RS, short term.
North Anna	1	1.000	RS, long term.
North Anna	2	0.740	LHSI, clean strainer head loss.
North Anna	2	1.500	RS, short term.
North Anna	2	1.000	RS, long term.
Oconee	1	0.006	Clean strainer head loss at 349 gpm and 54°F.
Oconee	2	0.006	Clean strainer head loss at 349 gpm and 54°F.
Oconee	3	0.006	Clean strainer head loss at 349 gpm and 54°F.
Palisades	1	1.026	Calculated values at 212°F and 3591 gpm.
Palo Verde	1	0.081	Value at a at a flow rate of 11,600 gpm; as the flow rate decreases to 6600 gpm, the head loss also decreases to 0.026 ft.
Palo Verde	2	0.081	Value at a at a flow rate of 11,600 gpm; as the flow rate decreases to 6600 gpm, the head loss also decreases to 0.026 ft.
Palo Verde	3	0.081	Value at a at a flow rate of 11,600 gpm; as the flow rate decreases to 6600 gpm, the head loss also decreases to 0.026 ft.
Point Beach	1	0.590	Calculated value at minimum sump temperature of 72°F. Calculated value is 212°F and design flow rate is 0.41 ft.
Point Beach	2	0.590	Calculated value at minimum sump temperature of 72°F. Calculated value is 212°F and design flow rate is 0.41 ft.
Prairie Island	1	0.020	
Prairie Island	2	0.020	
Robinson	2	1.585	The head loss through the strainer was calculated as 1.585 ft of water, which includes 0.021 ft of water for the head loss through a top hat.
Salem	1	2.880	At the two pump operation flow rate was 8850 gpm; the head loss through the strainer train and into the suction box.
Salem	2	2.880	At the two pump operation flow rate was 8850 gpm; the head loss through the strainer train and into the suction box.
San Onofre	2	0.230	At 60°F; calculated results; the individual top hat strainer head loss is not considered part of the "clean strainer head loss," since it is included in the prototypical strainer head loss testing results.
San Onofre	3	0.230	At 60°F; calculated results; the individual top hat strainer head loss is not considered part of the "clean strainer head

Plant Name	Unit	Clean HL, ft	Comments
			loss," since it is included in the prototypical strainer head loss testing results.
Seabrook	1	0.353	At 8050 gpm; this value is total head loss including plenum, etc.
Sequoyah	1	1.936	Tall stacks C and E, total strainer head loss including strainer assembly and discharge flow plenum.
Sequoyah	2	1.936	Tall stacks C and E, total strainer head loss including strainer assembly and discharge flow plenum.
Shearon Harris	1	0.120	The value of 0.12 ft for the clean strainer head loss was determined by prototype testing performed by Enercon with the debris bypass eliminator included. The clean strainer head losses, as determined by chemical-effects testing performed by Alion at the design flow rate, were 0.0404, 0.0443, and 0.0459 ft (for three tests with the debris bypass eliminator), and 0.0163 ft (for one test without the debris bypass eliminator).
South Texas	1	1.950	At 128°F.
South Texas	2	1.950	At 128°F.
St. Lucie	1	5.870	A calculated value for clean system head loss at 65°F. A clean strainer disc head loss of 0.107 ft was determined by testing. The total clean system head loss is 0.107 ft plus 1.854 or 1.961 ft.
St. Lucie	2	3.603	Worst-case single failure scenario. Including 10% uncertainty margin.
Summer	1	0.021	Calculated value (reported as 0.009 psi).
Surry	1	1.690	RS, analytical value at 170°F.
Surry	1	0.900	LHSI, analytical value at 170°F.
Surry	2	1.690	RS, analytical value at 170°F.
Surry	2	0.900	LHSI, analytical value at 170°F.
Three Mile Island	1	0.151	At 8800 gpm; this is the total head loss due to the strainer assembly support structure and the “top hat” modules including the DBE up to but not including the entrance loss to the suction pipes.
Turkey Point	3	0.090	At 3750 gpm.
Turkey Point	4	0.480	At 3750 gpm and 170°F.
Vogtle	1	0.175	RHR
Vogtle	2	0.175	RHR
Waterford	3	0.230	At 210°F.
Waterford	3	0.290	At 90°F.
Watts Bar	1	3.620	Calculated value.
Watts Bar	2	0.338	
Wolf Creek	1	0.642	Calculated value at 212°F; tested value is 0.3178 ft at 114.5°F.

Table A.2-9. Non-chemical Head Loss

Plant Name	Unit	Non-chemical HL, ft	Comments
ANO	1	0.917	Maximum head loss of 11".
ANO	2	0.870	Two-train HPSI and CSS pump flows with partial debris loading (conservatively applied as three days recirculation) and no chemical effects.
Beaver Valley	1	4.25	Total Debris and Strainer Head Loss at 212°F.
Beaver Valley	2	5.45	Total Debris and Strainer Head Loss at 212°F.
Braidwood	1	2.280	Reported as 68.1 mbar.
Braidwood	2	2.280	Reported as 68.1 mbar.
Byron	1	2.280	Reported as 68.1 mbar.
Byron	2	2.280	Reported as 68.1 mbar.
Callaway	1		Value not stated.
Calvert Cliffs	1	0.2743	Fiber/participate head loss for 5,000 gpm (strainer nominal flow rate - p. 21) = 8.2 mbar.
Calvert Cliffs	2	0.2743	Fiber/participate head loss for 5,000 gpm (strainer nominal flow rate - p. 21) = 8.2 mbar.
Catawba	1		Not specified.
Catawba	2		Not specified.
Comanche Peak	1	0.472	Calculated design value at 120°F.
Comanche Peak	1	0.607	Experimentally measured value at an average temperature of 95.1°F.
Comanche Peak	2	0.472	Calculated design value at 120°F.
Comanche Peak	2	0.607	Experimentally measured value at an average temperature of 95.1°F.
Crystal River	3		Not specified.
Davis Besse	1		Head loss testing not performed. No calculated value reported.
D.C. Cook	1	2.670	Unit I Loop 4 DEGB.
D.C. Cook	2	4.430	Unit 2 Loop 4 DEGB.
Diablo Canyon	1		Not specified.
Diablo Canyon	2		Not specified.
Farley	1	0.103	RHR A-Train, Debris Head Loss.
Farley	1	0.103	RHR B-Train, Debris Head Loss.
Farley	1	0.112	CSS A-Train, Debris Head Loss.
Farley	1	0.199	CSS B-Train, Debris Head Loss.
Farley	2	0.103	RHR A-Train, Head loss by fiber debris strainer only.
Farley	2	0.103	RHR B-Train, Head loss by fiber debris strainer only.
Farley	2	0.112	CSS A-Train, Head loss by fiber debris strainer only.
Farley	2	0.172	CSS B-Train, Head loss by fiber debris strainer only.
Fort Calhoun	1	2.440	LBLOCA 0.125 in thin bed testing; includes debris and clean head losses.

Plant Name	Unit	Non-chemical HL, ft	Comments
Ginna	1	0.990	95.2 mbar at 20°C was taken as the maximum sump strainer head loss due to debris on the strainer. This value is equivalent to 29.7 mbar (0.99 ft WC) corrected to the minimum containment recirculation pool design temperature of 195°F.
Indian Point	2	3.070	Maximum measured value.
Indian Point	3	3.070	Maximum measured value.
Kewaunee	1		Value not stated.
McGuire	1		Not specified.
McGuire	2		Not specified.
Millstone	2	0.059	Unit conversion: the maximum head loss for the worst-case debris load is 0.35 psi.
Millstone	3	5.382	The maximum debris bed head loss (5.1 ft) plus the maximum clean strainer head loss of 0.382 ft.
North Anna	1	1.707	LHSI test results prior to Al addition (0.74 psi). Debris bed only.
North Anna	1	0.692	RS test results prior to Al addition (0.3 psi). Debris bed only.
North Anna	2	1.707	LHSI test results prior to Al addition (0.74 psi). Debris bed only.
North Anna	2	0.692	RS test results prior to Al addition (0.3 psi). Debris bed only.
Oconee	1	0.026	Nominal debris loaded loss corrected to 212°F, based on Unit 1 scaling (largest HL).
Oconee	2	0.026	Nominal debris loaded loss corrected to 212°F, based on Unit 1 scaling (largest HL).
Oconee	3	0.026	Nominal debris loaded loss corrected to 212°F, based on Unit 1 scaling (largest HL).
Palisades	1		Value not stated.
Palo Verde	1		Not specified.
Palo Verde	2		Not specified.
Palo Verde	3		Not specified.
Point Beach	1	3.066	Corrected to 212°F (design basis). Numerous other head loss values are given on pp. 21, 22, 26, 48, 55, 60, 66, and 135 of ML092150636.
Point Beach	2	3.066	Corrected to 212°F (design basis). Numerous other head loss values are given on pp. 21, 22, 26, 48, 55, 60, 66, and 135 of ML092150636.
Prairie Island	1		Value not stated.
Prairie Island	2		Value not stated.
Robinson	2	3.385	Clean (1.585) + 1.8 ft debris only, adjusted for viscosity at 212°F (saturation temperature at 0 psig).
Salem	1	1.090	In Test 5 for Unit 1, the maximum head loss observed prior to the addition of chemical precipitates was 32.5 mbar (1.09 ft) at a temperature of 41.3°C (106°F). This is not total strainer head loss. Total is sum of this value and component head loss.

Plant Name	Unit	Non-chemical HL, ft	Comments
Salem	2	8.100	In Test 6 for Unit 2, the maximum head loss observed prior to the addition of chemical precipitates was 242.2 mbar (8.1 ft) at a temperature of 47.6°C (118°F). This is not total strainer head loss. Total is sum of this value and component head loss.
San Onofre	2	0.330	Mineral wool head loss testing.
San Onofre	3	0.330	Mineral wool head loss testing.
Seabrook	1		Not specified.
Sequoyah	1	0.245	Short, Total Strainer Head Loss.
Sequoyah	1	1.970	Tall, Total Strainer Head Loss.
Sequoyah	2	0.245	Short, Total Strainer Head.
Sequoyah	2	1.970	Tall, Total Strainer Head.
Shearon Harris	1	0.140	At 83°F.
South Texas	1		Not specified.
South Texas	2		Not specified.
St. Lucie	1	1.920	Strainer head loss, at 210°F.
St. Lucie	2	4.019	Clean+debris bed. Worst-case single failure scenario. Including 10% uncertainty margin.
Summer	1	6.280	Experimentally determined value at 104°F. Reported as 2.72 psid.
Surry	1	0.600	RS, Experimental value (no temperature stated). Reported as 0.26 psid.
Surry	1	0.250	LHSI, Experimental value (no temperature stated). Reported as 0.11 psid.
Surry	2	0.600	RS, Experimental value (no temperature stated). Reported as 0.26 psid.
Surry	2	0.250	LHSI, Experimental value (no temperature stated). Reported as 0.11 psid.
Three Mile Island	1		Not specified.
Turkey Point	3		Value not stated.
Turkey Point	4		Value not stated.
Vogtle	1		Value not stated.
Vogtle	2		Value not stated.
Waterford	3		Not specified.
Watts Bar	1	3.65	"Long" Strainer Type "A", Total Strainer Head Loss with temperature correction for post-LOCA temperatures applied.
Watts Bar	1	3.62	"Short" Strainer Type "B", Total Strainer Head Loss with temperature correction for post-LOCA temperatures applied.
Watts Bar	2	1.24	Total strainer head loss (clean + debris) with temperature correction.
Wolf Creek	1		Not specified.

Table A.2-10. Full Debris Head Loss

Plant Name	Unit	Full HL, ft	Comments
ANO	1	8.000	Maximum value.
ANO	2	3.400	For two-train HPSI and CSS pump flows with full 30-day debris loading and chemical effects (3.23 measured with 3.4 ft credited).
Beaver Valley	1	4.250	Calculated value at 212°F, based on the maximum head loss from the several debris mixes tested in the prototype strainer at the maximum expected sump flow rate.
Beaver Valley	2	5.450	Calculated value at 212°F, based on prototype testing with the plant specific debris loading including chemical effects, at the maximum expected sump flow rate.
Beaver Valley	2	2.680	Experimental head loss based upon Test 5 (approach velocity of 0.0104 ft/sec, corrected to 212°F).
Braidwood	1	2.760	Reported as 82.4 mbar.
Braidwood	2	2.760	Reported as 82.4 mbar.
Byron	1	2.760	Reported as 82.4 mbar.
Byron	2	2.760	Reported as 82.4 mbar.
Callaway	1		Value not stated.
Calvert Cliffs	1	23.750	The maximum head loss across the strainer perforated material and the accumulated debris including chemical precipitates is 710 millibar (10.2 psi) 700 millibar for the debris bed and strainer perforated face, and 10 millibar for the head loss.
Calvert Cliffs	2	23.750	The maximum head loss across the strainer perforated material and the accumulated debris including chemical precipitates is 710 millibar (10.2 psi) 700 millibar for the debris bed and strainer perforated face, and 10 millibar for the head loss.
Catawba	1	8.200	The maximum projected head loss at 30 days and 90°F with maximum flow rate of 16,000 gpm.
Catawba	2	8.200	The maximum projected head loss at 30 days and 90°F with maximum flow rate of 16,000 gpm.
Comanche Peak	1	1.742	Calculated design value at 120°F.
Comanche Peak	2	1.742	Calculated design value at 120°F.
Crystal River	3		"<0.1" is provided as the head loss based on head loss testing results at about 90°F.
Davis Besse	1		Head loss testing not performed. No calculated value reported.
D.C. Cook	1	3.830	
D.C. Cook	2	6.800	
Diablo Canyon	1	3.417	33 in. for the strainer screen and 8 in. for the strainer plenum; the maximum measured head loss was 31.5 in. during Test 11-S-PSG.
Diablo	2	3.417	33 in. for the strainer screen and 8 in. for the strainer plenum;

