**LA-UR-01-1595**

# BWR ECCS STRAINER BLOCKAGE ISSUE: SUMMARY OF RESEARCH AND RESOLUTION ACTIONS


**Prepared By:**
D. V. Rao, Clinton J. Shaffer, and Robert Elliott

**Los Alamos National Laboratory**
Probabilistic Risk and Hazard Analysis Group
Technology and Safety Assessment Division
Los Alamos, NM 87545


**Prepared For:**

**US Nuclear Regulatory Commission**
Office of Nuclear Reactor Regulation
11555 Rockville Pike
Rockville, Maryland


**Prepared: March 21, 2001**

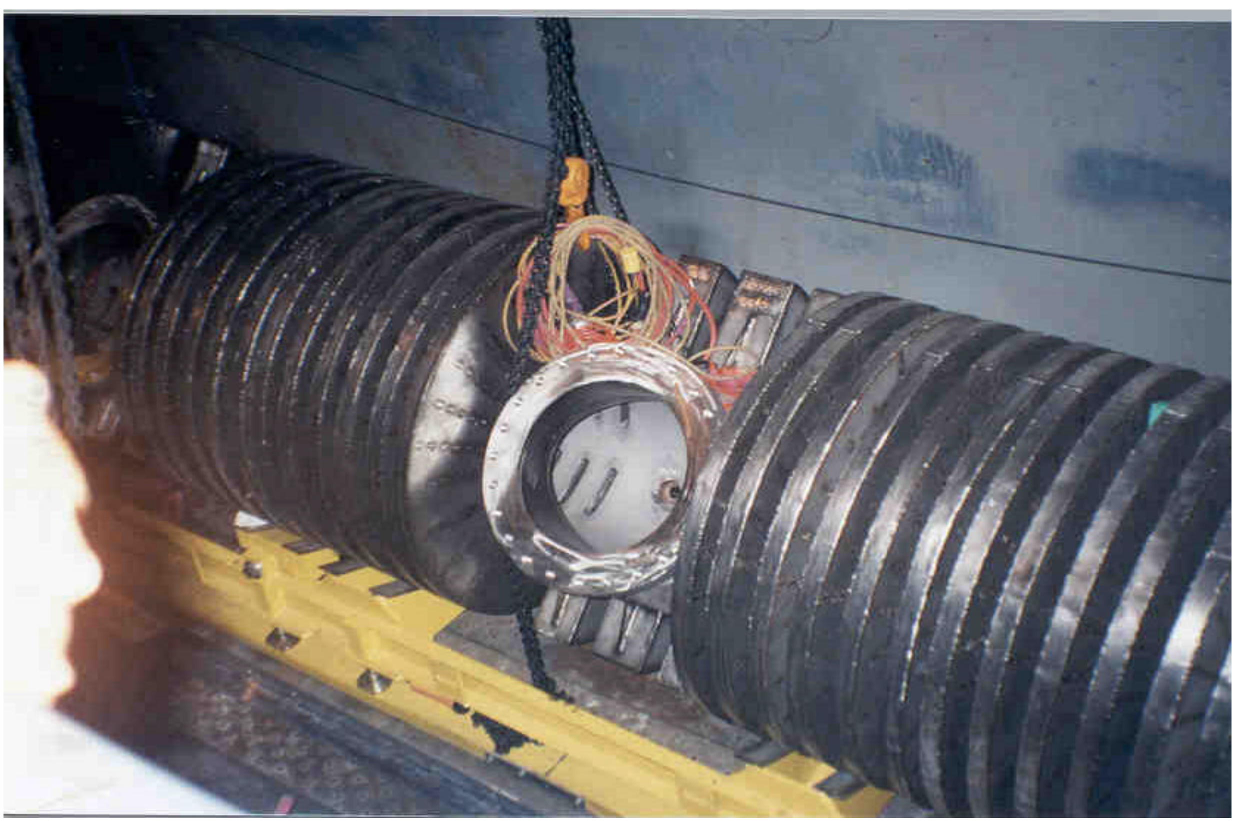
# BWR ECCS Strainer Blockage Issue: Summary of Research and Resolution Actions

**Prepared by**

**D. V. Rao**
**D-11, Los Alamos National Laboratory**

**Clinton J. Shaffer**
**ARES Corporation**

**Robert Elliott**
**Office of Nuclear Reactor Regulation**
**US Nuclear Regulatory Commission**



## ABSTRACT

The research and technical review efforts that form the basis for the resolution of the BWR strainer blockage issue by the United States Nuclear Regulatory Commission are summarized here. If a loss-of-coolant accident (LOCA) were to occur in a boiling-water reactor (BWR), insulation would be destroyed in a region close to the break. This insulation debris would be carried away from the break region by high-velocity break flow. Some portion of the entrained debris, in addition to other sources of debris, would be transported to the suppression pool and then subsequently deposited onto ECCS suction strainers where the debris would resist ECCS water flow. If sufficient debris were deposited onto the strainers, the head loss across the debris bed could compromise the operation of the ECCS by reducing flow below the minimum required to mitigate the accident or by completely blocking flow. Operational events demonstrated the need to address this concern for all BWR plants. The issue was initially studied during the review of unresolved safety issue (USI) A-43 in January 1979 and was considered resolved in 1985. However, subsequent ECCS strainer clogging and other events involving foreign material problems prompted a review of the strainer blockage issue. The events demonstrated that certain strainer clogging phenomena had not previously been recognized by the Nuclear Regulatory Commission (NRC) staff or the industry. The NRC sponsored research to evaluate the effectiveness of existing suction strainer designs in domestic BWR plants. The key technical findings from this research are summarized in this report. In addition, a summary of the actions taken by the nuclear power industry to ensure availability of long-term recirculation of cooling water in BWR plants is included.

On May 6, 1996, the NRC issued NRC Bulletin 96-03 “Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling-Water Reactors.” In the bulletin, the staff concluded that the strainer blockage issue must be resolved by licensees in order to ensure compliance with the regulations. All BWR licensees were requested to implement appropriate measures to ensure the capability of the ECCS to perform its safety function following a LOCA. The industry resolved the strainer blockage issue on a plant-specific basis by installing large-capacity passive strainers in each plant utilizing strainer design guidance provided by the BWR Owners Group (BWROG). The staff reviewed the BWROG guidance and performed detailed reviews of several plants. The results of the staff’s review are also summarized here.

## TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES

## LIST OF ACRONYMS

| | |
|---|---|
| ACRS | Advisory Committee on Reactor Safeguards |
| AJIT | Air Jet Impact Testing |
| ARL | Alden Research Laboratory |
| ASTM | American Society for Testing Materials |
| AWTS | Anticipated Transient Without Scram |
| BTP | Branch Technical Position |
| BWR | Boiling Water Reactor |
| BWROG | Boiling Water Reactor Owners Group |
| CDF | Core Damage Frequency |
| CDI | Continuum Dynamics, Inc. |
| CEESI | Colorado Engineering Experiment Station Inc. |
| CFD | Computational Fluid Dynamics |
| CFR | Code of Federal Regulations |
| CSB | Containment Systems Branch |
| CSNI | Committee on the Safety of Nuclear Installations |
| CSS | Containment Spray System |
| CST | Condensate Storage Tank |
| DB | Design Basis |
| DBA | Design-Basis Accident |
| DDTS | Drywell Debris Transport Study |
| DEGB | Double-Ended Guillotine Break |
| DGM | Debris Generation Model |
| ECCS | Emergency Core Cooling System |
| EDO | Executive Director for Operations |
| EOP | Emergency Operating Procedure |
| EPRI | Electric Power Research Institute |
| FME | Foreign Material Exclusion |
| FSTF | Full-Scale Test Facility |
| GDC | General Design Criteria |
| GE | General Electric Company |
| GUI | Graphical User's Interface |
| HPCI | High-Pressure Coolant Injection |
| IPE | Individual Plant Examination |
| ISLOCA | Interfacing Systems LOCA |
| ITS | Innovative Technology Solutions, Inc. |
| LANL | Los Alamos National Laboratory |
| LTR | Licensing Topical Report |
| LLOCA | Large Loss-of-Coolant Accident |
| LOCA | Loss-of-Coolant Accident |
| LPCI | Low-Pressure Core Injection |
| LPCS | Low-Pressure Core Sprays |
| MLOCA | Medium Loss-of-Coolant Accident |
| MSLB | Main Steam Line Break |
| NDE | Non-Destructive Evaluation |
| NEA | Nuclear Energy Agency |
| NPSH | Net Positive Suction Head |
| NRC | Nuclear Regulatory Commission |
| NRCB | Nuclear Regulatory Commission Bulletin |

## LIST OF ACRONYMS

| | |
|---|---|
| OECD | Organization for Economic Cooperation and Development |
| ORNL | Oak Ridge National Laboratory |
| PCI | Performance Contracting Inc. |
| PIRT | Phenomena Identification and Ranking Table |
| PNPP | Perry Nuclear Power Plant |
| PP&L | Pennsylvania Power and Light Company |
| PRA | Probabilistic Risk Assessment |
| PWG-1 | Principal Working Group 1 |
| PWR | Pressurized Water Reactor |
| QA | Quality Assurance |
| RCIC | Reactor Core Injection Cooling |
| RG | Regulatory Guide |
| RHR | Residual Heat Removal |
| RLB | Recirculation Line Break |
| RMI | Reflective Metallic Insulation |
| SEA | Science and Engineering Associates |
| SEM | Scanning Electron Micrograph |
| SER | Safety Evaluation Report |
| SKI | Statens Karnkraftinspektion [Swedish Nuclear Power Inspectorate] |
| SNL | Sandia National Laboratories |
| SPCP | Suppression Pool Cleanliness Program |
| SRP | Standard Review Plan |
| SRV | Safety Relief Valve |
| TER | Technical Evaluation Report |
| URG | Utility Resolution Guidance |
| USI | Unresolved Safety Issue |
| USNRC | United States Nuclear Regulatory Commission |
| ZOI | Zone of Influence |

**EXECUTIVE SUMMARY**

A high-energy pipe break (referred to here as a loss-of-coolant accident or LOCA) in a boiling water reactor (BWR) would destroy pipe insulation (fibrous, metallic, etc.) in the vicinity of the break, creating insulation debris. The area near the break where insulation debris is generated is called the zone-of-influence (ZOI). This debris would be driven away from the ZOI by high-velocity steam flow, in the case of a main steam line break (MSLB), or by steam-water mixtures, in the case of a recirculation line break (RLB). Some portion of the debris would likely be transported across the drywell, past/through structures such as gratings and through the downcomer vents to the suppression pool. Debris transported to the suppression pool, in addition to other sources of debris, could then be subsequently drawn to the emergency core cooling system (ECCS) suction strainers where the debris would resist ECCS water flow. If sufficient debris were deposited onto the strainers, the head loss across the debris bed could compromise the operation of the ECCS by reducing or completely blocking flow. Operational events have demonstrated the need to address this concern for all BWR plants.

An Unresolved Safety Issue (USI) was declared in January 1979, USI A-43, to address concerns regarding the availability of adequate recirculation cooling water following a LOCA when long-term recirculation must be initiated and maintained. Substantial experimental and analytical research was conducted to support the resolution of USI A-43. A main concern was that the formation of an air-core vortex would result in unacceptable levels of air ingestion and severely degrade pump performance; however, hydraulic tests showed that the potential for air ingestion was less severe than previously hypothesized. The regulatory analysis did not support a generic backfit action, but determined the issue resolution must be plant specific. The staff recommended that Revision 1 of the RG 1.82, "Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident," be used as guidance for the conduct of 10CFR50.59 reviews dealing with the changeout and/or modifications of thermal insulation installed on the primary coolant system piping and components. The 50% blockage criterion of Revision 0 of RG 1.82 was considered inadequate to address this issue. USI A-43 was declared resolved in 1985.

Subsequent to the closure of USI A-43, several ECCS strainer and foreign material discovery events prompted a review of the strainer blockage issue. Perhaps the most notable of these events occurred on July 28, 1992 while restarting Barsebäck Unit 2 in Sweden (similar to U.S. Mark II BWR plants). This event followed a discharge of steam from the spurious opening of a safety valve that impinged on thermal insulation, dislodging substantial quantities of mineral wool. Mineral wool debris transported to the suppression pool and partially plugged two of five ECCS suction strainers, leading to the loss of both containment sprays within one hour of the valve opening. Operators successfully backflushed the strainers and shut down the reactor. The Barsebäck event demonstrated that larger quantities of fibrous debris could reach the strainers than had been predicted by the models and analysis methods developed for the resolution of USI A-43. Analysis of Swedish experimental data showed that prior correlations for debris head loss tended to underestimated strainer head losses.

Instances of ECCS pump strainer clogging also occurred at U. S. plants, including two instances that occurred at the Perry Nuclear Plant and another at Limerick Unit 1. In these incidents, ECCS strainers were blocked with debris consisting of fibers, corrosion products, and miscellaneous materials filtered from the pool. In one Perry incident the strainers were deformed by excessive differential pressure across the strainers caused by debris. Fibrous material acted as a filter for suspended particles creating a fibrous/particulate debris bed that resulted in a much larger pressure drop across the strainers than would have been predicted for the fibers alone; a phenomenon not previously recognized by the staff or the industry. At Limerick, pump cavitation was indicated. Other strainer blockage incidents have occurred and substantial quantities of debris were discovered in suppression pools on other occasions.

All of these events occurred despite existing NRC regulations and regulatory guidance. The NRC has consistently emphasized the need for a strong foreign material exclusion (FME) program in all areas of BWR plants that may contain materials that could interfere with the successful operation of the ECCS and safety-related containment spray system (CSS). It was clear that additional research, guidance, and possibly plant modifications were needed to resolve this issue.

Investigations of post-resolution events leading to strainer clogging found that one key aspect of the issue had not been completely researched and addressed, specifically the impact of filtered particulate by fibrous debris beds on strainer head loss. The NRC sponsored research to estimate possible shortcomings of existing suction strainer designs in U. S. BWR plants. Key technical findings are summarized here 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. The NRC sponsored research included:

- A detailed plant-specific study of a BWR/4 reactor and a Mark I containment, referred to as the NUREG/CR-6224 study, where deterministic analysis focused on determining whether or not a postulated break in the primary system piping of the reference BWR plant could result in ECCS strainer blockage and loss of net positive suction head (NPSH). The study developed analytical models that would predict the generation and transport of debris to the suppression pool and then onto the strainers, and the head loss across the strainer due an accumulation of debris. Small-scale experiments were conducted to provide critical data and to gain insights into the behavior of debris in the suppression pool and acquire mixed bed head loss data. The results demonstrated that there was a high probability that the available NPSH margin for the ECCS pumps would not be adequate following dislodging of insulation and other debris caused by a LOCA and that the loss of NPSH could occur quickly.

- Probabilistic analysis was performed that focused on evaluating the likelihood of ECCS strainer blockage and blockage-related core damage from LLOCA-initiators. The essential elements of the probabilistic methods included: 1) the estimation of the break frequency for each weld located in the primary system piping, and 2) the development of a functional event tree that models accident progression for a LOCA initiator with specific relevance to the ECCS strainer blockage issue.

- The BLOCKAGE computer program was developed to calculate debris generation, debris transport, fiber/particulate debris bed head losses, and its impact on the available NPSH.

- The NRC initiated the drywell debris transport study (DDTS) to investigate debris transport in BWR drywells using a bounding analysis approach. The study included small-scale testing of fibrous insulation transport. The DDTS provided a description of the important phenomena and plant features that control and/or dominate debris transport and the relative importance of each phenomenon as a function of the debris size.

Regulatory Guide 1.82 was revised (Revision 2) in May 1996 to alter the debris blockage evaluation guidance for BWR plants thereby providing acceptable methods for implementing applicable design requirements as required by 10CFR50.46. The staff concluded that the strainer blockage issue must be resolved by licensees in order to ensure compliance with the regulations. The NRC staff issued NRCB 96-03, “Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling-Water Reactors,” on May 6, 1996. All BWR licensees were requested to implement appropriate measures to ensure the capability of the ECCS to perform its safety function following a LOCA. The staff identified three potential resolution options but allowed licensees to propose others that provided an equivalent level of assurance. Each BWR plant assessed their plant-specific situation and backfit their plant-specific resolution, as necessary, to resolve the issue. The BWR Owners Group (BWROG) supported the utilities by developing resolution guidance, referred to as the URG. The BWROG evaluated potential solutions and conducted tests to obtain needed data to develop the URG.

The NRC reviewed the BWROG URG document and issued the staff's Safety Evaluation Report (SER) on August 20, 1998. The URG was found to be a comprehensive document providing: 1) general guidance on resolution options, and 2) detailed guidance on performing plant specific analyses to estimate potential worst case debris loadings on ECCS suction strainers during a LOCA. However, due to incomplete guidance and inadequate supporting documentation or analysis in several areas, the staff was unable to determine if all of the methodologies, or combination of methodologies, were conservative. Therefore, the staff SER should be used in conjunction with the URG to ensure a consistent response by the industry to NRCB 96-03.

The staff was concerned that the NPSH available for ECCS and containment heat removal pumps may not be adequate under all design-basis accident scenarios. Specifically, the staff was concerned that changes to plant configuration, operating procedures, environmental conditions, or other operating parameters over the life of the plant could result in inadequate NPSH. On October 7, 1997, the NRC staff issued Generic Letter 97-04, "Assurance of Sufficient Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal Pumps." Some licensees discovered that they must take new credit for containment overpressure to meet the NPSH requirements of the ECCS and containment heat removal pumps and the overpressure being credited by licensees may be inconsistent with the plant's respective licensing basis. The staff further evaluated its position on use of containment overpressure in calculating NPSH margin and recommended that licensing basis changes not be used as a resolution option due to the substantial uncertainty associated with determining NPSH margin.

The industry addressed the requirements of NRC 96-03 by installing large capacity passive strainers in each plant. Four BWR plants were chosen for detailed audit by NRC staff; these plants are Limerick (BWR/4 Mark II), Dresden (BWR/3 Mark I), Duane Arnold (BWR/4 Mark I), and Grand Gulf (BWR/6 Mark III).

To put the importance of strainer blockage into perspective, the risk significance was explored using existing probabilistic evaluations, i.e., the NUREG-1150 risk study and the Individual Plant Examination (IPE) Program. The risk significance was explored by examining the effect of recirculation cooling unavailability with regard to its impact on CDF for various BWR and PWR accident classes. The results indicated that the unavailability of recirculation core cooling in BWRs would increase the baseline aggregate CDF values from the E-05/yr range to the E-03/yr range. The accident classes having their CDF values most affected by recirculation cooling unavailability are the LOCA and transient accident classes. The CDFs for the station blackout, ATWS, and ISLOCA accident classes were affected to a lesser extent if recirculation cooling is unavailable.

## 1.0 OVERVIEW OF BWR STRAINER BLOCKAGE ISSUE AND RESOLUTION

A high-energy pipe break (referred to here as a loss-of-coolant accident or LOCA) in a boiling water reactor (BWR) would destroy pipe insulation (fibrous, metallic, etc.) in the vicinity of the break creating insulation debris. The area near the break where insulation debris is generated is called the zone-of-influence (ZOI). This debris would be driven away from the ZOI by high velocity steam flow, in the case of a main steam line break (MSLB), or by steam-water mixtures, in the case of a recirculation line break (RLB). Some portion of the debris would likely be transported across the drywell, past/through structures such as gratings and through the downcomer vents to the suppression pool. Debris transported to the suppression pool, in addition to other sources of debris, could then be subsequently drawn to the emergency core cooling system (ECCS) suction strainers where the debris would resist ECCS water flow. If sufficient debris were deposited onto the strainers, the head loss across the debris bed could compromise the operation of the ECCS by reducing or completely blocking flow. Operational events have demonstrated the need to address this concern for all BWR plants.

The key technical findings of USNRC research supporting the resolution of the BWR strainer blockage issue are summarized here 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. As will be discussed in the historical overview, the potential for strainer blockage following a LOCA became an unresolved safety issue (USI) in 1979: USI A-43, “Containment Emergency Sump Performance” [NUREG-0933], which was subsequently resolved in 1985. However, investigation of strainer clogging events identified a key phenomenon had not been considered, specifically, the impact on strainer head loss of particulate filtration by fibrous debris beds. The NRC sponsored research to quantify this impact and to look more deeply into the strainer blockage issue in general. Each BWR plant assessed their specific situation and implemented their resolution, as necessary to resolve the issue. This report is intended to serve as a source of information regarding the strainer blockage issue, summarizing the key aspects of the issue and identifying the most important documents. The report is organized as follows.

- Section 1 provides an overview of the BWR strainer blockage issue and its resolution.
- Section 2 summarizes the NRC-sponsored research performed to gain an understanding and insights into the BWR strainer blockage issue.
- Section3 summarizes the NRC review of applicable research sponsored by the U. S. industry and by international organizations.
- Section 4 summarizes the NRC review of the BWROG issue resolution guidance to the industry.
- Section 5 summarizes the implementation of industry resolutions of the strainer clogging issue and the NRC’s review of individual plant strainer solutions.

### 1.1 Historical Overview

The chronology of the BWR strainer blockage issue and its resolution is illustrated in the timeline presented in Table 1.1 and each of these events is discussed below.

*Table 1.1. BWR Strainer Blockage Issue Timeline*

| Date | Event |
|---|---|
| January 1979 | NRC declared "Containment Emergency Sump Performance" as 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 Generic Letter 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. Licenses 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 | 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. 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 boiling water reactors 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 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 | 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 NRCB 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 Generic Letter 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 NRCB 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 Generic Letter 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 DB LOCA and interfere with the operation of the ECCS and safety-related containment spray system (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.'" |
| September 1999 | NRC published final results of DDTS [NUREG/CR-6369]. |
| January 1999 | NRC Audit of Limerick NRCB 96-03/95-02 Resolution |
| March 1999 | NRC Audit of Dresden NRCB 96-03/95-02 Resolution |
| August 1999 | NRC Audit of Grand Gulf NRCB 96-03/95-02 Resolution |
| October 1999 | NRC Audit of Duane Arnold NRCB 96-03/95-02 Resolution |
| April 2000 | NRC technically reviewed the licensee submittals regarding Brunswick Steam Electric Plant, Units 1 and 2, response to NRCB 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." |
| April 2000 | NRC technically reviewed the strainer design marketed by Performance Contracting, Inc. The finders were documented in LA-UR-00-5159, "Technical Review of Selected Reports on Performance Contracting, Inc. Sure-Flow Strainer™ Test Data." |
| 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)." |

USI A-43 dealt with concerns regarding the availability of adequate long-term recirculation cooling water following a LOCA. Substantial experimental and analytical research was conducted to support the resolution of USI A-43. USI A-43 was declared resolved in 1985. Subsequent to the closure of USI A-43, several ECCS strainer and foreign material discovery events prompted a review of the strainer blockage issue. The NRC sponsored research to estimate possible shortcomings of existing suction strainer designs in U. S. BWR plants and to evaluate the actions taken by the nuclear power industry to ensure availability of long-term recirculation of cooling water in BWR plants. The historical overview is presented chronologically in the following three subsections, i.e., 1) 1.1.1 Overview of USI A-43 Resolution, 2) 1.1.2 Overview of Subsequent BWR Strainer Clogging and Pump Failure Events, and 3) 1.1.3 Overview of NRC Research and Regulatory Actions and the BWR Issue Resolution.

### 1.1.1 Overview of USI A-43 Resolution

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 key aspects of the NRC research and findings leading to the resolution of USI A-43 are summarized here. USI A-43 dealt with concerns regarding the availability of adequate long-term recirculation cooling water following a LOCA. This cooling water must be sufficiently free of debris so that pump performance is not impaired and long-term recirculation flow capability is not degraded. Although USI A-43 was principally derived from concerns regarding pressurized water reactor (PWR) containment emergency sump performance, these concerns applied to BWR ECCS suction, as well. The BWR RHR system performs the low-pressure coolant injection (LPCI) function of the ECCS and safety-related containment spray system (CSS). In addition, BWR designs incorporate a low-pressure core spray (LPCS) system as part of the ECCS. The suction strainers located in the BWR suppression pool are analogous to the PWR sump debris screen.

The concerns regarding USI A-43 were published in NUREG-0510. The technical concerns applicable to BWR plants under USI A-43 were: 1) the RHR suction intake hydraulic performance under adverse post-LOCA conditions including air ingestion and subsequent pump failure, 2) the transport of LOCA-generated debris to the suction strainers and the potential strainer blockage leading to a reduction in NPSH margin below that required to maintain long-term cooling, and 3) the capability of ECCS pumps to continue pumping when subjected to possible air, debris, or other effects on pump seal and bearing systems.

Substantial experimental and analytical research was conducted to support the resolution of USI A-43. In 1985, the staff published a summary of the key technical findings for use as an information source [NUREG-0897]. The bases for these findings were documented in a series of NRC contractor reports, which are listed in the NUREG-0897 reference section. In NUREG-0897, the NRC concluded the following:

- At the time, the formation of an air-core vortex that would result in unacceptable levels of air ingestion and severely degraded pump performance was a concern. This concern was more applicable to PWRs but was still relevant to BWR plants. 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 is only slightly degraded when air ingestion is less than 2%.

- The effects of LOCA-generated insulation debris on RHR recirculation requirements depend on: 1) the types and quantities of insulation, 2) the potential of a high pressure break to severely damage large quantities of insulation, 3) the transport of debris to the sump screen or strainer, 4) the blockage potential of the transported debris, and 5) the impact on available NPSH. The effects of debris blockage on NPSH margin must be dealt with on a plant-specific basis. Insulation debris transport tests showed that severely damaged or fragmented insulation readily transported at relatively low velocities (0.2 to 0.5 ft/sec). 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's (distance divided by the pipe break diameter). Data showed that jet load pressures would inflict severe damage to insulation within 3 L/D's, and substantial damage 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 screens or suction strainers and reach the pump impeller should not impair long-term hydraulic performance. 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 due to 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 insulation types used, quantities and distribution of insulation, methods of attachment, components and piping insulated, variability of plant layouts, and sump designs and locations. The types of insulation found were categorized into two major groups: reflective metallic insulation (RMI) and fibrous insulations. The RMI was manufactured by at least four different manufacturers. The fibrous insulation included NUKON™ fiberglass blankets, fiberglass molded blocks, mineral wool fiber blocks, calcium silicate molded blocks, and expanded perlite molded block. Insulations were sometimes enclosed in an outer shell or jacket or cloth cover.

The NRC resolution of USI A-43 was presented to the Commission in October 1985 [SECY-85-349]. The resolution consisted of publishing NUREG-0897 as a summary of the key technical findings for use as an information source by applicants, licensees, and the staff, 2) revising the Standard Review Plan (SRP) Section 6.2.2 and Regulatory Guide (RG) 1.82, "Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident," to reflect the staff's technical findings, and 3) issuing Generic Letter 85-2, "Potential for Loss of Post-LOCA Recirculation Capability Due to Insulation Debris Blockage," to all holders of an operating license or construction permit outlining the safety concerns and recommending the use of RG 1.82, Revision 1 as guidance for conducting 10 CFR 50.59 analyses. In addition, a regulatory analysis was performed (see NUREG-0869) to serve as a basis for the final resolution of USI A-43.

The regulatory analysis did not support a generic backfit action because plant specific design features and post-LOCA recirculation flow requirements govern the debris blockage effects. As a result, the analysis conclusion was that the issue resolution must 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 primary coolant system piping and components. The 50% blockage criterion of Revision 0 of RG 1.82 was considered inadequate to address this issue.

### 1.1.2 Overview of Subsequent BWR Strainer Clogging and Pump Failure Events

Subsequent to the closure of USI A-43, several ECCS strainer and foreign material discovery events prompted a review of the strainer blockage issue for BWRs. Perhaps the most notable of these events occurred on July 28, 1992, during the startup of Barsebäck, Unit 2, in Sweden. This is discussed in NRC Information Notice (IN) 92-71, "Partial Blockage of Suppression Pool Strainers at a Foreign BWR," September 30, 1992. The Barsebäck plant is a BWR design similar to the designs of U. S. Mark II BWR plants. In this event, a spurious opening of a safety valve while the reactor was pressurized to 3100 kPa (435 psig) discharged steam into the drywell. This steam impinged on thermally insulated equipment and dislodged approximately 200 kilograms (kg) of metal-jacketed mineral wool. An estimated 100 kg of this insulation was subsequently transported into the suppression pool (approximately 30% driven by steam flow and 70% washed down by water). Mineral wool debris partially clogged two of five containment vessel spray system suction strainers leading to the loss of both containment sprays within one hour of the valve opening. The partial clogging significantly increased the pressure drop across the strainers causing indications of cavitation in one pump. Operators successfully backflushed the strainers and shut down the reactor. The Barsebäck-2 safety analysis had previously concluded that the strainers would not require backflushing during the first 10 hours following a LOCA. The regulatory authorities of Sweden and other northern and central European countries viewed the Barsebäck-2 incident as a precursor to potential loss of ECCS cooling due to LOCA-generated debris and initiated a safety reanalysis effort coupled with experiments. The results were compared with results obtained for resolution of USI A-43. The Barsebäck-2 event demonstrated that larger quantities of fibrous debris could reach the strainers than had been predicted by models and analysis methods developed for the resolution of USI A-43. Analysis of Swedish experimental data showed that prior correlations for debris head loss tended to underestimate strainer head losses.

ECCS suction strainer clogging events also occurred at U. S. plants, including two events that occurred at the Perry Nuclear Power Plant (PNPP). PNPP is a BWR/6 plant with a Mark III containment. This is discussed in NRC IN-93-34, "Potential for Loss of Emergency Cooling Function Due to a Combination of Operational and Post-LOCA Debris in Containment," May 6, 1993. On May 22, 1992, during a refueling outage inspection at the PNPP, debris was found on the suppression pool floor and on the RHR suction strainers. In addition, the buildup of debris on the strainer caused an excessive differential pressure causing deformation of the strainers. PNPP replaced the strainers and cleaned the suppression pool. Then in March 1993, several safety relief valves lifted and the RHR was used to cool the suppression pool. The strainers were subsequently inspected and found covered with debris. A test of the strainers in the as-found condition was terminated when the pump suction pressure dropped to zero. The debris on the strainers consisted of glass fibers (temporary drywell cooling filters inadvertently dropped into the suppression pool); corrosion products, and other materials filtered from the pool water by the glass fibers adhering to the strainer surfaces [IN-93-34, Supplement 1]. The suppression pool debris also consisted of general maintenance types of materials and a coating of fine dirt that covered most of the surface of the strainers and the pool floor. Fibrous material acted as a filter for suspended particles, a phenomenon not previously recognized by the NRC or the industry. This event suggested that filtering of small particles, such as suppression pool corrosion products (sludge), by the fibrous debris would result in significantly increased pressure drop across the strainers.

Another event occurred at the Limerick Generating Station, Unit 1 on September 11, 1995. This is discussed in NRC IN-95-47, "Unexpected Opening of a Safety/Relief Valve and Complications Involving Suppression Pool Cooling Strainer Blockage," November 30, 1995. A safety relief valve (SRV) opened on Unit 1 while at 100% power. Before the SRV opened, Limerick had been running Loop A of the RHR in suppression pool cooling mode. The operators initiated a manual scram in response to the SRV opening, and a second loop (Loop B) of suppression pool cooling. Approximately 30 minutes later, fluctuating motor current and flow were observed on Loop A. The cause was believed to be cavitation and Loop A was secured. Following the event, inspection by a diver revealed a thin mat of material covering the Loop A strainer. The mat consisted of fibrous material and sludge. The Loop B strainer had a similar covering, but to a lesser extent. Limerick subsequently removed about 635 kg of debris from the pool. Similar to the PNPP events, the mat of fibers on the strainer surface converted the strainer into a filter, collecting sludge and other material on the strainer surface.

Other debris related events have occurred. The Grand Gulf Nuclear Station experienced strainer blockage events on March 18, 1988 and on July 2, 1989. Both events occurred during testing of the RHR pumps. Pump suction pressures fell below the inservice inspection acceptance criteria [IN-93-34]. On October 10, 1994, divers discovered numerous pieces of cloth-like material on the bottom of the torus and on the ECCS strainers at Browns Ferry Nuclear Plant, Unit 2 [IN-95-06]. One of the two strainers was found with about 15% of its surface covered with debris. If all of the material had been drawn onto the strainers, about 25% of the strainer surface area would have been blocked.

Substantial quantities of debris were discovered in suppression pools on other occasions. On June 13, 1994, significant amounts of assorted debris were discovered in the suppression pool of the River Bend Nuclear Station, including a plastic bag on an RHR strainer. River Bend also found sediment in the suppression pool [IN-94-57]. Similarly, on April 26 and May 11, 1994, the LaSalle County Station found and removed an assortment of operational debris from the suppression pool [IN-94-57]. The diver also noted sediment on the suppression pool floor ranging in thickness from 0.3 to 5 cm (1/8 to 2 inches). Analysis showed the sediment consisted of over 99% iron oxide, or normal system corrosion products.

In other cases, plant inspections have found deteriorated insulation that would render these materials more likely to form debris following a LOCA. On March 14, 1988, Pennsylvania Power and Light notified the NRC of the deterioration of drywell insulation at the Susquehanna plant and the potential for the aluminum jacketing on the surface of the fiberglass insulation to block ECCS strainers following a LOCA [IN-88-28]. Extensive delamination of the aluminum jacketing was discovered during a refueling inspection. This event illustrated the need for plant operators to be alert to potential problems caused by inadequately maintained insulation.

In other plant inspections, previously unidentified unqualified coatings that could form debris following a LOCA have been found.

Examples noted in Generic Letter 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," include:

- Millstone Unit 1 found that most of the coating in the torus was unqualified (NRC Event Report 32161),

- Unqualified coatings were found on the T-quenchers in the suppression pool of the Browns Ferry Units,

- Significant degradation to protective coatings was found in the Clinton containment wetwell (NRC Event Report 32633).

All of these events occurred despite existing NRC regulations and regulatory guidance. Title 10, Section 50.46 of the Code of Federal Regulations (10 CFR Part 50.46) requires that commercial nuclear power plants have an ECCS designed to provide long-term cooling so that core temperatures can be maintained at an acceptably low value and decay heat can be removed for the extended period required by the long-lived radioactivity in the core. Foreign materials, degraded coatings inside the containment that detach from their substrate, ECCS components not consistent with their design basis, and LOCA-generated debris, are potential common-cause failure mechanisms for the ECCS and CSS. Debris may clog suction strainers, sump screens, filters, nozzles, and small-clearance flow paths in the ECCS and safety-related CSS, and interfere with the long-term cooling function, source-term reduction or and pressure reduction capabilities of the plant. The NRC has consistently emphasized the need to minimize the presence of foreign material in the containment (e.g., a strong foreign material exclusion (FME) program). All areas of BWR and PWR plants that may contain materials could interfere with the successful operation of the ECCS and safety-related CSS. FME and housekeeping programs, including periodic inspections and cleanings, minimize the amount of foreign material and suppression pool sludge that is present in the containment. Transient debris (e.g., foreign material) and suppression pool sludge must be considered along with LOCA-generated debris in strainer sizing analyses. Each plant determines the appropriate rigor of the FME and housekeeping controls, considering the trade off between operational flexibility and ECCS strainer capacity. The FME and housekeeping programs must maintain debris source terms at levels that do not threaten the operability of the ECCS systems.

The string of operational events described above demonstrated that:

- Larger quantities of debris could reach the ECCS strainers than had been predicted by models and analyses methods developed during the resolution of USI A-43.

- Fibrous material acts as a filter for suspended particles, a phenomenon not previously recognized by the NRC or the industry.

- Head loss correlations developed during the resolution of USI A-43 under predicted strainer head losses for combined fiber/particulate debris beds.

- Extensive quantities of foreign materials were being found in suppression pools despite the ongoing FME programs.

Based on these events, additional research was conducted, guidance was developed, and plant modifications were implemented to resolve the problem.

### 1.1.3 Overview of NRC Research, Regulatory Actions, and the BWR Issue Resolution

The ECCS strainer and foreign material discovery events prompted a review of the strainer blockage issue, hence the NRC sponsored research to estimate possible shortcomings of existing suction strainer designs in U. S. BWR plants and to evaluate the actions taken by the nuclear power industry to ensure availability of long-term recirculation of cooling water in BWR plants. An overview of this research is presented in this section.

Concerns generated by these strainer blockage events prompted the NRC to issue Bulletin 93-02, "Debris Plugging of Emergency Core Cooling Suction Strainers," on May 11, 1993 to both BWR and PWR licensees. Licensees were requested to 1) identify fibrous air filters and other temporary sources of fibrous material in the primary containment not designed to withstand a LOCA, and 2) take prompt action to remove the identified material, and 3) take any other immediate compensatory measures necessary to ensure the functional capability of the ECCS.

The NRC sponsored research to evaluate the adequacy of existing suction strainer designs in U. S. BWR plants. Preliminary calculations showed that the potential existed for the ECCS pumps to lose net positive suction head (NPSH) margin due to clogging of the suction strainers by LOCA-generated debris. As a result, the NRC initiated a detailed plant-specific study in September 1993 using a reference BWR/4 reactor with a Mark I containment. The results of this were released as a "Draft for Comment" report [NUREG/CR-6224] in August 1994. Comments were received from foreign nuclear regulatory organizations, American manufacturers of thermal insulation, and the BWR Owners Group (BWROG). All comments were reviewed and NUREG/CR-6224 was revised to incorporate the feedback from the comments. The final report was published in October 1995.

A deterministic analysis was performed to determine if a postulated break in the primary system piping of the reference BWR plant could result in ECCS strainer blockage and loss of NPSH. The analysis considered debris generation, drywell debris transport, suppression pool debris transport, and strainer blockage. The study developed analytical models applicable to the reference BWR that would predict the generation of debris, the transport of debris from the drywell to the suppression pool, the transport of debris within the suppression pool to the strainers, and the head loss across the strainer due an accumulation of debris.

The NUREG/CR-6224 study identified a lack of critical data needed to complete the study. As a result, the NRC sponsored a series of small-scale experiments designed to gain insights into the behavior of debris in the suppression pool and acquire mixed debris bed head loss data. Two sets of experiments were performed. The first set of experiments tested LOCA generated debris transport in the suppression pool during both the high-energy phase immediately following the postulated LOCA as well as during the relatively quiescent phase after the high-energy conditions subside. Tests were conducted in a reduced scale suppression pool test facility. Test debris included fibrous debris, RMI debris, and particulate debris. The phenomena examined included debris resuspension from the pool floor, debris mixing, and debris settling characteristics during both the high-energy and quiescent phases and fragmentation of fibrous debris subjected to high levels of turbulence. The second set of experiments examined the effect of debris on strainer head loss. Fibrous debris was tested with and without the addition of particulate debris and both the strainer head loss and the filtration efficiencies of fibrous debris beds (e.g. to filter and trap micron range sludge particles) were measured. RMI debris was tested both by itself and in combination with fibrous debris (mixed debris beds). A closed loop test facility was designed to conduct these experiments.

A computer program called BLOCKAGE was developed to calculate debris generation, debris transport, fiber/particulate debris bed head losses, and the impact of the debris on the available ECC NPSH. The BLOCKAGE code included models for transient debris bed formation and used a fiber/particulate head loss correlation developed during in the reference plant study. The head loss correlation, known as the NUREG/CR-6224 head loss correlation, is valid for laminar, transient, and turbulent flow regimes through mixed debris beds.

Probabilistic analyses were performed that focused on evaluating the likelihood of ECCS strainer blockage and blockage-related core damage from LLOCA-initiators. The major elements of the probabilistic analyses included: 1) estimation of the break frequency for each weld located in the primary system piping, and 2) development of a functional event tree that models accident progression for a LOCA initiator with specific relevance to the ECCS strainer blockage issue. Quantification of the event tree resulted in estimates of the core damage frequency (CDF) from the loss of ECCS due to strainer blockage following a LOCA.

The NRC also exchanged information and experience with the international community. The Swedish nuclear power inspectorate, Statens Kärnkraftinspektion (SKI), hosted a workshop to study the strainer blockage issue on January 26-27, 1994. The workshop was held in Stockholm, Sweden, under the auspices of the Committee on the Safety of Nuclear Installations/Principal Working Group 1 (CSNI/PWG-1). The workshop revealed a confusing picture of the available knowledge base, including examples of conflicting information and a variety of interpretations of the regulatory guidance in the NRC's RG 1.82, Rev. 1. Following this workshop, SKI requested the formation of an international working group under the auspices of the CSNI/PWG-1 committee to establish an internationally agreed-upon knowledge base for assessing the reliability of ECC water recirculation systems. The NRC compiled a source book of available knowledge for the CSNI of the Organization for Economic Cooperation and Development (OECD) Nuclear Energy Agency, which was published in February 1996. This source book is found in report NEA/CSNI/R (95) 11, "Knowledge Base for Emergency Core Cooling System Recirculation Reliability." At the time of its publishing, this knowledge base summarized the available experimental and analytical information/data on the following: debris generation, and debris sources, drywell debris transport, suppression pool debris transport, strainer head losses, related potential safety issues, and debris generation events (e.g., the Barsebäck-2 LOCA).

Based on the NRC's preliminary research and information learned at the OECD/Nuclear Energy Agency (NEA) workshop, the NRC issued Supplement 1 to Bulletin 93-02 on February 18, 1994 requesting BWR licensees to take further interim actions pending final resolution. These actions involved implementing operating procedures and conducting training and briefings designed to enhance the capability to prevent or mitigate loss of ECCS following a LOCA due to strainer clogging. The purpose of these interim actions was to ensure reliability of the ECCS so that the staff and industry would have sufficient time to develop a permanent resolution.

The NRC's investigation of the strainer blockage event at Limerick-1 identified additional concerns that prompted the NRC to issue Bulletin 95-02, "Unexpected Clogging of Residual Heat Removal (RHR) Pump Strainer While Operating in Suppression Pool Cooling Mode," on October 17, 1995 to all BWR licensees. A mat of fibers and sludge blocked a strainer at Limerick-1. Subsequent to the event approximately 635 kg of debris was removed from the pool. The Limerick event demonstrated the need to ensure adequate suppression pool cleanliness and it re-emphasized that materials other than fibrous insulation could also clog strainers. This bulletin requested actions be taken by BWR licensees to prevent unacceptable buildup of debris that could clog strainers does not occur during normal operation. Specifically, BWR licensees were requested to: 1) verify the operability of all their pumps drawing suction from the suppression pool when performing their safety function, 2) schedule a suppression pool cleaning, and 3) review FME procedures and their implementation to determine whether adequate control of materials in the drywell, suppression pool, and systems that interface with the suppression pool exists.