Plant Name	Unit	Full HL, ft	Comments
Canyon			the maximum measured head loss was 31.5 in. during Test 11-S-PSG.
Farley	1	3.530	Temperature-adjusted chemical effects head loss value is 42.4/12=3.53 ft at 120°F. Tested value is 4.61 ft at 96.3°F.
Farley	2	3.530	Temperature-adjusted chemical effects head loss value is 42.4/12=3.53 ft at 120°F. Tested value is 4.61 ft at 96.3°F.
Fort Calhoun	1	3.380	SBLOCA with chemical precipitates; The SBLOCA "not scaled for temperature" test head loss is 5.88 ft (70.6 in.) at 100°F; 3.38 ft was partially scaled to the plant head loss at 196.6°F.
Ginna	1	1.12	Total head loss (clean strainer + debris) under worst case conditions, at a flow rate of 2300 gpm.
Indian Point	2	21.880	Maximum measured extrapolated value.
Indian Point	3	21.880	Maximum measured extrapolated value.
Kewaunee	1	3.280	
McGuire	1	15.700	The maximum projected head loss at 30 days and 90°F with maximum flow rate of 16,000 gpm.
McGuire	2	15.700	The maximum projected head loss at 30 days and 90°F with maximum flow rate of 16,000 gpm.
Millstone	2	2.400	1.04 psi; maximum value in test.
North Anna	1	2.650	LHSI, Short term (after two sump turnovers), 0.93 clean + 1.72 debris bed.
North Anna	1	8.370	LHSI, Long term, 0.93 clean + 7.44 debris bed.
North Anna	1	2.210	RS, Short term, 1.5 clean + 0.71 debris bed.
North Anna	1	7.280	RS, Long term, 1.0 clean + 6.28 debris bed.
North Anna	2	2.650	LHSI, Short term (after two sump turnovers), 0.93 clean + 1.72 debris bed.
North Anna	2	8.370	LHSI, Long term, 0.93 clean + 7.44 debris bed.
North Anna	2	2.210	RS, Short term, 1.5 clean + 0.71 debris bed.
North Anna	2	7.280	RS, Long term, 1.0 clean + 6.28 debris bed.
Oconee	1	0.014	Clean + fiber, particulates, and chemicals; as adjusted to 235.4°F.
Oconee	2	0.014	Clean + fiber, particulates, and chemicals; as adjusted to 235.4°F.
Oconee	3	0.014	Clean + fiber, particulates, and chemicals; as adjusted to 235.4°F.
Palisades	1	1.310	Calculated value at 212°F and 3591 gpm.
Palisades	1	4.820	Calculated value at 212°F and 6894 gpm.
Palisades	1	0.740	Experimental value at 111.6°F.
Palo Verde	1	4.330	The total calculated head loss is 4.33 ft WC for the design temperature of 193.8°F (the margin is lowest at 193.8°F).
Palo Verde	2	4.330	The total calculated head loss is 4.33 ft WC for the design temperature of 193.8°F (the margin is lowest at 193.8°F).
Palo Verde	3	4.330	The total calculated head loss is 4.33 ft WC for the design temperature of 193.8°F (the margin is lowest at 193.8°F).
Point Beach	1	3.474	Experimental value corrected to 212°F (design basis). Numerous other head loss values are given on pp. 21, 22, 26,

Plant Name	Unit	Full HL, ft	Comments
			48, 55, 60, 66, and 135 of ML092150636.
Point Beach	2	3.474	Experimental value corrected to 212°F (design basis). Numerous other head loss values are given on pp. 21, 22, 26, 48, 55, 60, 66, and 135 of ML092150636.
Prairie Island	1	12.115	Test #2 (twice the design basis debris loading). Measured value at 50.1°F.
Prairie Island	1	7.766	Test #1. Measured value at 48.0°F.
Prairie Island	2	12.115	Test #2 (twice the design basis debris loading). Measured value at 50.1°F.
Prairie Island	2	7.766	Test #1. Measured value at 48.0°F.
Robinson	2	5.100	Clean + debris + chemical; adjusted for viscosity at 212°F (saturation temperature at 0 psig).
Salem	1	4.750	In Test 5 for Unit 1, the maximum head loss prior to observing the bore hole which led to the largest pressure drop was 142.0 mbar (4.75 ft) at a temperature of 46.2°C (115°F). This is not total strainer head loss. Total is sum of this value and component head loss.
Salem	2	9.780	In Test 6 for Unit 2, the maximum head loss prior to observing bore holes was 292.5 mbar (9.78 ft) at a temperature of 45.0°C (113°F). This is not total strainer head loss. Total is sum of this value and component head loss.
San Onofre	2	9.960	Mineral wool debris head loss testing; the maximum measured head loss was 9.31 ft, and extrapolated value was 9.99 ft. Corrected value for flow and temperature is 9.96 ft at 122°F. Full head loss is then 9.96 + 0.23 = 10.19 ft at 122°F.
San Onofre	2	4.140	Mineral wool debris head loss testing; corrected value for flow and temperature is 4.14ft at 202˚F. Full head loss is then 4.14 + 0.23 = 4.37ft at 202°F.
San Onofre	3	9.960	Mineral wool debris head loss testing; the maximum measured head loss was 9.31 ft, and extrapolated value was 9.99 ft. Corrected value for flow and temperature is 9.96 ft at 122°F. Full head loss including everything is then 9.96 + 0.23 =10.19 ft at 122°F.
San Onofre	3	4.140	Mineral wool debris head loss testing; corrected value for flow and temperature is 4.14ft at 202˚F. Full head loss is then 4.14 + 0.23 = 4.37 ft at 202°F.
Seabrook	1	0.643	At 8050 gpm; this value is a total head loss including plenum, etc.
Sequoyah	1		Detailed evaluations of chemical sump blockage effects are not warranted for Sequoyah, as would be the case if a fiber bed could form on the sump strainer surface. A 10% percent increase in the strainer debris head loss was applied.
Sequoyah	2		Detailed evaluations of chemical sump blockage effects are not warranted for Sequoyah, as would be the case if a fiber bed could form on the sump strainer surface. A 10% percent increase in the strainer debris head loss was applied.

Plant Name	Unit	Full HL, ft	Comments
Shearon Harris	1	2.340	Total; adjusted to 212°F to be consistent with the NPSH calculations; determined for the limiting break.
South Texas	1	6.504	At 171°F, 24 hr post-LOCA.
South Texas	1	8.745	For the design-basis debris test, the maximum corrected head loss (excluding clean strainer head loss and piping losses) was 8.745 ft at a flow rate of 355.857 gpm at a corrected temperature of 116.3°F.
South Texas	2	6.504	At 171°F, 24 hr post-LOCA.
South Texas	2	8.745	For the design-basis debris test, the maximum corrected head loss (excluding clean strainer head loss and piping losses) was 8.745 ft at a flow rate of 355.857 gpm at a corrected temperature of 116.3°F.
St. Lucie	1	9.780	The total head loss, including piping/plenum, at 210°F.
St. Lucie	2	4.019	Clean + debris bed. Worst-case single failure scenario. Including 10% uncertainty margin.
Summer	1	3.150	Experimentally determined value at 104°F.
Surry	1	3.100	RS, experimental value at 196°F.
Surry	1	1.770	LHSI, experimental value at 175°F.
Surry	2	3.100	RS, experimental value at 196°F.
Surry	2	1.770	LHSI, experimental value at 175°F.
Three Mile Island	1	1.700	The total strainer head loss including the impact of calcium phosphate precipitants is 1.7 ft at 83°F and a flow rate of 8800 gpm. This head loss value applies for sump temperatures above 140°F.
Three Mile Island	1	21.300	The total strainer head loss including the impact of calcium phosphate and aluminum precipitants is 21.3 ft at 85°F and a flow rate of 8800 gpm. This head loss value applies for sump temperatures below 140°F.
Three Mile Island	1	15.600	Maximum Strainer Head (Case I: Maximum Reactor Building Cooling).
Three Mile Island	1	12.100	Maximum Strainer Head (Case I: EQ Reactor Building Cooling).
Turkey Point	3	3.829	Value at 3750 gpm.
Turkey Point	4	0.628	Value at 3750 gpm and 170°F.
Vogtle	1	8.460	
Vogtle	2	8.460	
Waterford	3	3.95	At 90°F with additional margin.
Waterford	3	2.09	At 210°F with additional margin.
Watts Bar	1		No information found. "…will be addressed by implementing the test tank protocol similar to the protocol shown in Enclosure 3."
Watts Bar	2	1.428	Total strainer head loss with temperature correction for Post-LOCA temperatures applied (includes CSHL).
Wolf Creek	1	1.724	Testing of the design basis scenario (Test 3B) determined the

Plant Name	Unit	Full HL, ft	Comments
			temperature corrected head loss with the scaled RHR and CSS flow at 212°F was 1.724 ft of water.

Net Positive Suction Head (NPSH): NPSH Margin

The GL-04-02 database collected the information on the NPSH for each pump and for each reported scenario (such as SBLOCA). If provided, the information was recorded into the database for the required NPSH, available NPSH, and NPSH margin. If the NPSH margin is not provided, it is calculated in the database as available NPSH minus required NPSH.

Figure A.2-8 presents the range of the NPSH margin (either reported or calculated) for each plant. For three plants, the reported data were insufficient to calculate the NPSH margin. In some cases, for example, for Oconee plant, a negative NPSH margin value was provided in the GL-04-02 responses and was included in the database as such as it is showing in Figure A.2-8. (Note that Oconee has credit in their licenseing basis to use containment pressure to offset the short term deficit calculated using conservative methods. That type of information, however, is not included in the NPSH margin database)

Figure A.2-8 and several following figures show the data in the minimum/maximum range fashion. This form was selected for the presentation purposeds for this report only. In the actual database, several entires for each plant are allowed (such as NPSH margin for each pump). Since it would be impractical to plot each database entry for each plant, the figures below only show the range of the actual data recorded in the database as minimum and maximum values for each plant. In case of the NPSH margin, the minimum value is considered to be the most important parameter, such that the plants are sorted in Figure A.2-8 by the numimum value of NPSH margin in the database.

NPSH: Minimum Strainer Submergence

For this field, the minimum strainer submergence (usually, recorded in inches) was recorded for each plant and each case. Figure A.2-9 shows the range of the recorded strainer submergences for each plant.

NPSH: Submergence at Recirculation Switchover

The value of the strainer submergence (in %) at the time of the sump recirculation switchover was recorded in this field. For most plants, the GL-04-02 responses stated that the strainer is fully submerged at this point. In those cases, 100% was recorded in this field. Plants with partial strainer submergence, at least at some conditions (breaks), include Callaway-1, Comanche Peak 1 and 2, Diablo Canyon 1 and 2, Farley 1 and 2, Palisades-1, Sequyoah 1 and 2, and Watts Bar-1.

NPSH: Final Submergence

This field is similar to the previous one except the submergence is recorded for the final state. So far, full submergence was either reported by all plants or was assumed for the database entry.

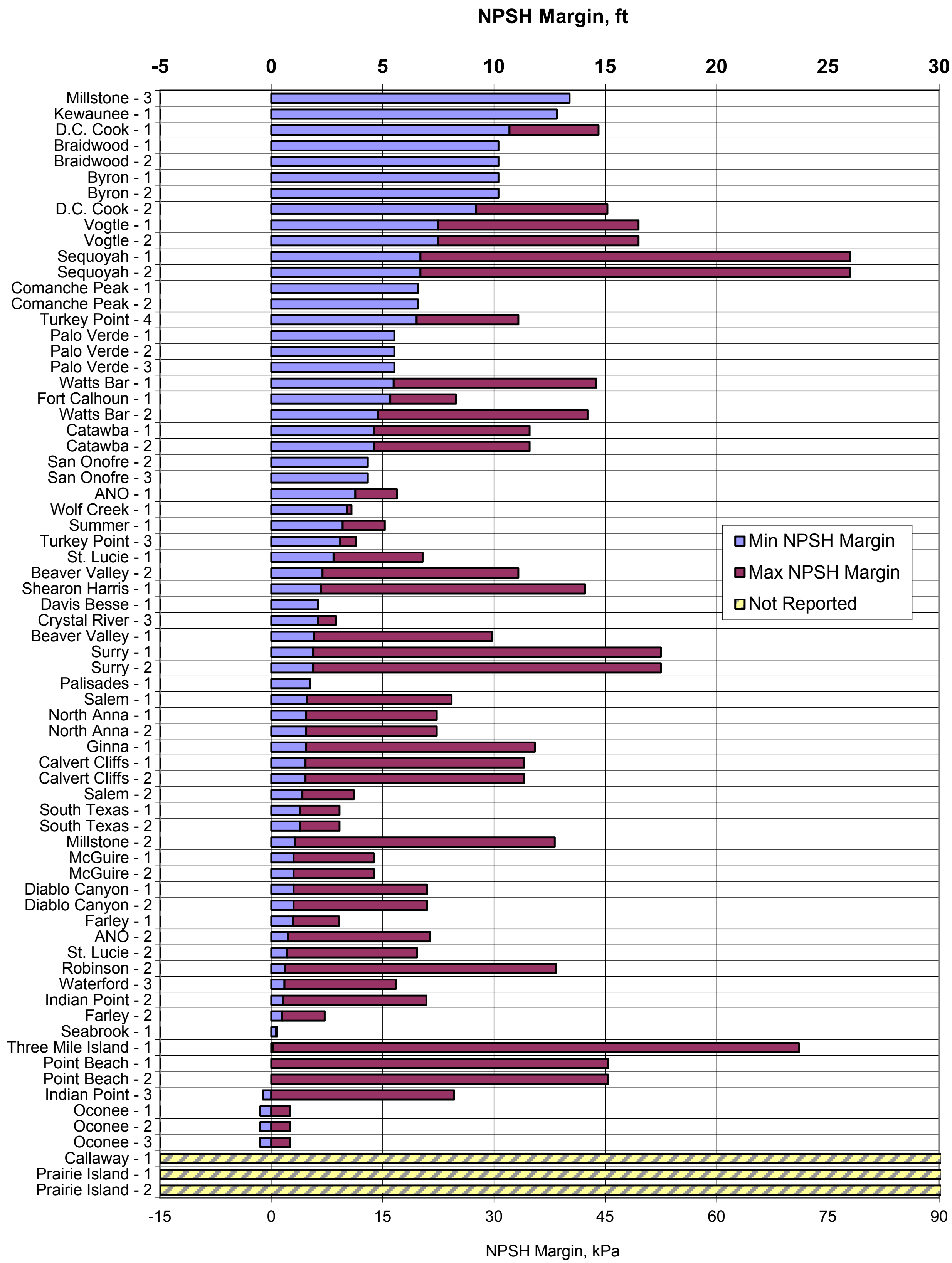

Figure A.2-8. NPSH Margin

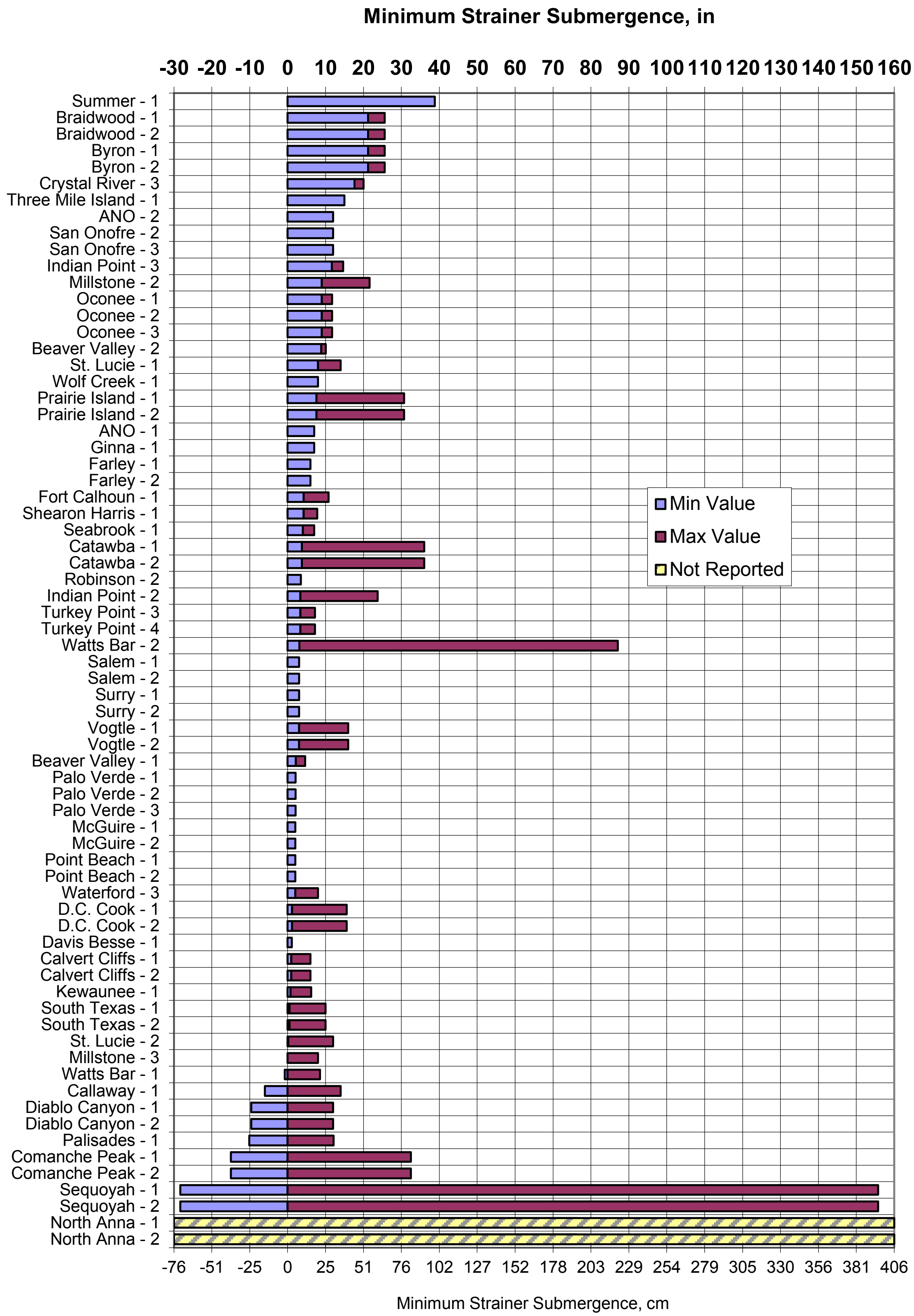

Figure A.2-9. Minimum Submergence

Debris: Latent Debris

In this field, the total amount of latent debris, as well as percentage of fiber, is recorded for each plant. Figure A.2-10 shows the total amount of the latent debris and its split between fiber and particulate as calculated by the database. Unlike previous plots, the bar lengths in Figure A.2-10 show the total amount of the debris, and the lengths for each color show the corresponding percentage of its components. For example, for ANO-1 plant, the total amount is 100 lbm, with 15 lbm of fiber and 85 lbm of particulate. To highlight this difference from other plots, the colors have been changed in this plot. For Calvert Cliffs plant the latent debris is stated to be all particulates.

Debris: Sacrificial Area

This field records the amount of the strainer area which is assumed to be not available for strainer operation due to foreign material (such as tags). The results are presented in Figure A.2-11. For Prairie Island plant, no data were reported for this field. Three other plants, St. Lucie-2, Wolf Creek-1, and Callaway-1, did not allow for any sacrificial area. Except for the D.C. Cook plant, all other plants reported the same sacrificial area for all their strainers, where applicable. The D.C. Cook plant reported separate values for its two strainers. Those values are shown as maximum/minimum in Figure A.2-11.

Debris: Scaling Factor

This field reports the ratio between the screen area used in tests and the original strainer screen area. If this value was reported in a GL-04-02 response, it was entered into the database directly. Otherwise, it was calculated as:

$$\text{Scaling factor} = \frac{\text{Test area}}{\text{Total strainer area} - \text{Sacrificial area}}$$

provided that all values in the above equation are available. Figure A.2-12 shows the scaling factors recorded in the GL-04-02 database. If one test was carried out to represent several strainers with different screen area, more than one entry was provided in the database, one for each scaling factor. Alternatively, several tests could be carried out with various screen areas of testing unit. In such cases, Figure A.2-12 shows the range (minimum and maximum values) of the scaling factors for a plant.

Debris: Amount

Several fields in the GL-04-02 database record the amount of the debris as used in the strainer analysis. The amount of the debris generated at a break is recorded in the Debris Amount – Analysis field for each type of the debris reported by a plant. If several break locations were analyzed, the worst case scenario (one that generates most debris) is selected for the database entry. Of that generated amount of debris, in general, only a fraction reaches the strainer. The latter amount, plus any possible margin for uncertainty, is used to determine the amount of the debris used for strainer testing. The Debris Amount – Test field records the amount of the debris used in the testing or the amount of the debris used to determine the testing conditions. There is a separate field in the database called Scaled? that specifies the meaning of the Debris Amount – Test field. If the value is Scaled? is Yes, that means that the debris amount was scaled for the testing conditions (with the scale factor described above). Otherwise, the Debris

Amount – Test field entry indicates the amount of the debris at full-size strainer (plus any uncertainty margin). Such logic was built-in into the GL-04-02 database since not all the plants reported the debris amount for the same conditions. In addition, the amounts of the debris are usually reported in different units, such that the debris units are recorded individually for each debris type. Also, in the situations where several break locations were analyzed, the worst case (usually meaning the most debris) was selected for the database entry.

Table A.2-11 shows an example of the debris amount data recorded for a single plant. Similar data were recorded for all other plants. The entire table is not reproduced here due to its large size – each plant reported 10 to 20 types of the debris, so the full table would include about 1000 lines. Table A.2-12 shows the surrogate debris types.

In addition to the type of the surrogate debris, the amount of the surrogate debris was also recorded where provided by the plants. The format is very similar to the Debris Amount – Test field described above.

Debris: Zone of Influence

The data on the debris zone of influence (ZOI) assumed for the strainer analysis were recorded in the database for each debris type. The recorded data are provided in Table A.2-13. In some cases, several ZOI values were used in different analysis for the same material, as indicated by multiple ZOI entires in Table A.2-13.

Debris: Chemical Buffer

The GL-04-02 database collected the information on the chemical (pH) buffer, including sodium hydroxide (NaOH), trisodium phosphate (TSP), and sodium tetraborate (STB). The information on whether a plant changed the buffer or its concentration in the response to the generic letter is also recorded in the database. The data on the chemical buffer is presented in Table A.2-14.