In order to provide time to conduct research to resolve the strainer clogging issue, the NRC first ensured that public health and safety were adequately protected. In responding to NRC Bulletin 93-02 and its supplement, BWR licensees implemented interim measures to ensure adequate protection of public health and safety. Specifically, licensees ensured that: 1) alternate water sources (both safety and non-safety-related sources) to mitigate a strainer clogging event were available, 2) emergency operating procedures (EOP) provided adequate guidance on mitigating a strainer clogging event, 3) operators were adequately trained to mitigate a strainer clogging event, and 4) loose and temporary fibrous materials stored in containment were removed. The responses to NRC Bulletin 95-02 showed that most suppression pools had already been cleaned recently, and that those licensees who had not cleaned their suppression pools recently were scheduled to do so during their next refueling outage. In addition, a generic safety assessment conducted by the BWROG concluded that operators would have adequate time to make use of alternate water sources (25-35 minutes), if needed, during a LOCA and that the probability of the initiating event is low. For these reasons, the NRC allowed continued operation by BWR licensees until the final resolution to the strainer clogging issue was developed and implemented. The NRC initiated the final resolution to the strainer issue with the issuance of NRC Bulletin 96-03. Satisfactory implementation of the requested actions in NRC Bulletin 96-03 will ensure that the ECCS can perform its safety function and minimize the need for operator action to mitigate a LOCA.

The final results of the reference plant study, documented in NUREG/CR-6224, demonstrated that for the reference plant, there was a high probability that the available NPSH margin for the ECCS pumps would be inadequate if insulation and other debris caused by a LOCA transported to the suction strainers. In addition, the study calculated that the loss of NPSH could occur quickly (less than 10 minutes into the event). The study also concluded that determining the adequacy of NPSH margin for a given ECCS system is highly plant-specific because of the large variations in such plant characteristics as containment type, ECCS flow rates, insulation types, plant layout, plant cleanliness, and available NPSH margin.

The Barsebäck event demonstrated that a pipe break could generate and transport sufficient quantities of insulation and other debris to the suppression pool to cause the ECCS to lose NPSH. The Perry events further demonstrated that fibrous debris combined with corrosion products present in the suppression pool (sludge) could exacerbate the problem. The effect of filtering sludge from the suppression pool water by fibrous debris deposited on the strainer surface was further confirmed in NRC-sponsored testing conducted at the Alden Research Laboratory (ARL). ARL's tests clearly demonstrated that the pressure drop across the strainer was greatly increased by this filtering effect [NUREG/CR-6367]. Additional NRC sponsored testing by the NRC at ARL demonstrated that suppression pool energy levels during the "chugging" phase of a LOCA are sufficient to suspend and evenly distribute fibrous debris and sludge throughout suppression pool. In addition, ARL demonstrated that debris could remain suspended for a long period allowing large debris quantities to be deposited onto the strainer surfaces. The NRC concluded that this problem is applicable to all domestic BWR plants because, (1) there do not appear to be any features specific to a particular plant, class of plants, or containment type that would mitigate or prevent the generation, the transport to the suppression pool, or the deposition on the ECCS strainers of sufficient material to clog the strainers, and (2) parametric analyses performed in support of the NUREG/CR-6224 study, using parameter ranges which bound most domestic BWR plants, failed to find parameter ranges that would prevent BWR plants with other containment types from being susceptible to this problem. Furthermore, the NRC study was conducted on a Mark I; Barsebäck had a strainer clogging event and is similar in design to a Mark II; and Perry, a Mark III, also had a strainer clogging event.

An essential aspect of predicting the potential for strainer clogging is the estimation of the amount of debris that is likely to transport from the drywell into the wetwell. The transport processes are complex, in that, they involve transport during both the reactor blowdown phase (i.e., entrainment in steam/gas flows) and the post-blowdown phase (i.e., via water flowing out of the break and/or containment sprays). The NUREG/CR-6224 analyses reasoned that the congested layout of the drywell would offer large surface areas for debris retention. However, due to the lack of applicable experimental or analytical data, the fraction of debris transported to the wetwell was estimated on the basis of engineering judgment derived from the analysis of Barseback-2 event data. However, the NRC concluded that any engineering judgment based on a scarce set of experimental data would have large uncertainties: Therefore, NUREG/CR-6224 transport factors could not be defended. As a result, Revision 2 of Regulatory Guide 1.82, the NRC recommended assuming 100% debris transport unless analyses or experiments justified lower transport fractions. However, limited existing data indicated that potentially much less than 100% would be transported. In order to facilitate a better understanding of debris transport, the NRC initiated a study in September 1996, referred to as the drywell debris transport study (DDTS), to investigate debris transport in BWR drywells using a bounding analysis approach. The focus of the DDTS was to provide a description of the important phenomena and plant features that control and/or dominate debris transport and the relative importance of each phenomenon as a function of the debris size. The results of the DDTS, documented NUREG/CR-6369, provide reasonable engineering insights that can be used to evaluate the adequacy of debris transport factors used in plant-specific strainer blockage analyses.

The NRC issued RG 1.82, Revision 2, in May 1996. This regulatory guide describes acceptable methods for implementing applicable design requirements for sumps and suppression pools functioning as water sources for emergency core cooling, containment heat removal, or containment atmosphere cleanup. In addition, guidelines for evaluating the adequacy of the sump and suppression pool for long-term recirculation cooling following a LOCA are provided. This regulatory guide was revised to update the BWR to debris blockage evaluation guidance because operational events, analyses, and research work since the issuance of 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 suction strainer debris blockage.

The NRC staff issued NRC Bulletin 96-03, "Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling-Water Reactors," on May 6, 1996. All BWR licensees were requested to implement appropriate measures to ensure the capability of the ECCS to perform its safety function following a LOCA. The staff had identified three potential resolution options but allowed licensees to propose others that provided an equivalent level of assurance. The three options identified by the staff were: 1) to install a large capacity passive strainer designed with sufficient capacity to ensure that debris loadings equivalent to a scenario calculated in accordance with Section C.2.2 of RG 1.82, Revision 2 and do not cause a loss of NPSH for the ECCS, 2) install a self-cleaning strainer that automatically prevents strainer clogging by providing continuous cleaning of the strainer surface with a scraper blade or brush, and 3) install a backflush system that relies on operator action to remove debris from the surface of the strainer to prevent it from clogging. Option 1 had the advantages of being completely passive so that operator intervention was not required and it did not require an interruption of ECCS flow. Licensees choosing Option 1 for resolution were required to establish new or modify existing programs, as necessary, to ensure that the potential for debris to be generated and transported to the strainer surface does not at any time exceed the assumptions used in estimating the amounts of debris for sizing of the strainers in accordance with RG 1.82, Revision 2. Option 2, like Option 1, would not rely on operator action or interrupt ECCS flow but it did rely on an active component to keep the strainer surface clean that would be fully exposed to the LOCA effects in the suppression pool, therefore, appropriate measures must be taken to ensure its operability. With the selection of Option 3, extensive measures had to be taken: 1) to maximize the amount of time before clogging could occur; 2) to ensure that instrumentation and alarms indicate when strainer differential pressure increases; 3) to institute operator training on recognition and mitigation of a strainer clogging event; and 4) to implement surveillances to ensure the operability of the strainer instrumentation and backflush system. All licensees were requested to implement these actions by the end of the first refueling outage starting after January 1, 1997.

It was recognized when NRCB 96-03 was issued that plant-specific analyses to resolve the strainer issue are difficult to perform because a substantial number of uncertainties are involved. Examples of these uncertainties include the amount of debris that would be generated by a pipe break for various insulation types; the amount of debris that would be transported to the suppression pool; the characteristics of debris reaching the suppression pool (e.g., size and shape); and head-loss correlations for various insulation types combined with suppression pool corrosion products, paint chips, dirt, and other particulates. Many of these uncertainties are plant-specific because of differences in plant characteristics such as plant layout, insulation types, ECCS flow rates, containment types, plant cleanliness, and NPSH margin. Testing was conducted to quantify many of these uncertainties.

The staff closely followed the BWROG's efforts to resolve this issue. The BWROG evaluated several potential solutions, and completed testing on three new strainer designs: two passive strainer designs and one self-cleaning design. The BWROG effort was consistent with the options proposed in NRCB 96-03 for resolution of the ECCS potential strainer clogging issue. The BWROG then developed topical report NEDO-32686, "Utility Resolution Guidance for ECCS Suction Strainer Blockage," November 1996, (the URG) to provide utilities with: 1) guidance on evaluation of the ECCS potential strainer clogging issue for their plant, 2) a technically sound, standard industry approach to resolution of the issue, and 3) guidance that is consistent with the requested actions in NRCB96-03 for demonstrating compliance with 10 CFR 50.46. The URG includes guidance on calculational methodologies for performing plant specific evaluations.

The BWROG and the industry conducted several small-scale tests to obtain data needed to develop the URG and to qualify plant-specific strainer designs. The URG included substantial portions of this data. As a result, this data was available for NRC for review. Specifically, these tests included:

- Air jet impact testing of fibrous and RMI insulation resulting in data relevant to debris generation and debris airborne transport including debris capture data, (e.g., by gratings).
- Scaled debris airborne transport for fibrous and RMI debris by steam and flashing water flows.
- Waterborne debris transport in a linear flume.
- Head loss tests for alternate strainer designs, i.e., truncated cone, stacked disk, and star designs.

The staff noted in NRC Bulletin 96-03 that much of the effort and discussion on this issue had focused on the threat caused by fibrous insulation. While the staff recognized that fibrous insulation represents the largest source of fibrous material in the containment, licensees were reminded in NRC Bulletin 96-03 that both the Perry and the Limerick events involved other sources of fibrous debris. In determining their resolution for this issue, licensees were reminded to focus on protecting the functional capability of the ECCS from all potential strainer-clogging mechanisms.

The NRC reviewed the URG and issued its Safety Evaluation Report (SER) on August 20, 1998 [NRC-SER-URG]. In the SER, the staff noted that the issue of potential strainer blockage is complex, in that, head loss across suction strainers is not only a function of the amount of debris, but also of the types (e.g., fibrous insulation, paint, reflective metallic insulation, dirt, corrosion products, etc.) and characteristics of the debris (size, shape, etc.). The analyst must evaluate the worst case for potential strainer debris loadings, consider the potential for foreign material to be introduced during normal plant evolutions such as refueling and maintenance outages, and evaluate maintenance practices including the maintenance of qualified coatings in the drywell and wetwell.

The staff found the URG to be comprehensive, providing general guidance on resolution options, and detailed guidance on performing plant specific analyses to estimate potential worst case debris loadings on ECCS suction strainers during a LOCA. For performing a plant-specific analysis, the URG provides methodologies for: 1) estimating the amounts and types of debris that could be generated by a LOCA, 2) estimating the amount of the generated debris which could be transported to the suppression pool, 3) estimating the amount of debris that could be entrained on the ECCS suction strainer surfaces, 4) determining the head loss caused by the estimated debris accumulation, and 5) calculating the NPSH margin. The URG provides flexibility to utilities by including multiple methods for performing each part of the plant-specific analysis. However, the URG lacks complete guidance and/or adequate supporting analysis in several areas. As a result, the staff was unable to determine if all of the methodologies, or combination of methodologies, were acceptable. Similarly, much of the general guidance on "resolution options" also lacked sufficient detail for the staff to review. Since insufficient detail and supporting justification on the "resolution options," was included in the URG, further supporting justification from a licensee or the BWROG was required for the staff to reach a conclusion on their acceptability. However, based on the information provided in the URC, the staff did conclude the use of self-cleaning strainers should be discouraged, and that backflushing should only be used as a defense-in-depth measure.

In the URG, the BWROG states that a licensee's resolution to the strainer clogging issue may include a licensing basis change. However, the URG specifically states that the use of credit for a containment overpressure is not recommended. The Advisory Committee on Reactor Safeguards (ACRS) agreed with the BWROG. In a letter from the ACRS to the NRC Executive Director for Operations (EDO) explicitly stated, "We believe that allowing some level of containment overpressure is not an acceptable corrective action because adequate overpressure may not be present when needed [ACRS-Letter]." The staff also concurred that additional containment overpressure (other than an amount already approved by the staff for the existing licensing basis on certain plants) should not be used as part of the resolution of this issue.

The NRC staff issued Generic Letter (GE) 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 on October 7, 1997. The staff wanted to ensure that the NPSH available for ECCS and containment heat removal pumps would be adequate under all design-basis accident scenarios. The staff was concerned that changes to plant configuration, operating procedures, environmental conditions, or other operating parameters over the life of the plant could result in inadequate NPSH. Some licensees discovered that they needed to have their licensing basis to include credit for containment overpressure to meet the NPSH requirements of the ECCS and containment heat removal pumps. Some licensees were assuming containment overpressure credit inconsistent with the plant's licensing basis. GL 97-04 requested addressees to provide current information regarding their NPSH analyses.

The staff evaluated its position on the use of containment overpressure in calculating NPSH margin as part of its review of industry responses to Generic Letter 97-04. The concerns that led to the issuance of GL-97-04 illustrated an existing uncertainty and variability in the application of the methods used to calculate NPSH margin. These concerns were confirmed by the review of the industry submittals [SEA97-3705]. Because there is substantial uncertainty associated with the strainer clogging issue, the staff did not recommend licensing basis changes as a "resolution option."

The technical evaluation report (TER), SEA97-3705, "Reliance on Containment Overpressure for Ensuring Appropriate NPSH," supporting GL-97-04 illustrated the uncertainty associated with overpressure analyses. Overpressure analyses are detailed and comprehensive analyses performed to conservatively predict the minimum containment pressure available during a DBA. All means of removing heat from the containment is considered including all installed pressure-reducing systems and processes. These systems and processes include heat transfer to structures, containment leakage, containment sprays, pool surface heat and mass transfer, fan coolers, RHR heat removal heat exchangers, and power conversion systems. Because the NPSH is strongly dependent upon the accident scenario, a comprehensive range of accident scenarios is evaluated to ensure that the minimum pressure is conservatively determined for the purpose of granting an overpressure credit.

The USNRC issued Generic Letter 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," on July 14, 1998 to all holders of operating licenses for operating nuclear power reactors. GL98-04 alerted addressees of additional strainer blockage concerns including problems associated with: 1) the material condition of Service Level 1 protective coatings inside the containment, 2) foreign material found inside operating nuclear power plant containments, and 3) design and construction deficiencies with the material condition of ECCS systems, structures, and components inside the containment. The NRC expected addressees to ensure that the ECCS and the safety-related CSS remain capable of performing their intended compliance. Addresses requested information under 10 CFR 50.54(f) so that the staff could evaluate the licensee programs for ensuring that Service Level 1 protective coatings inside containment do not detach from their substrate during a DBA and interfere with the operation of the ECCS and safety-related CSS. The NRC utilized this information to assess whether current regulatory requirements were being correctly implemented and to determine whether the requirements needed revision.

The industry addressed the requirements of NRC Bulletin 96-03 by installing large capacity passive strainers in each plant (NRCB 96-03 Option 1) with sufficient capacity to ensure that debris loadings equivalent to a scenario calculated in accordance with Section C.2.2 of RG 1.82, Revision 2 do not cause a loss of NPSH for the ECCS. Four BWR plants were chosen for detailed audits by the NRC staff. These plants are Limerick (BWR/4 Mark II), Dresden (BWR/3 Mark I), Duane Arnold (BWR/4 Mark I), and Grand Gulf (BWR/6 Mark III). The results of these plant audits are summarized in Table 1-2 and are described in greater detail in Section 5.2 of this report.

**Table 1-2. Issue Resolution Summary for Audited Plants**

| Plant | Design | Insulation Types Located in the Drywell | Plant Resolution | Resolution Basis | NRC Audit Findings |
|---|---|---|---|---|---|
| Grand Gulf Nuclear Station | BWR/6 Mark III | RMI*<br>Kaowool<br>Calcium-Silicate<br>Fiberglass | Increased existing strainer surface area from 170 $ft^2$ to 6253 $ft^2$ by installing passive large-capacity suction strainers. | Licensee based analyses on URG supported by ¼ scale testing. | Licensee conservatively estimated debris generation, transport, and strainer head loss. NRC estimated head-losses substantially less than licensee estimate. |

| | | | | | |
|---|---|---|---|---|---|
| Limerick | BWR/4 Mark II | NUKON * Min-K RMI** | Increased existing strainer surface area from 269 $ft^2$ to 2715 $ft^2$ by installing passive large-capacity suction strainers. | Licensee based analyses on URG. Head-loss estimate less than 4 ft-water and NPSH margin of 12 ft-water. | Licensee conservatively estimated debris generation, transport, and strainer head loss. NRC estimated head-loss less than 2 ft-water. |
| Duane Arnold | BWR/4 Mark I | NUKON * Calcium-Silicate** RMI** Lead Wool** | Increased existing strainer surface area from 38 $ft^2$ to 1359 $ft^2$ by installing passive large-capacity suction strainers. | Licensee based analyses on URG and GE head loss correlation. | Licensee used NRC-approved methods to estimate debris generation and transport, and estimated conservative strainer head loss. |
| Dresden | BWR/3 Mark I | RMI* NUKON Calcium-Silicate Asbestos** Amaflex** | Increased existing strainer surface area from 18.8 $ft^2$ to 475 $ft^2$ by installing passive large-capacity suction strainers. | Licensee based analyses on URG and plant specific alternate methods. | NRC determined licensee strainers adequately sized, although inconsistencies and deviations from URG found in licensee analyses. |

* Majority of total insulation of this type.
** Insulation screened out of analysis due to location, e.g., inside biological shield.

### 1.2 Regulatory Considerations

Federal regulations were established to govern design and operational aspects of nuclear power reactors that affect the safety of those plants. These regulations are codified in the 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 of facilities. The NRC published Regulatory Guidance (RG) documents to guide the nuclear power industry to compliance with the regulations. Regulations and regulatory guidance applicable to the strainer blockage issue are summarized in Sections 1.2.1 and 1.2.2, respectively.

#### 1.2.1 Code of Federal Regulations

This section provides a description of the regulations that apply to the strainer blockage issue. Title 10 of the *Code of Federal Regulations* 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. Some licensees may credit CSSs in the licensing basis for radioactive source term and pressure reduction. The capability of the ECCS and safety-related CSS 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 the loss of adequate NPSH and the resulting cavitation. Operational experience and detailed analysis demonstrated that excessive buildup of debris from thermal insulation, corrosion products, and other particulates on ECCS pump strainers is highly likely to cause a common-cause failure of the ECCS thereby preventing the ECCS from providing long-term cooling following a LOCA. Therefore, Section 50.46 clearly applies to the strainer blockage issue and licensees must resolve this issue for their respective plants in order to ensure 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 these GDC establish minimum requirements for the principal design criteria for water-cooled nuclear power plants similar in design and location to plants for which construction permits have been issued by the Commission. 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 leaktight 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 in 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 action shall be taken. Based on the criteria in the rule, the maintenance rule includes in its scope BWR suction strainers, all safety-related CSSs, and those non-safety-related CSSs 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 CSSs 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 safety-related equipment, e.g., suction strainers. 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: 1) fission product decay heat generation rate (impacts the calculated suppression 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 specifics that single failures be considered and the containment pressure to be used for evaluating cooling effectiveness.

### 1.2.2 Regulatory Guidance

This section provides a description of regulatory guidance that applies to the strainer blockage issue. The NRC provided guidance on ensuring adequate long-term recirculation cooling following a LOCA in Regulatory Guide 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, or 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. The first revision, 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 issue 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 screen area was blocked by debris. GL 85-22 recommended use of RG 182 Revision 1 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 reactors redundant 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.

RG 1.82 Revision 2 guidance addressed operational debris, as well as, debris generated by a postulated LOCA. Specifically, the RG 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 Rev. 2). Revision 2 also noted that debris could be generated and transported by the washdown process, as well as, 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, inservice 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.

RG 1.82 Revision 2 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 not sufficient, cavitation of the pumped fluid can occur, thereby significantly reducing the capability of the system to accomplish its safety functions. It is important that the proper performance of ECCS and containment heat removal systems be independent of calculated increases in containment pressure caused by postulated LOCAs in order to assure 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 adequate NPSH margin assuming the maximum expected temperatures of the pumped fluids and no increase in containment pressure from that present prior to postulated LOCAs.

The NRC issued Revision 1 of Regulatory Guide 1.54, "Quality Assurance Requirements for Protective Coatings Applied to Water-Cooled Nuclear Power Plants," in July 2000 to provide 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 encourages industry to develop codes, standards, and guide that can be endorsed by the NRC and carried out by industry. With noted exceptions, the ASTM standards cited in the Regulatory Position of Revision 1 for the selection, qualification, application, and maintenance of protective coatings in nuclear power plants have been reviewed by the NRC staff and found acceptable.

Additional guidance is found in the applicable sections of NRC Standard Review Plan (SRP) [NUREG-0800]. These sections include: 1) Section 6.2.2, “Containment Heat Removal Systems,” 2) Section 6.1.2, “Protective Coating Systems (Paints) – Organic Materials,” and 3) Section 6.2.1.5, “Minimum Containment Pressure Analysis for Emergency Core Cooling System Performance Capability Studies.”

### 1.3 Related International Experience

Many foreign countries look to the United States for guidance regarding nuclear power plant safety. Before the Barsebäck-2 strainer blockage event, international regulators of nuclear power plants and the nuclear power industry had considered safety questions related to strainer clogging as resolved [NEA/CSNI/R (95) 11]. Many European countries had applied the BWR strainer guidance contained in the RG 1.82, Revision 0 to PWR designs. However, data obtained from European experimental programs performed during the late seventies to determine the performance of strainers indicated that this guidance was not adequate.

In addition, Swedish utilities had used this guidance to assess ECCS’s performance in their plants. Analyses at that time had indicated that strainer clogging would not occur for at least ten hours after a LOCA. Since operation of the ECCS cooling would be required for a much longer time than ten hours, backflushing capabilities and strainer pressure drop monitors were installed in older Swedish BWR plants with smaller strainer areas. These actions (particularly the backflushing capability) were considered to adequately comply with NRC RG 1.82, Revision 1, issued in 1985. Safety questions related to strainer clogging were considered resolved until the Barsebäck-2 strainer clogging event, which showed that clogging and loss of NPSH margin could occur quickly. Although the event itself was not very serious, it revealed a weakness in the defense-in-depth concept, which under other circumstances could have led to the ECCS failing to maintain adequate cooling.

The Barsebäck event spurred immediate action on the part of regulators and utilities alike in several OECD countries (e.g., Sweden, Finland, Germany, Switzerland, and France). For example, the Swedish nuclear power inspectorate Statens Kärnkraftinspektion (SKI), required immediate measures to be taken to prevent strainer clogging in the five oldest Swedish BWRs. These plants had small strainers. Research and development efforts of varying intensity were launched in many countries and in several cases resulted in findings that earlier strainer clogging data were incorrect because essential parameters and physical phenomena (such as insulation aging) had not been previously recognized. As a result, many BWRs and some PWRs in several OECD countries upgraded their ECCS suctions to solve the problem.

Some members of the European nuclear community adapted an approach to resolving the ECCS clogging NPSH issue that was based on a three major mitigating actions. These actions include: 1) the use of larger strainer areas to reduce the likelihood of ECCS NPSH loss, 2) the installation of pressure differential sensors on the ECCS strainers to provide a means for operators to accurately diagnose a potential blockage condition, and 3) the installation of strainer backflushing equipment to provide operators with a means to restore operation to pumps following a loss of NPSH.

The United States has benefited substantially by the exchanged information and experience with the international community. The Europeans conducted several valuable experiments, with data that was directly applicable to U. S. plants. These tests are described in NEA/CSNI/R (95) 11, "Knowledge Base for Emergency Core Cooling System Recirculation Reliability," February 1996, compiled by the USNRC [NEA/CSNI/R (95) 11] for the CSNI of the OECD NEA, which was published in February 1996.

**1.4 Risk Significance of Strainer Blockage**

To put the importance of strainer blockage into perspective, the risk significance was explored using existing probabilistic evaluations. Data from two very substantial NRC sponsored risk studies were utilized for this purpose. First, detailed risk assessments were performed for five U. S. nuclear power plants including exhaustive predictions of plant core damage frequency (CDF). These assessments are reported in NUREG-1150, "Severe Accident Risks: An Assessment for Five U. S. Nuclear Power Plants," 1990. During the preparation of NUREG-1150, numerous supporting documents were created including the NUREG/CR-4550 reports. These reports were considered in the strainer blockage risk evaluation. The second risk study was the Individual Plant Examination (IPE) Program where plants chose to perform probabilistic risk assessments (PRA) after the NRC recognized that systematic examinations are beneficial in identifying plant specific vulnerabilities to severe accidents. Each operating nuclear power plant performed a plant specific probabilistic analyses that determined both the CDF and containment performance for accidents initiated by internal events. The NRC reviewed the plant IPE submittals and published the results of their review in NUREG-1560, "Individual Plant Examination Program: Perspectives on Reactor Safety and Plant Performance," 1997.

The risk significance of strainer blockage was evaluated in NUREG/CR-6224 but only for large LOCA scenarios. A more encompassing (but still screening level of effort) evaluation was conducted as part of the NRC review of the industry responses to GL-97-04 [SEA97-3705]. The risk significance was explored by examining the effect of recirculation cooling unavailability with regard to its impact on CDF for various BWR and PWR accident classes. Because CDF predictions varied substantially from one plant evaluation to the next, even for plants of similar design, generic failure data was used to quantify accident class scenarios and thereby estimate generic impacts on CDF. CDFs were estimated for individual accident classes that credited or did not credit the availability of recirculation cooling. Every effort has been made to generate results that reflect generic (typical) plants. Note that these results are limited to internal events (including internal flooding).

There are a number of considerations involved in estimating the contribution of ECCS NPSH loss to CDF. More important considerations include: 1) LOCA frequency, 2) ECCS NPSH loss probability, 3) the operator recognition of NPSH loss, 4) availability of backflushing, alternate means of providing reactor core cooling, 5) containment protection, 6) accident sequence timing, and 7) other operator recovery actions. The results of these surveys are summarized in Tables 1-3.

The results indicate that the unavailability of recirculation core cooling in BWRs would increase the baseline aggregate CDF values from the E-05/yr range to the E-03/yr range (a factor of 200 higher). The accident classes having their CDF values most affected by recirculation cooling unavailability are the LOCA and transient accident classes. While in some cases BWR LOCAs can be mitigated with injection from external water sources, timing considerations make it difficult to connect external water sources quickly enough to mitigate the larger break sizes. Thus, recirculation cooling has a very important role in mitigating LOCAs. While external water sources can also be used as a backup method of mitigating many types of BWR transient accidents, recirculation cooling would be the preferred method given depletion of the HPCI/RCIC CST supplies. Because the CDF calculations for BWR LOCAs and transients rely so heavily on credit for recirculation cooling, removal of credit for recirculation cooling has a major impact on these accident class CDF values. Table 1-3 indicates that unavailability of recirculation core cooling increases the baseline CDF values for the BWR LOCA and transient accident classes by more than an order of magnitude. Specifically, the small/medium LOCA CDF increases from 2E-06/yr to 3E-04/yr, and the transient CDF increases from 1E-05/yr to 4E-03/yr.

The CDFs for the remaining three BWR accident classes, station blackout, ATWS, and ISLOCA, are affected to a lesser extent if recirculation cooling is unavailable. In station blackout, there is a very good chance that electrical power will be recovered before CST inventory depletion occurs, thus avoiding recirculation cooling. Plant procedures are typically written so as to preserve CST inventory during station blackout by instructing operators to initially align HPCI to the suppression pool as a water source. This action extends the plant coping time, because use of the CST inventory is delayed until suppression pool conditions (generally high temperature) prevent HPCI pump suction from the pool. For ATWS conditions, feedwater can be used as an injection source. ISLOCA conditions generally involve discharge of coolant outside the primary containment structure; with the result that recirculation is not a viable method of long-term cooling. ISLOCA conditions can be mitigated with the injection of water from various external sources, such as RHR service water and firewater.

The impact of the unavailability of recirculation core cooling is shown again in Table 1-4, where the CDF is proportioned by accident classification. As shown, ~92.3% of the expected CDF was correlated with transient scenarios and ~7.4% with LOCA scenarios. The CDF of all other accident classes was much smaller. It is interesting to note that large LOCA, which are generally selected for analysis in strainer blockage evaluations, contributed only ~0.5% to the CDF predicted in these surveys, largely due to its relatively low initiating event frequency.

**Table 1-3. Impact of Recirculation Core Cooling on Typical Internal-Event BWR CDFs**

| Accident Class | CDF Crediting Recirculation Core Cooling Available (1/yr) | CDF Not-Crediting Recirculation Core Cooling Available (1/yr) | Ratio of Not-Crediting to Crediting Recirculation Core Cooling Available |
|---|---|---|---|
| LOCA - Large | 2E-07 | 2E-05 | 100 |
| LOCA – Small & Medium | 2E-06 | 3E-04 | 150 |
| Transient | 1E-05 | 4E-03 | 400 |
| Station Blackout | 1E-05 | 2.2E-5 | 2.2 |
| ATWS | 1E-06 | 2.3E-6 | 2.3 |
| ISLOCA | 2E-08 | 3E-08 | 1.5 |
| Total | **2.3E-05** | **4.4E-03** | **190** |

**Table 1-4. Distribution of Expected Risk Associated When Recirculation Core Cooling is Unavailable**

| Accident Sequence Type | Percentage of Total Expected CDF with Recirculation Core Cooling Unavailable |
|---|---|
| LOCA - Large | 0.5% |
| LOCA – Small/Medium | 6.9% |
| Transient | 92.3% |
| Other | 0.3% |

## 1.5 References

NUREG-0510, “Identification of Unresolved Safety Issues Relating to Nuclear Power Plants,” U. S. Nuclear Regulatory Commission, January 1979.

NUREG-0800, Revision 4, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants,” LWR Edition, Section 6.2.2: Containment Heat Removal Systems, U. S. Nuclear Regulatory Commission, June 1987.

NUREG-0869, Revision 1, A. W. Serkiz. “USI A-43 Regulatory Analysis,” U. S. Nuclear Regulatory Commission, October 1985.

NUREG-0897, Revision 1, A. W. Serkiz, “Containment Emergency Sump Performance,” U. S. Nuclear Regulatory Commission, October 1985.

NUREG-0933, R. Emrit, R. Riggs, W. Milstead, J. Pittman, “A Prioritization of Generic Safety Issues,” U. S. Nuclear Regulatory Commission, Revision 16, November 1993.

NUREG-1150, “Severe Accident Risks: An Assessment for Five U. S. Nuclear Power Plants,” U. S. Nuclear Regulatory Commission, December 1990.

NUREG-1560, “Individual Plant Examination Program: Perspectives on Reactor Safety and Plant Performance,” U. S. Nuclear Regulatory Commission, Final Summary Report, December 1997.

NUREG/CR-4550, M. T. Drouin, et al., “Analysis of Core Damage Frequency: Grand Gulf Unit 1,” Volume 6, Revision 1, SAND86-2084, September 1989.

NUREG/CR-6224, G. Zigler, R. Beaty, J. Bridaeu, L, Comes, D. V. Rao, N. Ruiz, F. Sciacca, C. Shaffer, W. Thomas, R. Walsh, “Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris,” Draft for Comment, U. S. Nuclear Regulatory Commission, August 1994.

NUREG/CR-6224, G. Zigler, J. Bridaeu, D. V. Rao, C. Shaffer, F. Souto, W. Thomas, “Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris,” Final Report, U. S. Nuclear Regulatory Commission, October 1995.

NUREG/CR-6367, D. V. Rao and F. Souto, “Experimental Study of Head Loss and Filtration for LOCA Debris,” U. S. Nuclear Regulatory Commission, December 1995.

NUREG/CR-6369, Volume 1, D. V. Rao, C. Shaffer, and E. Haskin, “Drywell Debris Transport Study,” U. S. Nuclear Regulatory Commission, SEA97-3501-A:14, September 1999.

NUREG/CR-6369, Volume 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-6369, Volume 3, C. Shaffer, D. V. Rao, and J. Brideau, "Drywell Debris Transport Study: Computational Work," SEA97-3501-A:17, 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.

RG-1.1, Regulatory Guide 1.1, “Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal System Pumps,” U. S. Nuclear Regulatory Commission, November 2, 1970.

RG-1.82, Regulatory Guide 1.82, Revision 1, “Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident,” U. S. Nuclear Regulatory Commission, November 1985.

RG-1.82, Regulatory Guide 1.82, Revision 2, “Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident,” U. S. Nuclear Regulatory Commission, May 1996.

10 CFR Part 50, Title 10, Code of Federal Regulations, published by the Office of the Federal Register, National Archives and Records Administration, U. S. Government Printing Office, January 1, 1997.

SECY-85-349, “Resolution of Unresolved Safety Issue A-43, ‘Containment Emergency Sump Performance,’” October 31, 1985.

GL-85-22, “Potential for Loss of Post-LOCA Recirculation Capability Due to Insulation Debris Blockage,” NRC Generic Letter to All Licensees of Operating Reactors, Applicants for Operating Licenses, and Holders of Construction Permits, December 3, 1985.

GL-97-04, "Assurance of Sufficient Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal Pumps," NRC Generic Letter to All Holders of Operating Licensees for Nuclear Power Plants, 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," NRC Generic Letter to All Holders of Operating Licensees for Nuclear Power Plants, July 14, 1998.

GL-99-04, "Potential for Degradation of the Emergency Core Cooling System and the Containment Spray System after a Loss-of-Coolant Accident Because of Construction and Protective Coating Deficiencies and Foreign Material in Containment," NRC Generic Letter to All Holders of Operating Licensees for Nuclear Power Plants, July 14, 1998.

Bulletin 93-02, "Debris Plugging of Emergency Core Cooling Suction Strainers," NRC Bulletin to Licensees, May 11, 1993.

Bulletin 93-02, Supplement 1, "Debris Plugging of Emergency Core Cooling Suction Strainers," NRC Bulletin to Licensees, February 18, 1994.

Bulletin 95-02, "Unexpected Clogging of a Residual Heat Removal (RHR) Pump Strainer While Operating in Suppression Pool Cooling Mode," NRC Bulletin to BWR Licensees, October 17, 1995.

Bulletin 96-03, "Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling-Water Reactors," NRC Bulletin to BWR Licensees, May 6, 1996.

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-91-12, "Potential Loss of Net Positive Suction Head (NPSH) of Standby Liquid Control System Pumps," NRC Information Notice, February 15, 1991.

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-93-34, "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-93-34, Supplement 1, "Potential for Loss of Emergency Cooling Function Due to a Combination of Operational and Post-LOCA Debris in Containment," NRC Information Notice, May 6, 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, Revision 1, “Unexpected Opening of a Safety/Relief Valve and Complications Involving Suppression Pool Cooling Strainer Blockage,” NRC Information Notice, November 30, 1995.

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-96-27, “Potential Clogging of High Pressure Safety Injection Throttle Valves During Recirculation,” NRC Information Notice, May 1, 1996.

IN-96-55, “Inadequate Net Positive Suction Head of Emergency Core Cooling and Containment Heat Removal Pumps Under Design Basis Accident Conditions,” NRC Information Notice, October 22, 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.

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 (PWG-1), International Task Group, Committee on the Safety of Nuclear Installations, Organization for Economic Cooperation and development (OECD) Nuclear Energy Agency (NEA), Restricted, February 1996.

NEDO-32686, Rev. 0, “Utility Resolution Guidance for ECCS Suction Strainer Blockage,” BWROG, November 1996.

NRC-SER-URG, “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.

ACRS-Letter, Letter from R. L. Seale to Mr. L. Joseph Callan, “Proposed Final Generic letter, ‘Assurance of Sufficient Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal Pumps,’” dated June 17, 1997.

SEA97-3705, Clint Shaffer and Willard Thomas, “Reliance on Containment Overpressure for Ensuring Appropriate NPSH,” Technical Evaluation Report to U. S. NRC, SEA97-3705-A:5, April 29, 1998.

LA-UR-00-2574, Dasari V. Rao, “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,” April 19, 2000.

LA-UR-00-5159, Dasari V. Rao, “Technical Review of Selected Reports on Performance Contracting, Inc. Sure-Flow Strainer™ Test Data,” Technical Review performed by Los Alamos National Laboratory for the Nuclear Regulatory Commission, April 27, 2000.

Letter from N. B. Le 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),” June 17, 1997.

Letter from D. H. Jaffe to L. Eliason, "Safety Evaluation for Hope Creek Generating Station – NRC Bulletin 96-03, (TAC No. M96150)" October 31, 1997.

Letter from A. B. Wang to M. Bellamy, "Pilgrim Nuclear Power Station – Issuance of Amendment Re: Use of Containment Overpressure (TAC No. MA7295)," October 6, 2000.

# 2.0 NRC SPONSORED RESEARCH

The NRC sponsored research to evaluate the adequacy of existing suction strainer designs in U.S. BWR plants. This research included a number of NRC sponsored small-scale tests, analytical studies, NRC review of U.S. industry sponsored tests, and NRC review of tests sponsored and conducted by European countries. This research provided the database needed to aid the resolution of the strainer blockage issue.

## 2.1 NRC Sponsored Testing

The NRC sponsored small-scale tests included:

- Tests designed to measure the pressure drops across combined fibrous/particulate debris beds and the filtration efficiency of the beds under a variety of test conditions (see NUREG/CR-6367).
- Tests designed to examine the debris mixing, debris fragmentation, and resuspension of debris from the suppression pool floor during the highly turbulent period immediately following a postulated LOCA and debris sedimentation within a suppression pool during the subsequent quiescent period (see NUREG/CR-6368).
- Tests designed to examine the transport and capture characteristics of debris within a drywell by steam and water depressurization flows (see NUREG/CR-6369).
- Tests designed to examine the transport and erosion characteristics of debris within a drywell by water washdown flows (see NUREG/CR-6369).
- Tests designed to examine the generation of RMI debris and the strainer head loss associated with RMI debris (see SEA-95-970-01-A:2).

The tests involving fibrous debris are discussed first in Section 2.1.1 followed by tests involving RMI debris in Section 2.1.2.

### 2.1.1 Fibrous Debris Testing

#### 2.1.1.1 Fibrous Bed Filtration and Head Loss Tests

The accumulation of debris on a pump suction strainer would resist water flow, thereby lowering the pressure inside the strainer. When fibrous debris accumulates on a flat plate or cone-shaped strainer, the debris tends to form an essentially uniform layer across the strainer surface. This layer, referred to as a debris bed, can then filter other debris (e.g. particulates like dirt, dust, corrosion products, etc.) that would ordinarily pass through the holes of the strainer, as was demonstrated by the events at Perry. At Perry, fibrous debris combined with corrosion products that were present in the suppression pool (sludge), thereby exacerbating the problem (i.e., significantly higher head loss than would previously been expected.) The NRC sponsored experiments designed to quantify the effect of particulate debris on the head loss across the fibrous debris bed, and the filtration efficiencies of the fibrous beds to filter and trap micron range sludge particles. Alden Research Laboratory (ARL) conducted these tests.

#### Test Objective

The primary focus was to obtain the required experimental data needed to validate the NRC reference plant fiber/sludge head loss correlation and to derive supporting models specifically applicable to analyzing the potential for strainer blockage in the reference plant analysis. Because the insulation used to insulate the primary system piping in the reference plant consisted predominantly of NUKON™ mats, the fibrous debris beds would be formed by the accumulation of NUKON™ insulation fragments. The particulate debris had the characteristics of sludge removed suppression pools of nuclear power plants. Previous studies and data were reviewed to guide the test apparatus design and the development of test procedures.

### Test Apparatus and Instrumentation

The test apparatus was primarily designed and instrumented to obtain head loss data. The test apparatus, shown in Figure 2-1, consisted of a closed loop where the same water was repeatedly forced through the strainer. A relatively uniform velocity profile at the strainer was achieved by implementing a long vertical 12-inch diameter pipe test section. The upstream approach to the strainer was 11-ft long and the downstream portion was another 4.5-ft in length. The remaining loop piping was constructed of 4-inch piping to keep flow velocities high enough to minimize debris settling within the horizontal portions of the loop. Resistance heating was used to maintain water temperature and the piping was insulated to minimize heat loss.

Debris introduced into the loop accumulated on the strainer. Debris beds consisted of fibers only or fibers intermixed with particulate debris depending upon test conditions. Particulate debris was filtered by the accumulated fibrous debris on the strainer, however a portion of the particles always passed through the fibrous bed to circulate the loop again. Therefore, the accumulation of particulate debris on the strainer was determined by measuring the particulate added to the loop and the subsequent concentration within the loop at the time of head loss measurement.

Because the flow velocity approaching typical semi-conical shaped BWR strainer is fairly uniform, a flat plate strainer was deemed adequate for the test apparatus. Note that the approach velocity for advanced strainer designs utilized in the resolution of the strainer blockage issue may not be uniform. The test strainer was constructed from 14-gauge stainless steel plate perforated with 1/8-inch holes with a density of 30 holes per square inch.

### Test Data

Fifty-two parametric tests were conducted that examined a variety of test conditions. The test parameters included:

- The thickness of the bed of debris.
- The flow velocity of the approaching water.
- The temperature of the water.
- The relative mixtures of particulate to fiber debris masses on the strainer.
- The size distribution of the fibrous and particulate debris forming the debris bed.

The development of the debris bed on the strainers surface (deposition morphology) was examined both macroscopically and microscopically using a scanning electron micrograph (SEM). The thickness of the bed depended primarily upon the quantity of fibrous debris introduced into the test loop. The accumulated particulate was interspersed among the bed fibers. Three mixtures of sludge were examined:

Sludge A, Sludge B, and Mix A. Sludge A approximated sludge actually removed from suppression pools. Sludge B provided an alternate set of data to determine head loss sensitivity to particulate characteristics. The Mix A simulant, consisting of 10% by weight of paint-chips and 90% by weight of Sludge A, was used to the impact of paint-chips on head loss.