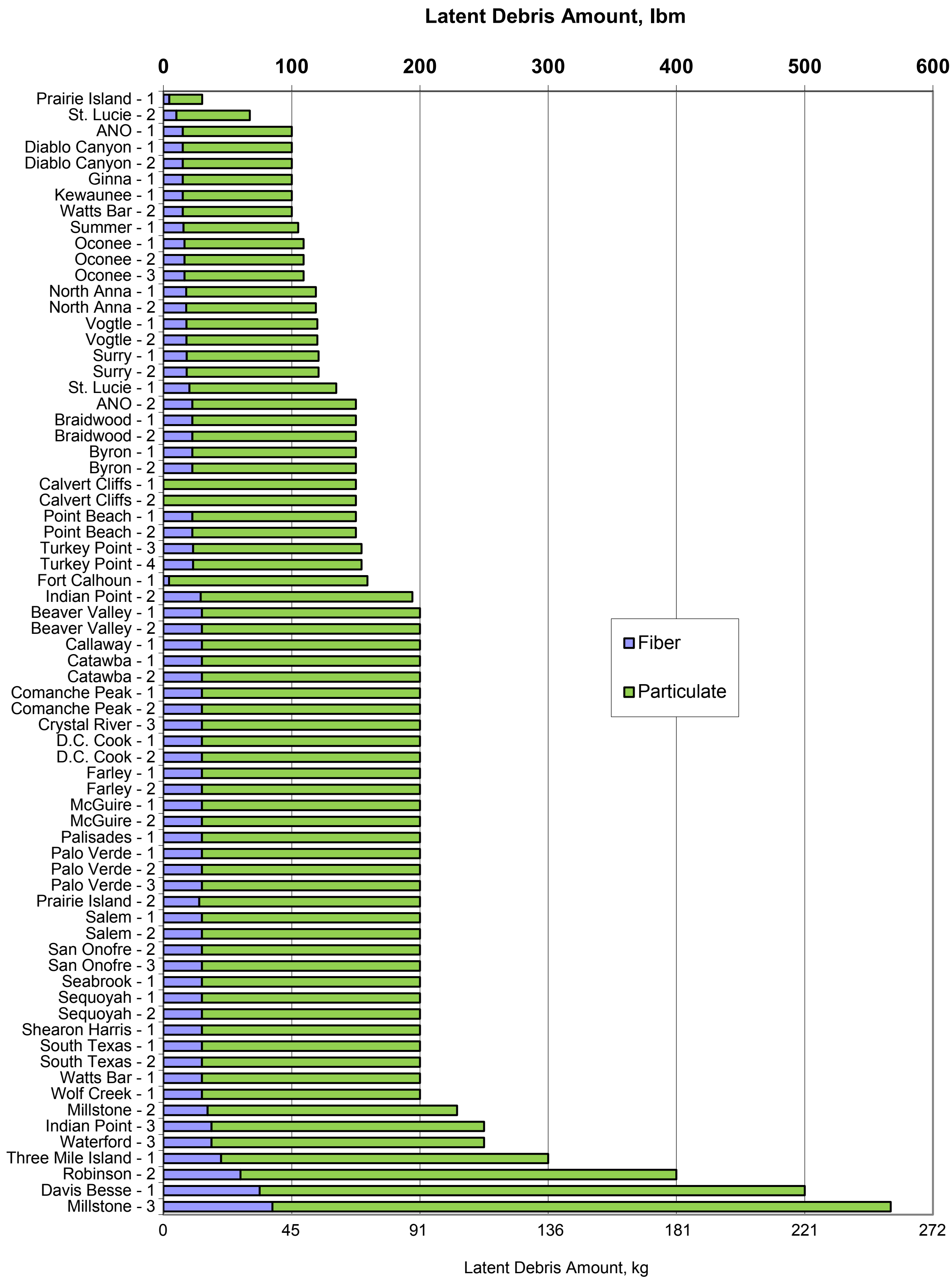

Figure A.2-10. Latent Debris Amount

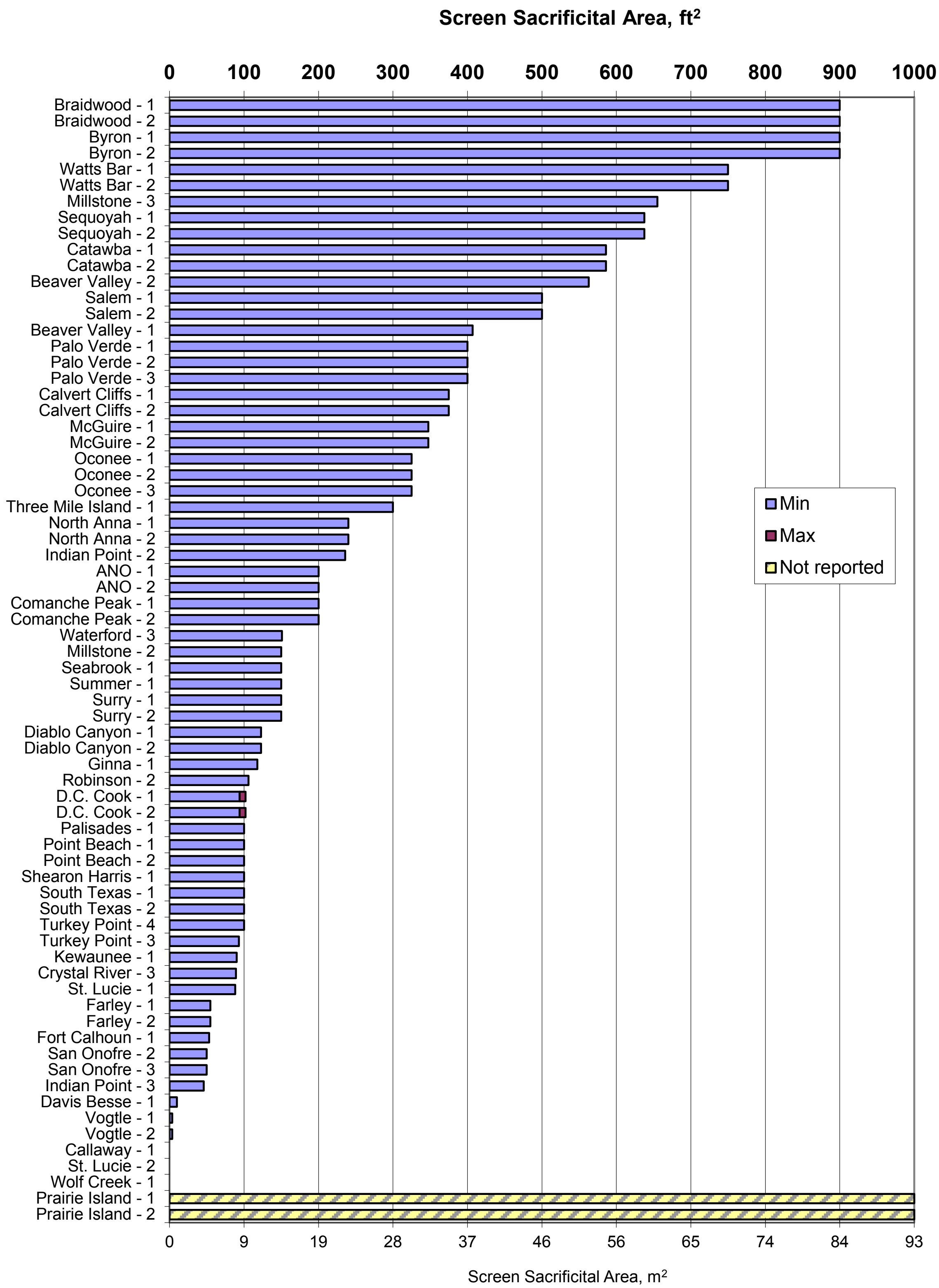

Figure A.2-11. Strainer Sacrificial Area

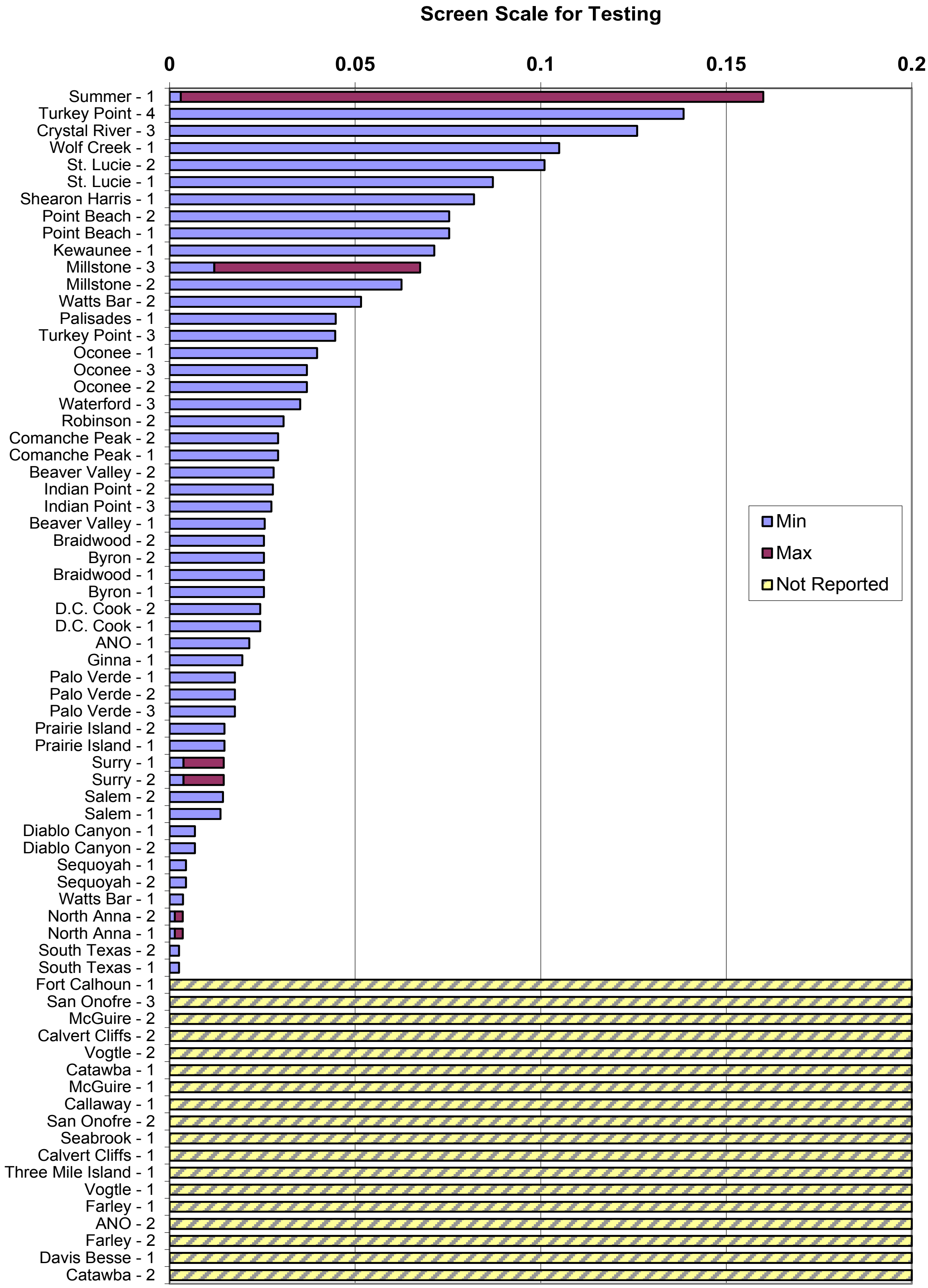

Figure A.2-12. Scale Factor for Testing

Table A.2-11. Example of the Debris Amount Data

Plant Name	Unit	Debris Type	Debris	Debris Amount (Analysis)	Debris Amount (Test)	Units	Scaled?
Millstone	2	Coatings	Qualified coatings	32.8	32.8	ft3	No
			Unqualified coatings	8.8	8.8	ft3	No
		Insulation	Claremont fiberglass	110.1	65.0	ft3	No
			Mineral fiber	297.3	297.3	ft3	No
			NUKON	1135.1	675.4	ft3	No
			Transco encapsulated mineral wool	159.4	159.4	ft3	No
			Transco RMI foil	1239.6	885.5	ft2	No
	3	Coatings	Margin for coatings		2.1	ft3	No
			Qualified concrete coatings	1.5	1.5	ft3	No
			Qualified steel coatings	8.9	8.9	ft3	No
			Unqualified coatings	10.5	10.5	ft3	No
		Insulation	Microtherm	1.1	1.2	ft3	No
			Transco thermal wrap	1219.0	755.2	ft3	No

Table A.2-12. Surrogate Debris Types

Surrogate	Debris	Debris Type	Plant Name	Unit
Acrylic chips	Degraded epoxy	Coatings	Point Beach	2
	Epoxy chips	Chips	South Texas	1
				2
	Other unqualified coatings	Unqualified coatings	Palisades	1
Acrylic coating	Qualified concrete and unqualified coatings		St. Lucie	1
Acrylic powder	Alkyd	Unqualified coatings	Palisades	1
	Aluminum paint	Qualified coatings	Palisades	1
	Carboline 3912	Qualified coatings	Palisades	1
	Carboline 890	Qualified coatings	Palisades	1
	Carboline-Flexxide thinner	Qualified coatings	Palisades	1
	Carboline-Multibond 120	Qualified coatings	Palisades	1

Surrogate	Debris	Debris Type	Plant Name	Unit
	Qual. epoxy	Coatings	Comanche Peak	1
				2
	Qual. Silicone	Coatings	Comanche Peak	1
				2
	Unqual. Alkyd	Coatings	Comanche Peak	1
				2
Aluminum	Aluminum		Turkey Point	3
Aluminum hydroxide	Aluminum hydroxide	Chemical	Prairie Island	1
				2
Aluminum Oxyhydroxide	AlOOH Precipitate	Chemical	Comanche Peak	1
				2
	Aluminum Oxyhydroxide	Chemical	Crystal River	3
			Diablo Canyon	1
				2
			Farley	1
				2
			Palo Verde	1
				2
				3
			Salem	1
				2
			San Onofre	2
				3
			Seabrook	1
			St. Lucie	2
			Three Mile Island	1
			South Texas	1
				2
		Chem. Precip.	Beaver Valley	1
				2
	NaAlSi308 Precipitate	Chemical	Comanche Peak	1
				2
	Sodium aluminum silicate	Chemical	St. Lucie	2
			Turkey Point	4
			Wolf Creek	1
			South Texas	1
				2
		Chemical debris	Kewaunee	1
Amerlock 400 NT	Phenolic paint chips	Particulate	Watts Bar	1
	Phenolic, alkyd and silicone coatings	Coatings	Watts Bar	2

Surrogate	Debris	Debris Type	Plant Name	Unit
	(chips)			
Ameron 90HS		Chips	Farley	1
				2
Boric acid	Boric acid	Chemical	Turkey Point	3
Cable insulation	Cable insulation	Fibrous	Kewaunee	1
Calcium carbonate	Calcium carbonate	Chemical	Prairie Island	1
				2
Calcium Phosphate	Calcium phosphate	Chemical	Crystal River	3
			Farley	1
				2
			Palo Verde	1
				2
				3
			San Onofre	2
				3
			St. Lucie	2
			Three Mile Island	1
			Waterford	3
			South Texas	1
				2
Calcium Silicate			Indian Point	2
				3
	Cal-Sil	Insulation	Turkey Point	4
	Calcium silicate	Fibrous	ANO	1
				2
			Beaver Valley	1
				2
	Cal-Sil		Diablo Canyon	1
				2
		Insulation	Point Beach	2
			Turkey Point	3
		Particulate	Fort Calhoun	1
Calcium Silicate Powder	Cal-Sil		St. Lucie	1
		Particulates	St. Lucie	2
Calcium Silicate smalls and powder	Calcium silicate cloth jacketed	Insulation	Palisades	1
	Calcium silicate jacketed	Insulation	Palisades	1
Carboline "Special Zinc Filler"	Qualified, unqualified, and damaged IOZ coatings	Particulate	Palo Verde	1
				2
				3
Carbon steel	Carbon steel		Turkey Point	3
Cerafiber	Asbestos		Surry	1
				2
	Cerafiber	Fibrous	Fort Calhoun	1

Surrogate	Debris	Debris Type	Plant Name	Unit
Ceramic fiber	Asbestos	Insulation	Point Beach	2
Chips (Carboline CarboGuard 890/891 epoxy coating, or similar type coating)	Epoxy, curled chips (1.5 in)	Chips	Wolf Creek	1
	Epoxy, fine chips (1/64 in)	Chips	Wolf Creek	1
Coating chips	Unqualified Alkyd and high heat Aluminum coatings	Chips	Diablo Canyon	1
				2
	Unqualified non-OEM alkyd (outside ZOI)	Particulate	D.C. Cook	1
				2
	Unqualified non-OEM epoxy (outside ZOI)	Particulate	D.C. Cook	1
				2
	Unqualified OEM alkyd (outside ZOI),	Particulate	D.C. Cook	1
				2
	Unqualified OEM epoxy (outside ZOI)	Particulate	D.C. Cook	1
				2
Concrete	Concrete		Turkey Point	3
Dirt			Indian Point	2
				3
	Latent particulate	Latent	Prairie Island	1
				2
Dirt and dust	Latent debris	Particulate	Turkey Point	4
	Latent particulate	Particulate	Waterford	3
Electro Carb black silicon carbide	Qualified epoxy coatings	Particulate	Fort Calhoun	1
Epoxy 4500 chips	Epoxy	Unqualified coatings	Summer	1
Epoxy chips	Unqualified epoxy Fines (1/64 in.)	Coatings	Comanche Peak	1
				2
	Unqualified epoxy fines (1/8"-1/4", 1/4"-1/2", 1/2"-1")	Coatings	Comanche Peak	1
				2
	Unqualified epoxy fines (6 mil)	Coatings	Comanche Peak	1
				2
	Unqualified epoxy large (I "-2")	Coatings	Comanche Peak	1
				2
Epoxy particulate with a median particle size of 10 microns	Qualified coatings	Coatings	Calvert Cliffs	1
				2
Fiber through debris chipper	NUKON (Smalls)	Fibers	St. Lucie	2
	NUKON larges	Fibrous	Wolf Creek	1
	NUKON smalls	Fibrous	Wolf Creek	1
Fiber through debris shredder	Latent fiber	Fibrous	Wolf Creek	1
	NUKON (Fines)	Fibers	St. Lucie	2

Surrogate	Debris	Debris Type	Plant Name	Unit
	NUKON Fines	Fibrous	Wolf Creek	1
Fiber through debris shredder (15% Fiber)	Latent Fibers	Fibers	St. Lucie	2
Fiberglass	Fiberglass	Insulation	Point Beach	2
	Owens-Corning Fiberglass	Fibrous	Salem	1
				2
Fiberglass insulation	Fiberglass pipe cover	Fibrous	Kewaunee	1
Glass from fluorescent tube.	Light bulbs	Foreign material	Braidwood	1
Ground silica		Coatings	Shearon Harris	1
	Epoxy (inside ZOI)	Particulate	Beaver Valley	1
	Qualified Carboline 191 HB	Particulate	Beaver Valley	2
	Qualified coatings	Particulate	Crystal River	3
	Qualified IOZ	Particulate	Beaver Valley	2
	Qualified Nutec 11S Epoxy	Particulate	Beaver Valley	2
	Qualified Nutec 1201 epoxy	Particulate	Beaver Valley	2
	Vi Cryl CP-10 (inside ZOI)	Particulate	Beaver Valley	1
Ground silica and paint chips	Alkyd enamel (outside ZOI)	Particulate	Beaver Valley	1
	Cold galvananizing (outside ZOI)	Particulate	Beaver Valley	1
	Epoxy (outside ZOI)	Particulate	Beaver Valley	1
	IOZ paint (outside ZOI)	Particulate	Beaver Valley	1
	Unqualified Alkyd	Particulate	Beaver Valley	2
	Unqualified Carboline 191 HB	Particulate	Beaver Valley	2
	Unqualified Carboline 4674	Particulate	Beaver Valley	2
	Unqualified cold galvanizing	Particulate	Beaver Valley	2
	Unqualified IOZ coatings	Particulate	Beaver Valley	2
Ground silica/silicon carbide		Particulate	Three Mile Island	1
Ground silica/silicon oxide flour	Qualified & unqualified coatings	Particulate	Catawba	1
				2
			McGuire	1
				2
Ground silicon carbide	Qualified and unqualified coatings	Particulate	San Onofre	2
				3
High-density fiberglass	High-density fiberglass	Fibrous	ANO	1
IIG Thermo Gold	Cal-Sil	Particulate	Robinson	2

Surrogate	Debris	Debris Type	Plant Name	Unit
	Kaylo	Particulate	Robinson	2
	Thermo 12 insulation	Particulate	Robinson	2
Inorganic Zinc Filler	Cold galvanized zinc	Coatings	Summer	1
	Cold galvanizing	Unqual. Coatings	Summer	1
	Inorganic zinc	Coatings	Summer	1
		Unqualified coatings	Summer	1
	Zinc (MobilZinc 7)	Qualified coatings	Summer	1
Johns-Mansville Cal-Sil	Cal-Sil / Asbestos	Insulation	Surry	1
				2
Kaowool	Kaowool	Fibrous	Diablo Canyon	1
				2
			Salem	1
				2
Knauf ET fibers	Thermal-Wrap	Fibrous	South Texas	1
				2
Knauf Pipe Insulation	Mineral fiber	Insulation	Millstone	2
Labels	Electromark labels, outer laminate area	Labels	Comanche Peak	1
				2
	Electromark labels, sub-layer	Labels	Comanche Peak	1
				2
	Unqualified Labels	Labels	Comanche Peak	1
				2
Lead blanket covers fiberglass fines	Lead blanket covers fiberglass fines	Blanket cover	Comanche Peak	1
				2
Lead blanket covers fiberglass large	Lead blanket covers fiberglass large	Blanket cover	Comanche Peak	1
				2
Marinite	Marinite		Diablo Canyon	1
				2
		Particulate	South Texas	1
				2
Marinite I powder	Marinite XL	Particulate	Summer	1
Microtherm	Microtherm	Insulation	Turkey Point	3
			Millstone	3
		Particulate	South Texas	1
				2
Microtherm (pulverized powder)	Microtherm	Particulate	Waterford	3

Surrogate	Debris	Debris Type	Plant Name	Unit
Mineral Wool			Indian Point	2
				3
	Mineral Wool	Fibrous	Diablo Canyon	1
				2
			San Onofre	2
				3
		Insulation	Point Beach	2
Mineral wool fines	Mineral wool jacketed	Insulation	Palisades	1
Min-K	Min-K	Fibrous	Beaver Valley	1
				2
		Particulate	Salem	1
				2
	Min-K fines (fibrous)	Insulation	Comanche Peak	1
				2
	Min-K fines (particulate)	Insulation	Comanche Peak	1
				2
Min-K (pulverized powder)	Min-K	Particulate	Waterford	3
Min-K fiber	Min-K fiber	Insulation	Watts Bar	1
Mylar chips	Unqualified epoxy curled (1/2"-2")	Coatings	Comanche Peak	1
				2
Na tetraborate	Na tetraborate	Chemical	Turkey Point	3
NUKON			Indian Point	2
				3
		Fibrous	Catawba	1
				2
			Crystal River	3
			McGuire	1
				2
			Three Mile Island	1
			Beaver Valley	1
	3M-M20C fiber	Insulation	Watts Bar	1
	Fiberglass (fines)	Insulation	Comanche Peak	1
				2
	Fiberglass (jacketed)	Insulation	Comanche Peak	1
				2
	Fiberglass (large)	Insulation	Comanche Peak	1
				2
	Fiberglass (small)	Insulation	Comanche Peak	1
				2

Surrogate	Debris	Debris Type	Plant Name	Unit
	Fiberglass, Temp-Mat, Cerablanket, and Latent fiber	Fibrous	Diablo Canyon	1
				2
	Kaowool	Fibrous	Robinson	2
	Latent fiber	Fibrous	San Onofre	2
				3
		Latent	Indian Point	2
				3
			Point Beach	2
			Prairie Island	1
				2
			Watts Bar	1
	Low Density Fiberglass	Fibrous	Robinson	2
	Nukon	Fibrous	Salem	1
				2
		Insulation	Point Beach	2
			Turkey Point	3
	NUKON and Latent fiber	Fibrous	Palo Verde	1
				2
				3
			South Texas	1
				2
	Temp Mat	Fibrous	Robinson	2
NUKON (shredded)	Latent fiber	Latent fiber	Comanche Peak	1
				2
NUKON fiber		Fibrous	Seabrook	1
NUKON fiberglass	Fiberglass	Insulation	Surry	1
				2
NUKON fines		Fibrous	Beaver Valley	2
	Additional Fiber	Fiber	Waterford	3
	Latent debris, fiber	Latent	Palisades	1
	Latent fiber	Fibrous	Turkey Point	4
		Fiber	Waterford	3
	Nukon	Insulation	Turkey Point	4
		Fiber	Waterford	3
	Transco MEI	Fiber	Waterford	3
NUKON smalls and fines	NUKON thermal wrap jacketed	Insulation	Palisades	1
	NUKON unjacketed	Insulation	Palisades	1
Owens Corning Fiberglass Insulation		Fibrous	Oconee	1
				2
				3
Paint chips		Chips	Crystal River	3
	Alkyds	Unqualified	Prairie Island	1

Surrogate	Debris	Debris Type	Plant Name	Unit
		coatings		2
	Carboline 195	Qualified coatings	Prairie Island	1
				2
	Carboline Carbozinc 11	Qualified coatings	Prairie Island	1
				2
	Carboline Phenoline 305 finish	Qualified coatings	Prairie Island	1
				2
	Carboline Phenoline 305 primer	Qualified coatings	Prairie Island	1
				2
	Unqualified coatings	Chips	Fort Calhoun	1
Paroc 140E	Paroc	Insulation	Surry	1
				2
Paroc Mineral Wool	Paroc mineral wool	Fibrous	North Anna	1
				2
PCI Nukon	Claremont fiberglass	Insulation	Millstone	2
	Latent fiber	Latent	Millstone	2
	Nukon	Insulation	Millstone	2
PCI PWR dirt mix	Dirt/dust	Latent particulate	Comanche Peak	1
				2
	Latent debris, particulate	Latent	Palisades	1
	Latent particulate	Latent	Point Beach	2
		Particulate	Wolf Creek	1
PCI PWR Dirt Mix (85% of Latent Debris)	Latent particulate	Particulates	St. Lucie	2
Pre-shredded foils 0.05 mm (0.002 in.) thick.	Mirror RMI pieces	Insulation	Braidwood	1
				2
			Byron	1
				2
Pulverized acrylic coating powder	Epoxy coatings, polyamide primer coatings, alkyd coatings, and baked enamel coatings	Particulate	South Texas	1
				2
Pulverized Amerlock 400 epoxy coating	Qualified epoxy and Alkyd	Particulate	Palo Verde	1
				2
				3
PWR dirt mix	Latent dirt/dust	Particulate	Diablo Canyon	1
				2
PWR dirt mix and Fiberglass tape	Mica tape		Diablo Canyon	1
				2
RMI (large pieces)	RMI (large pieces)	Insulation	Comanche Peak	1
				2

Surrogate	Debris	Debris Type	Plant Name	Unit
RMI (small pieces)	RMI (small pieces)	Insulation	Comanche Peak	1
				2
RMI smalls	Transco RMI	Insulation	Palisades	1
Sand	Latent dirt/dust	Particulate	Palo Verde	1
				2
				3
SiC; Amerlock 400 NT	Alkyd paint	Particulate	Watts Bar	1
	Silicone paint	Particulate	Watts Bar	1
Sil-Co-Sil			Indian Point	2
				3
SIL-CO-SIL 53		Coatings	Robinson	2
SIL-CO-SIL 53 powder	Dense aluminum	Unqualified coatings	Palisades	1
Sil-Co-Sil Sand	Qualified and unqualified IOZ coatings	Particulate	Diablo Canyon	1
				2
Silica Sand		Latent	Robinson	2
	Dirt/dust	Particulate	Beaver Valley	1
				2
	Dust/dirt	Latent	Turkey Point	3
	Latent dirt/dust	Particulate	Catawba	1
				2
			Crystal River	3
			McGuire	1
				2
			South Texas	1
				2
Silicon Carbide		Particulate	Farley	1
				2
			Seabrook	1
	Coatings (non-zinc)	Particulate	Turkey Point	3
	Latent particulate	Latent	Indian Point	2
				3
		Particulate	ANO	1
	Phenolic paint particles	Particulate	Watts Bar	1
	Phenolic, alkyd and silicone coatings (particulates)	Coatings	Watts Bar	2
	Qualified and unqualified coatings	Coatings	Indian Point	2
				3
Silicon Carbide + Carboline 890 chips	Coatings (total)	Particulate	ANO	1
				2
Silicon Carbide 10-micron	Qualified coatings	Particulate	Waterford	3
	Unqualified Coatings	Particulate	Waterford	3
Silicon Carbide and Amerlock 400 NT	Alkyds	Coatings	Sequoyah	1
				2

Surrogate	Debris	Debris Type	Plant Name	Unit
	Phenolic	Coatings	Sequoyah	1
				2
	Silicone	Coatings	Sequoyah	1
				2
Silicon carbide for latent particulate	Latent debris	Latent	ANO	2
Sodium Aluminum Silicate	Sodium aluminum silicate	Chemical	Crystal River	3
			Diablo Canyon	1
				2
			Farley	1
				2
			Fort Calhoun	1
			Palo Verde	1
				2
				3
			Salem	1
				2
			San Onofre	2
				3
			Three Mile Island	1
			Waterford	3
		Chemical debris	ANO	1
		Chemical Precipitates	Beaver Valley	1
				2
SS RMI foil	RMI foil	Insulation	Summer	1
Stainless Steel Foils		Metallic	Oconee	1
				2
				3
Stainless steel wool	Lead blanket,lead wool Fines	Blanket cover	Comanche Peak	1
				2
Stone Flour		Particulate	Oconee	1
				2
				3
	Alkyd paint (inside ZOI)	Particulate	D.C. Cook	1
				2
	Epoxy paint (inside ZOI)	Particulate	D.C. Cook	1
				2
	Latent dirt/dust	Particulate	Palo Verde	1
				2
				3
	Latent dust/Dirt	Latent	Ginna	1
	Phenolic Coatings	Coatings	Ginna	1
	Qualified and unqualified coatings;	Particulate	Salem	1
				2

Surrogate	Debris	Debris Type	Plant Name	Unit
	latent dirt/dust			
	Unqualified coatings	Coatings	Calvert Cliffs	1
				2
	Unqualified cold galvanizing compound	Particulate	D.C. Cook	1
				2
Stone flour with typical particle diameter of 7.7 µm	Fines	Qualified epoxy coatings	Braidwood	1
				2
			Byron	1
				2
Tape	Tape	Miscellaneous debris	Comanche Peak	1
				2
TempMat			Indian Point	2
				3
	Jacketed TempMat	Fibrous	Kewaunee	1
	TempMat	Insulation	Surry	1
				2
	TempMat	Fibrous	Fort Calhoun	1
			Beaver Valley	2
		Insulation	Point Beach	2
			Summer	1
TempMat fines	TempMat	Fibrous	Beaver Valley	1
TempMat Supplied by GLT Products	TempMat	Fibrous	North Anna	1
				2
Thermal wrap	Thermal wrap	Fibrous	ANO	1
Thermal-Wrap Supplied Transco Products	Fiberglass (unspecified)	Fibrous	North Anna	1
				2
	Transco Thermal-Wrap	Fibrous	North Anna	1
				2
Thermobestos	Jacketed thermobestos	Fiber/particulate mix	Kewaunee	1
Thermo-Lag 330	Thermo-Lag 330	Fibrous	Palo Verde	1
				2
				3
Thermo-Lag powder	Thermo-Lag	Particulate	Wolf Creek	1
Tin Particles	Inorganic zinc	Coatings	Sequoyah	1
				2
	Inorganic zinc (particulate)	Coatings	Watts Bar	2
Tin Powder	Carboline Carbozinc 11	Qual. coatings	Palisades	1
		Unqual. coatings	Palisades	1
	Coatings (zinc)	Particulate	Turkey Point	4
	Inorganic zinc	Coatings	Kewaunee	1
	Inorganic zinc silicate	Qualified	Palisades	1

Surrogate	Debris	Debris Type	Plant Name	Unit
		coatings		
	IOZ coating	Particulate	Wolf Creek	1
	IOZ Paint	Particulate	Watts Bar	1
	Qualified inorganic zinc	Coatings	Comanche Peak	1
				2
	Qualified and unqualifed IOZ	Particulate	South Texas	1
				2
	Qualified coatings - steel - epoxy	Coatings	St. Lucie	2
	Qualified coatings - steel - IOZ	Coatings	St. Lucie	2
	Qualified steel coatings		St. Lucie	1
	Unqualified inorganic zinc	Coatings	Comanche Peak	1
				2
	Unqualified coatings - IOZ	Coatings	St. Lucie	2
	Zinc chromate	Qualified coatings	Palisades	1
Transco	Latent fiber	Fibrous	Farley	1
				2
			Fort Calhoun	1
	LDFG/NUKON	Fibrous	Fort Calhoun	1
Transco Encapsulated Mineral Wool (Fibrex)	Transco encapsulated mineral wool	Insulation	Millstone	2
Transco RMI	Transco RMI	Insulation	Prairie Island	1
				2
Transco Stainless Steel Foil	Transco RMI	Metallic	North Anna	1
				2
Transco Stainless Steel RMI Foil	Transco RMI foil	Insulation	Millstone	2
Transco Tempmat	Transco TempMat	Fibrous	ANO	1
Transco Thermal Wrap	Latent fiber	Latent	Millstone	3
	Nukon	Insulation	Millstone	3
	Transco fiberglass	Insulation	Millstone	3
	Transco thermal-wrap	Insulation	Surry	1
				2
Transco Thermal Wrap (shredded)	Fiber		St. Lucie	1
Transco Thermal-Wrap	Latent fibers	Fibrous	North Anna	1
				2
Tubing	Hot tar tubing	Miscellaneous debris	Comanche Peak	1
				2