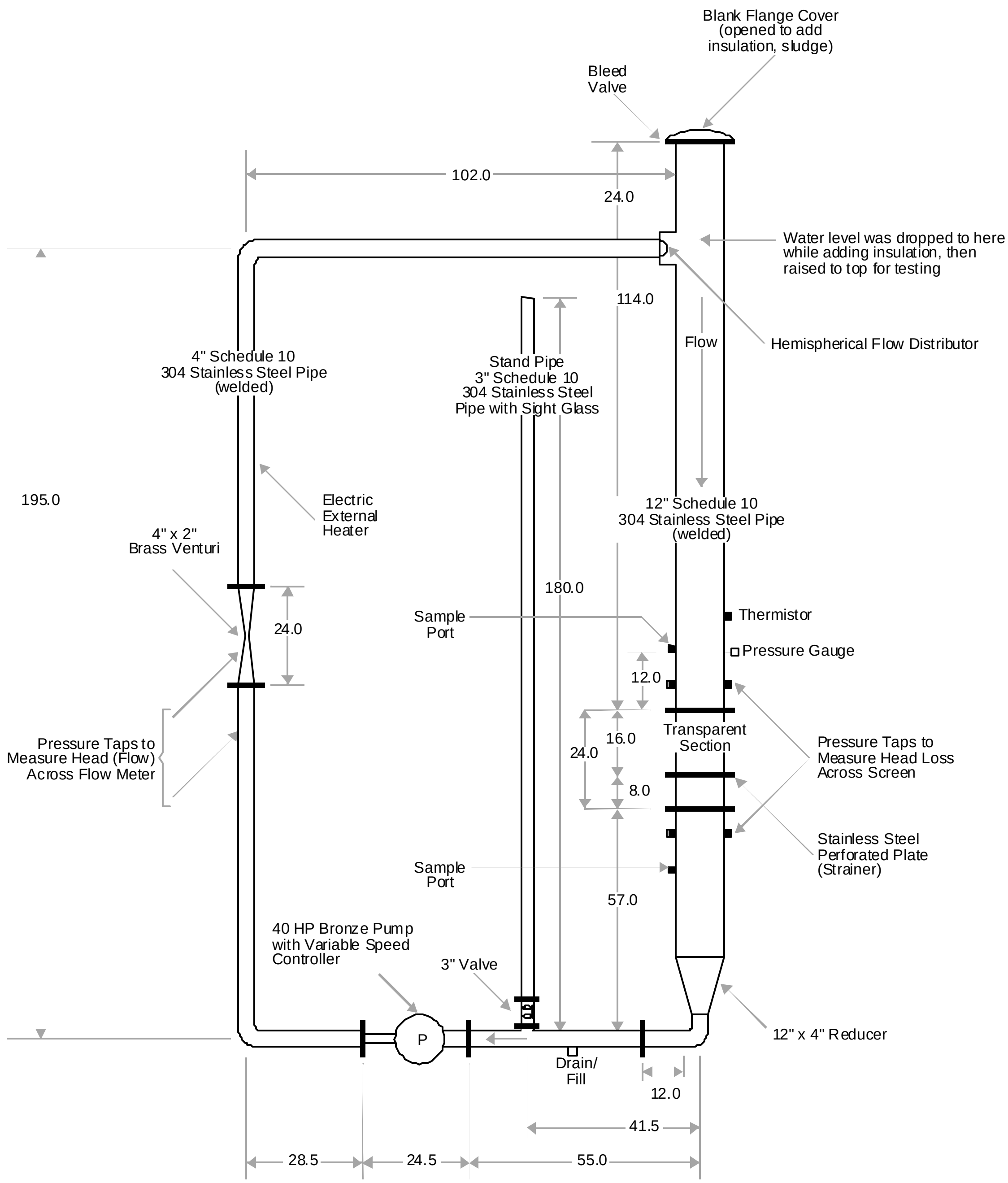



**Figure 2-1. Flow Loop of Head Loss Test Apparatus**

Head losses across the strainer were measured and the particulate content of the bed estimated at times of stable values. An example, head loss is shown in Figure 2-2 where the head loss is compared to the approach velocity as the loop flow rate was incrementally increased during the test.

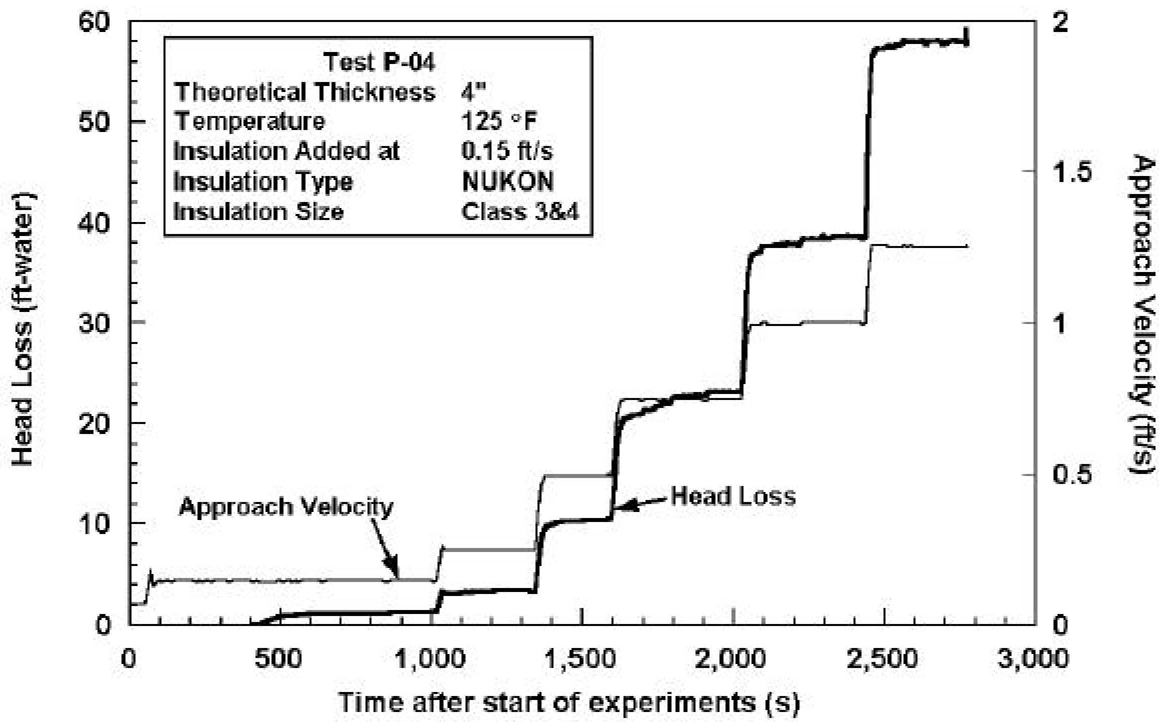



*Figure 2-2. Typical Transient Head Loss for a Pure Fiber Bed*

Within the ranges of tested parameters, the test data exhibited the following trends:

- The debris beds were compressible under the influence of head loss resulting from flow through the bed. Visual observations suggest that the compaction was higher for pure fiber beds than for beds containing significant particulate. The approach velocity did not significantly affect the formation of the bed and once the bed was compacted, it did not fully recover its original state after loop flow ceased. For mixed beds, the sludge particles were primarily intermixed with the fibers, leading to the formation of random mixed beds.

- The size of the pieces of fibrous debris (two class sizes tested) did not appear to significantly affect the head loss. Note that there was minimal structural difference between these two class sizes tested. There was some indication that beds formed of very small pieces of debris might induce larger head losses.

- Water temperature significantly affected the head loss. Specifically, head loss decreased as the water temperature increased, most likely due to the associated decrease in water viscosity.

- Particulate debris significantly increased the head loss across the debris bed. In some cases, the head loss increased by a factor of 100 with a mass ratio of sludge-to-fiber ratio equal to 10. Head loss differences among Sludge A, Sludge B, and Mix-A appeared to be marginal.

- The head loss was sensitive to the method by which sludge and fibrous debris were introduced into the test loop. Therefore, tests were conducted in a manner that simulated as closely as reasonably possible the actual conditions that prevail in a BWR suppression pool.

- Debris filtration efficiencies were estimated for the 'first flushing cycle' of the loop. Once-through filtration efficiencies typically ranged from 20 to 50% for the range of parameters tested. The efficiencies were weakly dependent upon the approach velocity and the fiber bed thickness. These values should be used within the tested ranges. It was noted that thin fiber beds (< 0.25-inches) would filter much less efficiently. Cumulative filtration, i.e., multiple loop flushing cycles, increased to a range of 50 to 90% and was found to be a strong function of the bed thickness.

As previously stated, a primary objective of the head loss tests was to obtain data to validate an appropriate head loss correlation, specifically the semi-theoretical head loss correlation used in the reference plant study. This correlation, equally applicable for both pure fiber beds and mixed beds, was found to predict head loss data within an acceptable accuracy range for test conditions where the beds were reasonably uniform.

## Documentation

A complete description of these tests, i.e., test apparatus, test procedures, and test data, was summarized in Appendix E of NUREG/CR-6224 and documented in detail in NUREG/CR-6367, "Experimental Study of Head Loss and Filtration for LOCA Debris," 1995.

### 2.1.1.2 Fibrous Debris Suppression Pool Sedimentation Tests

The BWR suppression pool following a postulated LOCA would experience a range of turbulence conditions. Specifically, a high level of turbulence immediately following the LOCA, a transition period, and then the longer-term relatively quiescent period once primary system depressurization is completed. During the period of high turbulence, debris transported from the drywell to the suppression pool would undergo mixing and potential fragmentation during the period of high turbulence. In addition, any debris previously located on the suppression pool floor would likely be resuspended. During the quiescent period, debris would gradually settle to the suppression pool floor. These phenomena govern the transport of debris within the suppression pool thereby determining the type, quantity, and form of debris deposited onto the strainers. The NRC sponsored tests conducted in a reduced scale suppression pool test facility to study these debris behaviors. ARL conducted these tests. The fibrous debris sedimentation tests are discussed in this section and the RMI debris sedimentation tests are discussed in Section 2.1.2.2.

## Test Objective

The overall purpose of the suppression pool tests was to provide insights into debris transport within a suppression pool following a LOCA. However, the underlying processes are too complex to be addressed by a single set of experiments. Based on scoping studies and discussions with experts in related fields, the phenomena selected for further study were:

- Debris transport and sedimentation within the suppression pool during the high-energy phase that would immediately follow a medium loss of coolant accident (MLOCA).

- Debris transport and sedimentation within the suppression pool during the post high-energy phase.

Note that the high-energy downcomer oscillations for a LLOCA would be initially driven by condensations oscillations for a relatively short period of time (about 30 s) and then be followed by chugging for the remainder of the blowdown phase. Because the condensation phase would be relatively short and more difficult to simulate experimentally, these tests focused on the chugging phase.

The primary focus was to obtain debris settling velocity data to support analytical evaluations, specifically analyses applicable to analyzing the potential for strainer blockage in the reference plant analysis. Because the insulation used to insulate primary system piping in the reference plant consisted predominantly of NUKON™ mats, the debris beds formed on the reference plant strainers were then expected to consist of primarily accumulated fragments of NUKON™ insulation with particulate debris embedded within its fibers. Therefore, NUKON™ debris and particulate debris with the characteristics of suppression pool sludge were used in these tests.

### Test Apparatus and Instrumentation

A water tank designed to simulate a segment of a Mark I BWR suppression pool was constructed of steel with the appropriate lower curvature. The tank sidewalls of the segment were made of Plexiglas to provide complete visibility of the debris in motion. Turbulent chugging associated with steam-water oscillations (condensation oscillations) during the depressurization of the primary system was simulated in these tests by including four 10-inch (0.25 m) diameter downcomers fitted with pistons. One of the downcomers was constructed of Plexiglas to facilitate visualization of debris transport. The test apparatus is shown in Figure 2-3.

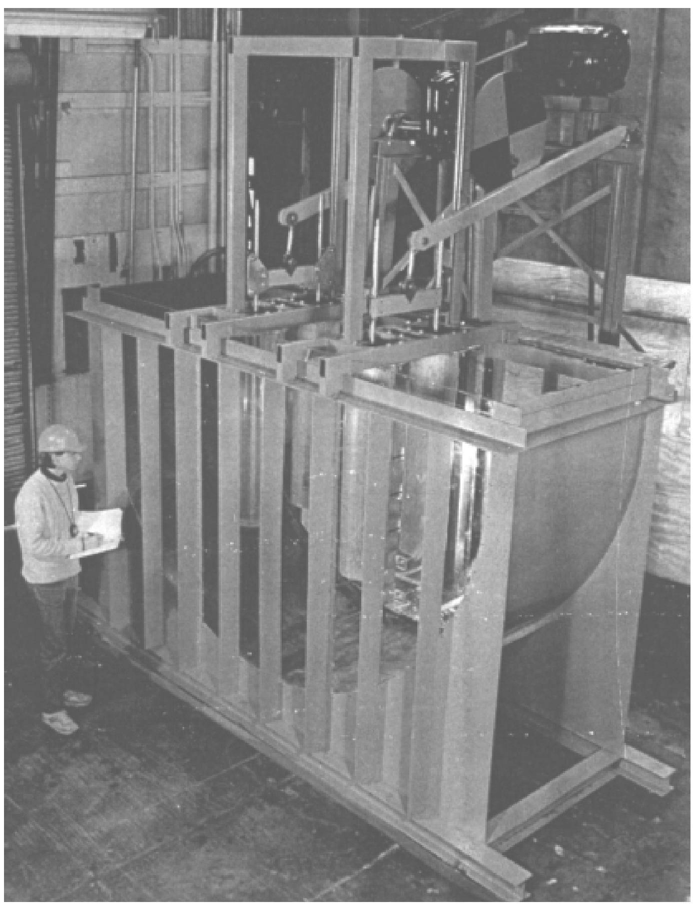


*Figure 2-3. Suppression Pool Sedimentation Test Apparatus*

The geometric scale of the tank was 1 to 2.4 and the radius of the test tank was 13.5-ft (4.11 m). The spacing between the downcomers and their clearance with respect to the floor were also scaled. The front and back walls were spaced one half the distance to the next pair of downcomers in either direction. Hence, the water volume of the tank per downcomer was scaled to the volume per downcomer of a typical BWR Mark I suppression pool.

The pool dynamic conditions associated with the high-energy phase of a MLOCA are usually referred to as chugging. Chugging occurs when water reenters the downcomers, as a result of decreasing steam flow, thereby condensing steam. The build up of non-condensable gases subsequently would push the water from the downcomers until sufficient non-condensable gasses escapes the downcomers to initiate another cycle. Energy input to the suppression pool during chugging was based on data obtained by General Electric (GE) in a full-scale test of a Mark I containment at their full-scale test facility (FSTF) [NEDE-24539-P]. Two types of chugging behavior were observed in test data for a MLOCA, these were:

- Type 1 where the neighboring downcomers oscillated in phase, i.e., oscillations were synchronized.

- Type 2 where the oscillations were relatively unsynchronized.

Because Type 1 chugging was deemed more prototypical of MLOCA, only Type 1 was studied in these tests. All downcomer pistons oscillated in phase to simulate Type 1 chugging. For several Type 1 chugs, the FSTF tests provided pressures measurements within a downcomer. Because GE did not directly measure the actual kinetic energy imparted to the suppression pool during each chug, an analytical model was devised to deduce the energy from the measured chugging pressures. This model was then used to estimate both the chugging period of downcomer oscillation and its amplitude of two-phase level movement. Since the dynamics of chugging changed continuously during primary system depressurization, the period and amplitude was estimated for initial, middle, and later stages of chugging. Further, these estimates were modified to reflect scaling considerations.

The test facility included a series of sampling ports to allow sampling debris concentrations at five equally spaced vertical locations at the center of the tank. The samples were filtered, dried, and weighed so that the concentrations could be expressed as the mass of debris per unit mass of water. A debris classification system was devised that classified pieces of debris into seven classifications. These are illustrated and described in Figure 2-4.

### Test Data

Fourteen parametric tests were conducted to examine a variety of test conditions. The test parameters included:

- The type, form, and quantity of insulation debris tested.

- The quantity of sludge tested.

- The period and amplitude of the downcomer piston chugging.

Within the ranges of tested parameters, the data exhibited the following trends:

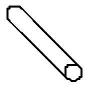
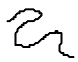
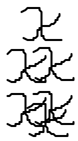
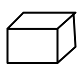
| Class No. | | Description | Settling Characteristics | Settling Velocity in Calm Pools | Strainer Filtration Efficiency |
|---|---|---|---|---|---|
| 1 |  | Very small pieces of fiberglass material, "microscopic" fines which appear to be cylinders of varying L/D. | Drag equations for cylinders are well known, should be able to calculate fall velocity of a tumbling cylinder in still water. | 1-3.5 mm/s<br>Based on Cal. for<br>0.5 - 2.54 cm long fibers | Unknown |
| 2 |  | Single flexible strand of fiberglass, essentially acts as a suspended strand. | Difficult to calculate drag forces due to changing orientation of flexible strand. | Same as above | Nearly 1.0 |
| 3 |  | Multiple attached or interwoven strands that exhibit considerable flexibility and which due to random orientations induced by turbulence drag could result in low fall velocities. | This category is suggested since this class of fibrous debris would likely be most susceptible to re-entrainment in the recirculation phase if turbulence and/or wave velocity interaction becomes significant. | 0.04 ft/s - 0.06 ft/s<br>(measured) | 1.0 (measured) |
| 4 |  | Formation of fibers into clusters which have more rigidity and which react to drag forces more as a semi-rigid body. | This category might be represented by the smallest debris size characterized by PCIs air blast experiments. | 0.08 - 0.13 ft/s<br>(measured) | 1.0 (measured) |
| 5 |  | Clumps of fibrous debris which have been noted to sink. Generated by different methods by various experimenters. | This category was characterized by the PCI air test experiments as comprising the largest two sizes in a three size distribution. | 0.13 - 0.18 ft/s<br>(measured) | 1.0 (measured) |
| 6 |  | Larger clumps of fibers. Forms an intermediate between Classes 5 and 7. | Few of the pieces generated in PCI air blast tests consisted of these debris types. | 0.16 - 0.19 ft/s<br>(measured) | 1.0 (measured) |
| 7 |  | Precut pieces (i.e. .25" by .25") to simulate small debris. Other manual/mechanical methods to produce test debris. | Dry form geometry known, will ingest water, should be able to scope fall velocities in still water assuming various geometries. | $^3$ 0.25 ft/s<br>(calculated) | 1.0 (estimated) |

**Figure 2-4. Fibrous Debris Classifications**

- Both the fibrous and particulate debris remained fully mixed in the tank during simulated chugging at all energies tested resulting in uniform vertical concentration profiles.
- Turbulence resuspended debris initially deposited onto the suppression pool floor during simulated chugging at all energies tested.
- Fibrous debris underwent further fragmentation into smaller sizes, including individual fibers, at all energies tested. In general, the fragmentation occurred near the downcomers where the fibrous debris was subjected to cyclic shear forces from the downward jet and ingestion into the downcomer.
- Visual observations suggested that the turbulence decays within a few minutes after termination of chugging simulation, thus enabling post-high energy phase debris settling. In the post-high energy phase, the vertical concentration profiles were slightly non-uniform. Ranges of settling velocities in calm pools (terminal velocity) are listed in Figure 2-4 for each debris size classification. The terminal settling velocity for fibrous debris is shown in Figure 2-5 as a function of debris weight.

- Measured concentrations showed that fibrous debris settled slower than the sludge, and that the settling behavior of each material is independent of the presence of the other material.

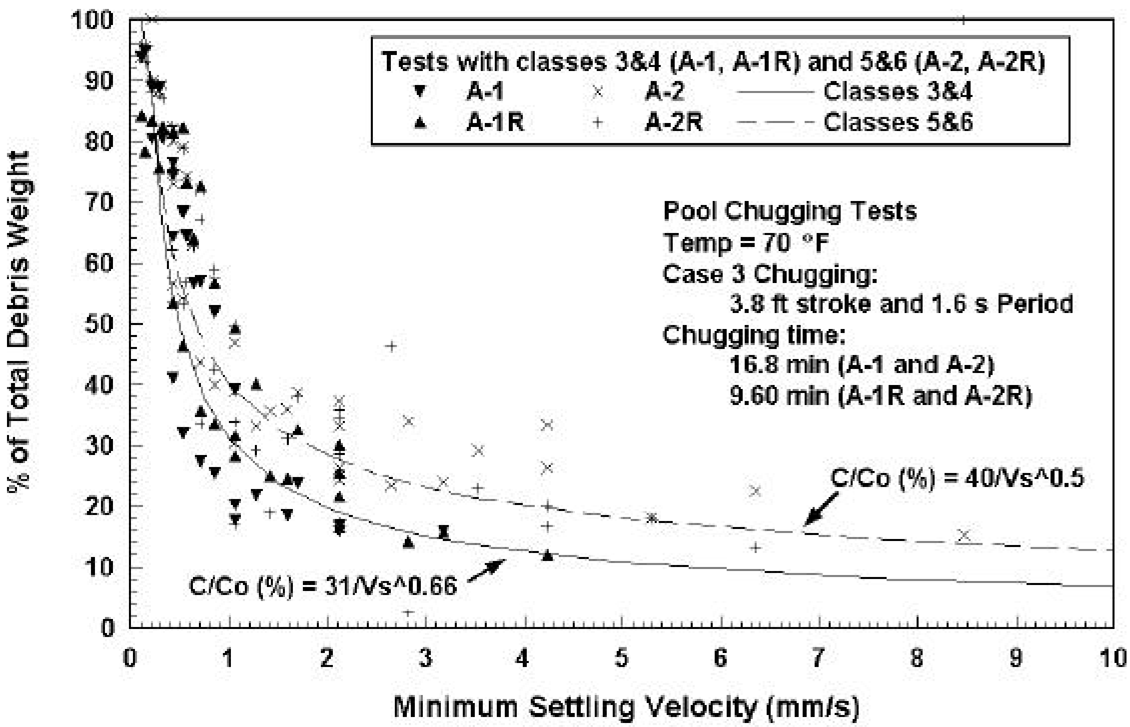



**Figure 2-5. Fibrous Debris Terminal Settling Velocities**

These results were deemed equally valid for other phases of accident progression and other sizes of LOCAs. These tests showed that the assumption of considering uniform debris concentration during strainer calculations is reasonable. However, it must be noted that the continuous operation of the recirculation ECC and the RHR systems in an actual BWR would add additional turbulence to the pool and that this type of turbulence was not considered in these tests. Therefore, applying these data to an actual plant analysis will require engineering judgment.

## Documentation

A complete description of these tests, i.e., test apparatus, test procedures, and test data, was summarized in Appendix E of NUREG/CR-6224 and documented in detail in NUREG/CR-6368, "Experimental Investigation of Sedimentation of LOCA-Generated Fibrous Debris and Sludge in BWR Suppression Pools,"1995.

### 2.1.1.3 Separate Effects Fibrous Insulation Debris Transport/Capture Tests

A postulated LOCA in a BWR whose primary piping is insulated with fibrous insulation would generate fibrous debris in a region close to the broken pipe. These insulation fragments, ranging in size from small fragments to partially damaged blankets, would be entrained by the fluid flow from the break (depressurization flow) and carried through the drywell to the suppression pool. For a main steam line break (MSLB), the debris would be carried primarily by high velocity steam. For a recirculation line break (RLB), a mixture of steam and water would carry the debris. Because a BWR drywell is congested with numerous structural elements (e.g., pipes, gratings, I-beams, and vents) debris transport through the drywell would be impeded. Debris impacting a structure could remain stuck (captured) on that structure. Surface wetting resulting from steam condensation enhances the efficiency of capture substantially. If debris remains attached to a structure, it will not be transported to a strainer. A series of tests were conducted to obtain a basic understanding of fibrous insulation debris capture on typical BWR drywell structures due to inertial capture. ARL conducted these tests.

### Test Objective

The primary objective of these tests was to provide a basic understanding related to inertial capture of small insulation debris generated by a postulated MSLB. The tests were designed to examine: 1) the role of debris inertia on the capture of debris on typical drywell structures during airborne transport, and 2) the impact of surface wetness on the retention of debris by impacted surfaces. A number of different structures were tested to examine the effects of shape and orientation relative to the direction of flow.

A secondary test objective was to study possible degradation and erosion mechanisms for large pieces during blowdown. Specifically, floor gratings will capture large debris that would then be subjected to high velocity steam flow intermixed with water droplets, thereby potentially further degrading the debris pieces.

### Test Apparatus and Instrumentation

A once-through flow tunnel was constructed of plywood panels with a blower at the upstream end and an air filtering plenum downstream of the test section. The primary test section had a cross section with inner dimensions of 4-ft by 4-ft and a length of 8-ft. Because airflow velocities within this test section were limited to about 50 ft/s, a smaller 2-ft by 2-ft test section was inserted within the larger test section in selected tests to achieve velocities up to 150 ft/s. The length of the smaller test section was 5-ft. The test apparatus is illustrated in Figure 2-6.

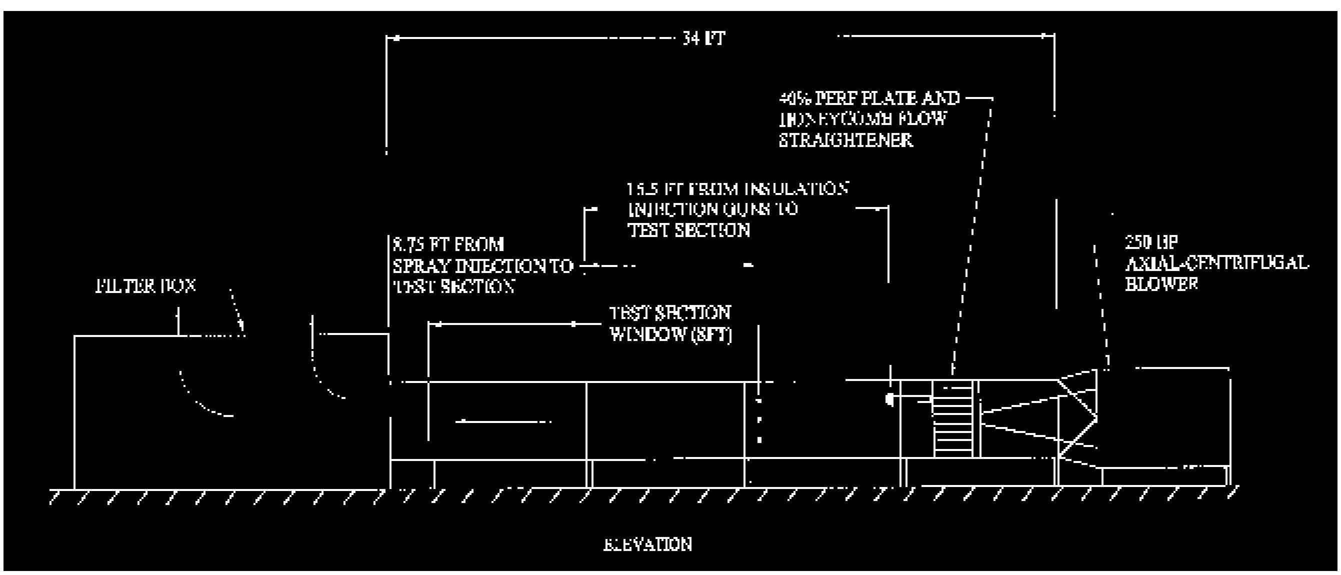



**Figure 2-6. Separate Effects Insulation Debris Transport/Capture Test Apparatus**

Perforated plates and a honeycomb structure were used to achieve a uniform velocity distribution. In addition, the head loss across this flow conditioning devise was calibrated with respect to tunnel velocities and later used to establish specified test section velocities.

Test obstructions consisted of single members and combinations of individual members. Single member tests involved mounting one or two objects side by side within the test tunnel with the objects being the same type, having identical cross sections, and being similarly aligned to the flow. In combined member tests, combinations of members (one or more shapes) were mounted with different orientations, i.e., different alignments to the flow, and positioned so that front-mounted members sometimes shielded rear-mounted members. Thus, the effects of member proximity wake effects, and shielding was evaluated. The individual components include I-beams, gratings, pipes, and a vent cover.

Obstruction surfaces were wetted in most tests by means of spray injection nozzles located upstream of the test section. The duration of the spray controlled the extent of surface wetness (either 10 or 30 seconds). Most tests were conducted with a 10 second pre-wet time.

The fibrous insulation debris was injected into the tunnel through a rupture disk capping one end of each of two pressurized 4-inch PVC pipe. The pipes sections were suspended from the tunnel ceiling downstream of the flow conditioning structure and filled with pre-shredded insulation. Air was pumped into the pipe until the rupture disk failed so that the jet of escaping air dispersed the insulation debris. The fibrous insulation debris was generated from heat-treated NUKON™ base wool blankets.

## Test Data

Forty-eight tests were conducted to examine a variety of test conditions. The test parameters included:

- The flow velocity (24-150 ft/s).
- The wetness of structure surfaces (dry to draining water film conditions).
- The type of structure (I-beams, piping, gratings, and Mark II vents).
- The approximate debris size.
- The debris loading (6.3 to 12.5 gm/ft$^2$).

Within the ranges of tested parameters, the test data exhibited the following trends:

- Gratings captured more fibrous insulation debris than other types of structures. For example, in combination member tests where the grating was placed downstream of other structures, i.e., pipes and I-beams, the grating captured substantially more debris than all other upstream structures combined.
- Surface wetness clearly influenced the extent of debris capture on structures, especially for pipes and I-beams. When pipes and I-beams were dry, these surfaces essentially did not capture debris. Floor gratings capture were affected by wetness but were less sensitive to the degree of wetness. Typical debris capture by a wetted pipe is shown in Figure 2-7.
- Tests with dual gratings in series showed substantially more debris capture on the upstream grating (averaging about 25%) than the downstream grating (about 12%), most likely because the largest debris was removed form the flow stream by the upstream grating. Note that capture percentages reflect the fraction of the mass of debris approaching a particular structure that was subsequently captured by that structure.

- Mark II vents with wetted surfaces captured about 12% of small debris on the cover plate and the simulated drywell floor.

- Break up or disintegration of debris captured on a grating was negligible when 6-inch by 6-inch thin pieces (1/8 to ½-in thick) of insulation were subjected to gas velocities approaching 140 ft/s.

- Gravitational settling (i.e., debris settling to the tunnel floor) was negligible for all tests except the Mark II vent geometry (settling was not included in the vent capture percentage).

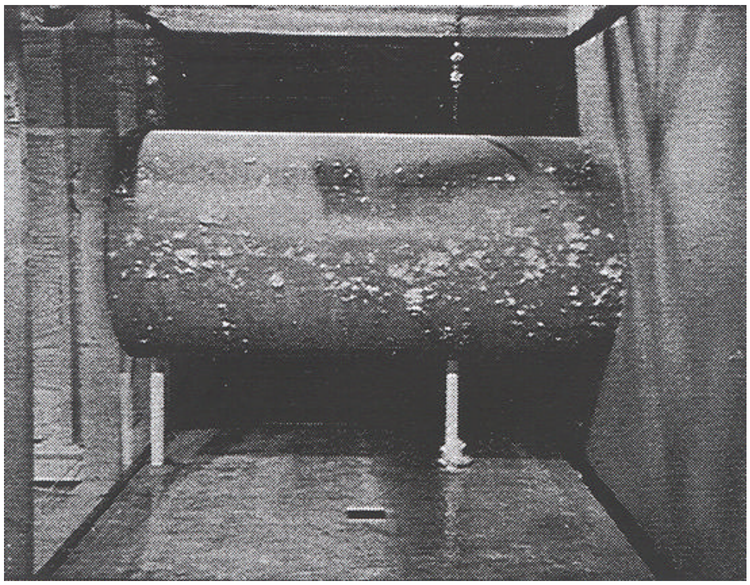


**Figure 2-7. Typical Debris Capture by a Wetted Pipe**

## Documentation

A complete description of these tests, i.e., test apparatus, test procedures, and test data, was documented in detail in Section 2 of NUREG/CR-6369, Volume 2. The report includes a number of photos showing debris captured on the surfaces of obstructions.

### 2.1.1.4 Integrated Effects Fibrous Insulation Debris Transport/Capture Tests

While the separate effects tests described in Section 2.1.1.3 provided valuable data, the tests had notable limitations of: 1) relatively light debris loadings on the structures compared to expected BWR conditions, 2) modest assortment of debris sizes, 3) non-prototypical congestion of structures, and 4) overly simplified flow fields approaching the structures. The debris loading approaching a structure refers to the density of debris pieces per unit of cross-sectional flow area. The principal concern was that debris captured on a structure could be knocked free (reentrainment) by the impact of additional debris under conditions of heavy debris loading, thereby effectively reducing the capture efficiency for that structure. To ensure conservative estimates for debris capture, data was needed for heavier, more prototypical, debris loadings. Additional experiments of a more representative and integrated nature were performed to further understand the role of fibrous insulation debris inertial capture within a BWR drywell.

## Test Objective

The primary objective of these tests was to provide integrated debris capture data to benchmark analytical models and methods used to predict debris transport within a BWR drywell. These tests were designed to minimize the limitations noted for the separate effects tests. These tests combined debris generation with debris transport. The insulation blankets were mounted and restrained in a manner designed to maximize their destruction, and therefore, maximize the amount of debris impacting the structures. Debris sizes ranged from individual fibers to partially intact blankets. The structures for debris capture were more complex and more prototypical than those used in the separate effects testing. The flow patterns in the integrated testing were also more complex, (i.e., more three-dimensional), than for the separate effects testing. The data from these integrated tests were compared to the data from the separate effects tests to look for insights regarding the effects of complex structural arrangements and fluid flows on debris capture.

## Test Apparatus and Instrumentation

The integrated debris transport tests were conducted at the Colorado Engineering Experiment Station Inc. (CEESI) air blast facility. The facility was capable of storing as much as 11,000 $ft^3$ of air at 2500 psia. In these tests, a dispersing 1100-psi air jet was used to destroy insulation blankets and then transport the debris through test chambers that contained obstructions.

The main test chamber, illustrated in Figure 2-8, consisted of a large horizontal cylinder with an inner diameter of 9.4-ft and a length of 93-ft. In addition, a 32-ft auxiliary chamber of the same diameter was attached with a flanged collar at the exit end of the main chamber in a horizontal “L” configuration. The upstream end of the main chamber (behind the air jet nozzle) was almost completely blocked so that only a small portion of the air could exit the chamber in the reverse direction. The purpose of the auxiliary chamber was to investigate debris capture associated with flows undergoing a change in direction; in this case a $90^o$ bend.

Target insulation blankets were mounted a few feet downstream of the air jet nozzle. The blankets were mounted on a 12.75-inch outer-diameter pipe that extended across the main test chamber at mid height and positioned directly in front of the air jet nozzle. The target pipe mount was secured to rails so that the target could be positioned any distance from the jet out to 30-ft from the nozzle.

Transco manufactured the insulation blankets used, except for one test where a NUKON™ blanket was provided by Performance Contracting Inc. (PCI). The Transco blankets were 3 ft in length compared to 1.5 ft for the PCI blanket. Stainless steel bands (either 2 or 3) were placed around the blanket to hold the blanket in place but a metal jacket did not encapsulate the blankets.

The structural test section contained an assemblage of structural components (e.g., gratings, pipes, and I-beams) designed to simulate a prototypical section of a BWR drywell. The design focused on maintaining the same surface to volume ratios as found in BWR containments and, to the extent practical, the structures were oriented in a manner analogous to the orientations found in the actual plant conditions. These structural components are shown schematically in Figure 2-8.

All I-beams were 12 inches from upper to lower flange and all pipes were 10 inches in diameter. I-beams were oriented with their web into the direction of airflow. Starting from the front (flow entrance) of the structural test section, the test section contains the following structural subassemblies:

- A continuous grating with two vertically oriented pipes directly behind,
- I-beams with a full length beam oriented vertically and a half beam oriented horizontally,
- I-beams with a full length beam oriented 45° from vertical,
- Horizontally oriented pipe with a half I-beam oriented vertically,
- Pipe oriented 45° from vertical,
- V shaped grating (approximately 56°) that obstructed about 57% of the total test chamber flow area.
- Two half section gratings separated axially by 22 inches, referred as the split grating.

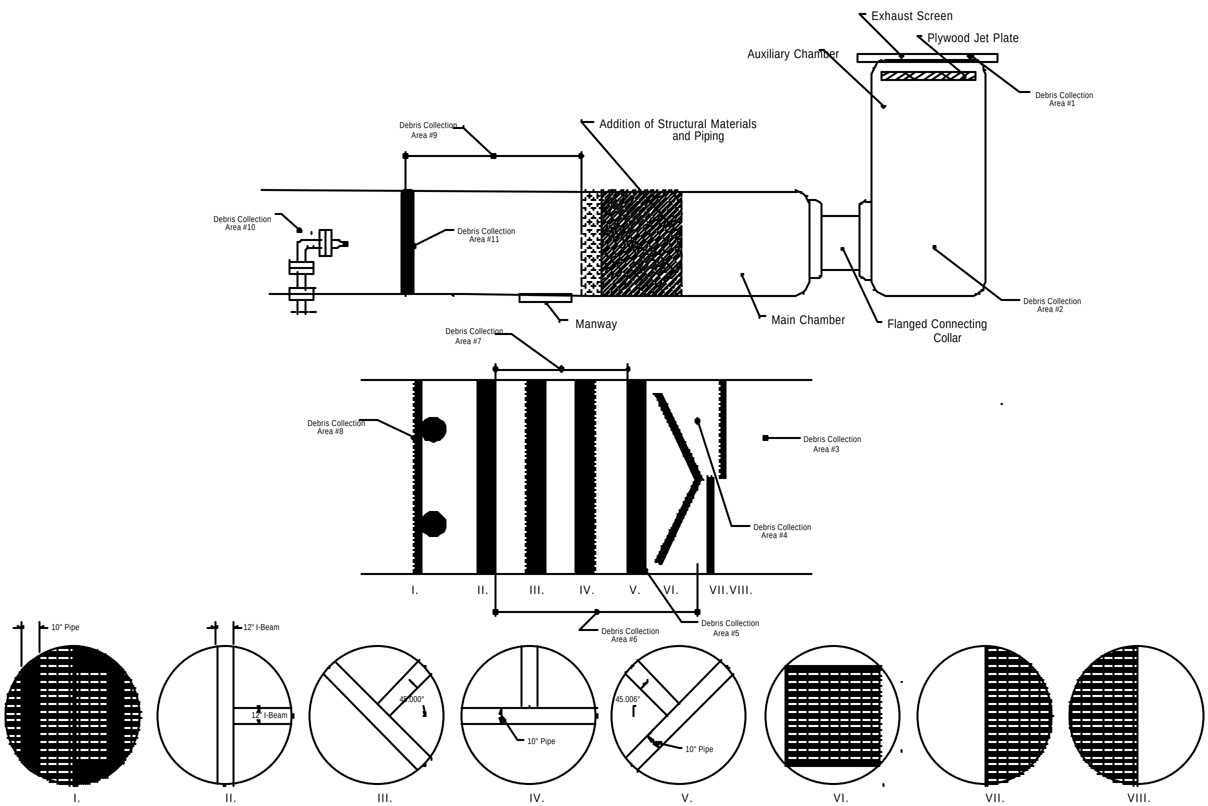



*Figure 2-8. CEESI Air Jet Test Facility*

Surface wetness was shown in the separate effects tests to profoundly impact the capture efficiency of structures. Therefore, surface wetness was a primary concern in the integrated tests. Structures were pre-wet in the CEESI tests with misters positioned throughout the test section. The mister system, constructed from PVC pipe, sprayed warm water as fine droplets from a high-pressure (150 psig) source. The misting system was operated long enough (approximately 10 minutes) to form a draining water layer.

The size of the jet nozzle was designed to minimize air usage while still allowing the jet to continue long enough for the debris generation and debris transport processes to complete (i.e., all debris was either deposited onto a surface or passed through the test chamber). The nozzle discharge was monitored and recorded. Developmental tests determined that at least 10 seconds was required for a 4-inch diameter nozzle and 12 seconds for 3-inch nozzle. Facility operators were able to approximate the jet duration time specified for a particular test. Air jet discharge was initiated using a rupture disk.

### Test Data

The developmental tests were instrumented with Pitot tubes to monitor and map the flow distributions before the flow entered the congested test section. The airflow velocities entering the area containing the congestion of structural components generally ranged from 25 to 50 ft/s. These velocities were in good agreement with velocities predicted for the tests using a commercially available CFD code. These velocities were also comparable to CFD predicted velocities for a typical BWR drywell. Once the flows dissipate into pressure-driven flows, BWR steam flow velocities were predicted to generally range from about 30 to 50 ft/s. Therefore, the airflow velocities in the CEESI tests were considered prototypical of steam flow velocities that would exist in a BWR drywell following a postulated LOCA.

Ten production tests were conducted that examined a variety of test conditions regarding debris transport. In addition, four of the developmental tests also provided useful debris transport data. The test parameters included:

- The nominal nozzle diameter, either 3 or 4-inches.
- The duration of the air jet flow (5 to 24 seconds).
- The surface wetness.
- The distance between the nozzle and the target.

Most of the tests were conducted using a nominal 4-inch diameter nozzle, flow duration of 12 to 17 seconds, and wet surfaces. One of debris transport tests (Test H7) was deliberately conducted with all surfaces maintained dry to illustrate the impact of surface wetness on debris capture. In addition, the mister system partially malfunctioned in two tests resulting in incomplete surface wetness and a subsequent reduction in debris capture.

The distance between the nozzle and the target was initially adjusted until the optimum distance for maximum target destruction was found. A distance of ~120-inches (L/D of 30) appeared to maximize destruction. Insulation debris consisted of pieces of bare fiberglass insulation of various sizes, pieces of shredded canvas, agglomerated pieces containing both insulation and canvas, and large sections of the canvas cover that remained relatively intact and sometimes contained substantial quantities of insulation. The bare insulation was divided into three general size groups, i.e., large, medium, and small. Samples of debris pieces are shown in Figure 2-9.

The tests demonstrated the ability of structural components to capture debris. The average overall transport fraction for small debris in the CEESI 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.

Once again gratings were found to be the most effective debris catcher. The debris captured by the split grating in Test H2 is shown in Figure 2-10. Note that the upstream gratings had already captured the large debris. The capture efficiencies for the split grating and for each test are plotted in Figure 2-11 as a function of debris loading. The corresponding separate effects data is also shown. This figure clearly illustrated the impacts of surface wetness and debris loading and the general agreement between the separate and integrated effects tests.