Surrogate	Debris	Debris Type	Plant Name	Unit
	Potable Water Tubing	Misc. debris	Comanche Peak	1
				2
Uncompressed fibrous insulation	Fines	Latent debris	Braidwood	1
				2
			Byron	1
				2
Wallnut Shells or Acrylic Coating	Qualified coatings - concrete - epoxy	Coatings	St. Lucie	2
	Unqualified coatings - epoxy	Coatings	St. Lucie	2
Walnut Shell Flour (325 mesh)	Alkyds	Coatings	Summer	1
	Coatings (all non-zinc)	Particulate	Turkey Point	4
	Damaged coatings	Particulate	North Anna	1
				2
	Enamel	Coatings	Kewaunee	1
	Epoxy	Coatings	Summer	1
	Epoxy (Amercoat 66)	Qualified coatings	Summer	1
	Epoxy (Ameron 89)	Qualified coatings	Summer	1
	Epoxy (Nu-Klad)	Qualified coatings	Summer	1
	Epoxy 4500	Coatings	Summer	1
	Epoxy 5000	Coatings	Summer	1
	Epoxy 6129	Coatings	Summer	1
	Epoxy 6548/7107	Coatings	Summer	1
	Factory coatings	Coatings	Kewaunee	1
	Latent particles	Latent debris	Surry	1
				2
	Latent particulate	Latent	Millstone	2
				3
		Particulate	North Anna	1
				2
	Phenolic epoxy	Coatings	Kewaunee	1
	Qualified coatings	Coatings	Surry	1
				2
	Qualified coatings	Coatings	Millstone	2
				3
		Particulate	North Anna	1
				2
	Unqualified & damaged coatings	Coatings	Surry	1
				2
	Unqualified coatings	Coatings	Millstone	2
				3
		Particulate	North Anna	1
				2

Surrogate	Debris	Debris Type	Plant Name	Unit
Walnut shells	Alkyd	Coatings	Point Beach	2
	Aluminum	Coatings	Point Beach	2
	Carboline 191 HB Epoxy	Particulate	Wolf Creek	1
	Carboline 195 surfacer epoxy	Particulate	Wolf Creek	1
	Carboline 4674 Acrylic	Particulate	Wolf Creek	1
	OEM/Other unqualified Alkyd	Particulate	Wolf Creek	1
	OEM/Other unqualified Epoxy	Particulate	Wolf Creek	1
	Qualified (ZOI) epoxy	Coatings	Point Beach	2
	Unqualified epoxy	Coatings	Point Beach	2
WCAP (NaAlSi)			Indian Point	2
				3
Wollastonite	Marinite 36 fines	Particulate	D.C. Cook	1
				2
	Marinite 36 large pieces	Particulate	D.C. Cook	1
				2
	Marinite 36 small pieces	Particulate	D.C. Cook	1
				2
Wollastonite 520H	Unibestos	Fibrous	Robinson	2
Zinc	Zinc in galvanized plate	Coatings	Turkey Point	3
Zinc Dust	Cal-Sil fines	Insulation	Ginna	1
	Qualified degraded IOZ coatings	Coatings	Ginna	1
	Qualified IOZ coatings	Coatings	Ginna	1
Zinc filler	Fines	Qualified IOZ Coatings	Braidwood	1
				2
			Byron	1
				2

Table A.2-13. Debris Zone of Influence

Plant Name	Unit	Debris Type	Debris	ZOI (in D)
ANO	1	Coatings	Total coatings (qualified and unqualified)	10
		Insulation	Calcium-silicate (SS cladding, SS banding)	5.45
			Transco RMI Foil	2
			Transco Temp Mat	11.7
			Thermal-Wrap Fiber	17
			Thermal-Wrap Fiber (SS cladding, SS banding)	5.45
	2	Coatings	Total coatings (qual. and unqual.)	10
		Insulation	Calcium-silicate (unbanded)	25

Plant Name	Unit	Debris Type	Debris	ZOI (in D)
			Calcium-silicate (banded)	5.45
			Mirror foil	28.6
			Transco RMI foil	2
			Transco Thermal Wrap	17
Beaver Valley	1	Coatings	Qualified coatings	5
		Insulation	Benelex 401	2
			Calcium silicate [aluminum cladding, stainless steel (SS) bands]	5.45
			Diamond Power Mirror RMI with standard bands	28.6
			Encapsulated Microtherm	4
			Encapsulated Min-K	28.6
			Fiberglas thermal insulating wool	17
			Fiberglass	17
			Foamglas	28.6
			Temp-Mat with SS wire retainer	11.7
			Transco RMI	2
			Transco Thermal Wrap	17
			Transite	1
	2	Coatings	Qualified coatings	5
		Insulation	Benelex 401	2
			Calcium silicate (aluminum cladding, SS bands)	5.45
			Diamond Power Mirror RMI with standard bands	28.6
			Encapsulated Microtherm	4
			Encapsulated Min-K	28.6
			Fiberglas thermal insulating wool	17
			Fiberglass	17
			Foamglas	28.6
			Temp-Mat with SS wire retainer	11.7
			Transco RMI	2
			Transco Thermal Wrap	17
			Transite	1
Braidwood	1	Insulation	Transco RMI	2.0
			Tempmat	11.7
			Reflective Mirror with Standard Bands	28.6
			Nukon (Thermal Wrap)	17.0
		Qualified epoxy coatings	Fines	10
		Qualified IOZ coatings	Fines	10
	2	Insulation	Mirror RMI pieces	2.9
				17

Plant Name	Unit	Debris Type	Debris	ZOI (in D)
				28.6
		Qualified epoxy coatings	Fines	10
		Qualified IOZ coatings	Fines	10
Byron	1	Insulation	Transco RMI	2.0
			Tempmat	11.7
			Reflective Mirror with Standard Bands	28.6
			Nukon (Thermal Wrap)	17.0
		Qualified epoxy coatings	Fines	10
		Qualified IOZ coatings	Fines	10
	2	Insulation	Mirror RMI pieces	2.9
				17
				28.6
		Qualified epoxy coatings	Fines	10
		Qualified IOZ coatings	Fines	10
Callaway	1	Insulation	AlphaMat D	28.6
			NUKON intact blankets	7
			NUKON large fines	7
			NUKON small fines	7
			RMI large pieces	28.6
			RMI small pieces	28.6
Calvert Cliffs	1		Marinite board	9.8
			Lead Blankets	2.5
		Coatings	Epoxy coatings	4
			Inorganic zinc coatings without topcoat	10
		Insulation	Calcium-silicate insulation	5.45
			Generic fiberglass insulation	17
			NUKON-jacketed w/standard bands	17
			NUKON jacketed w/Sure Hold bands	2.4
			Temp-Mat insulation	17
			Transco mineral wool	17
			Transco reflective metal insulation	2
			Transco Thermal Wrap	17
	2		Marinite board	9.8
			Lead Blankets	2.5
		Coatings	Epoxy coatings	4
			Inorganic zinc coatings without topcoat	10

Plant Name	Unit	Debris Type	Debris	ZOI (in D)
		Insulation	Calcium-silicate insulation	5.45
			Generic fiberglass insulation	17
			NUKON-jacketed w/standard bands	17
			NUKON jacketed w/Sure Hold bands	2.4
			Temp-Mat insulation	17
			Transco mineral wool	17
			Transco reflective metal insulation	2
			Transco Thermal Wrap	17
Catawba	1	Coatings	Protective coatings (epoxy & epoxy-phenolic paints)	5
		Insulation	Knauf insulation	17
			Mirror RMI	28.6
			NUKON insulation	17
			Thermal-Wrap insulation	17
	2	Coatings	Protective coatings (epoxy & epoxy-phenolic paints)	5
		Insulation	Knauf insulation	17
			Mirror RMI	28.6
			NUKON insulation	17
			Thermal-Wrap insulation	17
Comanche Peak	1	Blanket cover	Lead shielding blankets (fiberglass cover)	5
		Coatings	Qual. epoxy	4
			Qual. Inorganic zinc	10
		Insulation	Fiberglass (jacketed)	17
			Min-K fines (encapsulated)	2
			RMI	28.6
	2	Blanket cover	Lead shielding blankets (fiberglass cover)	5
		Coatings	Qual. epoxy	4
			Qual. inorganic zinc	10
		Insulation	Fiberglass (jacketed)	17
			Min-K fines (encapsulated)	2
			RMI	28.6
Crystal River	3	Coatings	DBA qualified epoxy coatings	4
			IOZ	4
		Insulation	Mineral wool encapsulated in 22 gauge corrugated sheet cover (SG and BD only)	17
			Mineral wool jacketed with 22 or 24 gauge 304SS (MS, FW, EFW Only)	4
			Mirror with standard bands	28.6
			Mirror with Sure-Hold bands	2.4
			Unjacketed NUKON-jacketed NUKON with standard bands	17

Plant Name	Unit	Debris Type	Debris	ZOI (in D)
D.C. Cook	1	Insulation	CalSil	6.4
			DP RMI	28.6
			Marinite I and Marinite 36	17
			Min-K	28.6
			Transco fiberglass	2
			Transco RMI	2
		Miscellaneous	Electromark labels	9.9
			Fireproof tape	17
	2	Insulation	CalSil	6.4
			DP RMI	28.6
			Marinite I and Marinite 36	17
			Min-K	28.6
			Transco fiberglass	2
			Transco RMI	2
		Miscellaneous	Electromark labels	9.9
			Fireproof tape	17
Davis Besse	1	Coatings	Qualified coatings	5.5
		Insulation	NUKON, large pieces	17
			NUKON, small fines	17
			RMI, large pieces	28.6
			RMI, small fines	28.6
Diablo Canyon	1		Aluminum tape	28.6
			Cable insulation/jackets	5
			Cable tray fire stop materials	28.6
			Light bulbs	28.6
			Miscellaneous debris	28.6
			Pressurizer heater cables	5
			Qualified coatings	5
			Vapor barrier material	3
		Insulation	Cal-Sil (12 in centers)	5.5
			Cal-Sil (3 in centers)	3
			Mineral wool	28.6
			RMI with standard band	28.6
			Temp-Mat with SS wire mesh, encapsulated in SS cladding	3.7
			Temp-Mat with SS wire retainer	11.7
			Transco RMI	2
	2		Aluminum tape	28.6
			Cable insulation/jackets	5
			Cable tray fire stop materials	28.6
			Light bulbs	28.6
			Miscellaneous debris	28.6
			Pressurizer heater cables	5

Plant Name	Unit	Debris Type	Debris	ZOI (in D)
			Qualified coatings	5
			Vapor barrier material	3
		Insulation	Cal-Sil (12 in centers)	5.5
			Cal-Sil (3 in centers)	3
			Mineral wool	28.6
			RMI with standard band	28.6
			Temp-Mat with SS wire mesh, encapsulated in SS cladding	3.7
			Temp-Mat with SS wire retainer	11.7
			Transco RMI	2
Farley	1	Coatings	Qualified coatings	4
		Insulation	Mirror RMI	28.6
			Transco RMI	2
	2	Coatings	Qualified coatings	4
		Insulation	Mirror RMI	28.6
			Transco RMI	2
Fort Calhoun	1	Coatings	Epoxy	5
		Insulation	CalSil	6.4
			LDFG/NUKON	17
			LDFG/NUKON (banded)	3
			RMI	17.1
			Temp-Mat	11.7
Ginna	1	Coatings	Qualified coatings	5
				10
		Insulation	CalSil	6.4
			RMI	2
			Temp-Mat	11.7
			Thermal Wrap	17
Indian Point	2	Coatings	DBA-qualified/acceptable epoxy	4
		Insulation	Asbestos with cloth	28.6
			Asbestos with jacket	6.4
			Fiberglass	17
			NUKON	17
			RMI	28.6
			TempMat	11.7
			Transco blanket	17
	3	Coatings	DBA-qualified/acceptable epoxy	4
		Insulation	Asbestos with jacket	6.4
			Calcium silicate with cloth	28.6
			Calcium silicate with jacket	6.4
			Fiber (Marinite) board /transite	6.4
			Fiberglass	17
			Mineral wool with jacket	17
			NUKON	17

Plant Name	Unit	Debris Type	Debris	ZOI (in D)
			RMI	28.6
			Temp-Mat	11.7
Kewaunee	1	Coatings	Enamel	10
			Factory coatings	10
			Inorganic zinc	10
			Phenolic epoxy	10
		Fiber/particulate mix	Jacketed Thermobestos	5.45
		Fibrous	Cable insulation	17
			Fiberglass pipe cover	17
			Jacketed TempMat	17
		Insulation	RMI (foils)	28.6
			RMI (intact pieces)	28.6
McGuire	1	Coatings	Protective coatings (epoxy & epoxy-phenolic paints)	5
		Insulation	Mirror RMI	28.6
			NUKON insulation	17
			Thermal-Wrap insulation	17
			Unjacketed NUKON	17
	2	Coatings	Protective coatings (epoxy & epoxy-phenolic paints)	5
		Insulation	Mirror RMI	28.6
			NUKON insulation	17
			Thermal-Wrap insulation	17
			Unjacketed NUKON	17
Millstone	2	Coatings		10
		Insulation	Cal-Sil	5.45
			Transco RMI	2
			Unjacketed NUKON, NUKON with standard bands Knaupf	17
	3	Coatings		5
		Insulation	Min-K	28.6
			Unjacketed NUKON, jacketed NUKON with standard bands	17
North Anna	1	Coating		5
		Insulation	Paroc mineral wool	5.4
			Temp-Mat	11.7
			Transco RMI	2
			Transco Thermal-Wrap	17
	2	Coating		5
		Insulation	Paroc mineral wool	5.4
			Temp-Mat	11.7
			Transco RMI	2
			Transco Thermal-Wrap	17