*Figure 2-9. Samples of Debris Generated in the CEESI Tests*

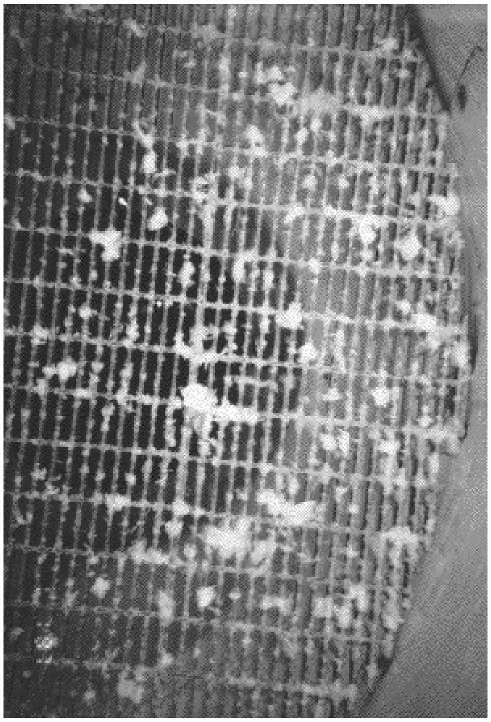


*Figure 2-10. Typical Debris Deposition on a Grating in CEESI Tests*

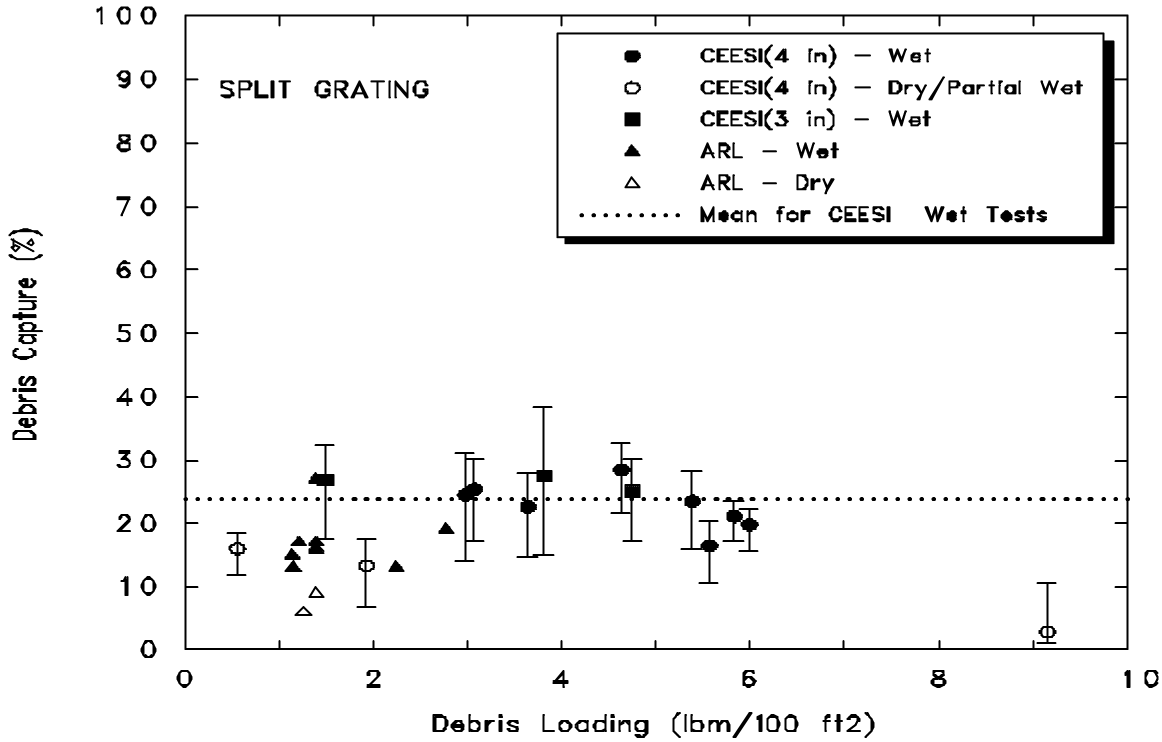



*Figure 2-11. Capture of Small Debris by Grating*

The average fractions of small debris captured by each test structure component are shown in Table 2-1. Note that the first continuous grating stopped almost all of the larger debris and that the capture fraction for the continuous grating was not obtained. This was due to the failure of the mister system to adequately wet the continuous grating (i.e., this grating illustrated dry behavior).

**Table 2-1: Small Debris Capture Fractions**

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

The 90° bend between the two chambers caused debris to be captured at the bend, which was maintained wet by a mister in the auxiliary chamber. 17% of the debris entering the auxiliary chamber was trapped on the chamber wall as a direct result of the bend. The I-beams and pipes captured a lesser amount, but still substantial.

The capture fractions were found to be relatively independent of the debris mass loading (i.e., lbm/ft$^2$) impacting the structures. The integrated effects tests capture data were consistent with the separate effects tests data indicating that the finer aspects of the local flow fields (e.g., eddies and wake) do not significantly influence debris capture. The separate-effects tests and integrated-effects tests clearly established that a fraction of the small and large debris would be deposited as the debris transport through the drywell following a blowdown. The likely locations for the deposition in a BWR are the floor gratings located at different elevations. These captured pieces would potentially be subjected to subsequent washdown water flows.

## Documentation

A complete description of these tests, including, test apparatus, test procedures, and test data, is documented in detail in Section 3 of NUREG/CR-6369, Volume 2. The report includes a number of photos showing debris captured on the surfaces of obstructions.

### 2.1.1.5 Fibrous Insulation Debris Washdown/Erosion Tests

Debris captured on structures during the blowdown phase following a LOCA would subsequently be subject to transport and/or erosion by water flows from long-term recirculation cooling and containment sprays (washdown phase). The primary concern here is the erosion and waterborne transport of debris captured on a floor grating directly below the broken pipe. In this situation, the debris would be pummeled by recirculation water flow that would cascade down from the break to the drywell floor. Pieces of debris continually impacted by falling water could erode, allowing debris to pass through the grating and continue traveling toward the strainers. A series of tests were conducted at a facility operated by Science and Engineering Associates, Inc. (SEA) to examine the potential impact of washdown/erosion.

## Test Objectives

The primary objective was to obtain experimental data that could be used to estimate the extent and timing of erosion during the washdown phase that would occur to insulation captured by floor gratings. The tests were to study the erosion of fibrous debris of different sizes at a variety of flow rates with the objective of answering the following questions:

- What fraction of a piece of debris would erode and subsequently be transported to the drywell floor?
- Does the rate of erosion decrease with time, potentially reaching an asymptotic behavior?

## Test Apparatus and Instrumentation

These tests were conducted within a 5-ft long 2-ft by 2-ft vertical test chamber constructed of 0.5-inch clear polycarbonate to allow complete visualization of the tests. A schematic of the test apparatus is shown in Figure 2-12. An aluminum grating with 1-inch by 4-inch cells, characteristic of gratings used in BWR drywells was placed at the bottom of this test chamber to hold the pieces of debris. Water was pumped into the top of the test chamber. Three simulated pipes were positioned to break up the structure of the injected flow before the water reached the debris. The simulated pipes were constructed of Plexiglas and were 2-inches in diameter.

A 400-gallon tank was used as a water reservoir for recirculation purposes. A 250 GPM centrifugal pump pumped water from this tank to the top of the test chamber through a 4-inch diameter PVC pipe. A debris catcher of fine-mesh wire screen was installed below the test chamber to catch insulation debris and erosion products, thereby preventing their recirculation back into the test chamber. A second filter was fitted to the pump suction to guarantee complete filtration of the debris from the pump inlet flow. A valve in the PVC pipe controlled the flow and the flow rate was monitored by a calibrated flow meter.

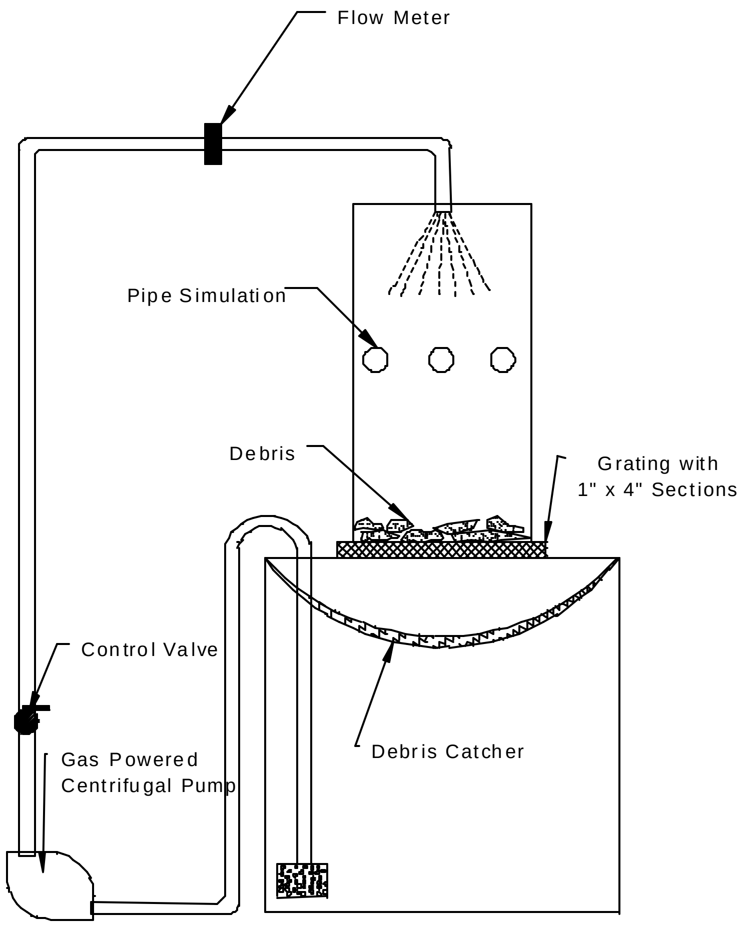



**Figure 2-12. Schematic of Washdown Test Apparatus**

The simulated pipes conditioned the flow entering at the top of the test chamber, i.e., the bulk flow was broken up in a prototypical fashion. In this manner, water impacting the debris was spread relatively uniformly across the test chamber. In tests simulating spray–induced washdown, a removable spray head was attached to the PVC outlet.

Debris of various sizes was placed on the gratings and pipes and subjected to water flow typical of containment spray nozzles and break flow. Tests were conducted with room temperature water using pieces of insulation generated by an air jet impingement.

## Test Data

Both the debris size and the water flow rate were varied to simulate washdown of small debris by containment sprays, as well as erosion and transport of large debris by break flows. Twenty-six parametric tests were conducted that examined a variety of test conditions. The test parameters included:

- The water flow rate.
- The type of flow conditioning, i.e., with or without the removable spray head.
- The duration of the flow.
- The size and condition of the debris.
- The mass of debris.
- The thickness of the debris bed.

Low-density fiberglass insulation called Thermal Wrap™ manufactured by Transco Products, Inc. was tested. Four sizes of debris were tested to represent the range of debris expected following a LOCA. These sizes were:

- Fine Debris This debris consisted of insulation pieces of loosely attached individual fibers less than an inch in length. This debris was obtained directly from the CEESI air jet transport tests. Such fines were typically found attached to wet surfaces such as pipes and gratings.
- Small Debris This debris was characterized as debris with a light, loose, and well-aerated texture with an average density lower than 0.25 $lbm/ft^3$. The pieces were typically about 1.5-inches in size and possessed little of the its original structure. This debris was also obtained from the CEESI air jet transport tests and was mainly used in the spray tests.
- Medium Debris This debris consisted of pieces of insulation typically about 4-inches by 6-inches in dimension. This debris was formed by one of the two following methods:
    - Generated in the CEESI air jet tests where, although torn, the pieces kept some of the original structure of the insulation.
    - Cutting intact insulation into medium sized pieces produced the pieces.
- Large Debris This debris consisted of relatively large pieces of insulation ranging in size from 10-inch by 10-inch to 18-inch by 18-inch. This debris was manually cut into predetermined sizes. Note that the air jet tests clearly demonstrated that large pieces of debris produced by jet impingement tended to retain most of the original insulation structure.

Within the ranges of tested parameters, the data exhibited the following trends:

- Little or no erosion is possible for insulation pieces covered in canvas when subjected to washdown flow resulting from either the break overflow or containment spray.
- Most of the small pieces of debris resting on the grating bars will be washed down by water within about 15 minutes after which the washdown reaches an asymptote.
- A significant fraction of the medium pieces would be eroded and transported.

- Large pieces will not be forced through the grating even at high flows. The pieces will remain on the grating and may erode with time. Erosion also exhibits an asymptotic behavior, as illustrated in Figure 2-13. The typical condition of debris after exposure to water is shown in Figure 2-14.

- The product of the erosion of large debris consists of fine debris, i.e., individual fibers and small clumps of fibers, likely to remain suspended in a pool of water with minimal turbulence.

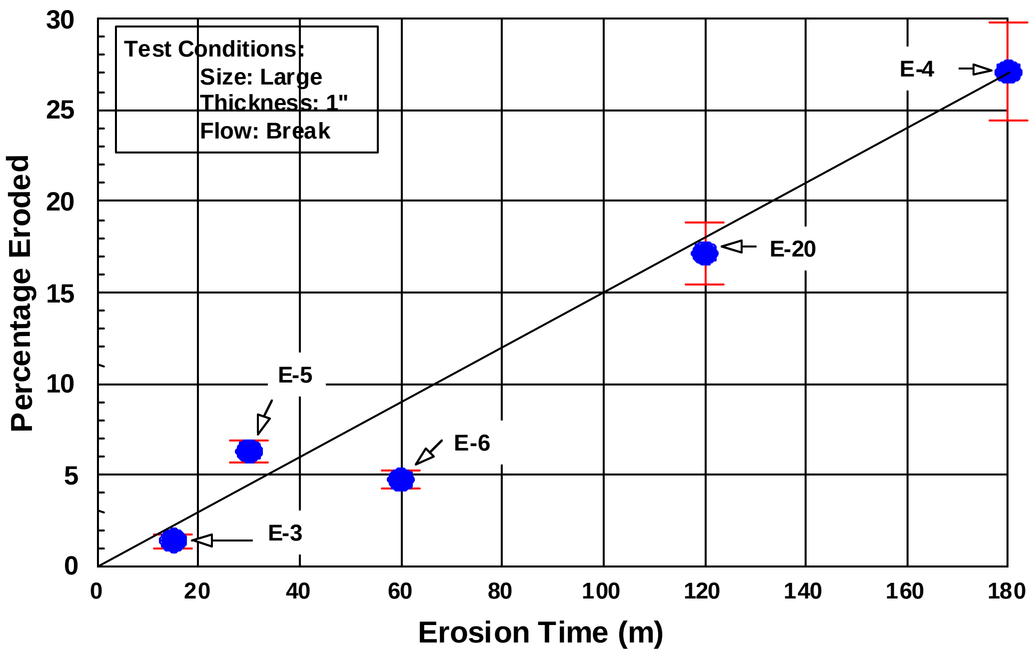



*Figure 2-13. Time-Dependency of 1-inch Insulation Blanket Material Under Break Flow Conditions*

Test Conclusions:

- All finer debris, smaller than the grating cells, captured on the grating as a result of inertial capture would most likely be washed down when subjected to break and/or containment spray flows.

- A significant fraction of the medium pieces would be transported. For break overflows, likely most of the medium pieces would transport. For containment spray flows, perhaps 50% would transport.

- Erosion of large debris is dependent upon both time and flow rate. At low flow rates typical of containment sprays, the erosion of large pieces is negligible; especially considering that containment sprays are only operated intermittently. At water flow rates typical of break flow, the rate of erosion is substantial (as high as 25% for a 3 hours duration). For such conditions, an erosion rate of 3 lbm/100-ft$^2$/hr is recommended.

### Documentation

A complete description of these tests, test apparatus, test procedures, and test data, is documented in detail in Section 4 of NUREG/CR-6369, Volume 2. The report includes a number of photos showing debris captured on the surfaces of obstructions.

*Figure 2-14. Typical Condition of Debris After Exposure to Water*

### 2.1.2 RMI Debris Testing

#### 2.1.2.1 RMI Debris Generation Tests

Reflective Metallic Insulation (RMI) is used in a large number of BWRs in the USA. In the event of a LOCA at a plant using RMI for insulation, it is anticipated that some fraction of damaged RMI would be transported to the suppression pool and then potentially transport to the ECCS suction strainers. Säteilyturvakeskus (STUK), the Finnish Centre for Radiation and Nuclear Safety issued a report, "Metallic Insulation Transport and Strainer Clogging Tests," [STUK-YTO-TR-73] that demonstrated experimentally that RMI can be transported to ECCS strainers and cause increased head loss (see Section 3.4.1). A key element of estimating the impact of RMI on loss of ECCS is adequate data for the size distribution and general shapes of RMI fragments caused by a double-ended guillotine break (DEGB).

Between October 1994 and February 1995, the Swedish Nuclear Utilities conducted metallic insulation jet impact tests at the Siemens AG Power Generation Group (KWU) test facility in Karlstein am Main, Germany [MIJIT]. Although the Swedish tests were reasonably extensive, only a general summary of the test results was released. Specific test data from the RMI debris generation tests was not made publicly available. In addition, the data is not directly applicable to U. S. power plants because the European RMI was designed substantially different from the RMI currently installed in U. S. power plants. In 1995, the NRC conducted a single debris generation test to generate representative RMI debris to obtain insights and data on the effects of RMI relative to U. S. plants. These tests were contracted to Siemens AG/KWU in Karlstein, Germany.

Test Objective

The primary objective was to investigate the destruction of RMI by a DEGB and to produce RMI debris prototypical of a postulated DEGB in a U. S. plant for subsequent hydraulic suspension and head loss testing. A major supplier of RMI to U. S. nuclear power plants, the Diamond Power Specialty Company, supplied Mirror® RMI cassettes for debris generation.

Test Apparatus and Instrumentation

The test was conducted at the Siemens Large Valve Test Facility (GAP) located at their Karlstein laboratory. The GAP facility, originally designed to test large valves, is capable of providing large flow rates of saturated steam (up to 2000 kg/sec at 90 bar), saturated water, or a two-phase mixture. Normal service conditions as well as, accidents can be simulated, especially those involving pipe breaks and steam-water discharge. The NRC test was carried out with saturated steam. The facility test loop consisted of a 4,593-$ft^3$ steam/water accumulator, 28-inch main steam line or a 16-inch main water line, and a quench pool with a maximum water volume of 24,000 $ft^3$ to condense the steam. A 22 MW oil-fired high-pressure boiler charged the accumulator.

The test loop, as configured for the NRC test, consisted of the accumulator filled with saturated water and steam, the 28-inch main steam line, an 8-inch discharge nozzle, a rupture disk device, and the DEGB-simulator. The quench pool was empty and dry. A perforated cylindrical cage (12.6 ft diameter and 28 ft length) surrounded the target rig to retain the bulk of the debris.

The DEGB-simulator was mounted directly on the rupture disk device and one target panel was mounted directly over the simulator. The construction of the DEGB-simulator limited the break flow to the circumference of the pipe, i.e., simulating a DEGB with both pipe ends remaining in the co-axial configuration. In fact, the pipe break probably would be better described as a circumferential line break than as a DEGB. With this configuration, the break flow was directed at the inner surface of the RMI target and at about the mid-length of the target.

Test Data

The test was conducted on May 31, 1995. Most of the RMI debris was recovered and categorized by location where it was found. Approximately 91% of the debris was recovered as loose foil pieces and the remainder was found wedged in place among the structures. The debris was analyzed with respect to size distribution. The overall size distribution for the total recovered debris mass is shown in Figure 2-15. A photo of typical RMI debris generated by a large pipe break is shown in Figure 2-16.

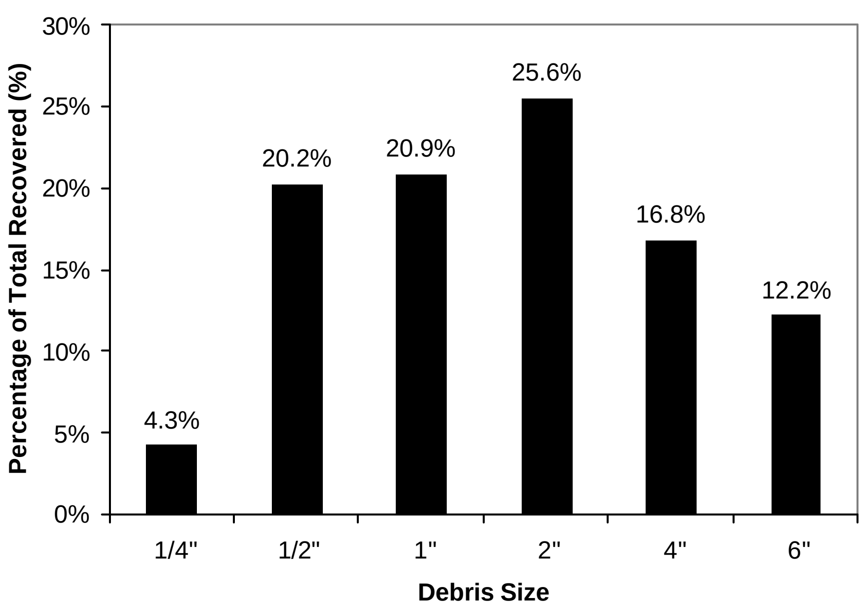



**Figure 2-15 Size Distribution of DEGB Generated RMI Debris**


**Figure 2-16. Typical RMI Debris Generated by Large Pipe Break**

Documentation

A compete description of the NRC sponsored SIEMENS RMI debris generation test is found in SEA-95-970-01-A:2, "Experimental Investigation of Head Loss and Sedimentation Characteristics of Reflective Metallic Insulation Debris," and NT34/95/e32, "RMI Debris Generation Testing: Pilot Steam Test with a Target Bobbin of Diamond Power Panels."

### 2.1.2.2 RMI Suppression Pool Sedimentation Tests

The potential for RMI debris transport within a suppression pool to an ECCS pump suction strainer was demonstrated experimentally. Another key element of estimating the impact of RMI on loss of ECCS is suppression pool debris transport characteristics. As discussed in Section 2.1.1.2, the BWR suppression pool following a postulated LOCA would pass through a range of turbulence conditions, i.e., a high level of turbulence immediately following the LOCA, a transition period, and then the longer-term quiescent period once primary system depressurization completes. Debris transported from a BWR drywell into a suppression pool would undergo mixing and potential fragmentation during the period of high turbulence. During the quiescent period, debris would settle to the suppression pool floor. These phenomena govern the transport of debris within the suppression pool thereby determining the type, quantity, and form of debris deposited onto the strainers. The NRC sponsored tests were conducted in a reduced scale suppression pool test facility to study RMI debris behaviors. ARL conducted these tests.

Test Objective

The RMI test objective was similar to that of the fibrous debris sedimentation tests. The overall purpose of the RMI suppression pool tests was to provide insights into RMI debris transport within a suppression pool following a LOCA. RMI debris transport and sedimentation within the suppression pool was studied both during the high-energy phase that would immediately follow a MLOCA and during the post high-energy phase. A primary focus was to obtain debris settling velocity data to support analytical evaluations.

### Test Apparatus and Instrumentation

The ARL facilities used to conduct the fibrous debris sedimentation tests were used to conduct the RMI debris sedimentation tests as well. A water tank designed to simulate a segment of a Mark I BWR suppression pool was constructed of steel with the appropriate lower curvature. This test apparatus is described in Section 2.1.1.2.

The RMI debris used in these tests was debris generated by the SIEMENS large pipe break debris generation test discussed in Section 2.1.2.1.

Test Data

Still water debris settling tests were performed on individual pieces of RMI debris with representatives from each of six size groupings. Each piece was placed individually in the suppression pool test tank and its time to settle a known distance measured. For all sizes less than 6-inches, the mean settling velocity was about 0.12 m/s (0.4 ft/s). The large 6-inch pieces settled about 20% slower than the smaller pieces.

Chugging energy and RMI debris size were varied to determine the effect on suspension of the RMI debris. A photo of 6-inch pieces of debris in suspension during chugging is shown in Figure 2-17. Approximate settling times after the simulated chugging ended were recorded for various sized of RMI shreds.

**Figure 2-17. Typical Large (6”) RMI Debris in Suspension During Chugging**

Approximately 2/3 of the RMI pieces remained suspended at the higher energy levels, whereas ~½ of the pieces remained suspended during the lower energy chugging phase. The effect of residual turbulence on settling times was significant for the small RMI debris size. After chugging, the turbulence decayed away allowing settling to occur. In the turbulent pool after chugging stopped, the larger RMI debris (2” to 6” category) settled up to two times faster than the smaller RMI debris (0.25" to 0.5" category). All RMI debris settled within two minutes after chugging ceased. The settling time after simulated chugging ended was independent of chugging energy. Concentration did not affect settling rates within the range of concentrations tested. However, for concentrations larger than about 2 gm/ft$^3$, interaction between RMI shreds on the floor of the tank somewhat inhibited re-entrainment during simulated chugging. Note that because suppression pool ECCS flow recirculation was not simulated in these tests, these results do not consider the effects of recirculation on material settling or possible resuspension.

Documentation

A compete description of the NRC sponsored ARL RMI debris sedimentation tests is found in SEA Report SEA-95-970-01-A:2, "Experimental Investigation of Head Loss and Sedimentation Characteristics of Reflective Metallic Insulation Debris," 1996, and ARL Report 170-95/M787, "Reflective Metallic Insulation Settling Following a LOCA in a BWR Suppression Pool," 1995.

#### 2.1.2.3 RMI Head Loss Tests

RMI debris deposited on an ECCS pump suction strainer will affect strainer head loss and could potentially compromise the pump. Data was needed to gain insights into RMI head losses and to derive models capable of predicting the head loss associated with RMI debris. The NRC sponsored a modest set of confirmatory head loss experiments to verify the results of tests conducted by BWROG using prototypical RMI debris (see Section 3.3.2). These tests were conducted at ARL.

Test Objective

Tests were conducted to quantify head losses across BWR suppression pool suction strainers associated with the accumulation of stainless steel RMI debris (aluminum RMI was not tested), with and without fibrous insulation debris and/or sludge. The test parameters included: RMI debris sizes and loadings (mass per unit strainer area), fibrous debris loadings (thickness of fiber bed), particulate to fiber mass ratio, and water flow approach velocity. The impact of the relative timing of debris accumulation on the strainer was explored, i.e., RMI debris and fibrous debris deposited in layers as opposed to being mixed.

Test Apparatus and Instrumentation

These tests were conducted using the same closed loop test facility used for the fibrous insulation head loss tests (see Section 2.1.1.1). The test apparatus, shown in Figure 2-1, consisted of a closed loop where the same water was repeatedly forced through the strainer. A relatively uniform velocity profile at the strainer was achieved by implementing a long vertical 12-inch diameter pipe test section. The upstream approach to the strainer was 11-ft long and the downstream portion was another 4.5-ft in length. The remaining loop piping was constructed of 4-inch piping to keep flow velocities high enough to minimize debris settling within the horizontal portions of the loop. Resistance heating was used to maintain water temperature and the piping was insulated to minimize heat loss.

Because the flow velocity approaching a typical semi-conical shaped BWR strainer is fairly uniform, a flat plate strainer was deemed adequate for the test apparatus. Note that the approach velocity for advanced strainer designs likely will not be uniform. The test strainer was constructed from 14-gauge stainless steel plate perforated with 1/8-inch holes with a density of 30 holes per square inch.

RMI debris introduced into the loop accumulated on the strainer. The RMI debris used in these tests was debris generated by the SIEMENS large pipe break debris generation test discussed in Section 2.1.6.

Test Data

For the conditions tested, the RMI head loss tests demonstrated that introduction of prototypical RMI debris, in combination with fibrous debris and sludge, does not cause significantly different head losses than those observed with only fiber and sludge loadings. In fact, the most significant finding was that when RMI debris was mixed with fibrous debris and sludge, the head losses appeared to decrease when compared to similar conditions without RMI debris. This finding is illustrated in Figure 2-18, which shows head loss as a function of RMI loading added to a ½" thick bed of NUKON™ and sludge. A typical RMI/NUKON/sludge post-test debris cake on the strainer plate is shown in Figure 2-19. The trend where the addition of RMI to fibrous bed reduced the head loss was not apparent in the tests without sludge.

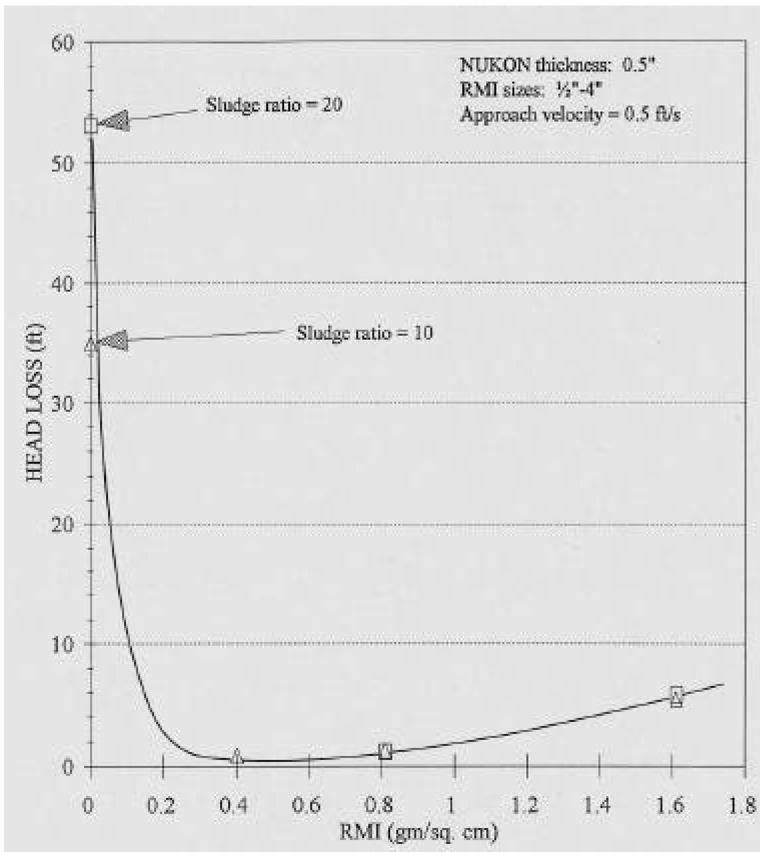



**Figure 2-18. Effect of RMI Debris on Head Loss When Mixed with Fibrous Debris**

Caution must be used in generalizing these specific conclusions and in applying the data to actual plant specific analyses since the number of experiments was limited, data scatter was significant, and not all prototypical situations were explored. Further, limited data from another test program conducted by the industry indicated that the head loss contribution due to the addition of RMI to a fiber/sludge bed could be significant in some situations. This finding contradicts the conclusion of these tests that RMI in mixed fiber/RMI beds does not contribute significantly to the head loss of the mixed bed. This issue is discussed further in Sections 4.4 and 5.3. It must be further cautioned that data collected for the flat test strainer likely will not be directly applicable to the advanced complex-geometry strainers employed by the strainer replacement program.

For the limited thicknesses and debris distributions tested, the mixed layers of RMI and fibrous insulation debris on the strainer produced higher head losses than did the layered (stratified) debris. Note that only layers of insulation formed with RMI debris on the bottom and fibrous debris on top were tested, but not the reverse order. A mixed debris condition is assumed to be typical for postulated LOCA scenarios, however, it is possible that actual deposition in selected scenarios may not result in homogeneous mixtures of debris at strainer surfaces.


**Figure 2-19. Typical RMI/NUKON/Sludge Post-Test Debris Cake**

When RMI debris was tested alone (no fibrous debris), the head losses were relatively small compared to the head losses of fibrous beds. Head losses for the RMI loadings tested (0.8 to 2.4 $gm/cm^2$), ranged from about 1 to 4 ft-water at an approach velocity of 1 ft/s.

<u>Documentation</u>

A complete description of the NRC sponsored ARL RMI debris head loss tests is found in SEA Report SEA-95-970-01-A:2, “Experimental Investigation of Head Loss and Sedimentation Characteristics of Reflective Metallic Insulation Debris,” 1996, and ARL Report 92-96/M787F, “Head Loss of Reflective Metallic Insulation Debris with and without Fibrous Insulation Debris and Sludge for BWR Suction Strainers,” 1996.

### 2.2 NRC Analytical Developments

For the NUREG/CR-6224 study, a deterministic analysis was performed to determine if a postulated break in the primary system piping of the reference BWR plant could result in ECCS strainer blockage and loss of NPSH. The analysis considered debris generation, drywell debris transport, suppression pool debris transport, and strainer blockage. The study developed analytical models applicable to the study’s reference BWR to predict the quantities of debris generated. The quantities of debris that would transport, from the drywell to the suppression pool, the quantities of debris within the suppression pool that would transport to the strainers, and the head loss across the strainer caused by accumulation of debris. The BLOCKAGE computer program was developed to calculate debris generation, debris transport, fiber/particulate debris bed head losses, and its impact on the available NPSH.

To further build on the NREG/CR-6224 study results, the NRC sponsored the drywell debris transport study (DDTS) to investigate debris transport in BWR drywells. The purpose of the study was to provide a description of the important phenomena and plant features that control and/or dominate debris transport and the relative importance of each phenomenon as a function of the debris size. The DDTS also provided reasonable engineering insights that can be used to evaluate debris transport fraction estimates used in utility strainer blockage analyses. To support the DDTS, the NRC convened a panel of recognized experts with broad based knowledge and experience to apply the Phenomena Identification and Ranking Table (PIRT) process to the transport of break-generated debris through BWR drywell. The PIRT process was designed to enhance the DDTS analysis by identifying processes and phenomena that would dominate the debris transport behavior. Further, these processes and phenomena were prioritized with respect to their contributions to the reactor phenomenological response to the accident scenario.

The NRC was concerned that new credit for containment overpressure would be required for some licenses to meet the NPSH requirements of the ECCS and containment heat removal pumps. As a result, the staff re-evaluated its position on use of containment overpressure in calculating NPSH margin.

### 2.2.1 Reference Plant Evaluation

The NRC sponsored research to evaluate the adequacy of existing strainer designs in U. S. BWR plants. In September 1993, the NRC initiated a detailed reference-plant study using a BWR/4 reactor with a Mark I containment. The analysis supporting the original resolution of USI A-43 was based on a reference PWR plant. As a result, a BWR plant-specific analysis was considered appropriate for evaluating the NRC's BWR strainer blockage concerns. Specific aspects of the issue not identified in the PWR study needed to be evaluated when considering BWRs. These aspects included BWR specific design issues, insulations used in BWR plants, and non-insulation debris found in BWR plants (e.g., suppression pool sludge).

#### Study Objective

The primary objective of the study was to determine the likelihood that a postulated break in the primary system piping of the reference BWR plant could result in the blockage of an ECCS strainer and the loss of pump NPSH. The analyses involved both deterministic and probabilistic techniques to arrive at its conclusions. The deterministic analyses focused on models to simulate phenomena governing debris generation, drywell and wetwell debris transport, and strainer head loss. The probabilistic analyses focused on evaluating the likelihood of core damage related to strainer blockage based on LLOCA-initiators.

#### Study Analytical Models

The reference plant selected for this study was selected because its design included the plant features under consideration and because the plant was considered to have a higher probability of experiencing a blockage of its strainer. For instance, the plant was a Mark I design with a relatively small suppression pool leading to comparatively faster strainer flow velocities than other BWR plants. In addition, more than 99% of the primary system piping was insulated with steel-jacketed fiberglass insulation.

The analyses methodologies broke the analytical problem down into several steps that were analyzed separately. These steps were:

- Pipe Break Analysis: All pipe welds were located and their corresponding probabilities for failure estimated. Note that historical evidence and pipe failure analyses suggest that pressure boundary failure would most likely occur at weld locations.

- Debris Generation Analysis: A model was developed to estimate the quantity of insulation debris that could be generated by the failure of each pipe weld. The debris quantity was estimated for each postulated weld failure.

- Drywell Debris Transport Analysis: A model was developed to estimate the quantity of insulation debris, once generated, that would be transport from the drywell into the wetwell.

- Suppression Pool Debris Transport Analysis: A model was developed to estimate the quantity of insulation debris, once in the suppression pool, that would transport to an ECCS suction strainer. In addition, the suppression pool model addressed the transport of sludge particles within the pool to a strainer.

- NPSH Analysis: A model was developed to predict the head loss across a strainer due to the accumulation of fiber and particulate debris on the strainer. The impact of debris head loss on pump NPSH was evaluated.

- Risk Analysis: A functional event tree was developed that modeled accident progression for a LLOCA-initiator with specific relevance to the ECCS strainer blockage issue. Quantification of the event tree resulted in estimates for the blockage-related CDF due to loss of ECCS following a LLOCA.

The debris generation model (DGM) was based on the locations of piping welds and the insulation that would be targeted by the break jet. A review of plant drawings identified all high-pressure welds in the primary system piping. The initial blast wave, ensuing break-jet expansion, impingement forces, type of insulation, and mode of insulation encapsulation were all dominant contributors to insulation debris generation following a LOCA. Of secondary importance, were other contributors, such as pipe whip and pipe impact. A three-region two-phase conical jet expansion model, described for PWR plants in both NUREG-0869 and NUREG-0897, was adapted for the reference plant study. This model, illustrated in Figure 2-20, defines a zone of influence (ZOI) over which the insulation would be destroyed and dislodged from the surrounding pipes. The ZOI in a BWR plant, with respect to a PWR, reflected: 1) the lower operating pressures of BWR plants, 2) the more dense pipe congestion in a BWR drywell which limits the free expansion of the break jet, and 3) simultaneous expansion in opposite directions of DEGB weld break jets. A spherical ZOI was assumed to extend from the location of the break to a distance of seven times the pipe diameter (i.e., L/D = 7). The DGM, as applied to the reference plant, assumed that:

- 75% of the insulation located within an L/D of 3 would be destroyed.

- 60% of the insulation located between L/D of 3 and L/D of 5 would be destroyed.

- 40% of the insulation located between L/D of 5 and L/D of 7 would be destroyed.

The DGM was used to estimate the quantity of fibrous debris generated by a postulated break. Other sources of LOCA generated debris included failed containment coatings and concrete dust.

Title:
Fg03-16.eps
Creator:
CLARIS EPSF Export Filter V1.0
Preview:
This EPS picture was not saved
with a preview included in it.
Comment:
This EPS picture will print to a
PostScript printer, but not to
other types of printers.

*Figure 2-20. Schematic Illustration of the Debris Generation Model*

Debris transport from the drywell to the suppression pool is strongly influenced by factors such as tortuosity of the transport pathways, flow velocity, and debris characteristics. This study postulated that debris transport from the drywell to the suppression pool would occur over two phases, i.e., the blowdown phase and the washdown phase. During the blowdown phase, debris would be carried by primary system depressurization flow to the suppression pool. During the washdown phase, debris would be carried to the suppression pool by the break overflow and by containment spray flow.

Debris transport phenomena was too complex to model accurately in this study, therefore a simplified parametric model was applied, i.e., a transport fraction was applied to each of three elevations within the drywell. The reference plant drywell was subdivided into three transport regions defined by the two main gratings within the drywell. It was assumed that:

- 75% of debris generated within the lowest region between the drywell floor and the lower grating would transport to the suppression pool.

- 50% of debris generated within the middle region between the lower grating and the upper grating would transport to the suppression pool.

- 25% of debris generated within the highest region above the upper grating would transport to the suppression pool.

The drywell debris transport was subsequently studied in detail in the Drywell Debris Transport Study (DDTS) discussed in Section 2.2.3 of this report.

The transport of debris within the suppression pool to the ECCS suction strainers is complicated by a variety of effects. Models for these effects were broken down into two main phases with an interim transition phase. During the blowdown phase, pool dynamics would be governed by the extremely dynamic primary system depressurization. The LOCA-induced pool turbulence such as condensation oscillations and chugging within the downcomers would re-suspend debris initially settled to the pool floor (i.e., sludge), uniformly distribute the debris throughout the suppression pool, and further breakup pieces of debris. During the relatively quiescent washdown phase, gravitational settling would be important as debris could once again settle to the suppression pool floor. Analytical models were developed that were based on and benchmarked to the experimental data collected for strainer head losses and suppression pool sedimentation, described in Sections 2.1.1.1 and 2.1.1.2, respectively. These time-dependent models were programmed into the BLOCKAGE code, discussed in Section 2.2.2. Then the BLOCKAGE code was used to predict debris quantities, by type and size that would accumulate on the strainers.

Accumulation of debris on the strainer would result in head loss and could cause loss of NPSH margin. For the reference plant, the debris bed on the strainer would consist primarily of fibrous insulation debris with suppression pool corrosion products (i.e., sludge) embedded within the fibers. Particles not filtered from the flow by the fibrous debris would pass through the strainer and either settle within the primary system or return to the containment by way of the break flow. At the time, the reference plant strainers employed simple truncated conical shaped strainers. Small and fine fibrous debris (the most transportable of the debris sizes) would accumulate on this type of strainer relatively uniformly. A uniform distribution of debris across the strainer surface area is generally considered the worst-case scenario because it provides the greatest head loss.

Experimental head loss data was obtained from fibrous bed head loss and filtration tests conducted by ARL (discussed in Section 2.1.1.1). These NRC sponsored tests studied head loss across beds formed of NUKON™ fibers and iron oxide particles ranging from less than 1 micron to greater than 300 microns in size. In addition to head loss measurements, Scanning Electron Microscope (SEM) images of the debris beds and visual observations of bed formation and bed compression were used to develop a semi-theoretical head loss correlation. Using this correlation to predict head loss measurements for available head loss tests validated the correlation. The correlation is:

$$\frac{\Delta H}{\Delta L_o} = Units\left[3.5\,S_v^{\,2}\,(1-e_m)^{1.5}\left[1+57\,(1-e_m)^3\right]m\,U + 0.66\,S_v\,\frac{(1-e_m)}{e_m}\,r_w\,U^2\right]\left(\frac{\Delta L_m}{\Delta L_o}\right)$$

Where $\Delta H$ = the strainer head loss (ft-water)
$\Delta L_o$ = the theoretical thickness (uncompressed) of fiber bed (inch)
$\Delta L_m$ = the actual thickness (compressed) of fiber bed (inch)
$S_v$ = the specific surface area of the fiber-particulate mixture ($ft^2/ft^3$)
$\varepsilon_m$ = the porosity of the fiber-particulate mixture
$U$ = the velocity of the water flow (ft/s)
$\mu$ = the viscosity of water (lbm/s-ft)
$\rho_w$ = the density of water ($lbm/ft^3$)
Units = $4.1528 \times 10^{-5}$ (ft-water/in/($lbm/ft^2/s^2$))

For an incompressible bed, the actual bed thickness is the same as the theoretical bed thickness, however visual observations have clearly determined that fibrous debris beds are highly compressible under the effect of differential pressure across the bed, which acts as a compacting force. The solution of the head loss correlation requires an expression for the bed compressibility. The following correlation was found to work well.

$$\frac{\Delta H}{\Delta L_o} = \left[ \left( \frac{1}{a} \right) \left( \frac{\Delta L_o}{\Delta L_m} \right) \right]^{\frac{1}{g}}$$

Regression analysis determined the values for the constants α and γ to be 1.3 and 0.38, respectively.

Blockage-related core damage accidents involve the failure of the ECCS pumps due to loss of NPSH and the subsequent failure to establish an alternative means for core cooling. A number of considerations were involved in estimating the contribution of ECCS strainer blockage to CDF, including:

- LOCA frequency.
- ECCS strainer blockage probability.
- Operator recognition of strainer blockage.
- Availability of back flushing.
- Alternative means of providing core cooling.
- Protection of containment integrity.
- Time available for operators to take mitigating actions.
- Additional operator recovery actions.

A simplified event tree model, representing the progression and expected outcomes of various possible LOCA sequences, was used to generate the CDF estimates.

### Study Conclusions

The results of the reference plant study demonstrated that with the existing ECCS pump suction strainers there was a high probability that the available NPSH margin for the ECCS pumps would be inadequate following a LOCA because of the transport of debris to the suction strainers. The pipe break frequency (per Rx-year) estimates for a DEGB postulated to occur on piping systems analyzed ranged from 3.2E-06 to 1.2E-04 and the overall pipe break frequency was estimated to be 1.5E-04. Almost all postulated DEGBs resulted in unacceptable strainer blockage leading to the loss of NPSH margin for the ECCS pumps. The overall loss of NPSH margin frequency was estimated to be 1.5E-04. The point estimates for the CDF due to blockage-related LOCA accident sequences for the reference plant ranged from 4.2E-06 to 2.5E-05. The simplified event tree is illustrated in Figure 2-21.

The temporal behavior of the head loss was evaluated for selected welds. For all welds examined, the NPSH margin was estimated to be lost within a few minutes (less than 10 minutes into the event) after full ECCS flow was achieved. An example of time-dependent suppression pool debris transport (Weld

RCA-J006) is shown in Figure 2-22; the corresponding head loss reached ~750 ft-water at 10 minutes and ~1500 ft-water at 1 hour (theoretical predictions using the BLOCKAGE code, see Section 2.2.2). In addition, an extended parametric analysis was performed to investigate the sensitivity of the temporal head loss estimates to each of 13 key parameters. The head loss estimates were found to be most sensitivity to the strainer surface area, the ECCS flow rate, the filtration efficiency, and the quantity of particulates. Within the variations of the parameters analyzed, the strainer area was found to be the only independent variable, which could effectively reduce the head loss below the available NPSH margin. By increasing the strainer area by a factor of 8, the loss of NPSH margin was no longer estimated to occur. Note that the reference plant strainer was replaced with a much larger strainer, thereby resolving the strainer blockage issue at that plant.

Title:
Fig8-02.eps
Creator:
CLARIS EPSF Export Filter V1.0
Preview:
This EPS picture was not saved
with a preview included in it.
Comment:
This EPS picture will print to a
PostScript printer, but not to
other types of printers.

***Figure 2-21. Simplified Event Tree for LLOCA at the Reference Plant***

The methodology developed for this study is sufficiently flexible to be extended to other types of insulation. The study also demonstrated that determining the adequacy of NPSH margin for an ECCS system is highly plant-specific because of the large variations in such plant characteristics as containment type, ECCS flow rates, insulation types, plant layout, plant cleanliness, and available NPSH margin. Several parameters, such as the insulation destruction fractions and the drywell transport fractions for the reference plant were determined using considerable engineering judgment based on limited data, therefore considerable caution must be exercised in assigning values to many of the parameters used by these models for other types of insulation and other drywell layouts. Based on today's knowledge and testing performed at CEESI (see Section 2.1.1.4), the NRC recommends basing the estimate of debris generation on test data. Note that uncertainty associated with assigning values for the drywell debris transport parameters prompted the DDTS.

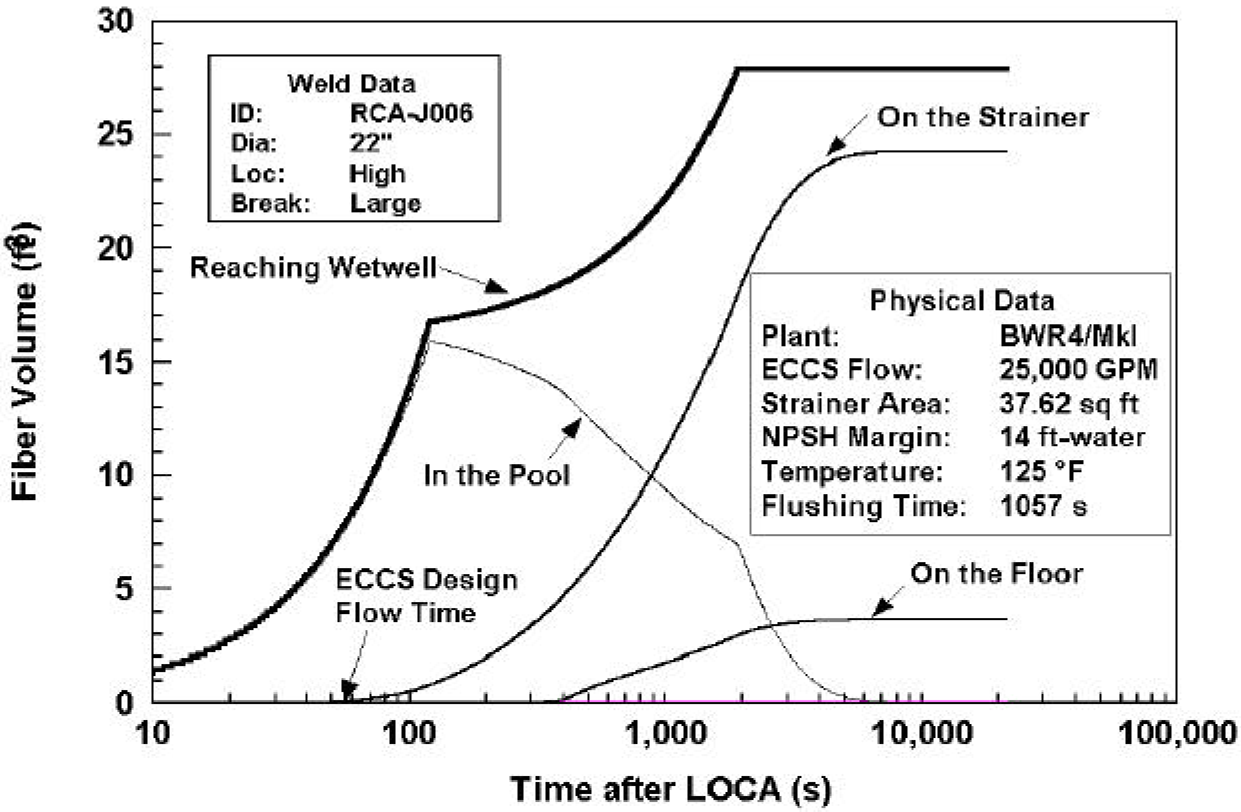



*Figure 2-22. Typical Fibrous Debris Transport in the Suppression Pool*

### Documentation

A complete description of this of study was documented in detail in NUREG/CR-6224. This report was released first published as a draft-for-comment in August 1994 and than as a final report in October 1995.

### 2.2.2 BLOCKAGE Computer Code

The complexity of all the phenomena associated with determining strainer head loss associated with debris blockage called for a computer program designed to quickly solve for the head loss given basis plant input data. The BLOCKAGE computer program was developed to calculate debris generation, debris transport, fiber/particulate debris bed head losses, and its impact on the available NPSH. The BLOCKAGE code included models for transient debris bed formation and used the fiber/particulate head loss correlation (known as the NUREG/CR-6224 head loss correlation) developed in the reference plant study. The correlation was validated for laminar, transient, and turbulent flow regimes through mixed beds.

### Software Description

BLOCKAGE Version 2.5 is an integrated calculational method with a graphic user's interface (GUI) for evaluating the potential for loss of emergency core cooling systems pump net positive suction head margin due to insulation and non-insulation debris buildup on suction strainers following a postulated loss of coolant accident in boiling water reactors. BLOCKAGE incorporates the results of multi-year NRC sponsored research documented in NUREG/CR-6224. It also provides a framework into which user can input plant specific/insulation-specific information for performing analysis in accordance with Revision 2 of Regulatory Guide 1.82.

### Software Capabilities

BLOCKAGE 2.5 allows the user to simulate debris generation and subsequent transport of multiple types of debris including fibers, particles, and metals, using either a three-zone destruction model or a user-specified quantity of debris for transport. The debris transport from the drywell to the wetwell can be location-dependent and time-dependent. The transport during the blowdown period due to depressurization flows is treated separately from the transport during the washdown phase, which is due to ECCS recirculation, containment spray, and steam condensate flows. Two sizes of pipe break scenarios are considered: large and medium LOCAs. 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 and each debris type. The suppression pool is treated as a single volume of water. Specifically, debris concentration does not vary with location in the pool. The user supplies several model parameters which are time-dependent: 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. Each pump is considered to fail by loss of NPSH margin when the strainer head loss exceeds its temperature-dependent NPSH margin. A debris bed filtration model estimates the quantities of debris that are entrained in the pump flow that are either deposited on the strainer or passes through the strainer and retained within the primary system.

Four user-head loss correlations including the NUREG/CR-6224 correlation, a BWR Owner's Group (BWROG) 1994 correlation, and two generic correlations are available to predict the strainer head losses. 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. When selected by the user, BLOCKAGE 2.5 can also write several probabilities reports that provide information regarding the plant-wide strainer blockage probabilities correlated by pipe diameter, piping system, and break location.

The GUI makes BLOCKAGE relatively easy to use and provides a graphical output capability. The GUI provides both front-end processing of the input data and back-end processing of the output including the plotting of time-dependent results. The user also executes BLOCKAGE from the GUI.

### Software Verification and Validation

The BLOCKAGE code was subjected to rigorous coding verification to ensure that the code performs as it was designed to perform. In general, extensive quality assurance (QA) was integrated into the development of the BLOCKAGE code. Methods of ensuring quality included line-by-line reviews of coding, calculating results by hand and verifying the results with analytical solutions. A complex analytical test problem was developed that solved the system of differential equations inherent in the numerical solution of BLOCKAGE. This test problem was solved by both BLOCKAGE and by commercially available mathematics software; their solutions were virtually identical. The output sensitivity to the time step selection was also tested.

BLOCKAGE was validated against applicable experiments. BLOCKAGE code predictions clearly were in good agreement with the experimental data. In all cases, the measured head loss was within 50% of

BLOCKAGE predictions, with BLOCKAGE predictions always higher than the experimental data. Considering that the experimental data is associated with large uncertainties (> ± 35%) such a comparison is exceptional.

### Software Limitations

At the time the BLOCKAGE code was developed, the approach velocities to existing plants strainers were relatively uniform even with the accumulation of debris. Hence, code models were based the assumptions of uniform approach velocity, uniform debris deposition, and constant surface area. More complex strainer designs were developed as part of the strainer clogging issue resolution, such as the stacked disk and star shaped designs. Debris deposition on strainers of these designs starts as a uniform deposition on the entire screen area but eventually debris shifts to fill the inner screen regions creating substantially non-uniform approach velocities and debris deposition. Once the inner spaces are filled, approach velocities and deposition again approaches uniformity. Hence, the BLOCKAGE code is appropriate to calculate head loss with small quantities of debris on the strainer and again when the substantial quantities of debris on the strainer but not in between. With small quantities of debris on the strainer, the entire strainer screen area would be used. With the large quantities of debris, the circumscribed area would be appropriate. BLOCKAGE could potentially be modified with a variable area that is a function of debris volume so that complex strainers could be modeled through the full range of debris deposition.

### Documentation

A complete description of the BLOCKAGE code was documented in detail in the User's Manual [NUREG/CR-6370] and the Reference Manual [NUREG/CR-6371]. The software is available from Oak Ridge National Laboratory (ORNL) Radiation Safety Information Computational Center as BLOCKAGE2.5R.

#### 2.2.3 Drywell Debris Transport Study (DDTS)

An essential aspect of predicting the potential for strainer clogging is the estimation of debris transport in the drywell, i.e., the fraction of the debris generated that is subsequently transported into the wetwell. The transport processes are relatively complex, in that, these processes involve the transport of debris both during the reactor blowdown phase by way of entrainment in steam/gas flows and during the post-blowdown phase by water flowing out of the break and/or containment sprays. The reference plant analyses (NUREG/CR-6224) assured that the congested layout of the drywell would offer large surface areas for debris retention. However, due to the lack of directly applicable experimental or analytical data, the fraction of debris transported to the wetwell was estimated based on engineering judgment derived from the analysis of Barseback-2 event data. However, the NRC concluded that any engineering judgment based on a scarce set of experimental data would be associated with large uncertainties, and therefore the reference plant transport fractions could not be applied to other plants. In September 1996, the NRC initiated a study, referred to as drywell debris transport study (DDTS), to investigate debris transport in BWR drywells using a bounding analysis approach. The focus of the DDTS was to provide a description of the important phenomena and plant features that control and/or dominate debris transport and the relative importance of each phenomenon as a function of the debris size.

#### 2.2.3.1 Phenomena Identification and Ranking Table (PIRT)

The NRC convened a panel of recognized experts with broad based knowledge and experience to apply the Phenomena Identification and Ranking Table (PIRT) process to the transport of debris generated by a high energy pipe break debris through a BWR drywell. The PIRT process was designed to enhance the

DDTS analysis by identifying processes and phenomena that would dominate the debris transport behavior. Further, these processes and phenomena were prioritized with respect to their contributions to the reactor phenomenological response to the accident scenario.

The PIRT process was conducted in parallel with the DDTS, thereby supporting the DDTS. In addition, the PIRT provided a rational framework for evaluating licensee submittals related to resolving the strainer blockage issue. The panel ranked the importance of processes and phenomena associated with drywell debris transport, but also evaluated proposed use of computer codes, evaluated the DDTS planned experimental program and reviewed both preliminary and final DDTS results. The panel addressed both high elevation main steam line breaks and recirculation line breaks low in the drywell. All three BWR containment designs were considered (i.e., Mark I, Mark II, and Mark III). When the panel identified a weakness in the DDTS methodologies steps were taken to minimize or eliminate that weakness in the DDTS.

The panel formulated the following observations regarding the DDTS methodology:

- The panel believed that the structure of the DDTS methodology provided a rational basis for reviewing licensee submittals.
- The panel believed that the structure of the DDTS methodology was sufficiently flexible that new evidence and assumptions, related to debris size and distribution, could quickly be accommodated.
- The panel found the methodology attractive in that, 1) it clearly delineated important phenomena in the BWR drywell, 2) readily incorporated, and linked, both experimental and analytical results, and 3) was comprehensible to engineers having less experience in the transport of debris.

The panel identified the following thermal hydraulic phenomena as highly important.

- Pressure driven flows including localized flow fields.
- Flashing of break liquid effluent.
- Density of drywell structures and streaming of ECCS recirculation deluge.
- Drywell floor pool formation, dynamics, and overflow into suppression pool.

The panel identified the following debris transport phenomena as highly important.

- Debris advection/slip.
- Debris impaction.
- Debris adhesion.
- Debris transport and settling within the drywell floor pool.

## Documentation

The complete description of the PIRT panel findings was documented in detail in INEL/EXT-97-00894, "BWR Drywell Debris Transport Phenomena Identification and Ranking Tables (PIRTs)," 1997 [PIRT].

### 2.2.3.2 Transport Analysis Methodology

Due to the complexity, the problem was broken down into several individual steps. Each step was then studied either experimentally or analytically and engineering judgment was applied where applicable data were not available. The results of the individual steps were quantified using a logic chart approach to determine transport fractions for: 1) each debris size classification, 2) each BWR containment design, 3) both upper bound and central estimates, and 4) each accident scenario studied. The complexity is illustrated in Figure 2-23 for both the blowdown and washdown phases.

Upper bound estimates provide transport fractions that are extremely unlikely to be exceeded. Because each upper bound estimate represents the compounding of upper bound estimates for each individual step, the overall upper bound transport fractions are highly conservative. The central estimates were developed using a more realistic yet conservative representation of each individual step. While the central estimate transport fractions were deemed closer to reality, the estimates lacked the assurance of not being exceeded under any accident condition.

Early in the study, the thermal and hydraulic conditions that would govern debris transport were assessed analytically by performing calculations referred to as end-to-end scoping calculations, that encompassed the possible debris transport and capture processes. These calculations included both a series of hand computations and system level computer code calculations (i.e., MELCOR, RELAP, and CFD). All calculations were designed to examine selected specific aspects of the overall problem. The calculations results were then used to subdivide the problem into several components that could be individually solved through the use of separate effects experiments, analytical modeling, and engineering calculations. The calculations also identified vital database elements necessary to quantify transport.

Experiments and further analytical studies were undertaken to provide a basis for quantifying debris transport during blowdown, washdown of debris by ECCS water flow, and debris sedimentation on the drywell floor. In particular, three sets of experiments, discussed in Sections 2.1.1.3, 2.1.1.4, and 2.1.1.5, were designed and conducted as part of this study. Detailed CFD simulations were used to determine likely flow patterns that would exist on the drywell floor during ECCS recirculation and the likelihood of debris sedimentation under these conditions.

Transport fractions were estimated for each of the BWR containment designs (i.e., Mark I, Mark II, and Mark III) for a spectrum of postulated accident scenarios. Two major types of piping breaks were studied: main steam line breaks (MSL) and recirculation line breaks (RL). Both throttled and unthrottled ECCS break overflow was considered. Containment sprays were considered to operate intermittently or not at all.

A simplified logic chart method was chosen to integrate the problem subcomponents into a comprehensive study. An example logic chart is shown in Figure 2-24. A separate logic chart was generated for each scenario and for each containment design. Individual steps in the logic charts were solved using available knowledge tempered by conservative engineering judgment. Finally, the logic charts were quantified and the results tabulated.

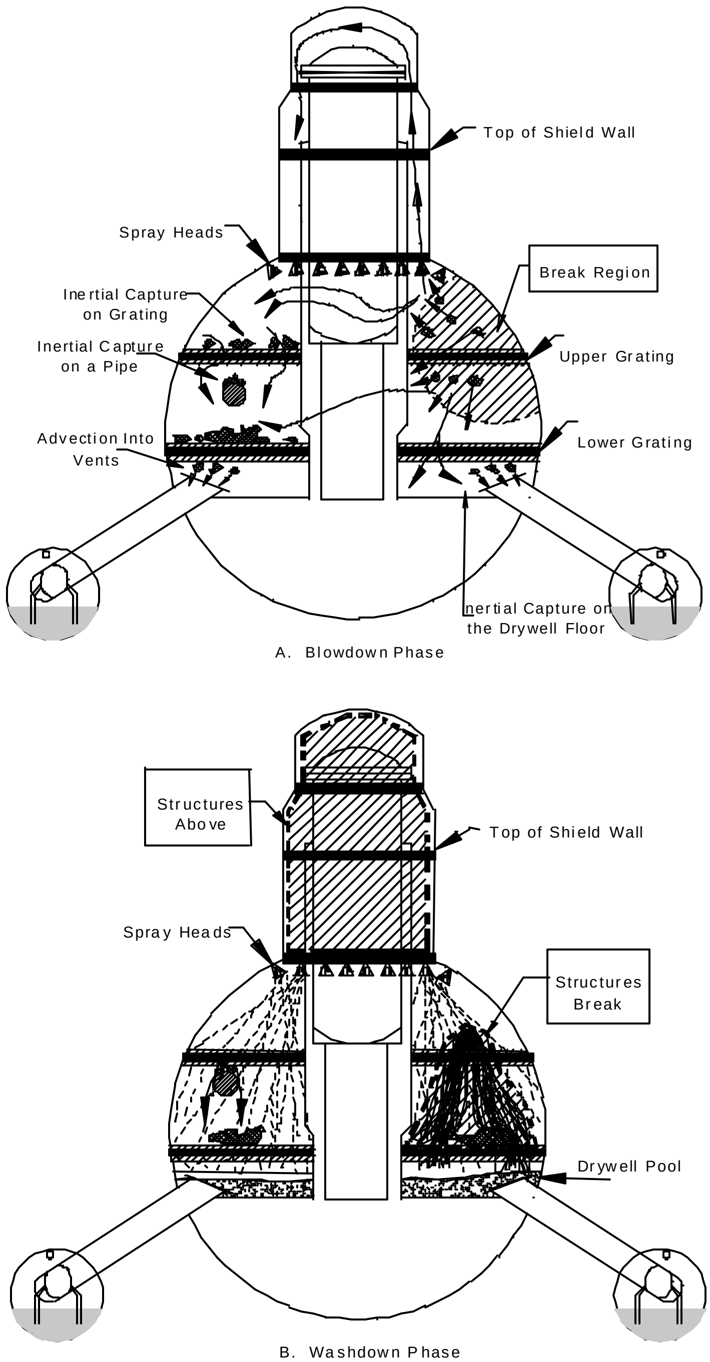



*Figure 2-23. Schematic Illustrating the Complexity of Drywell Debris Transport*

The logic chart subdivides the problem into five independent steps: (1) LOCA type, (2) debris classification, (3) debris distribution after blowdown, (4) erosion and washdown, and (5) sedimentation in the drywell floor pool. Note that because the debris size distribution was not within the scope of this study, a size distribution from a BWROG study [NEDO-32686] was used in the DDTS in order to illustrate the computation of overall debris transport fractions. Four size classifications are shown in the chart: small, large-above, large-below, and canvassed. Because large debris does not pass through floor grating, the large debris classification was subdivided into debris formed above any grating and debris formed below all gratings. Overall transport fractions were applied to all insulation within the ZOI.

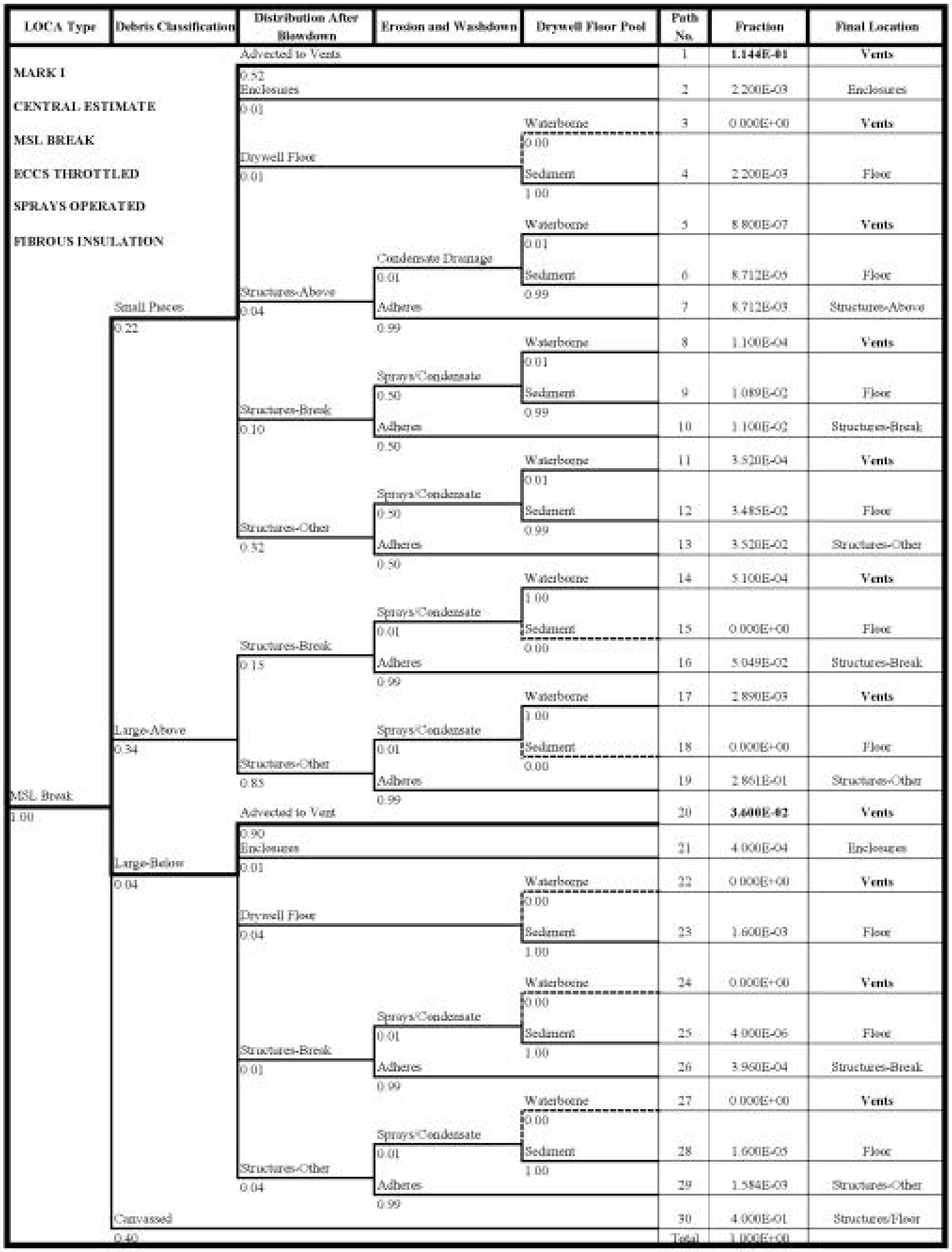



*Figure 2-24. Sample Drywell Debris Transport Logic Chart*

Accordingly, the canvassed classification included intact blankets located within the ZOI. The third column shows where the debris is expected to reside following the end of blowdown. Drywell structures were divided according to location in the drywell: structures located above the containment spray heads, since the sprays cannot reach these structures; structures located directly below the break (which can be subjected to recirculation break flows) and all other structures subjected to sprays but not break flows. Additionally, small debris can be deposited directly onto the floor by mechanisms such as vent capture or entrapment within an enclosure such as the reactor cavity. Large debris generated above any grating was assumed to reside on a grating either below the break or not below the break. Large debris deposited above the spray heads or in enclosures was not considered credible. Each branch in the erosion and washdown column simply calculated the amounts of captured debris that remained on the structures after being subjected to the appropriate washdown flows (i.e., recirculation break flow, containment spray flow, and condensate drainage). Similarly, each branch in the drywell floor pool column asks how much of the debris settles to the floor.

### 2.2.3.3 Controlling Phenome na and Plant Features

The determination of which processes/phenomena tends to control the transport of debris depends upon the debris characteristics (i.e., small versus large pieces or covered versus uncovered pieces. Insulation debris can be broadly divided into three size classes: small, large, and large-canvassed. Since each of these debris classifications followed different transport pathways, the analyses considered each classification separately. Small pieces of debris were small enough to easily pass through gratings. Fine particles such as individual fibers or groups of fibers were also considered small debris. Large and large-canvassed pieces of debris were too large to pass through a grating. The large-canvassed debris consisted of sections of intact or relatively intact canvas covered insulation within the ZOI. The large pieces were pieces of relatively intact insulation that were no longer covered by canvas. A medium category was originally considered but there was so little debris generated in this category that it was dropped from further consideration. A few pieces of debris, referred to as agglomerated debris, consisted of small pieces of insulation entangled in a web of canvas fibers, such that the piece transported as a large piece of debris. Sample of small, medium, large, and agglomerated debris were shown in Figure 2-9.

The processes/phenomena that tend to control the transport of small debris are: advection, inertial capture, washdown, and drywell floor pool hydrodynamics. Analyses and experiments suggest that small debris tend to stay fully suspended at airflow velocities higher than 10 ft/s, therefore gravitational settling of airborne debris during the blowdown phase is minimal. During blowdown, the gratings are the most likely locations for debris capture, followed by other structural congestion, vents, and the drywell floor.

The processes/phenomena that tend to control the transport of large debris are: advection of large pieces generated below the lowest grating and through discontinuities in the floor gratings, and erosion of large debris by break flow. Experiments verified that large pieces would not be forced through a grating due to high velocity steam flow, two-phase jet flow typical of a recirculation line break, or prolonged break/spray water flow.

The transport of large canvassed pieces was deemed unlikely either by advection or by erosion. The canvas protected the fibrous insulation from erosion. While, some possibility existed that a large canvassed piece, generated below the lowest grating, could pass through a downcomer vent, it was deemed unlikely that this would happen, based on experimental observations. Therefore, these pieces were treated as non-transportable in the DDTS.

Three plant features were found to control debris transport, these features were: 1) the number and arrangement of gratings with respect to the pipe break, 2) the vent and drywell floor design, and 3) the duration of unthrottled ECCS flow. Experimental data clearly illustrated that during blowdown, the drywell floor gratings provided the largest potential for capture of both small and large debris, with the capture efficiency between 15% and 30% (wetted-grating) for small debris and 100% for large debris (see Section 2.1.4 and Figure 2-10). The small pieces captured on gratings could be easily re-entrained by ECCS water flow during washdown. The only mechanism available for washdown of large pieces is erosion, which was found to be a relatively constant rate process. Therefore, the time assumed for unthrottled operation of ECCS plays a key role in determining the fraction of large pieces that would be washed down. Although vents may provide an effective location for capture during blowdown (10-15% for small debris and >30% for large pieces), the captured debris may become re-entrained depending on the drywell pool flow dynamics. Typically, higher flow velocities and turbulence levels characterize pools formed as a result of break overflow. Sedimentation of small or large debris in such pools is unlikely. On the other hand, sedimentation is likely in the pools formed by containment sprays.

**2.2.3.4 Specific Analytical Studies**

Analyses supporting the DDTS included a variety of calculations designed to examine selected specific aspects of the overall problem. These included hand calculations, system level code calculations, and CFD calculations. The following describes the computer code calculations that were performed is support of the DDTS.

<u>MELCOR Code Calculations</u>

The MELCOR code was used to examine thermal-hydraulic conditions within the drywell following a postulated LOCA. Insights were obtained regarding containment pressures and temperatures, bulk flow velocities, time required to clear the vent downcomer of water, rate of steam condensation on drywell structures and subsequent thickness of films, rate of accumulation of water on the drywell floor, transport of noncondensible gases to the wetwell. Key observations of these MELCOR calculations included:

- The containment pressures rapidly increased to about 3 atmospheres in about 1 second, corresponding to the clearing of the downcomer vents. Further pressurization was then prevented by the pressure suppression system. After a relatively short period of 5 to 10 seconds, the pressures decreased again.

- The water in the downcomer vent pipes was purged from the pipes in about one second.

- Steam immediately condensed upon contact with surface structures until the temperature of the surface equilibrated with the steam environment. The total rate of condensation within the drywell for the high MSL break, for example, peaked at 1170 lbm/s at about 2.5 seconds.

- Water films with a thickness of 200 to 400 microns accumulated on the structures in as little time as one second, depending upon the location of the surface relative to the pipe break.

- Peak flow velocities as high as 820 ft/s were found near the break and flow velocities through the vent downcomer pipes exceeded 660 ft/s. Elsewhere in the drywell the velocities varied considerably from one location to another.

- The majority of the nitrogen gas initially located in the drywell was forced into the wetwell in about three seconds. The residence time for a tracer gas injected into the drywell along with the break source was generally less than two seconds.

- A pool of water accumulated on the drywell floor and in the reactor cavity sumps as was expected. In the MSL breaks, the pool would not overflow into the downcomer vent pipes, because the depth of the water was only about a quarter of the depth required to overflow. In the recirculation line break (RLB), the results were considerably different. The overflow through the downcomer vent began at five seconds for the low RLB. The asymmetrical pressures acting on the drywell floor pool pushed the accumulated water to the backside of the pedestal from the break and after the drywell pressures peaked, the pool became two-phased. The swollen water level caused the water to overflow into the vents at the backside. The drywell pool, of course, leveled out again after the primary system was depressurized.

RELAP Code Calculations

Calculations were performed with the RELAP code to characterize the break flow, (i.e., rate of flow and thermodynamic state as a function of time). Following a main steam line break (MSLB), essentially dry steam expands into the containment. The steam mass flow rate falls from an initial value of close to 6,000 lbm/s (assuming blowdown from both ends of the broken pipe) to about 1,000 lbm/s within a period of 50 seconds, while the steam velocity remains essentially at the sonic velocity of about 700 ft/s. Water enters the drywell in the form of fine droplets (approximately 5 microns) of entrained water but the water content is not likely to be large enough to completely wet the debris during their generation.

Following a RLB, the initial flow would be mainly water, but after a period of five to ten seconds, a mixture of water and steam is discharged at high velocities. During this phase, the dynamic pressures far outweigh the corresponding pressures during the initial five seconds after the break. Since the debris generation is proportional to the dynamic pressure, these results suggest that for a RLB most of the fibrous insulation debris will be produced in the later stages of the accident. The total mass flow rate remains fairly high (approximately 20,000 lbm/s) throughout the blowdown phase of a RLB compared to a similar size MSLB; however, the water content of the exit flow is very large. In these conditions, it is expected that all of the structures located in the path of the jet will be drenched with water and the insulation materials in the vicinity of the break are likely to be thoroughly wet prior to the break jet producing significant debris. Additionally, it is likely that the majority of the debris generated will follow the steam component of the break flow rather than following the liquid component. The DDTS assumed that 80% of the debris would be transported with the steam and 20% with the water.

CFD Calculations

Substantial quantities of insulation debris could land on the drywell floor during the primary system depressurization or be washed down to the drywell floor from drywell structures after being captured during depressurization. From here, the debris could then be transported from the floor into the vent downcomers. Therefore, determining the potential for debris to remain captured on the floor was a necessary step in the overall debris transport study. This determination was made based on simulating the drywell floor pool for a variety of conditions using a commercially available CFD code. The primary objective of this analysis was to evaluate the potential for debris to settle in drywell pools and to estimate fractions of debris that would be transported to the suppression pool. The study considered Mark I, II, and III designs for variations in pool depth and entrance conditions to the pools.

Benchmarking the CFD results to prototypical experimental data was needed in order to correlate pool turbulence levels with conditions that allowed debris to settle. This was accomplished by simulating the ARL Pennsylvania Power and Light Company (PP&L) flume tests with the CFD code and then correlating the code predicted turbulence level for a given test with the test results showing whether or not debris actually settled in that test. The PP&L flume tests are documented in EC-059-1006, "Results of Hydraulic Tests on ECCS Strainer Blockage and Material Transport in a BWR Suppression Pool," 1994, and discussed in Section 3.1.1. Maximum levels of turbulence that allowed debris to settle were determined and applied to the drywell floor pool simulation results. Two maximum levels were determined, one for small debris and one for large debris.

The results of each of the drywell floor pool simulations consisted of graphical pictures showing pool flow behavior such as two and three-dimensional color pictures of flow velocities and flow turbulence in the form of specific kinetic energy. These turbulence levels were then compared to the maximum levels for debris settling determined by the code calibration. If pool turbulence were higher than a maximum level, then debris would not likely settle. An example flow simulation is shown in Figure 2-25. The figure shows velocity contours (lines of equal velocity), for one-half of a Mark I drywell floor pool. On the basis of this graphical data, engineering judgment was applied to determine the likelihood for debris settling for each pool configuration. With noted design-specific exceptions, drywell floor pools formed by recirculation break flows are considered likely to transport the majority of insulation debris into the vent downcomers and pools formed by the containment sprays are likely to retain debris.

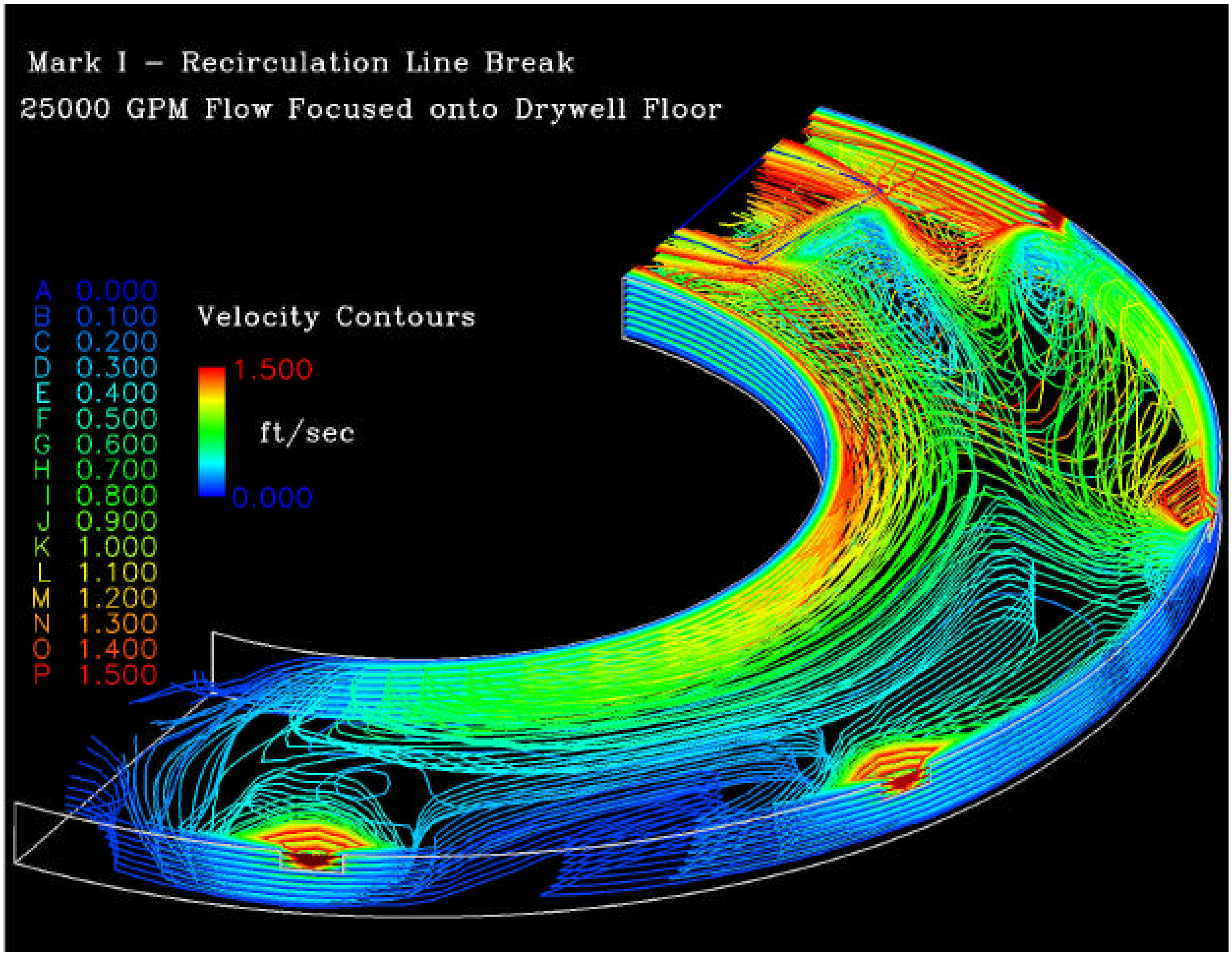



**Figure 2-25. CFD Simulation of Mark I Flow Patterns**

### 2.2.3.5 Debris Transport Quantification Results

A summary of the upper bound and central estimate transport fractions for a postulated LOCA in the mid-region of the drywell are presented in Tables 2-2 and 2-3 for the main steam line breaks and the recirculation line breaks, respectively. A complete set of results can be found in NUREG/CR-6369.

The central estimate transport fractions shown in Table 2-2 are the fractions for the MSLB scenarios where the operators throttle the ECCS back to the steaming mode and the containment sprays are operated intermittently. This scenario was chosen for summary purposes because it is the most likely scenario that operators would follow. Conversely, the upper bound estimate transport fractions in Table 2-2 are the fractions for the MSLB scenarios where the ECCS is not throttled back to the steaming mode and the sprays are operated. This scenario was chosen for the upper bound estimate because it represents the worst-case scenario in terms of debris transport. Similarly, the transport fractions shown in the Table 2-3 summary for RLB scenarios are those for ECCS throttling and spray operation for the central estimates and no throttling and spray operation for the upper bound.

Transport fractions corresponding to Tables 2-2 and 2-3 for all of the insulation initially located within the ZOI was provided in Table 2-4. These transport fractions were determined using the BWROG debris size distribution of 0.22, 0.38, and 0.40 for small, large, and canvassed debris. The large debris was then further subdivided into large-above and large-below using engineering judgment. These subdivisions were 80% and 90% above the grating for the central and upper bound estimates, respectively.

**Table 2-2: Study Transport Fractions for Main Steam Line Breaks**

| Plant Design | Central Estimate | | | Upper Bound Estimate | | |
|---|---|---|---|---|---|---|
| | Small Debris | Large Debris | | Small Debris | Large Debris | |
| | | Above | Below | | Above | Below |
| Mark I | 0.52 | 0.01 | 0.90 | 1.0 | 0.05 | 1.0 |
| Mark II | 0.74 | 0.01 | 0.90 | 1.0 | 0.05 | 1.0 |
| Mark III | 0.55 | 0 | 0.90 | 0.93 | 0.03 | 1.0 |

**Table 2-3: Study Transport Fractions for Recirculation Line Breaks**

| Plant Design | Central Estimate | | | Upper Bound Estimate | | |
|---|---|---|---|---|---|---|
| | Small Debris | Large Debris | | Small Debris | Large Debris | |
| | | Above | Below | | Above | Below |
| Mark I | 0.86 | 0.02 | 0.94 | 1.0 | 0.30 | 1.0 |
| Mark II | 0.89 | 0.02 | 0.95 | 1.0 | 0.30 | 1.0 |
| Mark III | 0.72 | 0.01 | 0.90 | 1.0 | 0.30 | 1.0 |

**Table 2-4: Study Transport Fractions for All Insulation Located in ZOI**

| Plant Design | Main Steam Line Break | | Recirculation Line Break | |
|---|---|---|---|---|
| | Central | Upper Bound | Central | Upper Bound |
| Mark I | 0.15 | 0.31 | 0.23 | 0.39 |
| Mark II | 0.20 | 0.31 | 0.24 | 0.39 |
| Mark III | 0.16 | 0.29 | 0.20 | 0.39 |

Several general conclusions can be drawn from these results:

- The total fraction of debris transported depends strongly on the assumed size distribution of the debris and the location of the break.
- Small debris readily transport towards the vents entrances with a substantial amount captured primarily by the gratings.
- A majority of the large debris generated above any grating is not likely to transport to the vents.
- A majority of the large debris generated below all gratings will likely transport into the vents.

The study concluded that the URG-recommended transport fractions for Mark II containments underestimate debris transport. For Mark I and Mark III drywells, the study concluded that the URG appears to provide reasonable estimates, provided the plant contains a continuous lower grating with no large holes. On the other hand, while the RG 1.82, Rev. 2 recommended assuming 100% transport of transportable debris was found to provide a reasonable upper bound for breaks located below the lowest grating, the recommendation greatly overestimates debris transport for breaks located above the lowest grating. Finally, the study concluded that licensees should pay close attention to plant features that are unique to their plant and how they were modeled in this study. If necessary, the logic charts provided in this study can be easily modified to account for plant-specific features, such as number and arrangement of floor gratings. Also, they are flexible enough to accommodate new evidence and assumptions related to debris size and distribution.