Plant Name	Unit	Debris Type	Debris	ZOI (in D)
Oconee	1	Coatings		10
		Insulation	Generic fiberglass	28.6
			RMI	28.6
	2	Coatings		10
		Insulation	Generic fiberglass	28.6
			RMI	28.6
	3	Coatings		10
		Insulation	Generic fiberglass	28.6
			RMI	28.6
Palisades	1	Insulation	Calcium silicate cloth jacketed	28.6
			Calcium silicate jacketed	5.45
			Low-density fiberglass jacketed	17
			Low-density fiberglass unjacketed	17
			Mineral wool jacketed	17
			NUKON thermal wrap jacketed	7
			NUKON unjacketed	17
			Transco RMI	2
		Qual. coatings	Aluminum paint	10
			Carboline 3912	10
			Carboline 890	10
			Carboline Carbozinc 11	10
			Carboline-Flexxide thinner	10
			Carboline-Multibond 120	10
			Inorganic zinc silicate	10
			Zinc chromate	10
Palo Verde	1	Coatings	Qualified epoxy coatings	4
			Qualified IOZ	5
		Insulation	Equipment Transco RMI	2
			Min-K/Microtherm	28.6
			NUKON	17
			Piping RMI	28.6
			Temp-Mat	11.7
			Thermo-Lag	28.6
	2	Coatings	Qualified epoxy coatings	4
			Qualified IOZ	5
		Insulation	Equipment Transco RMI	2
			Min-K/Microtherm	28.6
			NUKON	17
			Piping RMI	28.6
			Temp-Mat	11.7
			Thermo-Lag	28.6
	3	Coatings	Qualified epoxy coatings	4
			Qualified IOZ	5

Plant Name	Unit	Debris Type	Debris	ZOI (in D)
		Insulation	Equipment Transco RMI	2
			Min-K/Microtherm	28.6
			NUKON	17
			Piping RMI	28.6
			Temp-Mat	11.7
			Thermo-Lag	28.6
Point Beach	1	Insulation	Asbestos	10
			CalSil	14.5
			Fiberglass	5.5
			Mineral Wool	8
			NUKON	2.4
			Temp-Mat	11.8
	2	Insulation	Asbestos	10
			CalSil	14.5
			Fiberglass	5.5
			Mineral Wool	8
			NUKON	2.4
			Temp-Mat	11.8
Prairie Island	1	Coatings	Carboline 195	10
			Carboline Carbozinc 11	10
			Carboline Phenoline 305 finish	10
			Carboline Phenoline 305 primer	10
			Qualified coatings total	10
		Insulation	Mirror RMI (standard bands)	28.6
			Mirror RMI large debris (standard bands)	28.6
			Misc. fiber	5.4
			Transco RMI	2
			Transco RMI (large debris)	2
	2	Coatings	Carboline 195	10
			Carboline Carbozinc 11	10
			Carboline Phenoline 305 finish	10
			Carboline Phenoline 305 primer	10
			Qualified coatings total	10
		Insulation	Mirror RMI (standard bands)	28.6
			Mirror RMI large debris (standard bands)	28.6
			Misc. fiber	5.4
Robinson	2	Coatings		10
		Insulation	Asbestos	28.6
			Cal-Sil	5.5
			Kaowool	28.6
			Kaylo	28.6
			Low-density fiberglass	28.6
			NUKON	17
			RMI	2

Plant Name	Unit	Debris Type	Debris	ZOI (in D)
			Temp-Mat	11.7
			Unibestos	28.6
Salem	1	Coatings	Qualified epoxy coatings	5
		Insulation	Jacketed NUKON	7
			Transco RMI	2
	2	Coatings	Qualified epoxy coatings	5
		Insulation	Jacketed NUKON	7
			Transco RMI	2
San Onofre	2	Coatings	Qualified epoxy coatings	5
		Insulation	Microtherm	4
			SS encapsulated mineral wool	4
			Transco RMI	2
	3	Coatings	Qualified epoxy coatings	5
		Insulation	Microtherm	4
			SS encapsulated mineral wool	4
			Transco RMI	2
Seabrook	1	Coatings	Qualified concrete coating	4
			Qualified steel coating	4
				10
		Insulation	Insulation Jacketing	7
			Jacketed NUKON	7
			Transco RMI	2
			Unjacketed NUKON	17
Sequoyah	1	Coatings	Epoxy and epoxy-phenolic paints	10
		Insulation	Mirror RMI	28.6
	2	Coatings	Epoxy and epoxy-phenolic paints	10
		Insulation	Mirror RMI	28.6
Shearon Harris	1	Coatings	Qualified coatings	5
		Insulation	Microtherm	28.6
			Min-K	4
			Mirror RMI	28.6
			NUKON	17
			Temp-Mat	11.7
			Thermal-Wrap	17
South Texas	1	Coatings	Qualified epoxy/IOZ coatings	5
		Insulation	Marinite	2
			Microtherm	28.6
			NUKON	7
			Thermal-Wrap	7
			Transco RMI	2
	2	Coatings	Qualified epoxy/IOZ coatings	5
		Insulation	Marinite	2
			Microtherm	28.6
			NUKON	7

Plant Name	Unit	Debris Type	Debris	ZOI (in D)
			Thermal-Wrap	7
			Transco RMI	2
St. Lucie	1	Coatings	Qualified coatings	4
		Insulation	CalSil reinforced	3
			CalSil unreinforced	5.45
			NUKON	17
			RMI	2
			Transco Thermal-Wrap	17
	2	Coatings	Qualified coatings	4
		Insulation	Cal-Sil	5.45
			Fiberglass (NUKON/Knaupf)	17
			Foamglass	17
			Jacketing	17
			Mirror RMI	28.6
			Transco RMI	2
Summer	1	Insulation	RMI	28.6
		Qual. coatings	Epoxy (Amercoat 66)	4
			Epoxy (Ameron 89)	4
			Epoxy (Nu-Klad)	4
			Zinc (MobilZinc 7)	4
Surry	1		Asbestos	7
		Coatings	Qual. coatings	10
		Insulation	CalSil/asbestos	7
			Cloth insulation jacketing	11.7
			Fiberglass	17
			Metal insulation jacketing	11.7
			Paroc	5.4
			Silicone Foam	28.6
			TempMat	17
			Transco RMI foil	2
			Transco Thermal Wrap	17
	2		Asbestos	7
		Coatings	Qual. coatings	10
		Insulation	CalSil/asbestos	7
			Cloth insulation jacketing	11.7
			Fiberglass	17
			Metal insulation jacketing	11.7
			Paroc	5.4
			Silicone foam	28.6
			TempMat	17
			Transco RMI foil	2
			Transco Thermal Wrap	17

Plant Name	Unit	Debris Type	Debris	ZOI (in D)
Three Mile Island	1	Coatings	Qualified coatings	5
		Insulation	Jacketed NUKON	7
			ThermoLag 330-1	28.6
			Transco RMI	2
			Unjacketed NUKON	17
Turkey Point	3	Coatings	Qualified - concrete	4
			Qualified - steel	4
		Insulation	Cal-Sil	5.45
			Fiber	17
			Microtherm,	28.6
			RMI/jacketing	28.6
	4	Coatings	Qual. concrete	4
			Qual. steel	4
		Insulation	Cal-Sil	5.45
			NUKON (piping)	17
			NUKON (Steam Gen.)	7
			RMI Darchem/Transco	2
			RMI mirror	28.6
		Insulation jacketing	Mirror	28.6
			RMI Darchem/Transco	2
Vogtle	1	Insulation	Jacketed NUKON	8
		Qual. coatings	Concrete coatings	4
			Steel coatings	4
	2	Insulation	Jacketed NUKON	8
		Qual. coatings	Concrete coatings	4
			Steel coatings	4
Waterford	3	Coatings	Qualified coatings	4
		Insulation	Jacketed NUKON	17
			MEI	4
			Microtherm	28.6
			Min-K	28.6
			Transco RMI	2
			Unjacketed NUKON	17
Watts Bar	1	Fire barrier	3M-M20C fiber	11
		Insulation	Min-K fiber	10
			RMI (stainless steel)	28.6
		Particulate	3M M20C particulate	11
			Alkyd paint	10
			Carboline 295	10
			Epoxy paint	10
			Min-K Si0 2	10
			Min-K TiC 2	10
			Phenolic paint	10
			Silicone paint	10

Plant Name	Unit	Debris Type	Debris	ZOI (in D)
	2	Coating	Protective Coatings (epoxy and epoxy-phenolic paints)	10
		Insulation	RMI	28.6
Wolf Creek	1	Coatings	Qualified epoxy coatings	4
			Unqualified coatings under destroyed insulation	10
			Untopcoated IOZ primers	5
		Insulation	Cerablanket	28.6
			Foamglass	28.6
			Jacketed NUKON	5
			Min-K	0
			RMI with standard band	28.6
			Thermal Wrap	5
			Thermo-Lag	28.6

Table A.2-14. Chemical Buffer

Plant Name	Units	Sodium Hydroxide (NaOH)	Trisodium Phosphate (TSP)	Sodium Tetraborate (STB)	Changed	Comments
ANO	1	■			■	In December 2007, a design modification was implemented to reduce the concentration of the sodium hydroxide (NaOH) chemical buffer.
ANO	2			■	■	The chemical buffer was changed to STB from TSP during the 2R19 refueling outage (spring 2008).
Beaver Valley	1	■				Not clearly stated: "BVPS-1 and BVPS-2 are most closely represented by the conditions in ICET #4 - fiberglass and calcium silicate insulation, and sodium hydroxide (NaOH) pH buffer."
Beaver Valley	2			■	■	BVPS-2 will be changing buffers from sodium hydroxide to sodium tetraborate during the fall 2009 refueling outage.
Braidwood	1, 2	■				
Byron	1,2	■				
Callaway	1		■			
Calvert Cliffs	1			■	■	During the 2010 Refueling Outage the Unit I buffer was changed to sodium tetraborate decahydrate (STB).
Calvert Cliffs	2			■	■	The buffer material change was completed during the refueling outage in 2009 for Unit 2.
Catawba	1,2			■		
Comanche Peak	1,2	■				Changed concentration of NaOH.
Crystal River	3		■			
D.C. Cook	1,2			■		
Davis Besse	1		■			
Diablo Canyon	1,2	■				
Farley	1,2		■			
Fort Calhoun	1			■	■	Trisodium phosphate (TSP), the previous containment sump buffer was replaced with sodium tetraborate (STB) to reduce formation of chemical precipitates
Ginna	1	■				
Indian Point	2			■	■	STB replaces TSP in Unit 2
Indian Point	3			■	■	STB replaces NaOH in Unit 3

Plant Name	Units	Sodium Hydroxide (NaOH)	Trisodium Phosphate (TSP)	Sodium Tetraborate (STB)	Changed	Comments
Kewaunee	1	[green shaded]				
McGuire	1,2			[green shaded]		
Millstone	2,3		[green shaded]			
North Anna	1,2	[green shaded]				
Oconee	1,2,3		[green shaded]			
Palisades	1			[green shaded]	[red shaded]	The containment sump buffer was changed from trisodium phosphate (TSP) to sodium tetraborate (STB)
Palo Verde	1,2,3		[green shaded]			
Point Beach	1,2	[green shaded]				
Prairie Island	1,2	[green shaded]				
Robinson	2	[green shaded]				
Salem	1,2	[green shaded]				
San Onofre	2,3		[green shaded]			
Seabrook	1	[green shaded]				
Sequoyah	1,2			[green shaded]		
Shearon Harris	1	[green shaded]				
South Texas	1,2		[green shaded]			
St. Lucie	1	[green shaded]				
St. Lucie	2		[green shaded]			
Summer	1	[green shaded]				
Surry	1,2	[green shaded]				
Three Mile Island	1		[green shaded]		[red shaded]	TMI Unit 1 filled the 23 installed TSP baskets with the TSP buffer chemical, and isolated the NaOH Tank, containing the removed buffer.
Turkey Point	3,4			[green shaded]		In the September 1, 2005 response to GL 2004-02, future plans to change the buffering agent to TSP prior to startup from the Turkey Point fall 2006 refueling outage were discussed. Based upon the review of the IN, this buffer change will not be implemented.
Vogtle	1,2		[green shaded]			
Waterford	3		[green shaded]			
Watts Bar	1,2			[green shaded]		
Wolf Creek	1	[green shaded]				

Green shaded box indicates which buffer type is used
Red shaded box indicates the buffer type was changed

Downstream: Models

This field records the models used for the analysis of the components located downstream of the strainer. The models used for the ex-vessel and in-vessel analyzes are recorded separately in the GL-04-02 database.. In both cases, the models are grouped by exact spelling of the database entry such that "WCAP-16793-NP" and "WCAP-16793-NP, Revision 0", for example, are treated as different entries.

Downstream: Strainer Bypass

This field records the amount of the debris that bypasses the strainer. The primary goal is to collect the bypass amount characterized in parts per million (ppm). Table A.2-15 shows all the data provided for the strainer bypass in ppm units. In addition to that data, all other information relative to the bypass characteristics of strainers were collected in this field. In that case, the Bypass Amount field was left blank, and all additional information was reported in the Comments.

Downstream: Fuel Type

The GL-04-02 database also incorporates the fuel type currently loaded in the reactors. That information was provided directly by NRC (i.e., it wasn't collected from GL-04-02 responses) in the form shown in Table A.2-16. That table was included entirely, without any modifications, into the GL-04-02 database. Table A.2-17 shows the same information grouped by the fuel type.

Downstream: Core Head Loss

The intent of this field was to collect the information on the pressure loss through the core. However, only one plant, Diablo Canyon, has reported a value of 2 ft (measured value at 41.1 gpm) for the core head loss in GL-04-02 responses. No other plant provided the information on the core head loss.

Table A.2-15. Strainer Bypass Amount

Plant Name	Unit	Debris	Bypass Amount, ppm	Comments
Comanche Peak	1	Coatings	5927.36	Consists of qualified and unqualified epoxy, qualified CZ-11, and unqualified inorganic zinc and alkyd.
		Fibrous	1.54	Consists of fiberglass, lead blanket fiberglass, Min-K, lead wool, and latent fibers.
		Particulate	39.67	Consists of Min-K and latent particulate.
	2	Coatings	5927.36	Consists of qualified and unqualified epoxy, qualified CZ-11, and unqualified inorganic zinc and alkyd.
		Fibrous	1.54	Consists of fiberglass, lead blanket fiberglass, Min-K, lead wool, and latent fibers.
		Particulate	39.67	Consists of Min-K and latent particulate.
Diablo Canyon	1	Coatings	278.2	The mass of debris in the recirculating fluid that passes through the sump is characterized in terms of parts per million (ppm).
		Fibrous	8.2	The mass of debris in the recirculating fluid that passes through the sump is characterized in terms of parts per million (ppm).
		Particulate	87.2	The mass of debris in the recirculating fluid that passes through the sump is characterized in terms of parts per million (ppm).
	2	Coatings	278.2	The mass of debris in the recirculating fluid that passes through the sump is characterized in terms of parts per million (ppm).
		Fibrous	8.2	The mass of debris in the recirculating fluid that passes through the sump is characterized in terms of parts per million (ppm).
		Particulate	87.2	The mass of debris in the recirculating fluid that passes through the sump is characterized in terms of parts per million (ppm).
Ginna	1		497.8	The heat exchangers, orifices, and spray nozzles were evaluated for the effects of erosive wear for a constant debris concentration of 497.8 ppm over the mission time of 30 days.
Indian Point	2		822.1	
	3		818.6	
Salem	1	Particulate	390	Test 4; Initial concentration was 3320 ppm and it decreased to 390 ppm after 3.5 hrs. Bypass samples were taken starting after the first fibers were introduced into the test loop from a sample line downstream of the strainer in the horizontal return line. After the initial sample, samples were taken every 3 minutes beginning with the initiation of the test until 15 samples had been taken. After the 15th sample was taken, a sample was taken

Plant Name	Unit	Debris	Bypass Amount, ppm	Comments
				at 1 hour and then samples were taken every 30 minutes until the end of the test. The samples were taken in 500 ml bottles. Also, for downstream wear evaluation, 1.4% of the bypass factor was utilized.
	2	Particulate	390	Test 4; Initial concentration was 3320 ppm and it decreased to 390 ppm after 3.5 hrs. Bypass samples were taken starting after the first fibers were introduced into the test loop from a sample line downstream of the strainer in the horizontal return line. After the initial sample, samples were taken every 3 minutes beginning with the initiation of the test until 15 samples had been taken. After the 15th sample was taken, a sample was taken at 1 hour and then samples were taken every 30 minutes until the end of the test. The samples were taken in 500 ml bottles. Also, for downstream wear evaluation, 1.4% of the bypass factor was utilized.
South Texas	1	Coatings	744	The mass of debris in the recirculating fluid that passes through the sump is characterized in terms of parts per million (ppm). For downstream effects, the total initial debris concentration comprised of the individual debris concentrations is defined as the ratio of the solid mass of the debris in the pumped fluid to the total mass of water that is recirculated by the ECCS and CSS.
		Fibrous	5.6	The mass of debris in the recirculating fluid that passes through the sump is characterized in terms of parts per million (ppm). For downstream effects, the total initial debris concentration comprised of the individual debris concentrations is defined as the ratio of the solid mass of the debris in the pumped fluid to the total mass of water that is recirculated by the ECCS and CSS.
		Particulate	72.6	The mass of debris in the recirculating fluid that passes through the sump is characterized in terms of parts per million (ppm). For downstream effects, the total initial debris concentration comprised of the individual debris concentrations is defined as the ratio of the solid mass of the debris in the pumped fluid to the total mass of water that is recirculated by the ECCS and CSS.
	2	Coatings	744	The mass of debris in the recirculating fluid that passes through the sump is characterized in terms of parts per million (ppm). For downstream effects, the total initial debris concentration

Plant Name	Unit	Debris	Bypass Amount, ppm	Comments
				comprised of the individual debris concentrations is defined as the ratio of the solid mass of the debris in the pumped fluid to the total mass of water that is recirculated by the ECCS and CSS.
		Fibrous	5.6	The mass of debris in the recirculating fluid that passes through the sump is characterized in terms of parts per million (ppm). For downstream effects, the total initial debris concentration comprised of the individual debris concentrations is defined as the ratio of the solid mass of the debris in the pumped fluid to the total mass of water that is recirculated by the ECCS and CSS.
		Particulate	72.6	The mass of debris in the recirculating fluid that passes through the sump is characterized in terms of parts per million (ppm). For downstream effects, the total initial debris concentration comprised of the individual debris concentrations is defined as the ratio of the solid mass of the debris in the pumped fluid to the total mass of water that is recirculated by the ECCS and CSS.
Watts Bar	1	Coatings	593	
		Fibrous	3	
		Particulate	308	
		Total debris	903	
	2	Coatings	593	
		Fibrous	1	
		Particulate	241	
		Total debris	835	
Wolf Creek	1	Chemical	13	The mass of debris in the recirculating fluid that passes through the sump is characterized in terms of parts per million (ppm).
		Coatings	26	The mass of debris in the recirculating fluid that passes through the sump is characterized in terms of parts per million (ppm).
		Fibrous	85	The mass of debris in the recirculating fluid that passes through the sump is characterized in terms of parts per million (ppm).
		Particulate	14	The mass of debris in the recirculating fluid that passes through the sump is characterized in terms of parts per million (ppm).

Table A.2-16. Fuel Type

Plant Name	Unit	Westinghouse /CE	AREVA	AREVA Fuel Type	AREVA LA
ANO	1	FALSE	TRUE	Mark-BHTP	
	2	TRUE	FALSE		
Beaver Valley	1	TRUE	FALSE		
	2	TRUE	FALSE		
Braidwood	1	TRUE	TRUE	Adv. Mark-BW(A)	LAs
	2	TRUE	TRUE	Adv. Mark-BW(A)	LAs
Byron	1	TRUE	FALSE		
	2	TRUE	FALSE		
Callaway	1	TRUE	FALSE		
Calvert Cliffs	1	TRUE	TRUE	Adv. 14x14 HTP	LAs
	2	TRUE	TRUE	Adv. 14x14 HTP	LAs
Catawba	1	TRUE	TRUE	Adv. Mark-BW MOX 17x17	LAs
	2	TRUE	TRUE	Adv. Mark-BW MOX 17x17	LAs
Comanche Peak	1	TRUE	FALSE		
	2	TRUE	FALSE		
Crystal River	3	FALSE	TRUE	Mark-BHTP	
D.C. Cook	1	TRUE	FALSE		
	2	TRUE	FALSE		
Davis Besse	1	FALSE	TRUE	Mark-BHTP	
Diablo Canyon	1	TRUE	FALSE		
	2	TRUE	FALSE		
Farley	1	TRUE	FALSE		
	2	TRUE	FALSE		
Fort Calhoun	1	TRUE	TRUE	14x14 HTP	
Ginna	1	TRUE	FALSE		
Indian Point	2	TRUE	FALSE		
	3	TRUE	FALSE		
Kewaunee	1	TRUE	FALSE		
McGuire	1	TRUE	FALSE		
	2	TRUE	FALSE		
Millstone	2	FALSE	TRUE	14x14 HTP	
	3	TRUE	FALSE		
North Anna	1	TRUE	TRUE	Adv. Mark-BW 17x17	
	2	TRUE	TRUE	Adv. Mark-BW 17x17	

Plant Name	Unit	Westinghouse /CE	AREVA	AREVA Fuel Type	AREVA LA
Oconee	1	FALSE	TRUE	Mark-BHTP	
	2	FALSE	TRUE	Mark-BHTP	
	3	FALSE	TRUE	Mark-BHTP	
Palisades	1	FALSE	TRUE	15x15 HTP	
Palo Verde	1	TRUE	TRUE	16x16 HTP	LAs
	2	TRUE	TRUE	16x16 HTP	LAs
	3	TRUE	TRUE	16x16 HTP	LAs
Point Beach	1	TRUE	FALSE		
	2	TRUE	FALSE		
Prairie Island	1	TRUE	FALSE		
	2	TRUE	FALSE		
Robinson	2	TRUE	TRUE	15x15 HTP	
Salem	1	TRUE	FALSE		
	2	TRUE	FALSE		
San Onofre	2	TRUE	TRUE	16x16 HTP	LAs
	3	TRUE	FALSE		
Seabrook	1	TRUE	FALSE		
Sequoyah	1	TRUE	TRUE	Mark-BW 17x17	LAs
	2	TRUE	TRUE	Mark-BW 17x17	
Shearon Harris	1	FALSE	TRUE	17x17 HTP	
South Texas	1	TRUE	FALSE		
	2	TRUE	FALSE		
St. Lucie	1	FALSE	TRUE	14x14 HTP	
	2	TRUE	FALSE		
Summer	1	TRUE	FALSE		
Surry	1	TRUE	FALSE		
	2	TRUE	FALSE		
Three Mile Island	1	FALSE	TRUE	Mark-BHTP	
Turkey Point	3	TRUE	FALSE		
	4	TRUE	FALSE		
Vogtle	1	TRUE	FALSE		
	2	TRUE	FALSE		
Waterford	3	TRUE	FALSE		
Watts Bar	1	TRUE	FALSE		
Watts Bar	2		FALSE	Unit 2 is not operational yet	
Wolf Creek	1	TRUE	FALSE		

Table A.2-17. Plants by Fuel Type

Fuel Type	Plant Name	Unit			
		1	2	3	4
AREVA	ANO	■			
	Crystal River			■	
	Davis Besse	■			
	Millstone		■		
	Oconee	■	■	■	
	Palisades	■			
	Shearon Harris	■			
	St. Lucie	■			
	Three Mile Island	■			
Westinghouse/CE	ANO		■		
	Beaver Valley	■	■		
	Byron	■	■		
	Callaway	■			
	Comanche Peak	■	■		
	D.C. Cook	■	■		
	Diablo Canyon	■	■		
	Farley	■	■		
	Ginna	■			
	Indian Point		■	■	
	Kewaunee	■			
	McGuire	■	■		
	Millstone			■	
	Point Beach	■	■		
	Prairie Island	■	■		
	Salem	■	■		
	San Onofre			■	
	Seabrook	■			
	South Texas	■	■		
	St. Lucie		■		
	Summer	■			
	Surry	■	■		
	Turkey Point			■	■
	Vogtle	■	■		
	Waterford			■	
	Watts Bar	■			
	Wolf Creek	■			
Both	Braidwood	■	■		
	Calvert Cliffs	■	■		
	Catawba	■	■		
	Fort Calhoun	■			
	North Anna	■	■		
	Palo Verde	■	■	■	
	Robinson		■		
	San Onofre		■		
	Sequoyah	■	■		

NRC FORM 335 (12-2010) NRCMD 3.7 U.S. NUCLEAR REGULATORY COMMISSION **BIBLIOGRAPHIC DATA SHEET** *(See instructions on the reverse)*	1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.) NUREG/CR-7172
2. TITLE AND SUBTITLE Knowledge Base Report on Emergency Core Cooling Sump Performance in Operating Light Water Reactors	3. DATE REPORT PUBLISHED MONTH: January YEAR: 2014 4. FIN OR GRANT NUMBER N6954
5. AUTHOR(S) K. Natesan, A. Moisseytsev, C. Bahn, and D. R. Diercks Argonne National Laboratory and C. Shaffer, ARES Corporation	6. TYPE OF REPORT Technical 7. PERIOD COVERED (Inclusive Dates) Sept. 2009 - July 2013

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

Argonne National Laboratory 9700 S. Cass Avenue, Argonne, IL 60439
and
ARES Corporation, 851 University Blvd SE, Ste 100 Albuquerque, NM 87106

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above", if contractor, provide NRC Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address.)

Division of Engineering
Office of Nuclear Regulatory Research
U. S. Nuclear Regulatory Commission
Washington DC 20055-0001

10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This report describes the current status of the knowledge base regarding the performance of long-term core in operating light water reactors. The report discusses the knowledge that has been amassed as a result of the research on clogging issues related to the suction strainers in boiling water reactors and pressurized water reactors. These issues concern the potential insulation and other debris generated in the event of a postulated loss-of-coolant accident within the containment of a light water reactor and the subsequent transport to and accumulation on the recirculation strainers. This debris accumulation could potentially challenge the plant's capability to provide adequate long-term cooling water to the pumps in the emergency core cooling and in the containment spray systems.

The report briefly discusses the historical background on the sump performance issue and presents the NRC regulatory considerations, with emphasis on guidance provided by NRC to the licensees during recent years. The report presents the current state-of-the-art resolution methodology for understanding the strainer blockage phenomena and processes that have evolved over the years. In particular, the report discusses the details of plant-by-plant licensee responses to the NRC Bulletin 2003-01 and the NRC Generic Letter 2004-02. The licensee responses were collected in several areas such as strainer characteristics, physical and plant modifications, head loss testing procedures, head loss test information, net positive suction head data, debris generation, debris characteristics, coating debris, chemical effects, downstream effects, etc. as well as assessment of net positive suction head requirements

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)	13. AVAILABILITY STATEMENT: unlimited
Generic Safety Issue 191 ECCS stainer clogging Generic Letter 2004-02	14. SECURITY CLASSIFICATION *(This Page)* unclassified *(This Report)* unclassified
	15. NUMBER OF PAGES
	16. PRICE

Printed on recycled paper

Federal Recycling Program

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001

OFFICIAL BUSINESS

NUREG/CR-7172 **Knowledge Base Report on Emergency Core Cooling Sump Performance in Operating Light Water Reactors** **January 2014**