Documentation

The drywell debris transport study is documented in the three-volume report, NUREG/CR-6369. The main volume, Volume 1, summarizes the overall study, in particular, the debris transport quantification and transport fractions. The experiments conducted specifically to support this study are documented in detail in Volume 2. The analyses conducted specifically to support this study are documented in detail in Volume 3. The DDTS reports provide reasonable engineering insights that can be used to evaluate the adequacy of debris transport fractions used in the utility strainer blockage analyses.

### 2.2.4 Reliance on Containment Overpressure Credit

The NRC was concerned that licensees would take new credit for containment overpressure to meet containment heat removal and ECCS pump NPSH requirements. Therefore, the staff evaluated its position on use of containment overpressure in calculating NPSH margin. The staffs' position is that small amounts of overpressure credit may be granted by the NRC when justified.

On October 7, 1997, the NRC staff issue Generic Letter 97-04, "Assurance of Sufficient Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal Pumps," to all holder of operating licenses for nuclear power plants. The staff's concerns leading to the issuance of GL-97-04 illustrated an existing uncertainty and variability in the application of the methods used to calculate NPSH margin. The staff was concerned that the NPSH available for ECCS and containment heat removal pumps may not be adequate under all design-basis accident scenarios. Specifically, the staff was concerned that changes to plant configuration, operating procedures, environmental conditions, or other operating parameters over the life of the plant could result in inadequate NPSH. Some licensees discovered that they must take new credit for containment overpressure to meet the NPSH requirements of the ECCS and containment heat removal pumps and the overpressure being credited by licensees may be inconsistent with the plant's respective licensing basis. Generic Letter 97-04 requested that addressees provide current information regarding their NPSH analyses. A review of the industry submittals [SEA97-3705] confirmed the basis for these concern. There is a substantial amount of uncertainty associated with the strainer clogging issue, and as a result, the staff did not recommend licensing basis changes as a "resolution option."

#### 2.2.4.1 Summary GL-97-04 Submittals

The comments received in response to GL-97-04 were reviewed to determine the level of utility reliance on overpressure for an adequate NPSH margin, and for general trends and insights into compliance to with regulatory guidance and approved methodologies. GL-97-04 requested information from all holders of operating licenses for operational nuclear power plants, except those that have permanently ceased operations and certified that all fuel had been permanently removed from the reactor vessel. GL-97-04 specifically requested information necessary to confirm the adequacy of NPSH available for ECC and containment heat removal pumps. It should be noted that BWR plants were into the strainer replacement process in response to NRC Bulletin 96-03 at the time this information was requested and that NPSH analyses supporting strainer replacements could alter the information received in response to GL-97-04.

The following insights regarding BWR plants were drawn from the review:

- BWR licensees generally interpreted regulatory guidance (RG 1.1, RG 1.82, and the SRP) correctly.

- All NPSH analyses were based on the design basis accident (DBA) LOCA. A few plants analyzed a small LOCA in addition to the DBA LOCA. None of the analyses included non-LOCA scenarios, e.g., transient scenarios.

- Most of the BWR plants indicated that their design basis was still RG 1.82, Rev. 0. Note that Rev. 0 requires NPSH analyses to consider partial loss of screen area, rather than the more uniformly covered strainers typical of fibrous debris deposition.

- Because most plants still based their analyses on RG 1.82, Rev. 0 and because Rev.0 did not address air ingestion (or vortex suppression), most plants had not addressed this issue.

- The review suggested that licensees had significantly changed their NPSH calculations since their last NRC review. In some cases, changes included taking credit for containment overpressure without documented minimum pressure analyses that confirmed the availability of the credited pressure.

- Ten BWR plants with Mark I containments explicitly took credit for containment overpressure above the vapor pressure corresponding to suppression pool maximum temperature. The overpressure credit for four of those plants exceeded 6 psi with one of those plants crediting 9 psi. In addition, one BWR took credit for operating with a negative NPSH margin. Plant confirmatory analysis did not appear consistent with guidance provided in Containment Systems Branch (CSB) 6-1. CSB 6-1 provides guidance in the performance of a minimum containment pressure analysis.

### 2.2.4.2 Technical Assessment

The technical evaluation supporting GL-97-04 [SEA97-3705] illustrated the additional uncertainty associated with overpressure analysis. Overpressure analysis must be rather detailed and comprehensive to ensure a conservative determination of the minimum containment pressure available for credit in NPSH analyses. All means of removing heat from the containment must be considered including all installed pressure-reducing systems and processes. These systems and processes include heat transfer to structures, containment leakage, containment sprays, pool surface heat and mass transfer, fan coolers, RHR heat removal heat exchangers, and power conversion systems. Because the NPSH is strongly dependent upon the accident scenario, a comprehensive range of accident scenarios must be examined to ensure that a conservative minimum pressure is determined for the purpose of granting overpressure credit. In fact, the ACRS recommended that the decision making process consider the time variation of NPSH for a broad range of accident sequences such as typically found in a probabilistic risk assessment [ACRS Letter from R. L. Seale, Chairman of ACRS to The Honorable Shirley Ann Jackson, Chairman of U. S. Nuclear Regulatory Commission, “Credit for Containment Overpressure to Provide Assurance of Sufficient Net

Positive Suction Head for Emergency Core Cooling and Containment Heat Removal Pumps," December 12, 1997].

An overly simplified analysis is not likely to predict a conservative minimum containment pressure. Time-dependent analysis is needed to complete two aspects of NPSH analysis, i.e., the calculation of the maximum pool temperature and the calculation of the minimum available containment pressure. The time-dependent analysis for determining the maximum pool temperature can be greatly simplified by conservative assumptions, such as ignoring the effects of heat transfer to structures or neglecting non-safety rated systems. However, the time-dependent analysis to determine the minimum available containment pressure cannot be simplified by neglecting either pressure reducing systems or processes, rather the required calculations must be comprehensive and detailed. These calculations must consider a complete spectrum of applicable accidents scenarios, transients as well as LOCAs, because it is not reasonable possible to predetermine the worst-case scenario with respect to minimum pressure.

**2.3 References**

NUREG-0869, Revision 1, A. W. Serkiz. "USI A-43 Regulatory Analysis," U. S. Nuclear Regulatory Commission, October 1985.

NUREG-0897, Revision 1, A. W. Serkiz, "Containment Emergency Sump Performance," U. S. Nuclear Regulatory Commission, October 1985.

NUREG/CR-6224, G. Zigler, R. Beaty, J. Bridaeu, L, Comes, D. V. Rao, N. Ruiz, F. Sciacca, C. Shaffer, W. Thomas, R. Walsh, "Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris," Draft for Comment, U. S. Nuclear Regulatory Commission, August 1994.

NUREG/CR-6224, G. Zigler, J. Bridaeu, D. V. Rao, C. Shaffer, F. Souto, W. Thomas, "Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris," Final Report, U. S. Nuclear Regulatory Commission, October 1995.

NUREG/CR-6367, D. V. Rao and F. Souto, "Experimental Study of Head Loss and Filtration for LOCA Debris," U. S. Nuclear Regulatory Commission, December 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," U. S. Nuclear Regulatory Commission, December 1995.

NUREG/CR-6369, Volume 1, D. V. Rao, C. Shaffer, and E. Haskin, "Drywell Debris Transport Study," U. S. Nuclear Regulatory Commission, SEA97-3501-A:14, September 1999.

NUREG/CR-6369, Volume 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-6369, Volume 3, C. Shaffer, D. V. Rao, and J. Brideau, "Drywell Debris Transport Study: Computational Work," SEA97-3501-A:17, 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.

NEDE-24539-P, "Mark I Containment Full Scale Test Program," Final Report, General Electric, 1979.

RG-1.82, Regulatory Guide 1.82, Revision 2, "Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident," U. S. Nuclear Regulatory Commission, May 1996.

PIRT, G. Wilson, et al., "BWR Drywell Debris Transport Phenomena Identification and Ranking Tables (PIRTs)," Final Report, INEL/EXT-97-00894, Lockheed Martin Idaho Technologies Co., Idaho Falls, ID, September 1997.

NEDO-32686, Rev. 0, "Utility Resolution Guidance for ECCS Suction Strainer Blockage," BWROG, November 1996.
EC-059-1006, Rev. 0, K. W. Brinkman and P. W. Brady, "Results of Hydraulic Tests on ECCS Strainer Blockage and Material Transport in a BWR Suppression Pool," Pennsylvania Power and Light Company, May 1994.

ACRS, Letter dated December 12, 1997, from R. L. Seale, Chairman of ACRS, to The Honorable Shirley Ann Jackson, Chairman of U. S. Nuclear Regulatory Commission, Subject: "Credit for Containment Overpressure to Provide Assurance of Sufficient Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal Pumps."

SEA97-3705, Clint Shaffer and Willard Thomas, "Reliance on Containment Overpressure for Ensuring Appropriate NPSH," Technical Evaluation Report to U. S. NRC, SEA97-3705-A:5, April 29, 1998.

STUK-YTO-TR-73, Juhani Hyvärinen and Olli Hongisto, "Metallic Insulation Transport and Strainer Clogging Tests," Finnish Centre for Radiation and Nuclear Safety, June 1994.

MIJIT, Johan Trybom, "Metallic Insulation Jet Impact Tests (MIJIT)," Vattenfall GEK 77/95, June 1995.

NT34/95/e32, D. Hoffmann and A. Knapp, "RMI Debris Generation Testing: Pilot Steam Test with a Target Bobbin of Diamond Power Panels," SIEMENS Technical Report, Restricted, July 3, 1995.

SEA-95-970-01-A:2, G. Zigler, et al., "Experimental Investigation of Head Loss and Sedimentation Characteristics of Reflective Metallic Insulation Debris," Letter Report to U. S. Nuclear Regulatory Commission, May 1996.

92-96/M787F, A. B. Johnson, et al., "Head Loss of Reflective Metallic Insulation Debris with and without Fibrous Insulation Debris and Sludge for BWR Suction Strainers," Alden Research Laboratory, Inc., May 1996.

170-95/M787, A. B. Johnson, et al., "Reflective Metallic Insulation Settling Following a LOCA in a BWR Suppression Pool," Alden Research Laboratory, Inc., December 1995.

EC-059-1006, K. W. Brinckman, "Results of Hydraulic Tests on ECCS Strainer Blockage and Material Transport in a BWR Suppression Pool," Revision 0, May 1994.

## 3.0 NRC REVIEW OF OTHER RESEARCH

In addition to the NRC-sponsored research, NRC evaluations and decision-making related to the BWR strainer blockage issue have also relied upon data and analyses compiled by U.S. nuclear industry and international organizations. Publicly available information from these sources were reviewed by the NRC and, in some cases; incorporated into other NRC sponsored research. The following sections summarize some of the key information utilized by the staff.

### 3.1 NRC Compilations and Analysis of U. S. Industry Data

#### 3.1.1 Susquehanna Blockage & Transport Tests

In 1994, Pennsylvania Power and Light Company (PP&L) sponsored tests conducted at the ARL to investigate issues relating to plugging of suppression pool suction strainers for ECCS pumps in BWR power plants [PP&L]. These tests, commonly referred to as the PP&L tests, were conducted in the following two phases:

- Phase 1 involved material transport tests performed to quantify the transport velocities and turbulence required to keep debris suspended in water where it could contribute to strainer plugging.
- Phase 2 involved the investigation of strainer head loss due to an accumulation of NUKON™ insulation debris with and without particulate debris.

<u>Phase 1 Test Objective/Scope</u>

The transport tests were conducted to investigate the transport characteristics of the various materials found in the Susquehanna Steam Electric Station, Units 1 and 2. The tests were conducted in a linear water flume, and were designed to determine whether fluid velocities similar to those expected in the suppression pool would keep materials of interest suspended. The test conditions were similar to those expected in the suppression pool when flow is induced by ECCS injection and the circulation of water from the suppression pool to the reactor with water returning to the suppression pool via the drywell downcomer vents. No attempt was made to test the type of flow and turbulence created by steam blowdown into the suppression pool. The transport tests provided a basis for determining how much material will settle to the pool floor where it would not be available to contribute to strainer plugging in the long term.

The transport of material over a weir was also investigated. Tests were conducted to quantify flow rates required to draw the different debris types over a weir acting as a barrier to debris transport. This data was useful in assessing whether debris would remain on the drywell floor or be drawn over the drywell downcomer weir by recirculating water flow spilling out of the broken pipe in a LOCA scenario.

The materials tested in the water flume included: NUKON™ insulation debris, inorganic-zinc paint particles and flakes, iron oxide rust chips, iron oxide particulate, RMI, and Koolphen K vapor barrier foil paper.

### Phase 2 Test Objective/Scope

Strainer head loss tests were conducted to determine the head loss resulting from an accumulation of fibrous and particulate debris. Tested materials included NUKON™ insulation debris, paint chips and rust, and sludge. A ¼-scale ECCS T-strainer model was used to correlate strainer head loss with debris accumulation and test the effectiveness of backflushing strainers with air and nitrogen.

The test matrix was designed to provide head loss data as a function of material accumulation on the strainer and the approach velocity. Approach velocities ranged from 0.67 to 0.96 ft/s. The head loss tests were conducted using NUKON™ insulation debris (the primary material with potential to produce strainer plugging at Susquehanna) with or without prototypical sludge. The sludge consisted of iron-oxide particulate with a density of approximately 300 lbm/ft$^3$ and an average particle size less than 50 microns.

### Phase 1 Test Apparatus and Instrumentation

The test flume had a rectangular cross-section measuring 22-inches wide, 16-inches deep, and 18-ft in length. The flume had one glass side to allow visualization of debris movement. Water was introduced at the upstream end of the flume and then passed through flow straighteners to remove turbulence prior to entering the test section. The influence of turbulence, such as that caused by return flow through downcomers to the suppression pool, on debris suspension was investigated by discharging jets downward into the flume beneath the water surface. The downward jets were introduced via three 1-inch pipes distributed along the flume length. The weir was place at the end of the flume for those tests involving a weir.

### Phase 2 Test Apparatus and Instrumentation

The test strainer drew water from a steel test tank that was designed to keep material suspended and well mixed in order to provide a uniform debris concentration to the strainer. The tank was 5-ft wide, 16-ft long, and 9-ft high with one side made of glass panels for visualization. The tank was sectioned into two 8-ft lengths with one section used for these tests. The water depth was maintained at approximately 6-ft resulting in a water volume of approximately 240 ft$^3$ in the active section of the tank.

A 1:4 geometric scale model of one of the RHR strainers was constructed with its size, shape, and orientation all simulated to the selected scale. The strainer holes were prototypically 1/8-inch in diameter. The total surface area of the strainer was approximately 2.7 ft$^2$.

A centrifugal pump taking suction from the tank through the strainers circulated water back into the tank. The water rate was measured using a calibrated orifice plate in the loop piping. Constant flow water circulation drew debris onto the strainer where the head loss versus time was measured and recorded. Tests were conducted at two flow rates giving the strainer approach velocities of 0.67 ft/sec corresponding to a containment spray pump and 0.96 ft/sec corresponding to an RHR pump.

Water samples were taken at regular intervals to provide data on sludge concentrations. The accumulation of sludge on the strainer was derived from the measured decay in sludge concentration within the tank.

<u>Phase 1 Test Results</u>

Material transport properties were observed in the flume; specifically, whether or not debris settled at a given flow velocity and turbulence level. For the debris and conditions tested, it was found that the heavier debris such as paint flakes, rust chips, and RMI readily settled on the bottom of the test rig. Accordingly, it was concluded that these same debris types would likely settle to the suppression pool floor following the completion of the LOCA steam blowdown phase and turbulent conditions in the suppression pool subside. It was further concluded that some of the sludge material will settle to the pool floor but most will remain suspended when water flow velocities exceed 0.3 ft/sec. The NUKON™ debris was readily entrained and remained suspended with relatively little turbulence.

Phase 2 Test Results

Plots of strainer head loss versus time were recorded for each test. The combination of fibrous debris with sludge resulted in larger strainer head losses, when compared to fibrous debris alone. When sludge was introduced along with fibrous debris, the head loss increased dramatically. In fact, strainer plugging occurred with only 0.25-inches of debris on the strainer with a combined fiber/sludge debris bed. The effect of sludge accumulation on head loss was both dramatic and difficult to correlate. Debris accumulation on the strainer tended to be uniform. Sludge passed through the strainer until sufficient insulation debris accumulated to effectively filter out the sludge particles.

NRC Review

The NRC staff reviewed the PP&L test data and used the data to support other NRC sponsored research. The PP&L strainer head loss data was used to further validate the NUREG/CR-6224 compressible fiber/particulate bed head loss correlation.

The PP&L head loss data was obtained using a once-through facility. In these tests, a predetermined quantity of sludge was added to the mixing tank along with a known quantity of fibers. No additional sludge was added during the experiment, but additional quantities of fibrous material were added to maintain a certain fiber concentration level in the tank. The fibrous materials were characterized as fibers and the sludge was characterized as coarse particulates with a size distribution ranging from 75 microns to 3 mm. Head loss across the strainer was measured as a function of time. The tests were terminated once the head loss approached 22 ft-water (0.07 MPa). The head loss measurements as a function of time were correlated against the fiber and sludge loadings on the strainer surface. The sludge and fiber loadings were calculated assuming a filtration efficiency of 1 for both fibers and particulate sludge. Considering that these filtration efficiencies have only been achieved with thicker beds, it is reasonable to assume that better agreement would be obtained closer to the end of the experiment.

The comparison of the NUREG/CR-6224 correlation with the test data is shown in Table 3-1 and in Figure 3-1. Good agreement between the experiment and the model is observed.

**Table 3-1. Comparison of NUREG/CR-6224 Correlation with PP&L Head Loss Data**

| Test | Time (Min) | Approach Velocity (ft/sec) | Insulation Thickness (ft) | Sludge-to-Fiber Mass Ratio | Head Loss PP&L ft-water | Head Loss Correlation ft-water |
|---|---|---|---|---|---|---|
| 26 | 6.5 | 0.65 | 0.033 | 3.37 | 28.1 | 28.31 |
| 27 | 22.7 | 0.65 | 0.098 | 0.07 | 21.7 | 11.5 |
| 29 | 40.5 | 0.67 | 0.021 | 7.62 | 22.9 | 26.03 |
| 31 | 4.8 | 0.629 | 0.041 | 9.9 | 27.9 | 61 |
| 32 | 4.0 | 0.593 | 0.037 | 3.04 | 27.8 | 27.7 |
| 33 | 24.3 | 0.67 | 0.25 | 0.23 | 26.3 | 23.7 |
| 34 | 5.4 | 0.84 | 0.028 | 4.06 | 19.9 | 23.75 |

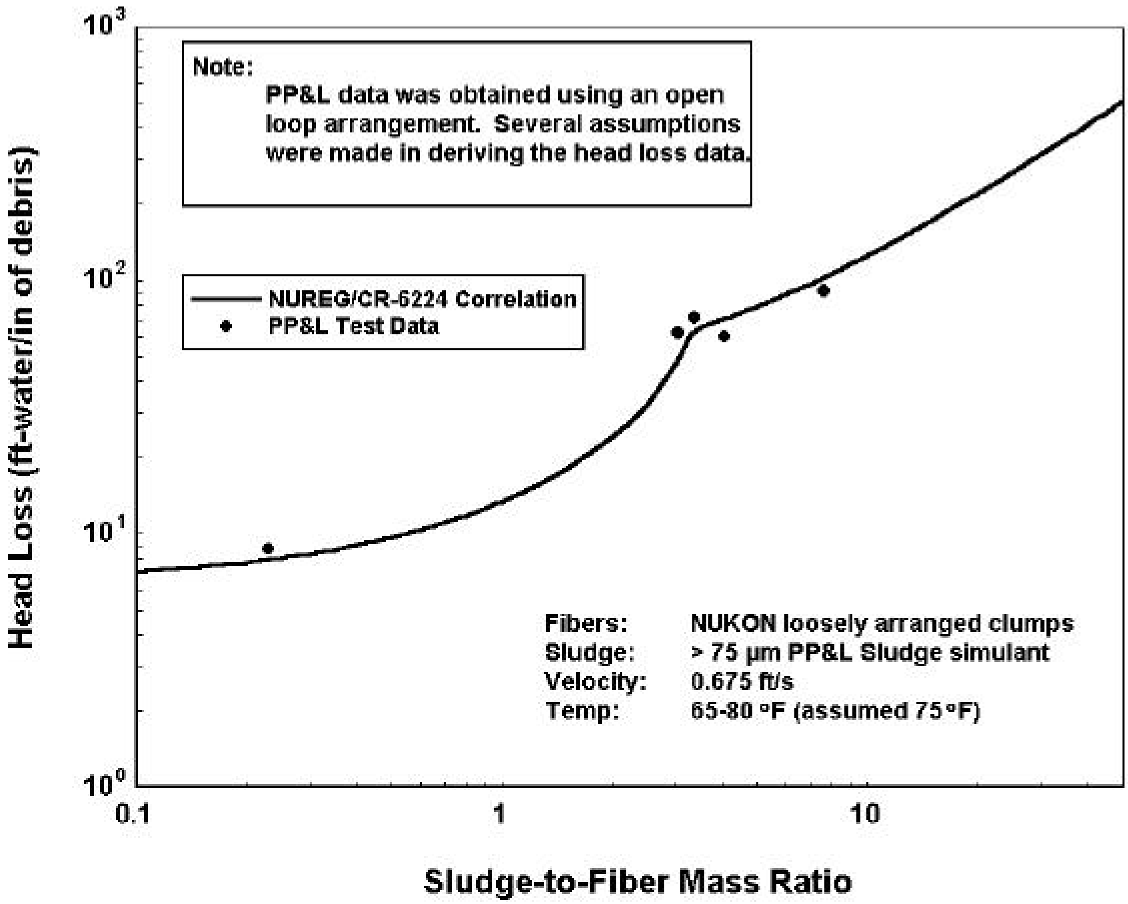



**Figure 3-1. Comparison of NUREG/CR-6224 Correlation with PP&L Head Loss Data**

The PP&L flume test data were used to calibrate the drywell floor pool CFD calculations in the DDTS study (see Section 2.2.3) [NUREG/CR-6369]. In other words, the maximum turbulence levels, as predicted by the code, that would allow fibrous insulation debris to settle were determined by comparing the code predicted turbulence levels in the flume test simulations to experimentally determined debris settling results. The simulations of the ARL PP&L flume tests are reported in Appendix A of NUREG/CR-6369, Vol. 3. The following is a brief summary of the results of those simulations.

Several of the ARL PP&L flume tests, that tested the transportability of fibrous insulation debris, were considered to be applicable to the DDTS study, because the test conditions were prototypical of a BWR drywell floor. The flume used in these tests was 22 inches wide, 16 inches, deep, and 18 ft long. A weir wall, one foot high, was installed at the end of the flume to simulate flow over the top of the downcomer vent pipes. Flow velocities for debris transport ranged up to 1 ft/sec. Flow turbulence levels were controlled using flow straighteners on the main inlet flow and small downcomer pipes that injected turbulent flow at specified positions and flow rates. These tests were considered prototypical because of the pool depth, the flow velocities and turbulence levels, and the type and sizes of debris studied. These parameters were in the range of expected parameters for the drywell floor pool in Mark I and Mark II plants. The results of the CFD simulations of the flume tests are summarized in Table 3-2.

The conclusions drawn from the flume test simulations regarding debris transport in a drywell pool were:

- If the CFD code predicted value for specific kinetic energy was greater than about 0.01 $ft^2/sec^2$, then both large and small debris would remain suspended and well mixed in the drywell floor pool.
- If the predicted value was less than about 0.001 $ft^2/sec^2$, then all debris would settle to the drywell floor with settling velocities akin to the settling velocities measured for insulation debris settling in still water.
- If the predicted value was between 0.001 and 0.01 $ft^2/sec^2$, then the large debris would settle but the small debris would remain suspended.

These conclusions are summarized in Table 3-3.

**Table 3-2: Results of the CFD Simulations of the ARL PP&L Flume Tests**

| ***est No.*** | **Flume Transport Flow Velocity (ft/sec)** | **Turbulence Introduced by Downcomer Pipes** | **Weir Wall Used** | **Debris Transport Results** | | **CFD Code Predicted Turbulence Level ($ft^2/sec^2$)** |
|---|---|---|---|---|---|---|
| | | | | Small Pieces | Large Pieces | |
| 1 | 0.27 | No | No | Settled | Settled | K.E. < 0.0012 |
| 2 | 0.56 | No | No | Settled | Settled | K.E. < 0.0012 |
| 3 | 1.00 | No | No | Transported | Settled | 0.0012 < K.E. < 0.014 |
| 4 | 0.27 | Yes | No | Transported | Settled | 0.0012 < K.E. < 0.014 |
| 5 | 0.56 | Yes | No | Transported | Transported | K.E. > 0.014 |
| 6 | 0.27 | No | Yes | Settled | Settled | K.E. < 0.0012 |
| 7 | 0.56 | No | Yes | Transported | Settled | 0.0012 < K.E. < 0.014 |

***Table 3-3: Debris Behavior Based on Turbulence Levels***

| **Specific Kinetic Energy ($ft^2/sec^2$)** | **Behavior of Small Debris** | **Behavior of Large Debris** |
|---|---|---|
| K.E. < 0.001 | Settles | Settles |
| 0.001 < K.E. < 0.01 | Suspended | Settles |
| K.E. > 0.01 | Suspended | Suspended |

Documentation

The PP&L tests are documented in detail in EC-059-1006, Rev. 0, "Results of Hydraulic Tests on ECCS Strainer Blockage and Material Transport in a BWR Suppression Pool" [PP&L]. The comparison of the NUREG/CR-6224 compressible fiber/particulate bed head loss correlation with the PP&L strainer head loss data was reported in Appendix B of NUREG/CR-6224. The CFD simulations of the ARL PP&L flume tests are reported in Appendix A of NUREG/CR-6369, Vol. 3.

### 3.1.2 BWROG Head Loss Tests

The BWR Owners Group (BWROG) conducted head loss tests to gather data on alternate ECCS suctions strainer designs as a possible resolution to the strainer-clogging problem. The strainer head loss tests were conducted at the Electric Power Research Institute (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.

<u>Test Objective</u>

The overall objective of the full-scale test program was to develop and test strainer concepts that could be utilized 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 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. The primary objective of the backflushing tests was to determine the effectiveness of removing accumulated debris from the strainer surfaces by reversing flow through the strainer. The primary objective of the self-cleaning strainer was to determine its performance under a variety of debris loading conditions.

The primary objective of supplemental gravity head loss testing at CDI was to determine the relative increase in head loss resulting from the addition of specific debris types to a bed of insulation fiber, corrosion products, and/or RMI. In addition, the gravity head loss testing evaluated the different types of stainless steel and aluminum RMI.

<u>Test Scope</u>

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) 2/3 of the 60-point star design (i.e., sheet metal covered 1/3 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 (passive mode). For passive strainers, tests were conducted to evaluate the maximum fiber and corrosion product capacity, the effect of thin fiber beds, the feasibility of backflushing and the effect of RMI on head loss. Tested debris included: prototypical fibrous insulation, RMI, and 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 its start up capability after a period at a minimum flow condition.

Gravity head loss tests were conducted to quantify the effect of miscellaneous debris, such as paint chips and sand, when combined with fibrous insulation and/or RMI. Gravity head loss tests were conducted with two types of stainless steel RMI and two types of aluminum RMI to examine the effects of different materials on head loss.

## Test Apparatus and Instrumentation

Two centrifugal pumps connected in parallel with a combined capacity of 10,000 GPM pumped water from a 50,000-gallon tank and subsequently returned the flow to the tank. The test strainer was attached to the pump suction inlet piping. Strainers could be mounted with either vertically or horizontally. Aligning one pump to pull water from the tank through alternate suction piping and then discharging the water back through the test strainer performed the strainer backflush operation.

The primary measurements for these tests were: 1) strainer head loss, 2) system flow rate, 3) plow/brush rotation rate and strainer torque on the self-cleaning strainer, and 4) the masses of insulation debris, corrosion products and other debris introduced into the vessel.

BWROG Test Results

The BWROG arrived at a number of general conclusions. For fibrous debris testing these conclusions were:

- Corrosion products, when mixed with fibrous insulation, greatly increased the head loss over that of fibrous insulation by itself. This reaffirms the results of the PP&L tests (see Section 3.1.1) and the NRC-sponsored tests at ARL (see Section 2.1.1.1)

- Lower approach velocities produce lower head losses. Over the range of flow rates and strainer sizes tested, the head loss increased nonlinearly with increases in velocity.

- The addition of miscellaneous debris can also create significant increases in head loss as compared to fiber alone. Supplemental gravity head loss testing quantified the effects of individual debris types.

- Thin debris bed tests indicated a fibrous bed thickness slightly greater than 1/8-inch was sufficient to cause high head loss on the truncated cone but not the alternate strainer designs.

- The measured amount of fibrous NUKON™ insulation that passed through the truncated core-strainer was 0.4% of the total fiber in the tank for a specific flow rate and strainer head loss.

- Passive strainers with improved performance over existing designs were identified. These 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 summarized results for RMI testing are:

- Tests with RMI indicated that RMI collecting on a strainer reached some maximum or saturation quantity after which further RMI is not retained on the strainer. Specifically, at some radius of the debris bed, the settling velocity of the RMI foils exceeds the strainer approach velocity effectively preventing further accumulation of RMI debris on the strainer.

- Below a given approach velocity, RMI falls off the strainer (this approach velocity depends upon the RMI settling velocity).

- When the strainer head loss is predominantly due to fibrous debris and corrosion products, RMI in combination with this debris produces approximately the same head loss as the other debris alone.

The summarized results for backflushing are:

- The truncated core strainer was successfully backflushed under all conditions.

- Although some relief was obtained for the 60-point star and the stack-disk strainer designs tested, debris was not adequately removed at flow rates up to the maximum backflushing 5,000-GPM flow when fibrous insulation was used.

- With the exception of some RMI wedged in the internal portions of the stars of the 60-point strainer, the RMI by itself was successfully removed by shutting off pump suction flow (i.e., no backflush required).

The summarized results for self-cleaning testing are:

- The active front portion of the strainer was kept clean for all debris types and loadings tested at the design flow rate of 5,000-GPM. The head loss across the strainer was found to be essentially constant at a given flow rate and independent of the debris loading.

- It is possible that sufficient debris can accumulate on the active portion of the strainer under a low-flow start-up condition to prevent subsequent plow/brush rotation at design flow rates.

- Although the strainer maintained a clean front surface, the head loss across the clean strainer and the torque generated by the turbine were higher than expected.

The summarized results of the gravity head loss testing with miscellaneous debris are:

- Constants for determining relative increases in head loss were generated for eight different types of debris in combination with three types of fibrous insulation.

NRC Review Conclusions

The BWROG devoted considerable resources to explore various generic designs for large passive strainers that could be used to replace the existing truncated cone strainers. The NRC noted that the BWROG obtained head loss data for each design at various combinations of fibrous insulation debris, RMI insulation debris, sludge, paint and concrete chips, and miscellaneous debris. The NRC staff agreed that the general characteristics (size, shape, etc.) of the debris tested were consistent with those tested in the NUREG/CR-6224 study. The staff further noted that the NUREG/CR-6224 study selected debris with characteristics designed to maximize the resulting head loss.

One important NRC staff of the BWROG tests was that reasonable steady-state conditions were not achieved in a significant number of the tests. This 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 steady head loss was achieved. Therefore, the debris bed composition was relatively unknown during transient conditions.

The BWROG developed two correlational methods based on these test data that can be used to estimate head loss across the strainers. The first method provided a non-dimensional head loss correlation that could be used to estimate head loss across an alternate strainer design valid at lower debris loadings. The second method provides a six-step process for estimating the strainer's RMI capacity and head loss across RMI debris beds. The NRC staff conducted confirmatory calculations to validate the BWROG calculational procedures and to examine their applicability to the actual plant conditions. The staff found the URG to contain valuable and useful data for predicting strainer head loss; however, the staff's review revealed several concerns regarding the quality and applicability of these data. On the basis of these analyses, the staff concluded that the head loss correlation in the URG is unreliable and incomplete for plant analyses, and is, therefore, unacceptable. The staff strongly recommended that utilities use vendor-provided data to qualify strainer designs, rather than relying on the correlations and calculational procedures specified in the URG. In addition, the staff recommended that licensees' designs should be able to accommodate experimental uncertainties associated with correlations and/or calculational methods developed by the vendors. These confirmatory calculations are discussed in more detail in Section 4.4.

Documentation

The BWROG strainer head loss tests are documented in Volume I: Technical Support Documentation of NEDO-32686,"Utility Resolution Guidance for ECCS Suction Strainer Blockage." The NRC review comments are documented in a Safety Evaluation Report (SER), August 20, 1998 [NRC-SER-URG].

### 3.1.3 GE Stacked Disk Strainer Testing

General Electric (GE) supplied an advanced passive stacked-disk strainer to the nuclear industry that was designed to alleviate the strainer blockage problem. The GE design (proprietary) offered an improvement over the conventional stacked-disk strainers tested by the BWROG (see Section 3.1.2). A relatively large cavity volume was designed into the GE strainer to accommodate larger volumes of insulation debris without a substantial increase in the head loss. Each GE strainer would be designed specifically to suit a particular plant application to meet specific requirements for the estimated debris and hydrodynamic loadings.

The NRC reviewed the GE's Licensing Topical Report (LTP) [NEDC-32721P], "Application Methodology for GE Stacked-Disk ECCS Suction Strainer," dated December 23, 1998, and associated documents. The NRC's review is documented in LANL Technical Evaluation Report LA-CP-99-7, "Technical Review of GE LTR NEDC-32721P: Application Methodology for GE Stacked-Disk ECCS Suction Strainer," dated December 23, 1998. The GE application methodology included: 1) hydraulic performance design methodology and 2) procedures for calculating hydrodynamic loads for new strainer installations that can be used in the structural analysis of the torus penetration, the strainer supports, and the strainer itself. GE applied this methodology to design replacement ECCS suction strainers in response to NRC Bulletin 96-03. The NRC reviewed the topical report focusing on determining whether the overall methodology captured all the important plant phenomena and whether the methodology is generically acceptable for designing strainers. Confirmatory analyses were performed as part of this review.

GE Program

GE fabricated a prototype strainer and tested its hydraulic performance at the EPRI NDE Center. The facility and testing procedures were the same as those used in the BWROG test program. The tests involved both fibrous debris and RMI debris. In each test, predetermined quantities of fibrous debris, corrosion products, and RMI debris were added to the test tank and kept in suspension by pumped-flow recirculating flow patterns. Sufficient time was allowed for debris to accumulate on the strainer surface, and then the head loss was measured at varying flow velocities. The objective was to examine the effect of velocity on debris bed compression without the results being affected by filtration. The actual quantity of debris deposited on the strainer surfaces was not directly measured.

GE sought an empirical approach to correlate the experimental data obtained for fiber and corrosion product mixtures. The GE correlation was intended for application within the range of tested parameters and GE noted three limitations to their correlation. These are:

- It is applicable only to NUKON™ insulation.

- The distance between the stacked disks must be greater than a specified gap width.
- The ratio of the outer strainer diameter to the diameter of the suction flange should be similar to that of the prototype strainer tested.

GE planned to follow the BWROG URG methodology for RMI debris beds and to use bump-up factors to account for miscellaneous debris. The GE topical report does not discuss the applicability of their head loss correlation to other types of debris (e.g., Temp Mat and Min-K).

NRC Review of the GE Program

The NRC reviewed the GE methodology (GE LTR NEDC-32721P) for determining the head loss across GE stacked disk strainers. In addition, the NRC sponsored two sets of confirmatory analyses to evaluate the GE head loss methodology. In the first analysis, the NRC examined: 1) the actual range of experimental parameters explored in the GE tests and compared the parameters with those of the proposed plant applications, and 2) the process used to develop the correlation and the generic acceptability of the correlation. The second set of calculations compared GE test data with the predictions of a modified version of NUREG/CR-6224 correlation. This effort was used to draw inferences regarding bounds within which usage of GE correlation is acceptable.

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 is acceptable, however the staff still had concerns regarding the validity and use of this correlation. GE adopted an empirical means for correlating the fiber/sludge debris bed head loss test data. Because GE chose to correlate head loss in terms of superficial parameters (such as circumscribed velocity) that are easy to determine in plant applications, concerns were identified regarding the generic applicability of the GE correlation, especially application beyond the test range. The GE head loss correlation was based on test data generated over a narrow range of test parameters. The GE correlation does not account for the geometric effects systematically. For example, in none of the GE tests involving sludge and fiber combinations was debris loading sufficient to fill the gaps. Therefore, in all those tests, head loss actually was induced by low-velocity flow through the debris bed confined within the gaps. The controlling parameter then is the flow velocity in the gap near the plate. Instead, the correlation relates the head loss simply to a nonphysical 'circumscribed' velocity. Further, the staff was concerned about the use of the GE correlation for plants where the debris bed would consist mostly of Min-K insulation debris, such as Susquehanna. It was not clear how GE intended to account for the Min-K effect on head loss.

GE responded that they intend to only apply the correlation within the narrow range of parameters for which test data were obtained. However, the staff was still concerned that several plant applications lay outside the range over which the GE prototype strainer was tested. In particular, the staff believed that the application of the GE test data (or the correlation) would be inappropriate without additional testing for the Susquehanna plant (a plant with a sludge-to-fiber mass ratio in excess of those tested). GE conducted an additional test to address this concern. Upon further review, the staff believes the 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. Further, the staff concluded that the use of GE's hydraulics design method is acceptable for all the BWR plants, with the exception of the Susquehanna plant. For this plant, the staff identified the following specific concerns relative to the use of the GE correlation. First, neither the GE nor the NUREG/CR-6224 correlations were ever tested to the sludge-to-fiber ratios approaching the value for this plant (i.e., thin-bed effects) and second, the controlling insulation in this case may be a different type of fibrous insulation for which no head loss data had previously been obtained. Therefore, the GE's approach of validating its hydraulics methodology using head loss data from that additional test is the most prudent approach.

GE proposed to use the BWROG URG methods for estimating head loss across RMI beds. The staff comments regarding these methods were documented in their review of the URG (see Section 4.4). GE's approach to estimate the head loss contribution from RMI debris appears reasonable; however, the staff notes that GE should ensure that the NRC comments provided in Appendix K to the staff's safety evaluation report on the URG [NRC-SER-URG] are properly reflected in any GE plant-specific analyses. Specifically, GE should not neglect the potential contribution of RMI debris to strainer head loss without supporting analyses establishing that RMI contribution is negligible. The staff was unable to verify the contribution to strainer head loss from RMI debris because GE did not provide information relative to the assumed RMI loadings for any of the plants using GE strainers.

GE developed a simple fluid-velocity based head loss correlation for a clean-strainer. Although the staff believes that this correlation can predict clean-strainer head loss to within about 0.5 ft-water, the staff was concerned that the correlation could be slightly non-conservative for some plants. This concern was due to the fact that the correlation was developed using data obtained for a single prototype strainer and may not adequately account for all-important geometric effects. Therefore, the staff recommended that GE apply this correlation carefully, if possible after benchmarking it with data from another strainer with a different geometry. Another alternative would be for GE to ensure that sufficient margin exists in the overall analysis to account for this uncertainty.

The usage of bump-up factors is reasonable as stated in the URG SER. The staff finds that use of bump-up factors yields conservative predictions. As of this date, the hydrodynamic loads portion of the GE methodology is still under review.

Documentation

The GE methodology is documented in the GE's Licensing Topical Report (LTP) [NEDC-32721P], "Application Methodology for GE Stacked-Disk ECCS Suction Strainer," dated December 23, 1998 (Proprietary). The NRC's review of the GE methodology for determining the head loss across GE stacked-disk strainers is documented in a LANL Technical Evaluation Report (TER) entitled, "Technical Review of GE LTR NEDC-32721P: Application Methodology for GE Stacked-Disk ECCS Suction Strainer," dated December 23, 1998 (Proprietary). The NRC's review of the BWROG URG is documented in the NRC safety evaluation report, "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," August 20, 1998 [NRC-SER-URG].

### 3.1.4 PCI Stacked Disk Strainer Testing

Performance Contracting Inc. (PCI) also supplied advanced passive stacked-disk strainers to the nuclear industry that was designed to alleviate the strainer blockage problem. PCI developed and tested two prototype stacked-disk strainers. The PCI strainer concept, referred to commercially under the trademark Sure-Flow strainer, consists of a stack 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.

PCI Program

PCI fabricated and tested several prototypes over a period of nine months to evaluate the head loss performance of the Sure-Flow strainers. The hydraulic performance testing was conducted at the EPRI NDE Center. 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-inch core tube, a 30-inch outside diameter, and was a 2.5-ft long. A larger prototype, referred to as Stacked-Disk #2, was a 4-ft long strainer with a core tube diameter of 26-inches and a stack outer diameter of 40-inches. Both the BWROG and PCI tested the head loss performance of these strainers. An engineering correlation of the test data was proposed by PCI but with several limitations.

The Sure-Flow strainer is not a standardized strainer i.e., one size fits all. Instead, the concept promoted by PCI is to use similarly designed strainer modules of various sizes and quantities as necessary for each plant. The overall approach is that the individual plant would first determine the anticipated debris loading and the strainer design criteria applicable to that plant. PCI and its associated contractors would determine the size and number of stacked-disk modules necessary to meet the design criteria. For this approach to be successful, the PCI team needed a model that accurately predicted the head loss performance of a generic PCI Sure-Flow strainer. PCI team member, the Innovative Technology Solutions (ITS) Corporation, adapted a generic head loss model used in the NUREG/CR-6224 study and extended it to the stacked-disk strainer geometry. ITS developed a proprietary computer code named HLOSS to automate the head loss calculations performed for each plant. The overall technical approach for using the NUREG/CR-6224 correlation to predict PCI Sure-Flow strainer performance was validated by comparing the correlation predictions with the head loss data.

NRC Review of the PCI Strainer Program

Because the PCI test data and the ITS head loss models were used by many licensees, the NRC's contractor, LANL performed an in-depth review of the PCI head loss data and evaluated the adequacy of the head loss models. The results of this review are summarized in LANL TER LA-UR-00-5159, entitled "Technical Review of Selected Reports on Performance Contracting, Inc. Sure-Flow Strainer™ Test Data,' dated April 27, 2000.

Head loss data were obtained for the two prototype PCI strainers described above. These were obtained for NUKON™ fibrous debris, with and without sludge, and for RMI debris. The dean strainer head losses were measured to estimate frictional losses resulting from the structure of the strainer itself. The clean-strainer head losses for the PCI stacked-disk strainers were about the same as would be expected for a typical truncated cone strainer. PCI developed an empirical correlation for the clean-strainer head loss that the LANL found to perform well.

LANL's review of the fibrous debris data revealed:

- The particulate filtration efficiency of the fibrous debris bed was relatively high. With the exception of one test, the efficiency ranged from 75% to 97% for the PCI prototype #2 strainer. The exception was for a test with a relatively thin layer of fibrous debris; its efficiency was 40%. However, the use of these higher efficiencies must consider the fact that the tests were conducted in a closed-loop system, i.e., the sludge was recycled several times. Eventually the rate of particle capture will equilibrate with the rate at which captured particles escape the bed. In a once through system, the capture efficiency could be substantially reduced.

- In selected experiments, PCI measured the actual debris volume on the strainer to determine the compressibility of the fibrous debris (i.e., the volume of the fibrous debris on the strainer as it is subjected to compression forces divided by the volume of the debris without the compression forces, often referred to as the theoretical volume). The NUREG/CR-6224 suggested compression equation was found to perform well for NUKON™ debris deposited on the stacked-disk strainers.

PCI developed a purely empirical equation to predict the head loss performance of the PCI strainer loaded with fibrous and particulate debris. PCI acknowledged that the correlation validity could not be assured because the correlation does not relate head loss to fundamental strainer properties. LANL agreed with PCI observations regarding the validity of the correlation.

Selected PCI tests evaluated the impact of adding RMI debris to a fibrous/sludge debris bed. Comparing two tests where the test parameters were essentially identical with the exception of the addition of RMI debris in one of the two tests, clearly demonstrated that the addition of the RMI increased the head loss significantly for higher flow rates (e.g. greater than 7500 GPM). Therefore, strainer head loss analyses should consider the contribution to head loss made by the RMI in mixed fiber/RMI debris beds.

Documentation

The PCI head loss data is documented in the PCI report "Summary Report on Performance of Performance Contracting, Inc.'s Sure-Flow™ Suction Strainer with Various Mixes of Simulate Post-LOCA Debris," dated September 1997 [PCI-97]. The results of this review are summarized in LANL TER LA-UR-00-5159, entitled "Technical Review of Selected Reports on Performance Contracting, Inc. Sure-Flow Strainer™ Test Data,' dated April 27, 2000.

### 3.1.5 NRC Adaptation of the NUREG/CR-6224 Correlation to PCI Stacked-Disk Strainers

At the staff's request, LANL explored the possibility of adapting the NUREG/CR-6224 compressible fiber/sludge bed head loss correlation to stacked-disk strainers. Note that this correlation was developed for strainers where the approach velocity was constant over the entire strainer area; and therefore, debris deposition on the strainer is relatively uniform. The correlation would perform best on a flat plate or a truncated cone strainer. The purpose of this exploration was:

- To provide an independent tool that can be used by the staff to evaluate the performance of strainers installed at various operating BWR plants.

- Because the basic NUREG/CR-6224 correlation was previously validated over a wide range of operating parameters (debris loads, sludge to fiber mass ratios, etc.), the staff needed the adapted correlation to predict a strainer performance for a parameter range beyond which the strainer was originally tested.

- The adaptation analysis provided additional assurance that the proposed ITS-method of correlating PCI strainer head loss data was adequate.

A NUREG/CR-6224 correlation was found easily adaptable to predicting head losses for more complex shapes, such as the GE and PCI stacked-disk strainers. Two areas have generally been used to describe these strainers: the total perforated plate area and the strainer projected area (referred to as the circumscribed area). Debris deposition on the more complex strainers starts as a uniform deposition on the entire screen area but eventually debris shifts to fill the inner screen regions creating substantially non-uniform approach velocities and debris deposition. Once the inner spaces are filled, approach velocities and deposition again approach uniformity.

The NUREG/CR-6224 correlation is appropriate to calculate head loss with small quantities of debris on the strainer, and with large quantities of debris on the strainer such that the gap volumes are filled and the debris layer begins to encompass the strainer circumference. The correlation has been shown to be unreliable for debris loading in between the two extremes. With small quantities of debris on the strainer, the entire strainer screen area would be used. With the large quantities of debris, the circumscribed area would be appropriate. Thus, the effective strainer deposition area changes with the volume of debris deposited on its surface from the entire screen area to the circumscribed area. The controlling geometric parameters are the plate surface area and the gap volume. This concept is illustrated in Figure 3-2.

The ITS-method essentially determined the head loss for the thin layer fibrous debris deposition using NUREG/CR-6224 correlation and again for the circumscribed deposition, and then applies an interpolation scheme to approximate the head loss for debris depositions between the two extreme cases of light and heavy loadings. The NRC review compared the ITS-method prediction to the PCI head loss data and that comparison suggested the ITS-method (PCI approach) is probably accurate, assuming their model was appropriately implemented into the HLOSS code.

LANL estimated the effective strainer deposition areas for the PCI tests by solving the NUREG/CR-6224 head loss correlation in reverse (i.e., the head loss was an input and the strainer area was the output. This was accomplished using the BLOCKAGE code. It was determined that the effective area could be correlated to the volume of debris deposition onto the strainer, as shown in Figure 3-3. Therefore, it was determined that the NUREG/CR-6224 head loss correlation could be modified to simulate debris deposition on a stacked-disk strainer if sufficient test data were available to derive a particular strainer's effective area curve. Once this area data is available, the analysis determines debris loading, the effective area for that loading, and then the head loss. The BLOCKAGE code could potentially be modified with a variable area input capability that is a function of debris volume so that complex strainers could be modeled through the full range of time-dependent debris deposition.

### Documentation

This evaluation is summarized in LANL TER LA-UR-00-5159, entitled "Technical Review of Selected Reports on Performance Contracting, Inc. Sure-Flow Strainer™ Test Data,' dated April 27, 2000.

### 3.1.6 Mark III Quarter-Scale Testing

The Mark III Grand Gulf Nuclear Station (GGNS) conducted extensive quarter-scale pool-transport and head-loss testing for their replacement strainer design and small-scale testing for a segment of the design. The NRC audited the Grand Gulf strainer clogging issue resolution in August 1999. 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. RMI was not considered in their debris-generation, debris-transport, or head-loss calculations because RMI debris was observed to not accumulate or remain attached to the strainer under design approach velocities (approximately 0.02 ft/s). Therefore, the primary concern was estimating the combined effects of fibrous debris (Kaowool and fiberglass) and particulate debris (calcium silicate). Grand Gulf replaced its existing truncated cone strainers that had a net surface area of 170 $ft^2$ with large-capacity passive strainers having a combined area of 6253 $ft^2$ (~37 fold increase). The replacement strainers, designed by Enercon Services, Inc., are combined into a large single strainer that circumscribes the suppression pool near the floor, as shown in Figure 3-4. This strainer 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. The NRC staff evaluated the application of quarter-scale testing to the GGNS plant analysis.

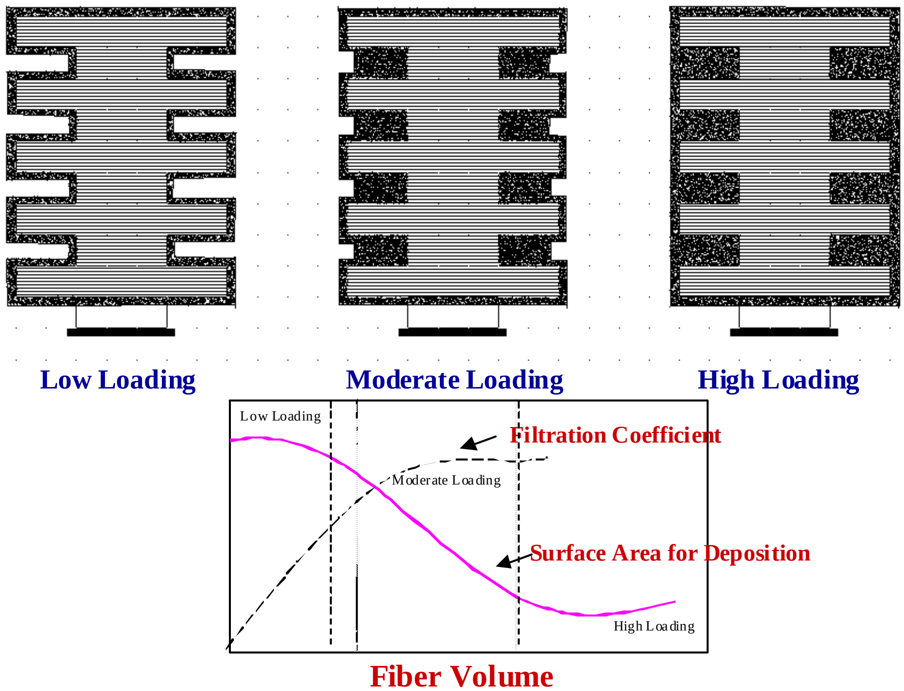



*Figure 3-2. Schematic Illustration of Debris Bed Buildup on Stacked-Disk Strainers*

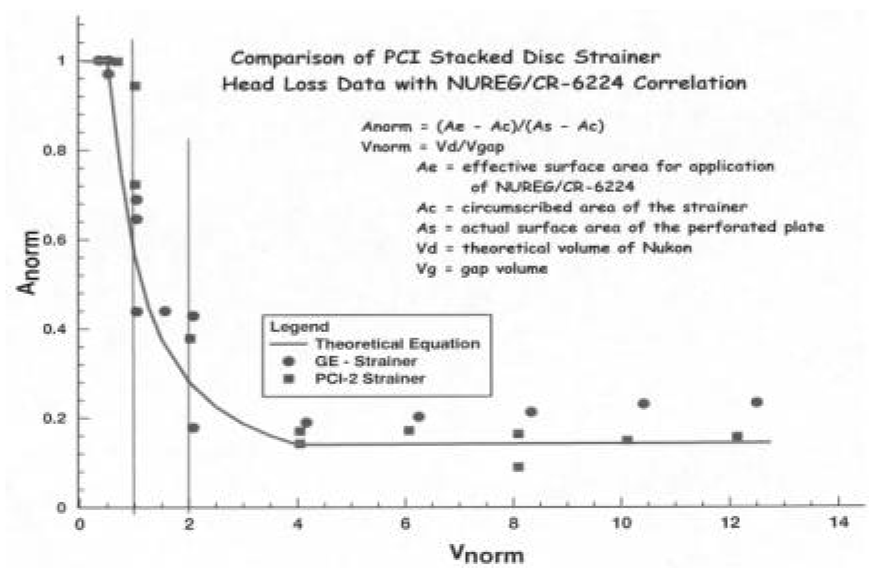



*Figure 3-3. Strainer Effective Surface Area Correlated with Volume of Deposited Debris*

Grand Gulf Quarter-Scale Test Program

GGNS sponsored a research program to study head loss performance of their replacement strainer. A quarter-scale strainer was built and installed in the Mark-III quarter-scale test facility. Geometric, operational, and debris loading parameters were all scaled to the GGNS plant values. The flow velocity and debris bed thickness were monitored in the tests to ensure that the measured head loss caused by the debris buildup could be used directly in the plant NPSH analysis.

NRC Review of Grand Gulf Quarter-Scale Test Program

The staff compared the scaled test parameters to those of the plant and determined that the quarter-scale testing adequately simulated important flow parameters. In particular, the licensee ensured that 1) the approach velocity at the strainer surface was the same as the approach velocity in the plant, and 2) the debris loadings per unit area of the strainer in the tests were the same or greater than those expected in the real plant. There are two geometrical differences between the quarter-scale test setup and the plant: 1) the quarter-scale tests used a significantly lower number of strainer sections compared to the plant, and 2) the construction of these strainer segments was different with respect to specifics such as the number of ribs and the plate thickness. These differences mean that clean-strainer head losses measured in the quarter-scale test setup were not directly scalable to the GGNS plant application. However, the licensee performed detailed analyses to correct for these differences.

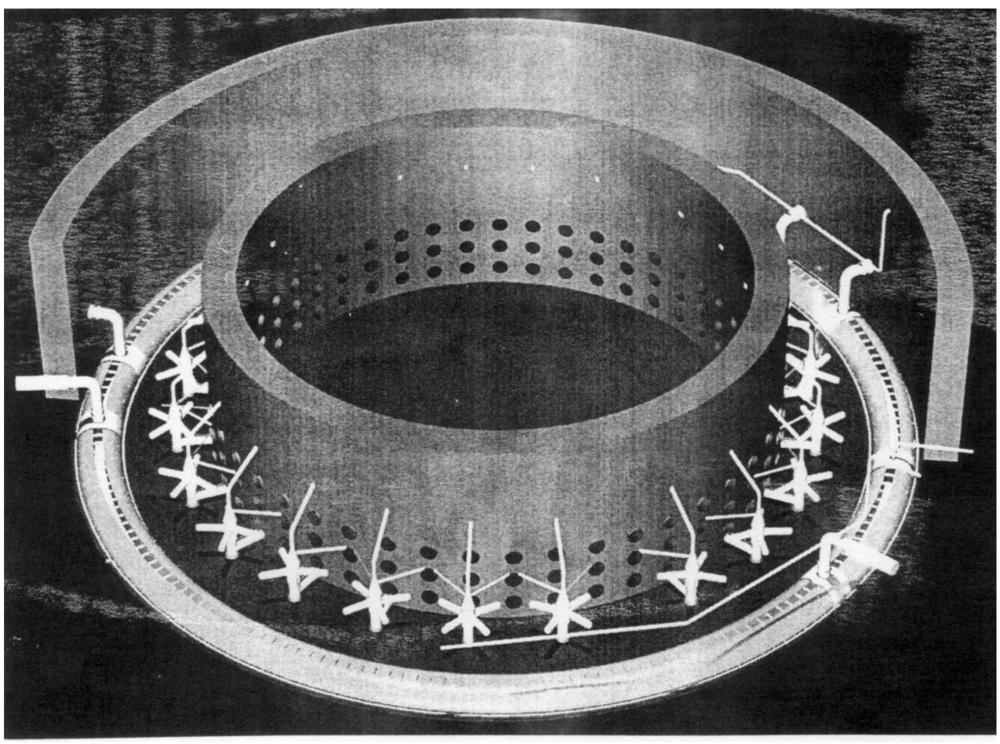


**Figure 3-4. Annular Arrangement of Grand Gulf ECCS Strainer in Mark III Containment**

All of the tests were conducted at 75°F whereas the suppression pool temperatures were expected to reach approximately 185°F. The licensee used the results directly in their NPSH margin evaluation; however, this was conservative because using the lower test temperature results in higher head loss due to viscous effects. The clean-strainer head loss for the quarter-scale geometry was about 3-inches of water at the conditions representing runout ECCS flow.

The licensee sponsored five tests directly applicable to GGNS. The staff drew the following conclusions regarding the GGNS quarter-scale testing program and its results:

- The licensee test program was extensive with great attention to detail.
- The data repeatability was acceptable. Head loss variations of 2-ft-water or less were measured for repeatability tests and the plant has sufficient margin to account for these uncertainties.
- The head loss tests indicate 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.
- Cal-Sil and Kaowool combinations resulted in high head losses, even though the approach velocity was relatively slow (0.016 ft/s). This finding is significant, because such data was previously not available. It should also be noted that the licensee continued selected testing after the staff completed their review to better understand head loss implications of calcium silicate insulation debris.

<u>Documentation</u>

A review of the Grand Gulf strainer testing is found in a LANL TER, titled "On-Site Audit of the Grand Gulf Nuclear Station Emergency Core Cooling System Strainer-Blockage Resolution," dated January 3, 2000 [LA-CP-00-18].

### 3.1.7 LaSalle Tests

In 1998, Commonwealth Edison Company sponsored a series of plant-specific tests to study head loss resulting from 1.5-mil Aluminum RMI and NUKON™ fiberglass insulation. These experiments supported the strainer replacement for the LaSalle County Station plant. These experiments were conducted using the same test facility used by the BWROG (see Section 3.1.2). The strainer tested was a stacked-disk strainer with a total screen area of 48.6 $ft^2$. The NRC reviewed tested documented in the test report TPP-VL0400 –006 entitled: "Test Evaluation Report for Test TPP-VL0400-005: LaSalle Strainer Fiber and RMI Debris Tests," dated June 6, 1998 [LaSalle-98].

Six tests were conducted, in which flow rates varied between 2000 and 5000 GPM and RMI debris loading reached as high as 2250 $ft^2$ of foil. In all the tests, the RMI fragments used were crumpled pieces with the dominant length scale less than 2-inches, therefore very compact beds would be expected. The measured head loss was tabulated as a function of the flow rate through the strainer and the quantity of insulation added to the pool. The LaSalle test report contained references to visual observations regarding the fraction of the debris that actually reached the strainer in each test. It also provided pictorial evidence of debris bed buildup on the strainer, both for RMI, and mixed beds.

Test 1 simulated pure fiber debris buildup on the strainer. Based on analysis of the test conditions, it was found that all the fiber volume could easily be accommodated in the strainer disk cavities, where it would be subjected to low water velocities. The pictorial evidence confirmed this finding. As a result, calculated head losses were small and compared well with the measured head loss of 1.5 ft-water at 4000 GPM. The NUREG/CR-6224 correlation predicted the Test 1 head losses to within 20%.

Tests 2 and 4 examined pure RMI debris buildup on the strainer surface. In Test 2, RMI debris (2250 $ft^2$) was added incrementally over a long duration (test lasted 27,000 seconds). In Tests 4, all the RMI debris was added instantaneously and then allowed to accumulate on the strainer. From the head loss traces, it appears that accumulation occurred over a period of 10,000 seconds, with head loss reaching the steady state value at the end. In both these tests, a total of 2250 $ft^2$ of RMI foil were added to the pool and allowed to accumulate on the strainer. Head loss predictions obtained using NRC RMI head loss correlation compared well with the test data from Tests 2 and 4. The correlation predictions were within $\pm$30% of the test data. The licensee did not believe that the variability between Tests 2 and 4 is a result of 'randomness' associated with debris buildup. Instead, the licensee postulated that the difference is due to the fact that insulation was added incrementally over a much longer period of time in Test 2 (27000 seconds). It was reasoned that slow addition allows for gradual building of the debris bed resulting in formation of more compact beds. The licensee however stated that Test 2 is not prototypical of postulated accident conditions in LaSalle plant, and hence should not be used in assessing their strainer performance. Nevertheless, they forwarded the data purely for the insights it has provided them. Licensee's interpretation of data is new and has not been observed previously in any of the investigations that used 'prototypical debris'. It is not to say that licensee's interpretation is wrong, but simply that it could not be independently confirmed. Nevertheless, this analysis suggests that when applied consistently NRC RMI correlation does a reasonable job at predicting such data.

Tests 5 and 6 examined mixed bed buildup on the strainer. In Test 5, a total of 2250 ft2 of RMI and a total of 9 lbs of fiber were added to the pool. At the end of the test (approximately 10000 seconds), the licensee noted that approximately 75% of the insulation accumulated on the strainer and the remaining insulation settled on the floor. The measured head loss was about 5 ft-water corresponding to a strainer flow rate of 2000 GPM. Test 6 is a repeat of Test 5. Pictorial evidence of mixed debris bed buildup on the strainer suggested that fiber and RMI debris buildup rather uniformly through out the volume of the debris bed, and furthermore that the debris bed far extends outside the circumscribed surface area of the strainer.

For estimating head loss using NRC RMI correlation, the thickness of the debris layer must be estimated and a shape for the debris layer buildup must be assumed to estimate the bed thickness. The actual bed resembles a distorted sphere, which confirms BWROG observation. Head losses caused for such a shape is difficult to predict, without undertaking a complex flow analysis. Instead, the head loss estimates can be bounded by assuming that all the debris bed builds-up over the circumscribed surface area, as defined by the BWROG. Another option is to assume that bed builds up uniformly over the entire circumscribed surfaces, including both ends of the strainer. Reality is somewhere in between these two extremes. Estimates for head losses were obtained by simply adding the RMI induced head loss to fiber induced head loss; i.e., by treating the individual contributions as additives. A treatment that was consistent with Appendix-K guidance.

<u>Documentation</u>

The LaSalle tests are documented in the test report TPP-VL0400 –006 entitled: "Test Evaluation Report for Test TPP-VL0400-005: LaSalle Strainer Fiber and RMI Debris Tests," dated June 6, 1998 [LaSalle-98].

### 3.2 NRC Compilations and Analysis of International Test Data

#### 3.2.1 Finnish RMI Testing

RMI is used in a large number of BWRs in the USA. In the event of a LOCA at a plant using RMI for insulation, it is anticipated that some fraction of damaged RMI would be transported to the suppression pool and then potentially transported to the ECCS suction strainers. Sateilyturvakeskus (STUK), the Finnish centre for radiation and nuclear safety conducted tests to probe the transport and clogging properties of RMI [STUK-YTO-TR-73] to provide data for evaluation of their influence on ECCS and containment spray systems of the Finnish BWRs in the event of a design basis accident. These tests clearly demonstrated that RMI can be transported to ECCS strainers and cause increased head loss.

Tests were conducted to investigate transport properties of the foil pieces, starting from sedimentation in a stagnant pool of water and proceeding to transport in horizontally and vertically circulating flows. The sedimentation velocities were found to be rather moderate, 0.04 to 0.08 m/s for the stable descent mode of flat pieces. In the vertical circulation tests, all tested pieces were found to become waterborne as the upward vertical velocity exceeds the sedimentation velocity of a piece.

The basic test facility consisted of a water tank (25 $m^3$) and a water recirculating system. In the strainer clogging tests, a strainer model was installed on the recirculating system pump suction piping inside the tank. The model represented 1/3 of the width and 2/5 of the height of the actual sump screen and had a total perforated area of 4.55 $m^2$ (parts of the area were blanked off for certain tests).

The clogging tests addressed the differential pressures obtained due to an accumulation of both pure metallic and a mixture of metallic and fibrous (mineral wool) debris. For purely metallic insulation, it was found that the strainer pressure drop approximately varied proportional to the square of the strainer approach velocity. The strainer pressure drops were dependent upon the size of the debris; the pressure drops were more moderate for small pieces. There were indications of strong interactions between various sizes of pieces. The results were also sensitive to the type of the foil used; dimpled foils seemed to produce smaller pressure drops. A mixture of fibrous debris and metallic foil pieces reacted more aggressively than either of the constituents would alone.

A key element of estimating the impact of RMI on loss of ECCS is adequate data regarding the size distribution and general shapes of RMI fragments caused by a DEGB. The specific metallic insulation tested was DARMET provided by Darchem Engineering Limited, England. DARMET minimizes the heat losses by creating air pockets between the alternate layers of course and finely dimpled foil. These inner foils are encased in an outer casing made 0.7 mm thick stainless steel. The inner foils are typically made of 0.06 mm thick stainless steel. By comparison, there are two RMI designs predominate in the United States. Transco products Inc and Diamond Power Specialty Company (MIRROR system) manufacture these insulations. While a small minority of U.S. plants has other RMI systems, no domestic nuclear power plants have installed DARMET. The typical Transco system has 0.051 mm thick inner foils encased in 0.6 mm stainless steel. In the Transco design, a single waffle, or 'crumpled' design is used. The MIRROR RMI system consists of an inner and outer casing made of stainless steel that are 0.38 and 0.94 mm thick, respectively. The inner stainless steel foils are 0.0635 mm thick. Note that number of foils per unit thickness varies from application to application. Also note that the primary difference between DARMET foils and those used in U.S. plants is their method of introducing air pockets (i.e., dimpled foils versus crumpled foils).

The Finnish tests used a wide range of sizes and shapes of foil pieces that were generally flat dimpled pieces, not crumpled. Debris tested in the U.S. tests (see Sections 2.1.2 and 2.1.3) was crumpled in nature as shown in Figure 2-16. MIRROR RMI debris was created using a saturated steam jet for use in U. S. tests (see Section 2.1.1). In the Finnish head loss tests, the RMI pieces were typically cut into strips from the DARMET inner foils and laid on top of a support net in the test section in the desired geometry or placed stamp-like on the strainer plate. In other words, the bed geometry was controlled. For comparison, in the U.S. tests, the debris accumulates on the test strainer in a random like manner.

There has been some controversy about the magnitude of flow resistance that RMI debris can cause on ECCS strainer surfaces following a LOCA [OECD/NEA/CSNI PWG-1]. The RMI head loss tests conducted in the U. S. generally produced lower head losses than did the Finnish RMI tests. The differences in head loss data have been attributed primarily to the differences in the characteristics of the RMI debris utilized for testing and the method of debris accumulation on the strainer. In the case of the Finnish tests, the debris consisted of strips of dimpled DARMET placed on the strainer in a predetermined geometry, whereas in the U. S. tests, 'crumpled' debris was randomly drawn onto the strainer by the water flow. These differences impacted the physical mechanisms that induced the flow resistance. This controversy is discussed in more detail in Section 5.2.2.

Documentation

The information presented here was summarized from the following two technical reports: 1) STUK-YTO-TR-73, entitled "Metallic Insulation Transport and Strainer Clogging Tests," dated July 1994 and 2) MRI-1194-TRR1, entitled "Comparison of Test Results on Metallic Reflective Insulation as performed by the Finnish Centre for Radiation and Nuclear Safety (STUK) and the Materials and Configurations used in Boiling Water Reactor Plants in the United States," dated November 30, 1994.

### 3.4.2 Vattenfall Mineral Wool Testing

Following the Barsebäck strainer blockage event, a design review of the Ringhals recirculation function was made in 1993 [IWG]. Ringhals 2 is a 3-loop Westinghouse PWR in operation since 1974. This review concluded that the recirculation function in Ringhals needed improvements. The main reason was that a tank test in Alvkarleby Laboratory showed that the earlier design basis for debris settlement was not correct. The tests showed that recirculating water falling via floors would not only prevent settling of fibers, but also cause larger pieces of insulation material to be broken down into smaller fibers and fines. CFD calculations and model testing of the reactor containment pool flows were made. New sump screens with a total area of 190 $m^2$ were developed. Part of the sump screen we designed to make cleaning possible. Alvkarleby Laboratory also performed testing of the sump screen design to determine the capacity for various kinds of debris, self-cleaning qualities and function of the sump screen differential pressure measurement system. The new screens were installed in Ringhals 2 in 1995. Pump suction was originally taken from two cage type sump screens each having an area of 7 $m^2$ that were designed in conformance with RG 1.82, Rev. 0 published in June 1974.

Vattenfall and the insulation supplier performed insulation tests. The Ringhals 2 containment contains the following types of insulation: RMI, fiberglass, mineral wool, polyurethane, and reinforced cement (Linpac). The Vattenfall tests showed that nuclear grade fiber insulation without jacketing could be fragmented at a distance of 35 pipe diameters from a pipe break. The new sump screen design was based on a total of 45 $m^3$ of fiberglass insulation debris and 12 $m^3$ of mineral wool debris. In addition, RM1 debris as well as other debris was considered. The design was based on the empirical experience that 2/3 of the insulation would reach the pool and no sedimentation would occur due to the stirring effect of the recirculation water falling into the pool. To compensate for uncertainties, a small part of the strainers were designed with self-cleaning capabilities; achieved without backflushing or moving parts. Based on test data, neither vortices nor air ingestion would be created at rated flow conditions. The strainers were equipped with head loss measurement capability including a control room alarm.

Extensive testing was conducted. Tests were conducted to verify the behavior of fiber and RMI insulation material subjected to jets and their transport behavior in the containment pool. Testing was conducted to verify the behavior of the sump screens. Sump screen head loss tests were conducted for steam-fragmented fiber and RMI insulation materials, as well as, for recirculation water fragmented fiber insulation. Head loss tests were also conducted for combinations of fibers and impurities such as lubrication oil and carbon using PWR chemistry water.

Documentation

The information presented here was summarized from the International Working Group (IWG) on Sump Screen Clogging technical report, entitled "Modification of Sump Screens in Ringhals 2," dated May 10-11, 1999.

**3.3 References**

NEDO-32686, Rev. 0, "Utility Resolution Guidance for ECCS Suction Strainer Blockage," BWROG, November 1996.

NRC-SER-URG, "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.

PP&L, K. W. Brinkman and P. W. Brady, "Results of Hydraulic Tests on ECCS Strainer Blockage and Material Transport in a BWR Suppression Pool," Pennsylvania Power and Light Company, EC-059-1006, Rev. 0, May 1994.

NUREG/CR-6224, G. Zigler, J. Bridaeu, D. V. Rao, C. Shaffer, F. Souto, W. Thomas, "Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris," Final Report, U. S. Nuclear Regulatory Commission, October 1995.

NUREG/CR-6369, Volume 3, C. Shaffer, D. V. Rao, and J. Brideau, "Drywell Debris Transport Study: Computational Work," SEA97-3501-A:17, September 1999.

NEDC-32721P, Rev. 0, GE Licensing Topical Report, "Application Methodology for GE Stacked Disk ECCS Suction Strainer," General Electric Nuclear Energy, Proprietary, March 1997.

Bulletin 96-03, "Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling-Water Reactors," NRC Bulletin to BWR Licensees, May 6, 1996.

LA-CP-99-7, D. V. Rao, "Technical Review of GE LTR NEDC-32721P: Application Methodology for GE Stacked-Disk ECCS Suction Strainer," NRC Technical Evaluation Report, RP12-TER-98-02, Proprietary, December 23, 1998.

PCI-97, R. A. Biasca, "Summary Report on Performance of Performance Contracting, Inc.'s Sure-Flow™ Suction Strainer with Various Mixes of Simulate Post-LOCA Debris," Revision 1, September 1997.

LA-UR-00-5159, D. V. Rao, "Technical Review of Selected Reports on Performance Contracting, Inc. Sure-Flow Strainer™ Test Data,' Prepared for U. S. Nuclear regulatory Commission, April 27, 2000.

LA-CP-00-18, Bruce Letellier, and D. V. Rao, "On-Site Audit of the Grand Gulf Nuclear Station Emergency Core Cooling System Strainer-Blockage Resolution," Los Alamos Technical Evaluation Report, January 3, 2000.

STUK-YTO-TR-73, Juhani Hyvärinen and Olli Hongisto, "Metallic Insulation Transport and Strainer Clogging Tests," Finnish Centre for Radiation and Nuclear Safety (STUK), July 1994.

MRI-1194-TRR1, "Comparison of Test Results on Metallic Reflective Insulation as performed by the Finnish Centre for Radiation and Nuclear Safety (STUK) and the Materials and Configurations used in Boiling Water Reactor Plants in the United States," Transco Products Inc. Document, Revision 1, Proprietary, November 30, 1994.

LaSalle-98, "Test Evaluation Report for Test TPP-VL0400-005: LaSalle Strainer Fiber and RMI Debris Tests," Duke Engineering &Services, TPP-VL04 00 –006, June 6, 1998.

OECD/NEA/CSNI PWG-1, Juhani Hyvärinen and Nina Lahtinen, "On the Mechanics of Metallic Insulation Pressure Drop Generation," Finnish Centre for Radiation and Nuclear Safety (STUK), July 1994.

IWG, Lars-Eric Bjerke and Mats Henriksson, "Modification of Sump Screens in Ringhals 2," International Working Group (IWG) on Sump Screen Clogging, Stockholm, May 10-11, 1999.

EC-059-1006, Rev. 0, K. W. Brinkman and P. W. Brady, "Results of Hydraulic Tests on ECCS Strainer Blockage and Material Transport in a BWR Suppression Pool," Pennsylvania Power and Light Company, May 1994.

## 4.0 RESOLUTION METHODOLOGY

The NRC issued NRC Bulletin 96-03, "Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling-Water Reactors," on May 6, 1996. All BWR licensees were requested to implement appropriate measures to ensure the capability of the ECCS to perform its safety function following a LOCA. The staff had identified three potential resolution options but allowed licensees to propose others that provided an equivalent level of assurance. The three options identified by the staff were: 1) to install a large capacity passive strainer designed with sufficient capacity to ensure that debris loadings equivalent to a scenario calculated in accordance with Section C.2.2 of RG 1.82, Revision 2 do not cause a loss of NPSH for the ECCS, 2) install a self-cleaning strainer that automatically prevents strainer clogging by providing continuous cleaning of the strainer surface with a scraper blade or brush, and 3) install a backflush system that relies on operator action to remove debris from the surface of the strainer to prevent it from clogging. All licensees were requested to implement these actions by the end of the first refueling outage starting after January 1, 1997.

The bulletin noted that plant-specific analyses to resolve this issue are difficult to perform because a substantial number of uncertainties are involved. Examples of these uncertainties include the amount of debris that would be generated by a pipe break for various insulation types; the amount of debris that would be transported to the suppression pool; the characteristics of debris reaching the suppression pool (e.g., size and shape); and head-loss correlations for various insulation types combined with suppression pool corrosion products, paint chips, dirt, and other particulates. Many of these uncertainties would be plant-specific because of the differences in plant characteristics such as plant layout, insulation types, ECCS flow rates, containment types, plant cleanliness, and NPSH margin. As discussed earlier in this report, testing was conducted to quantify many of these uncertainties.

The bulletin further noted that the staff closely followed the work of the BWROG to resolve this issue and demonstrate compliance with 10 CFR 50.46 and Regulatory Guide 1.82, Revision 2. The BWROG had evaluated several potential solutions and completed testing on three new strainer designs: two passive strainer designs and one self-cleaning design. The BWROG effort was consistent with the options proposed in NRCB 96-03 for resolution of the ECCS potential strainer clogging issue. The BWROG then developed the URG [NEDO-32686-A] to provide utilities with: 1) guidance on the 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 includes guidance on a calculational methodology for performing plant specific evaluations.

The NRC reviewed the BWROG URG document and issued the staff's Safety Evaluation Report (SER) on August 20, 1998 [NRC-SER-URG]. The SER should be used in conjunction with the URG to ensure an acceptable and consistent response by the industry to NRC Bulletin 96-03. In the SER, the staff noted that the issue of potential strainer blockage is complex, in that, head loss across suction strainers is not only a function of the amount of debris, but also of the types (e.g., fibrous insulation, paint, reflective metallic insulation, dirt, corrosion products, etc.) and characteristics of the debris (size, shape, etc.). The analyst must evaluate the worst case for potential strainer debris loadings, consider the potential for foreign material to be introduced during normal plant evolutions such as refueling and maintenance outages, and evaluate maintenance practices including the maintenance of qualified coatings in the drywell and wetwell.

The NRC concluded that the URG was a comprehensive document providing: 1) general guidance on resolution options, and 2) detailed guidance on performing plant-specific analyses to estimate potential worst case debris loadings on ECCS suction strainers during a LOCA. For performing a plant-specific analysis, the URG provides methodologies for: 1) estimating the amounts and types of debris that could be generated by a LOCA, 2) estimating the amount of the generated debris which could be transported to the suppression pool, 3) estimating the amount of debris that could be entrained on the ECCS suction strainer surfaces, 4) determining the head loss caused by the estimated debris accumulation, and 5) calculating the NPSH margin. In order to provide flexibility to the utilities, the URG provides multiple methods for performing each part of the plant-specific analysis. However, due to incomplete guidance and inadequate supporting documentation or analysis in several areas, the staff was unable to determine if all of the methodologies, or combination of methodologies, were conservative. Similarly, much of the general guidance on "resolution options" also lacked sufficient detail for the staff to review. Since the staff lacked sufficient detail and supporting justification on many of the "resolution options," these were generally considered unacceptable without further supporting justification from a licensee or the BWROG. This section presents highlights of the URG and the findings of the NRC review of the URG.

### 4.1 Evaluation of URG Resolution Options

URG Guidance

The BWROG recommended plants replace their existing strainers with one of the alternate designs that have demonstrated better performance characteristics. For plants that have more than a minimal amount of fibrous insulation, the URG recommends that licensees size their strainers as large as possible without violating their penetration hydrodynamic load limits. Licensees should then evaluate the strainer performance with the calculated debris loading to ensure that it provides adequate performance for maintaining the ECCS pump NPSH margin. For plants with almost all reflective metallic insulation (RMI), the URG suggested two methodologies: 1) sizing the strainers based on the head loss when the strainer is loaded at the saturation level with RMI and/or 2) sizing the strainer based on a calculated expected debris loading.

The URG recommended and discussed nine resolution options available to licensees for resolving the strainer clogging issue for their BWR plant. These options were:

1. Refine containment debris source analyses in order to reduce the estimates of debris reaching the strainers, i.e., reduce conservatisms in analytical assumptions.

2. Replace the existing strainer with an alternate passive design such as the stacked disk or star strainer designs to increase the debris capture capability of the strainer leading to a lower head loss for a comparable debris loading. Note that this was also the NRC Option 1 in NRCB 96-03.

3. Install insulation blanket jacketing with appropriate attachment mechanisms to inhibit debris generation. The URG noted that BWROG test data showed that metal-jacketed insulation generated less debris than its unjacketed counterpart.

4. Implement an additional foreign material exclusion (FME), housekeeping controls, and/or more frequent suppression pool cleaning to reduce transient debris.

5. Pursue a licensing basis change with the NRC, such as using a more realistic decay heat curve in lieu of the conservative curve used in the original licensing basis to lower predicted suppression pool temperatures following a LOCA to improve the calculated NPSH margin. Note that the BWROG does not recommend crediting containment overpressure in calculating NPSH margins.

6. Re-evaluate ECCS suction line penetration loads without reopening the licensing basis for containment loads. The BWROG does not recommend reopening the licensing basis for containment loads.

7. Partially replace fibrous insulation with RMI to reduce the potential for generating fibrous debris.

8. Install a backflush system as a defense-in-depth measure. BWROG does not recommend this option as a primary mitigating strategy because it would likely increase operator burden, especially early in the accident.

9. Install self-cleaning strainers, however BWROG notes that licensees would need to resolve significant design, qualification, and surveillance issues before implementation.

NRC Evaluation

Three of the nine URG options are consistent with the resolution options proposed in NRCB 96-03: the installation of alternate passive design strainers, self-cleaning strainers, or backflush. However, in the opinion of the staff, the remaining six URG options are not “resolution options,” because they are insufficient by themselves to resolve this issue for any plant. On the basis of current knowledge of existing plant strainer designs and the deleterious phenomena that can affect head loss across the strainer and NPSH margin, the staff does not believe that any BWR licensee can justify maintaining their existing strainer design for resolution of the strainer clogging issue. Rather, the other six URG resolution options discussed are better characterized as potential licensee actions, which could help licensees reduce the size of the strainer needed to resolve the issue. However, the resolution options lack substantial detail on the technical basis for these options and the specific detail information on how to apply each option. For this reason, a licensee should resolve the staff’s concerns for each option in a plant-specific submittal prior to using the option to as a part of their resolution for the strainer clogging issue.

Additional specific concerns/comments of the staff included:

- The staff recommends that licensees use vendor specific data based on the licensee’s analyzed conditions as the basis for determining head loss across the strainer.

- The staff was unable to reach any conclusion regarding the acceptability of installing jackets around insulation blankets due to a general lack of definitive guidance to utilities for installing jackets and estimating their associated reduction in debris.

- The staff has concerns regarding specifically incorporating FME or housekeeping programs into a licensee’s strainer blockage issue resolution. Given the numerous events reported over the last few years related to FME issues, the industry has not demonstrated that FME controls alone are effective in ensuring that materials are not left in the drywell, wetwell, or suppression pool. As such, the staff believes that regular inspections of the suppression pool and ECCS suction strainers, and cleanings when necessary, should be conducted every refueling outage until licensees have demonstrated over time the ability to control foreign materials. The staff believes it is more prudent to add margin when sizing strainers to account for the uncertainty in the effectiveness of housekeeping controls.

- The staff concurs that additional containment overpressure (other than an amount already approved by the staff for the existing licensing basis) should not be used as part of the resolution of this issue.

- The staff cautions that licensees making changes to hydrodynamic load calculation coefficients and/or methodologies should not do so without testing to demonstrate the validity of the revised calculations.

- The staff agrees that partially replacing fibrous insulation with RMI to reduce the potential for generating fibrous debris is an appropriate action, however, licensees should reassess breaks to ensure that the changes do not affect which break is the most limiting in term of NPSH margin. In addition, licensees must consider head loss in terms of combined fibrous/RMI debris beds.

- Regarding the backflush option, the staff concurs with the BWROG that backflush is a more viable option as a defense-in-depth measure. The also believes that, if used as a primary means of ensuring adequate ECCS flow, backflushing should be combined with the installation of a large-capacity passive strainer to maximize the time before backflush initiation would be required.

- Regarding self-cleaning strainers, the staff agrees with the BWROG that such a design is less desirable than a passive strainer for resolving the issue and that such a strainer should only be used if a passive strainer solution is not viable.

The staff also noted that a good practice would be to maintain defense-in-depth because of the uncertainties associated with any resolution of this issue. The staff strongly encouraged the enhancement of alternate water sources, operator training, and EOPs to ensure that operators can mitigate any situation involving loss of ECCS flow due to strainer clogging.

**4.2 Debris Sources**

Sources of debris contributing to the potential clogging of an ECCS strainer have been generally categorized into three groups for analyses. These groups are insulation debris generated within the drywell by a LOCA, debris other than insulation that originate from the drywell, and debris that originate in the wetwell.

**4.2.1 LOCA Generated Insulation Debris**

The URG presented methodologies that the BWROG recommended for calculating the amount of LOCA-generated debris from piping insulation. The guidance provided included guidance for determining the pipe break locations to be analyzed, the zone of influence (ZOI) for the break jet, and the destruction factors for piping insulations typically used in domestic BWRs. In the URG, the destruction factors were combined with drywell transport fractions; therefore destruction factors are discussed in Section 4.3.1.

**4.2.1.1 Pipe Break Selection**

<u>URG Guidance</u>

Postulated pipe breaks in a BWR plant include main steam, recirculation, and feed water line pipes that can be grouped as small, medium, or large breaks. Because it is difficult to analyze each postulated break, a criterion is needed to select the bounding breaks that maximize head loss across the ECCS pump suction strainers. NRC Regulatory Guide 1.82, Rev. 2, states that as a minimum, licensees should consider the following postulated break locations:

- Breaks on the main steam, feedwater, and recirculation lines with the largest amount of potential debris within the expected ZOI.

- Large breaks with two or more different types of debris within the expected ZOI.

- Breaks in areas with the most direct path between the drywell and wetwell.

- Large and medium breaks with the largest potential particulate debris-to-insulation ratio by weight.

The URG reiterated the RG 1.82, Rev. 2 guidance and included he following additional provisions:

- Plants licensed in accordance with the NRC's Standard Review Plan (SRP) and Branch Technical Position (BTP) MEB 3-1 need not analyze all of the identified break locations. Instead, such plants may evaluate only those breaks that are most likely to occur.

- Other plants may use the guidance from RG 1.82, or other guidance consistent with 10CFR50.46. However, licensees should exercise care to differentiate between pipe break locations used for ECCS evaluation and those that are in the plant's licensing bases.

- Plants employing alternate high-capacity strainer designs need not analyze large and medium breaks with the largest potential debris-to-insulation ratio by weight.

<u>NRC Evaluation</u>

The staff concluded that:

- Licensees should evaluate a sufficient number of breaks to ensure that the most limiting breaks are analyzed and should include pipe sections or welds in the area of the drywell where the highest density of fibrous insulation is installed.

- RG 1.82, Rev. 2, provides the complete spectrum of breaks that should be analyzed to meet the intent of 10CFR50.46.

- The staff considered SRP Section 3.6.2 and BTP MEB 3-1 inappropriate for demonstrating 10CFR50.46 compliance. SRP Section 3.6.2 does not provide guidance or acceptance criteria for demonstrating compliance with 10CFR50.46. The BWROG did not demonstrate that break locations selected consistent with SRP Section 3.6.2 would bound the worst-case debris generation scenarios.

- Licensees may screen out large breaks with the highest particulate-to-fiber debris ratio by weight and medium LOCAs in performing their plant-specific analyses, if their resolution includes both the following:

    - Installation of a strainer similar to the stack disk prototype number 2, star strainer, or another geometric similar strainer with deep crevices.

    - The licensee has adequate assurance from the strainer vendor that the screened out breaks would be less limiting in terms of head loss across the strainer. The vendor should have adequate test data to support the screening of these breaks.

#### 4.2.1.2 Zone of Influence

URG Guidance

Postulated breaks in the primary piping would destroy insulation located in the region closely surrounding the separated broken ends due to the combined effects of blast wave and jet impingement. The ZOI over which the destruction occurs strongly depends on the type of insulation and mode of encapsulation in addition to the type of break and the subsequent motion of the broken ends. The BWROG developed the URG guidance using experimental data obtained from Air Jet Impact Testing (AJIT) and the results of the associated computational fluid dynamics (CFD) modeling. The URG provided four options (or methods) for selecting the ZOI over which LOCA jets would damage the insulation. Each method was less conservative relative to the preceding method; conversely, the licensee required more rigorous analysis as the relative conservatism was lessened. The licensee selects the method based on resources balanced against the need to reduce its drywell insulation debris source. These methods are:

1. The ZOI is assumed to encompass the entire drywell, i.e., all insulation located within the drywell is assumed damaged.

2. The ZOI is defined by determining the spatial volume enveloped by a specific damage pressure of interest for a jet expanding in free space and mapping a spherical ZOI of equal volume surrounding the break. This means that the ZOI is defined as the spherical volume for which the break damage pressure exceeds the minimum or onset pressure for material damage. The pressure required to damage insulation material is specific to each material. In this method, the material with the lowest dynamic destruction pressure is used to define the ZOI, i.e., the ZOI is largest for the weakest material. Full separation of both ends of a double-ended guillotine break (DEGB) is assumed resulting in continuous blowdown from both ends.

3. Method 3 is similar Method 2 but with some differences. The licensee is allowed to take credit for pipe restraints and to evaluate axial and radial offsets consistent with those restraints. The licensee is also allowed to take credit for a single-ended blowdown. With this method, the licensee maps different ZOIs for each different insulation material.

4. With this method, CFD modeling in conjunction with AJIT data is used to define the ZOI.

Note that the ZOI depends upon the break selected for analysis. There will be as many ZOIs as there are selected breaks. All of the insulation contained within the ZOI is assumed damaged (but not necessarily transportable). The licensee can either assume that all damaged insulation is transportable to the suppression pool or classify the debris into two bins for subsequent transport analysis. These bins are 1) debris generated above the lowest elevation grating, and 2) debris generated below the lowest elevation grating. Debris size distribution was however not addressed.

NRC Evaluation

The staff conducted independent analyses to assess if the URG guidance is appropriate and bounding. The staff concluded that:

- Method 1 is clearly bounding and conservative since the entire inventory of drywell insulation was assumed damage.

- Method 2 would result in a ZOI sufficiently large to envelop the entire destruction zone. Method 2 is sufficiently conservative and, therefore, is considered acceptable for use on insulations with low destruction pressures. However, for insulations with high destruction pressures, the staff recommends that licensees develop the ZOI on the basis of the target-area-averaged-pressures instead of the jet-centerline pressures.

- Method 3 is acceptable with the same comments applying to Method 3 as were applied to Method 2.

- Method 4 is unacceptable at the time because the URG lacked any detailed guidance regarding this method. Licensees using this method should address the staff's concerns including the validation of the selected CFD code.

Damage pressures (i.e., the lowest jet-centerline pressure for which damage is expected), were estimated by the BWROG based on AJIT data. Each type of insulation will damage at a different pressure and its damage pressure is further dependent upon the method of installation. The NRC staff performed confirmatory analyses to confirm these damage pressures and to assess their scalability to BWR drywells. These analyses were documented in Appendix B of URG-SER. The NRC confirmatory damage pressures are compared to the corresponding URG pressures in Figure 4-1. Except for a few modest reductions in pressures, the NRC pressures generally agreed well with the URG pressures.

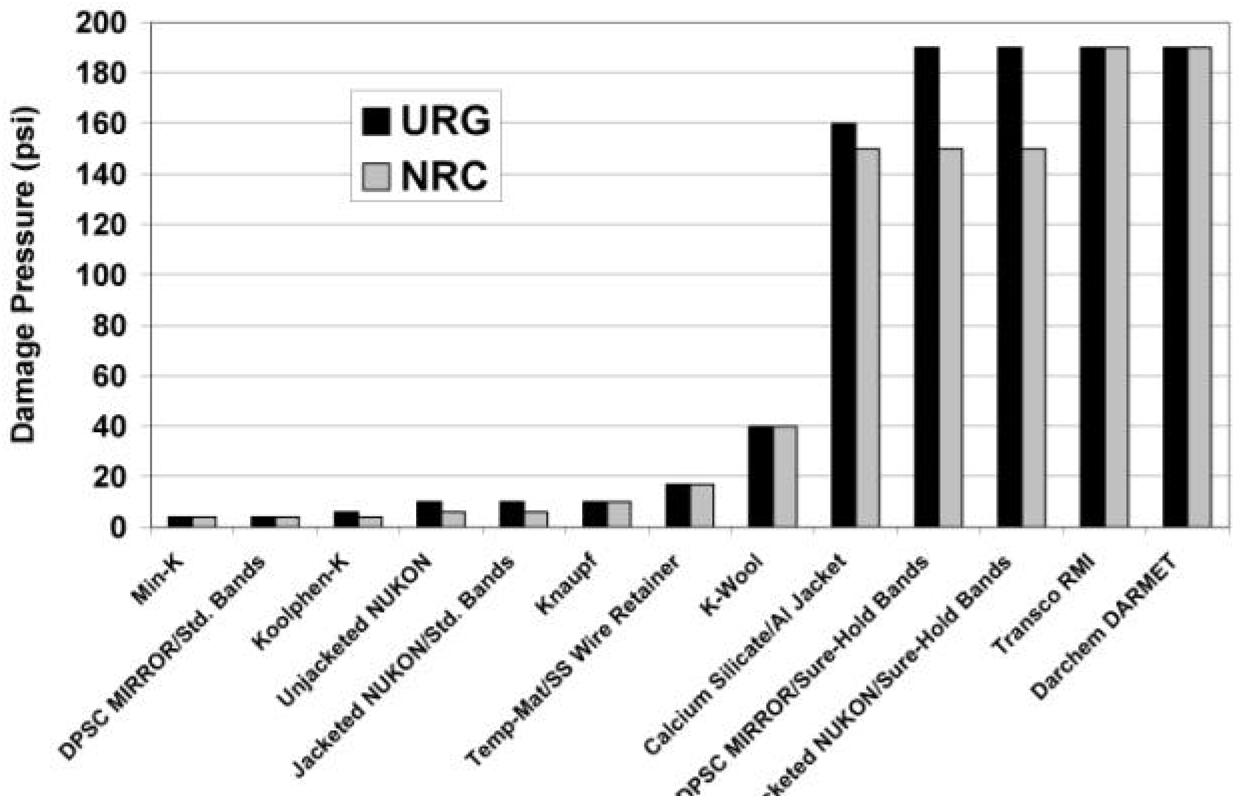



**Figure 4-1. Damage (Onset) Pressures for Various Insulations**

The staff concluded that the BWROG's basis for using the jet centerline pressure as the insulation's characteristic damage pressure is inadequately supported by analysis or data. The staff's review of the data and independent CFD calculations led to the conclusion that incipience of damage is more accurately characterized by the target-area-averaged-pressures or total jet impingement load rather than local maximum pressure. The staff believes that this concern should be addressed on a plant-specific basis.

The staff notes that the URG does not provide guidance regarding the types of analyses that licensees must undertake to determine the extent of axial and radial separations of the broken ends. Licensees taking credit for limited separation of the broken ends of pipes due to pipe restraints or single-ended blowdown should conduct and retain supporting analyses.

### 4.2.2 Drywell Debris Sources Other Than Insulation Debris

The URG categorized other 'non-insulation' type of debris as transient, fixed, or latent debris. The URG defines transient debris as non-permanent plant material brought into the drywell, typically during an outage (e.g., tools, rags, and temporary filters). Fixed debris is part of the plant, and only becomes debris during a LOCA (e.g., paints and coatings delaminated from the coated surface by direct steam impingement from a pipe break). Latent debris would appear after a prolonged exposure to a LOCA environment for instance, an unqualified coating, which is not directly impinged upon by the LOCA break jet, may subsequently fail as a result of prolonged exposure to the temperature, pressure, and radiation of the post-LOCA environment.

<u>URG Guidance</u>

The URG provides guidance that licensees can use to identify other sources of debris in the drywell and to estimate the quantities of such debris that should be used in the ECCS strainer analysis. The URG specifically identified the following other sources of debris:

- <u>Dirt/Dust</u> The URG suggests that licensees assume 150 lbm of dust/dirt for estimating the strainer head loss. This estimate was based on engineering judgment.

- <u>Other Transient Debris</u> The URG does not provide a specific value. Individual utilities should use their best judgment.

- <u>Rust from Unpainted Steel Surfaces</u> The URG recommends a value of 50 lbm on the basis of engineering judgment.

- <u>Particulate Debris</u> The URG does not provide a specific value. Individual utilities should use their best judgment.

- <u>Paints/Coatings</u> The URG recommends values of 47 lbm for inorganic zinc coatings, 85 lbm for inorganic zinc top-coated with epoxy, and 71 lbm for 100% epoxy coating. These estimates were predicted by a study conducted by Bechtel Power Corporation.

- <u>Concrete</u> The URG does not provide a specific value. Individual utilities should use their best judgment.

- <u>Unqualified/Indeterminate Paint/Coatings</u> The URG does not provide a specific value. Individual utilities should use their best judgment. As an alternative, the URG notes that licensees may remove the unqualified or indeterminate coatings, or attempt to qualify them through *in situ* qualification. The URG does not provide guidance regarding how licensees should accomplish *in situ* qualification.

The URG cautions licensees that their FME, housekeeping, and inspection programs must be adequate to ensure that the quantities of each of these types of materials do not exceed the quantities assumed in the plant's evaluation of ECCS strainer loading.

NRC Evaluation

The staff compared the URG recommended values with estimates previously developed as part of the NRC sponsored reference plant study (see Section 2.2.1) [NUREG/CR-6224]. On the basis of this comparison, the staff found that most of the values suggested in the URG are either about the same or larger than the corresponding reference plant study values. The staff concluded that the generic values provided in the URG for other sources of debris are acceptable, however, the staff noted differences exist between a specific plant and the reference Mark I plant. Due to these differences, the staff believes that some individual licensees may wish to evaluate the applicability of the recommended values for their specific plant. The staff provided some suggestions on estimating the sources of dirt, dust, and rust in the containment, as well as paints/coatings for plants with unqualified or indeterminate coatings. These suggestions by the staff were provided for informational purposes and are not considered a requirement for use.

The staff notes that the sensitivity of the head loss calculations to these numbers may vary with the assumptions and the resolution option selected by each licensee. The significance of these values escalates, for instance, if the licensee attempts to justify their strainer with assumptions that are as "realistic" as possible. On the other hand, when justifying the installation of a large passive strainer, sensitivity analyses could well demonstrate that variations in the quantities of dirt, dust, rust flakes, etc. may not significantly affect the overall head loss across the strainer.

The staff concluded that licensees should be cautioned to carefully evaluate the potential impact of unqualified and indeterminate coatings on ECCS suction strainer head loss. Some licensees may wish to evaluate the applicability of the conclusion of the Bechtel coatings report for their plant. If available, licensees are encouraged to use test data to support their evaluation of coatings. Unless data is available supporting use of other assumptions, the staff suggests that licensees assume that all unqualified and indeterminate coatings are transported to the strainer surface.

### 4.2.3 Suppression Pool Debris

Both transient debris and sludge are potentially present in the suppression pool at any given time. URG guidance was developed, in part, on the basis of an extensive BWROG survey of suppression pools of selected BWR plants in the United States.

URG Guidance

The BWROG survey [BWROG Letters OG95-388-161 and OG96-321-161] showed that suppression pools would likely contain various types of debris unrelated to a LOCA. This debris could be transported to the ECCS suction strainers and contribute to head loss across the strainer. The URG provided guidance related to identifying various sources of debris and important considerations that should be used to estimate the quantities of such debris. The URG identified the following sources of suppression pool debris:

- Fibrous debris entrained in the suppression pool prior to a LOCA.
- Non-fibrous debris entrained in the suppression pool prior to the LOCA.

- Dirt/dust above the pool that could wash down into the pool during pool swell.

- Other potential debris, such as operational debris and unqualified/indeterminate coatings.

During its evaluation of the strainer clogging issue, the BWROG conducted a survey to estimate the quantities of sludge (primarily corrosion products from carbon steel piping systems) entrained in the suppression pools. The medium sludge generation rate for the 12 surveyed plants was 88 lbm/year (dry weight). On the basis of this survey, the BWROG recommended a sludge generation rate of 150 lbm/year (dry weight), however, licensees should review available data on their plant specific conditions and make a determination as to whether this suggested rate is conservative for their plant. This sludge generation rate can be coupled with frequency of pool cleaning to estimate the total quantity of sludge for use in the analysis of ECCS strainer blockage.

The URG does not specify generic estimates for any other types of debris. However, the URG does list the considerations that licensees should address while estimating the quantities of other debris to be used in the analysis of ECCS strainer blockage. The URG cautions licensees to recognize that the operability of the ECCS system may be challenged if the licensee cannot demonstrate that suppression pool debris source terms will be controlled at values less than assumed in the strainer sizing calculations.

NRC Evaluation

The staff evaluated the adequacy of the BWROG recommended sludge masses and their tractability and the staff finds no deficiencies in the recommendations documented in the URG. The staff concluded that the BWROG interpretation of the survey information and the URG guidance are acceptable but the staff reiterated the importance of the FME program to minimize the quantity of other potential debris.

### 4.3 Transport of Debris

Debris transport analyses were broken down into drywell and wetwell transport analyses. Drywell transport processes are governed primarily by primary system depressurization flows and subsequent break overflow and containment spray flows. The wetwell transport considers debris transport and settling within the suppression pool.

#### 4.3.1 Drywell Debris Transport

URG Guidance

The BWROG provided guidance regarding various options for estimating the fraction of the damaged insulation generated in the drywell that would be subsequently transported to the suppression pool. The BWROG approach combined debris generation and drywell debris transport into a combined methodology, such that the URG recommend fractions of the damaged insulation within the ZOI that should be considered likely to transport to the suppression pool for each type of insulation.

A number of aspects were considered by the BWROG in determining these recommended fractions. First of all, the debris was categorized into three groups, such that the transport of each group could be considered independently of the other groups. Based on the condition of debris recovered in the AJIT tests, the damaged fibrous insulation was categorized as:

- Fines
- Large Pieces

- Blankets

The damaged RMI debris was categorized as:

- Small Pieces (<6 in$^2$)
- Large Foils (>6 in$^2$)
- Intact Assemblies

The fibrous "fines" and the RMI "Small Pieces" were generally considered transportable because they would pass through a typical grating with ease. A continuous grating would stop virtually all of the other debris categories.

For fibrous debris, the "large pieces" and "blankets" were effectively treated in the BWROG analyses as a combined group referred to as "blanket material". In both cases, a grating effectively stopped both from transporting and both were subjected to erosion by break overflow. The insulation within the inner 3 L/D was assumed completely destroyed into transportable debris.

The BWROG used AJIT data to derive the relative fractions of the insulation destroyed into one of three size categories. These fractions depended upon the type of insulation and for some insulation types, depended upon whether the insulation was originally located above or below the lowest elevation grating in the drywell. The BWROG calculated these fractions as integral values averaged over the entire ZOI. These URG fractions are listed in Table 4-1. For example, 77% of the damaged NUKON™ within the ZOI was considered "Blanket Material" and the remaining 23% was "fines."

***Table 4-1. Fractions of Blanket Material with Low Transport Efficiency***

| Insulation Material | Fraction of Blanket Material with Low Transport Efficiency |
|---|---|
| NUKON™ | 0.77 |
| Temp Mat™ | 0.84 |
| K-Wool | 0.78 |
| Knauf® | 0.70 |
| NUKON™ Jacketed with Sure-Hold Bands | 0.85 |
| Calcium Silicate with Aluminum Jacketing | 0 |
| Koolphen-K® | 0.74 |

The BWROG estimated the transport fractions for each debris category for both fibrous and RMI debris. These fractions are listed in Table 4-2. The BWROG recommended that 100% of the fibrous fines and the RMI small pieces be considered as transported to the suppression pool for Mark I and Mark III plants as a combined result of both blowdown and washdown processes and for both MSL and RL breaks. However, for Mark II plants, the BWROG limited the transport of fibrous fine debris to 50% for MSL breaks and 56% for RL breaks and RMI small debris to 10% for MSL breaks and 5%C for RL breaks. These estimates were based on small-scale experimental data and the analysis of the water flow on drywell floors.

For larger debris, either fibrous or RMI, no direct transport to the suppression pool was assumed for debris generated above the lowest grating. For larger pieces of fibrous debris generated below the lowest grating, a fraction of this debris was assumed to directly transport to the suppression pool. For Mark I and Mark III plants, this fraction was estimated at 70% but for Mark II plants, the estimate was reduced to

30%. Larger pieces of RMI were not assumed to transport to the suppression pool (generated either above or below a grating). The remaining mode of transport, applicable to fibrous debris, was erosion by break overflow. Here, an assumed 25% of blanket-material remaining in the drywell would be located so that it would be plummeted by the break overflow and the 25% of this material would be eroded away and transported to the suppression pool, resulting in 6.25% of blanket-material transporting to the suppression pool. Lacking appropriate data, an erosion fraction of 1.0 was assumed for calcium silicate, Koolphen-K, and Min-K insulations (non-fibrous). The URG did not address breaks that could result in debris being generated both above and below the lowest grating. Further, the URG did not specifically address offset or splits gratings where depressurization flows could partially bypass the gratings.

*Table 4-2. URG Drywell Transport Fractions*

| Fibrous Insulation Debris | | RMI Debris | |
|---|---|---|---|
| **Size Category** | **Transport Fraction** | **Size Category** | **Transport Fraction** |
| Fines | 1.0 for Mark I & III<br><br>0.5 for Mark II MSLB<br>0.56 for Mark II RLB | Small Pieces | 1.0 for Mark I & III<br><br>0.1 for Mark II MSLB<br>0.05 for Mark II RLB |
| Blanket Material Above Grating | No Direct Transport<br>25% Erosion of 25% of Pieces = 6.25% | Large Foils Above Grating | No Transport<br>No Erosion |
| Blanket Material Below Grating | 70% Direct + 6.25% Erosion of Remaining 30% for Mark I & III<br><br>30% Direct + 6.25% Erosion of Remaining 70% for Mark II | Large Foils Below Grating | No Transport<br>No Erosion |

These debris generation and transport fractions were further developed into combined debris generation and transport factors for each type of insulation. Unjacketed NUKON™ debris generated above the lowest grating for example, 23% of the damaged insulation was turned into fine debris that subsequently transport directly to the suppression pool. Then, 6.25% of the remaining 77% (blanket material) was eroded away and also transported for a total of 28% of the ZOI insulation transported into the suppression pool (i.e., 0.23 + 0.0625 x 0.77 = 0.28). Below the lowest grating, the total debris transported would consist of the 23% fines, 70% of the 77% blanket material, and 6.25% of the non-transport blanket-material that was subsequently eroded (i.e., 0.23 + 0.70 x 0.77 + 0.0625 x 0.30 x 0.77 = 0.78). Combined debris generation and transport fractions for the Mark I and the Mark III plants are listed in Table 4-3.

The BWROG did not develop transport factors for materials other than insulation materials. Where an approved transport factor is not available, licensees should either assume a factor of 1.0 or perform the testing/analysis necessary to justify another factor.

NRC Evaluation

The URG recommendations were based primarily on data from small-scale debris generation and transport tests conducted by the BWROG. Because the staff had several concerns related to scaling small-scale transport test data to BWR conditions, the staff conducted confirmatory research to verify the accuracy of guidance provided by the URG. Specific concerns included whether or not the flow rates and flow durations in the small-scale tests were prototypical of conditions that would exist in BWR drywells following a LOCA. The staff's analysis indicated the BWROG test flow velocities were on the order of 50% of prototypical velocities for a postulated large MSL break. It was not clear to the staff in evaluating the BWROG test program whether the test results were reasonable, conservative, or non-conservative if scaled to a full-sized plant. Therefore, the staff concluded that there is inadequate substantiation for the BWROG claim that the use of these test results would conservatively bound the drywell transport fraction. The NRC sponsored drywell debris transport study (see Section 2.2.3) [NUREG/CR-6369] demonstrated that a high percentage of fine debris could transport to the suppression pool and that the transport of the debris is both plant-specific and break-specific.

**Table 4-3. Combined Debris Generation and Transport Fractions for Mark I, III***

| Material | Above Grating | Below Grating |
|---|---|---|
| Darchem DARMET® | 0.50 | 0.50 |
| Transco RMI | 0.50 | 0.50 |
| Jacket NUKON™ with modified Sure-Hold Bands, Camloc® Strikers, and Latches | 0.15 | 0.15 |
| Diamond Power MIRROR® with modified Sure-Hold Bands, Camloc® Strikers, and Latches | 0.50 | 0.50 |
| Calcium Silicate with Aluminum Jacketing | 0.10 | 0.10 |
| K-Wool | 0.27 | 0.78 |
| Temp-Mat™ with Stainless Steel Wire Retainer | 0.21 | 0.76 |
| Knauf® | 0.34 | 0.80 |
| Jacketed NUKON™ with Standard Bands | 0.28 | 0.78 |
| Unjacketed NUKON™ | 0.28 | 0.78 |
| Koolphen-K® | 0.45 | 0.45 |
| Diamond Power MIRROR® with Standard Bands | 0.50 | 0.50 |
| Min-K | 1.0 | 1.0 |

* Same fractions used for steam and water breaks.

Estimating the erosion of large fibrous debris depends upon estimating the quantity of debris subjected to erosion, the rate of erosion, and the duration of the erosion. The URG estimate of 25% of the debris being subjected to erosion was based on engineering judgment and was considered by the BWROG to be sufficiently conservative to ensure that a conservative estimate of the mass of eroded debris. The staff evaluation of the URG guidance for assuming erosion of large fibrous debris concluded that the guidance is adequate provided that the unthrottled ECCS flow does not continue for more than 3 hours. If unthrottled flow continues for more than three hours, the staff concluded that licensees should determine an appropriate fraction for their analysis. Note that NRC sponsored research demonstrated that erosion of NUKON™ occurs at a linear rate (see Section 2.1.1.5), which facilitates scaling NUKON™ erosion. Based on the overall level of conservatism in the URG guidance, the staff concluded that the URG guidance regarding the prediction of the erosion of large fibrous debris by break overflow was acceptable.

The staff reviewed the URG destruction fractions, i.e., the determination of the fractions of the destroyed insulation that would remain in "blanket material" form with low transport efficiency. On the basis of NRC-sponsored research, the staff noted a number of strengths and conservatisms associated with the URG guidance. The blanket arrangement used in the BWROG tests was conservative, (e.g., the orientation of blanket seams and jacket latches relative to air jet nozzle). The BWROG tests oriented seams and latches to maximize blanket destruction. In BWR drywells, insulation blankets could well be protected by other structures located in the jet pathway and that this protection was not accounted for in the tests. In the BWROG air jet tests, the insulation blankets were oriented normal to the air jet to maximize destruction, but in BWR drywell, the majority of the piping (>65%) and therefore the insulation blankets would be located parallel to the jet flow. Thus, much less of the blanket would be subjected to the full jet flow. The weakness of the BWROG tests data was that the test data was very limited for several types of insulation, specifically Temp-Mat, K-wool, and some of the RMI, however the staff concluded that the URG methods for determining the ZOI and debris generation are sufficiently conservative to outweigh this weakness.

The primary criticism of the URG drywell debris transport guidance was the substantially reduced transport fractions applied to the Mark II containments relative to the Mark I and III containments. The NRC sponsored tests of the Mark II geometry did not identify any basis to conclude that the transport fraction for a Mark II containment would be different from that of a Mark I or a Mark III containment. Given the uncertainty associated with estimating the debris transport fraction, which includes the uncertainty associated with estimating size distribution and quantities of insulation damaged, the staff concluded that the BWROG transport fractions for fibrous debris in Mark II containments are both non-conservative and unacceptable and that Mark II containments should use the same transport fractions as the Mark I and Mark III containments.

### 4.3.2 Suppression Pool Debris Transport

The staff extensively considered the transport of debris within the suppression pool. NRC sponsored experiments [NUREG/CR-6224] explored the transport of both fibrous and RMI debris when subjected to chugging and post-chugging periods following a LOCA. The BWROG primarily relied on these experiments to develop guidance documented in the URG.

URG Guidance

The recommends that:

- Licenses not take credit for settling of debris in the pool during the high-energy phase of an accident during which the suppression pool undergoes through mixing.

- Licensees assume that all suppression pool debris will be resuspended during this phase.

- Licensees have the option to:

    - Determine the post-energy phase settling rates using the methods described in Appendix B to NUREG/CR-6224 or

    - Assume that there will be no settling of debris in the pool even after the high-energy phase terminates and the pool returns to quiescent conditions.

NRC Evaluation

The staff found no deficiencies in the recommendations documented in the URG, therefore the URG guidance for debris transport within the suppression pool is acceptable. However, the staff notes that Appendix B to NUREG/CR-6224 provides the required data only for selected types of insulation and particulates and licensees using the methods described therein for other types of insulation debris should be cautious about extrapolating the experimental data and models.

## 4.4 Strainer Head Loss

The BWROG devoted considerable resources to explore various generic designs for large passive strainers that can be used to replace the existing truncated core strainers. The four designs that were explored included: the 20-point star strainer, 60-point star strainer, a small-stacked disk strainer, and a large-stacked disk strainer. For each design, the BWROG obtained head loss data for various combinations of fibrous insulation debris, sludge, miscellaneous debris (referred to as the Recipe in the URG), and RMI debris. The general characteristics (size, shape, etc.) of the debris used in the BWROG head loss tests (see Section 3.3.2) were consistent with those used in the NUREG/CR-6224 study. Note that the debris characteristics selected for use in the NUREG/CR-6224 study were selected to maximize the resulting head loss.

URG Guidance

On the basis of the BWROG head loss test data, the BWROG developed two analytical methods to estimate head loss across the strainers; one method applied to fibrous/particulate debris beds and the other to metallic debris beds.

The fibrous/particulate debris beds method provided a non-dimensional head loss correlation that can be used to estimate the head loss across an alternate strainer design. The URG specified that this correlation is valid for lower debris loadings. For higher debris loadings, the correlation is not applicable and the URG recommends that licensees conduct strainer-specific testing.

The RMI debris bed method provided a stepwise process for estimating the strainer's RMI capacity and head loss across RMI debris beds. This method recognizes that RMI beds on strainers reach a saturation thickness beyond which flow-induced drag forces are not large enough to retain the RMI pieces on the strainer surface. The URG specified this saturation thickness as a function of the type of RMI debris and provided a correlation to estimate head loss across the RMI debris beds.

For mixed beds (i.e., fiber/particulate and RMI), the URG suggests that RMI does not contribute additional head loss in combination with other types of debris and that it may actually reduce the head loss. On that basis, the URG states that head loss for mixed beds can be evaluated by ignoring RMI altogether and estimating the head loss resulting from the other debris. Note that subsequent to the NRC review, the BWROG agreed to the NRC position that this may not be true in all situations, thereby agreeing to resolve the mixed bed issue on a plant-specific basis.

### NRC Evaluation

The staff found the URG to contain valuable and useful data for predicting strainer head loss; however, the staff's review revealed several concerns regarding the quality and applicability of these data. Therefore, the staff conducted several confirmatory calculations to validate the calculational procedures provided in the URG and to examine the applicability of the calculational procedures to the actual plant conditions. On the basis of these analyses, the staff concluded that the head loss correlation in the URG is unreliable and incomplete for plant analyses, and is, therefore, unacceptable. The staff strongly recommends that utilities use vendor-provided data to qualify strainer designs, rather than relying on the correlations and calculational procedures specified in the URG. In addition, the staff recommended that licensees' designs should be able to accommodate experimental uncertainties associated with correlations and/or calculational methods developed by the vendors.

Specific criticisms and reasons leading to the rejection of the URG head loss correlations are:

- The URG model was developed with limited ranges of data i.e., debris loadings and debris compositions, strainer approach velocities, and strainer design: therefore, the use of the model beyond these limitations is especially risky because the models are non-mechanistic in nature. Specifically:

  - The fibrous or RMI correlations are based on data obtained for lower debris loadings than would be expected in many plants and the non-mechanistic correlations cannot be extrapolated to higher loadings without additional substantive experimental or analytical work. The correlations were based on data where the debris loading was not sufficient to fill the troughs in the strainer. The staff believes that an extrapolation will lead to non-conservative head loss estimates.

  - The correlations are specific to the limited types of insulations tested. The model was developed using data for NUKON™ insulation; therefore, its extension to other fibers is inappropriate without additional substantive experimental or analytical work.

  - The RMI saturation thickness guidance was primarily developed using data for a star strainer an assumption that the debris bed would resemble a sphere. Therefore, the RMI conclusions are specific to the strainer design tested and the type of RMI used in the test. No basis was provided for extrapolating to their RMI types and strainer designs. Further, the RMI debris size distributions, as tested, were limited.

- The staff has shown that, in many cases, the URG model under predicted the experimental data used to develop the model; therefore, a licensee would need to review each head loss prediction in detail relative to the applicable data, to ensure a valid prediction.

- The BWROG used limited data to develop the “bump-up” factor used to account for miscellaneous debris. Although the bump-up factors provide a conservative means for extending the fiber/particulate bed correlation to include other miscellaneous debris, this factor can create severe design impacts if used, because the factor was found to severely over predict the head loss in many cases.

- Reasonable steady-state conditions were not achieved in a significant number of the test runs that were used to develop the URG models.

- Some of the tests were conducted with thin fiber beds and large amounts of particulate debris. In these tests, the BWROG assumed that the debris bed captured all particulate debris. This assumption is incorrect because the amount of particulate captured in these tests was indeterminate and use of this data may lead to erroneous head loss predictions.

- The URG did not specify model validation, parameter sensitivity, or uncertainty analysis. This omission leaves open the question of whether a particular combination of input parameters could cause the URG model to severely under predict head loss.

The staff concluded that the BWROG generalized statement regarding the head loss of a fiber plus particulate debris bed bounding the head loss of a fiber, particulate, and RMI debris bed does not hold true in all situations. On the basis of the staff’s analysis, the staff believes this issue should be resolved on a plant-specific basis. Licensees should ensure that their strainer vendor review the debris combinations of interest for their plant and ensures that the vendor data supports the head loss used in their plant-specific analysis.

The staff had the following specific concerns regarding the application of the URG:

- The staff is concerned that applying the URG strainer head loss model by blindly plugging numbers into a cookbook step-by-step procedure as outlined in the URG may lead to erroneous head loss predictions.

- The head loss predictions should use the same NUKON™ debris properties that were employed in developing the URG model because the models are not sufficiently mechanistic to account for the effects of varying these properties.

- The staff is concerned that applying the URG head loss prediction models to plant conditions that differ markedly from those conditions tested could lead to erroneous head loss predictions.

- The staff was concerned that the fibrous correlation might be used under high debris loading conditions where it is clearly invalid.

- While the staff conditionally agrees with the BWROG that the "thin-bed effects" are not likely to be an issue for the alternate strainer designs tested, particularly for strainers with deep crevices, the staff is concerned that experimental data are neither complete nor supported by sufficient qualitative analytical reasoning to substantiate the URG statement that the thin-bed effect is not a concern for alternative strainers.

### 4.5 Available Net Positive Suction Head (NPSH)

URG Guidance

The URG provides the BWROG guidance related to evaluating ECCS pump NPSH. The important points are:

- Licensees should not credit for containment overpressure greater than atmospheric pressure in determining available NPSH, unless such credit is in conformance with the plant's existing licensing basis.

- When evaluating available NPSH, licensees should consider a range of expected fluid temperatures unless the plant's licensing basis specifies the maximum expected fluid temperature. If specified, this temperature should be used unless plant's licensing basis is changed. The fluid temperature affects both the available NPSH margin and the head loss across the strainer.

- All strainers can be expected to be clean at the start of the postulated LOCA (i.e., it is not necessary to assume pre-existing blockage).

- If ECCS blockage analysis uses reduced ECCS flow through the strainers in order to meet NPSH requirements, licensees should exercise care to ensure that changes in ECCS flow rates are consistent with inputs and assumptions used in the evaluation model required by 10 CFR 50.46 to calculate ECCS cooling performance. Also, licensees should ensure that appropriate operating and emergency procedures are in place.

- Licensees should carefully evaluate the applicability of head loss correlations before applying such correlations to estimate head loss across the strainers.

- The ECCS strainer design should be consistent with the plant's limiting single-failure assumptions.

The BWROG notes in the URG that a part of a licensee's resolution to the strainer clogging issue could include a licensing basis change.

NRC Evaluation

The staff finds no deficiencies in the recommendations presented in the URG. The staff has the following additional comments:

- Licensees should ensure that their calculations are consistent with their licensing bases. For instance, no operator action is typically credited for the first 10 minutes during a postulated LOCA, therefore NPSH should be evaluated at runout flow until the plant's licensing basis allows otherwise.

- Licensees are strongly encouraged to design strainers with performance characteristics that increase the NPSH margin above the minimum required.

- The staff concurred that additional containment overpressure (other than an amount already approved by the staff for the existing licensing basis) should not be used as part of the resolution of this issue.

### 4.6 References

RG-1.82, Regulatory Guide 1.82, Revision 2, "Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident," U. S. Nuclear Regulatory Commission, May 1996.

Bulletin 96-03, "Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling-Water Reactors," NRC Bulletin to BWR Licensees, May 6, 1996.

NEDO-32686, Rev. 0, "Utility Resolution Guidance for ECCS Suction Strainer Blockage," BWROG, November 1996.

NRC-SER-URG, "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.

10 CFR Part 50, Title 10, Code of Federal Regulations, published by the Office of the Federal Register, National Archives and Records Administration, U. S. Government Printing Office, January 1, 1997.

NUREG/CR-6224, G. Zigler, J. Bridaeu, D. V. Rao, C. Shaffer, F. Souto, W. Thomas, "Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris," Final Report, U. S. Nuclear Regulatory Commission, October 1995.

NUREG/CR-6369, Volume 1, D. V. Rao, C. Shaffer, and E. Haskin, "Drywell Debris Transport Study," U. S. Nuclear Regulatory Commission, SEA97-3501-A:14, September 1999.

NUREG/CR-6369, Volume 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-6369, Volume 3, C. Shaffer, D. V. Rao, and J. Brideau, "Drywell Debris Transport Study: Computational Work," SEA97-3501-A:17, September 1999.

BWROG Letter OG95-388-161, Attachment 4, “BWR Owners Group Suppression Pool Sludge Generation Rate Data,” June 1995.

BWROG Letter OG96-321-161, Attachment 2, “Suppression Pool Sludge Particle Distribution Data – Averaged Distribution Calculation,” September 1994.

(This page intentionally left blank)

## 5.0 INDUSTRY IMPLEMENTATION

As discussed earlier in this report, the NRC staff issued NRC Bulletin 96-03, "Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling-Water Reactors," on May 6, 1996. All BWR licensees were requested to implement appropriate measures to ensure the capability of the ECCS to perform its safety function following a LOCA. The staff had identified three potential resolution options but allowed licensees to propose others that provided an equivalent level of assurance. The three options identified by the staff were: 1) to install a large capacity passive strainer designed with sufficient capacity to ensure that debris loadings equivalent to a scenario calculated in accordance with Section C.2.2 of RG 1.82, Revision 2 and do not cause a loss of NPSH for the ECCS, 2) install a self-cleaning strainer that automatically prevents strainer clogging by providing continuous cleaning of the strainer surface with a scraper blade or brush, and 3) install a backflush system that relies on operator action to remove debris from the surface of the strainer to prevent it from clogging. Option 1 had the advantages of being completely passive so that operator intervention was not required and it did not require an interruption of ECCS flow. Licensees choosing Option 1 for resolution were required to establish new or modify existing programs, as necessary, to ensure that the potential for debris to be generated and transported to the strainer surface does not at any time exceed the assumptions used in estimating the amounts of debris for sizing of the strainers in accordance with RG 1.82, Revision 2. Option 2, like Option 1, would not rely on operator action or interrupt ECCS flow but it did rely on an active component to keep the strainer surface clean that would be fully exposed to the LOCA effects in the suppression pool, therefore, appropriate measures must be taken to ensure its operability. With the selection of Option 3, extensive measures had to be taken: 1) to maximize the amount of time before clogging could occur; 2) to ensure that instrumentation and alarms indicate when strainer differential pressure increases; 3) to institute operator training on recognition and mitigation of a strainer clogging event; and 4) to implement surveillance to ensure the operability of the strainer instrumentation and backflush system. All licensees were requested to implement these actions by the end of the first refueling outage starting after January 1, 1997.

The BWROG undertook a research program with the intent 1) to evaluate several potential solutions for resolving the BWR strainer blockage, and 2) to develop a standard industry approach to resolution of the issue that complies with 10 CFR 50.46 and regulatory guidance provided in RG 1.82, Rev. 2. Among the resolution options explored experimentally by the BWROG included 1) several concepts for passive strainer designs, 2) passive strainers with backflush capability and 3) one self-cleaning strainer. In addition, BWROG carried out engineering studies to examine feasibility of adopting European solutions to the US BWR nuclear power plants. Based on the research, the BWROG concluded that replacing the existing strainers with large-capacity passive strainers is the preferred option. Furthermore, it is recommended that backflush should be considered for installation as a "defense-in-depth" option, but not as a front-line option. Similarly, BWROG concluded that although a self-cleaning strainer installation is a feasible option, licensees would have to resolve significant design, qualification and surveillance issues with the NRC on a plant specific basis. Thus BWROG all but ruled out all options other than installation of replacement passive strainers that are large and would reliably mitigate adverse impacts of debris accumulation and maintain sufficient NPSH Margin through out the accident.

The BWROG research into passive strainer design was limited in scope, with the primary focus of evaluating feasibility of certain concepts, such as star strainer and stacked-disk strainer. This research program and the results are summarized in the BWROG URG Volume 2 [NEDO-32686]. The primary design concept is to maximize the strainer surface area (i.e., area of the perforated surface through which water flows into the strainer) while minimizing the strainer circumscribed surface area. These design concepts were further refined or reengineered as required by the strainer vendors to suit a particular plant need.

## 5.1 Replacement Strainer Designs

Four types of passive strainer designs were ultimately installed at one or more US Nuclear Power Plants. Although these designs differ significantly from each other, with the exception of some Mark III designs, the designs had one common feature in that the designs all rely on cavities, or troughs or traps where debris can collect on the strainer surface without significantly increasing the head loss across the strainers. Some Mark III designs simply relied upon lowering the strainer approach velocity.

<u>PCI Stacked Disk Strainers</u>

PCI strainers were designed, fabricated and installed by the Performance Contracting Incorporated (PCI). Figure 5-1 is a photograph of the PCI strainers installed at one of the BWRs. Among the unique design features of PCI strainer is the internal core tube incorporated to ensure uniform approach flow. The core tube is shown in Figure 5-2. Several prototypes of the PCI stacked disk strainer were tested for head loss measurements at the Electric Power Research Institute (EPRI) test facility and other test facilities. PCI reports provide a description of the test program and the results [PCI-97, PCI-NPD-CE03, CDI-96-22]. The hydraulic performance of PCI strainers was also tested by the BWROG [NEDO-32686] and as part of qualification testing by Commonwealth Edison [LaSalle-98]. LANL review of the PCI strainer design and performance characteristics is summarized in LA-UR-00-5159.

<u>GE Stacked Disk Strainers (Proprietary)</u>

The GE stacked disk strainer design differs from the conventional stacked disk strainer designs. The design details of the strainer and the hydraulic performance characteristics of the strainer were provided to NRC for review by GE [NEDC-32721P]. NRC review of the GE strainer performance and important conclusions are summarized in LA-CP-99-07 and the NRC safety evaluation report dated February 9, 1999. As of the date of this report, GE's hydrodynamic loads methodology is still undergoing NRC review. GE strainers were installed at Duane Arnold, Hatch-1, Oyster Creek, River Bend, Cooper, Fermi-2, Susquehanna –1, 2, Nine Mile Point – 2, Brown Ferry – 2, 3.

<u>ABB Combustion Engineering Strainers (Proprietary)</u>

The ABB strainers use another innovative type of approach to extend the screen area and thus reduce the approach velocity at the plate. The design was tested and demonstrated by ABB at the EPRI facility [ABB-97]. The ABB strainers were installed at Peach Bottom – 2, 3 and Limerick – 1, 2. LANL review of ABB strainer performance and related issues are summarized in the Limerick audit report entitled, "On-Site Audit of the Limerick Nuclear Power Plant Emergency Core Cooling System Strainer Blockage Resolution," dated January 21, 2000 [LANL-UR-00-426] and the NRC audit report [Memo-14-00].

Mark III Strainers

The Mark-III BWR owners sponsored a research program to design and qualify a special strainer that is best suited for Mark III containments. This design takes advantage of the Mark III containment layout. The strainers are very large and are located on the floor of the suppression pool. Figure 5-3 is a photograph of an individual strainer module from the ¼ scale test facility. Several (up to 50) of these full-scale strainer modules are joined together to form the strainer in the plant. Figure 5-4 provides a pictorial representation of the assembled strainer. The resulting strainers have surface areas in excess of 6000 $ft^2$. These strainers were tested at the quarter scale testing. NRC review comments on the testing program and the application of the test results in the plant submittals are summarized in the Grand Gulf Audit Report and LANL TER [LA-CP-00-18]. This strainer is also installed at Perry and Clinton.

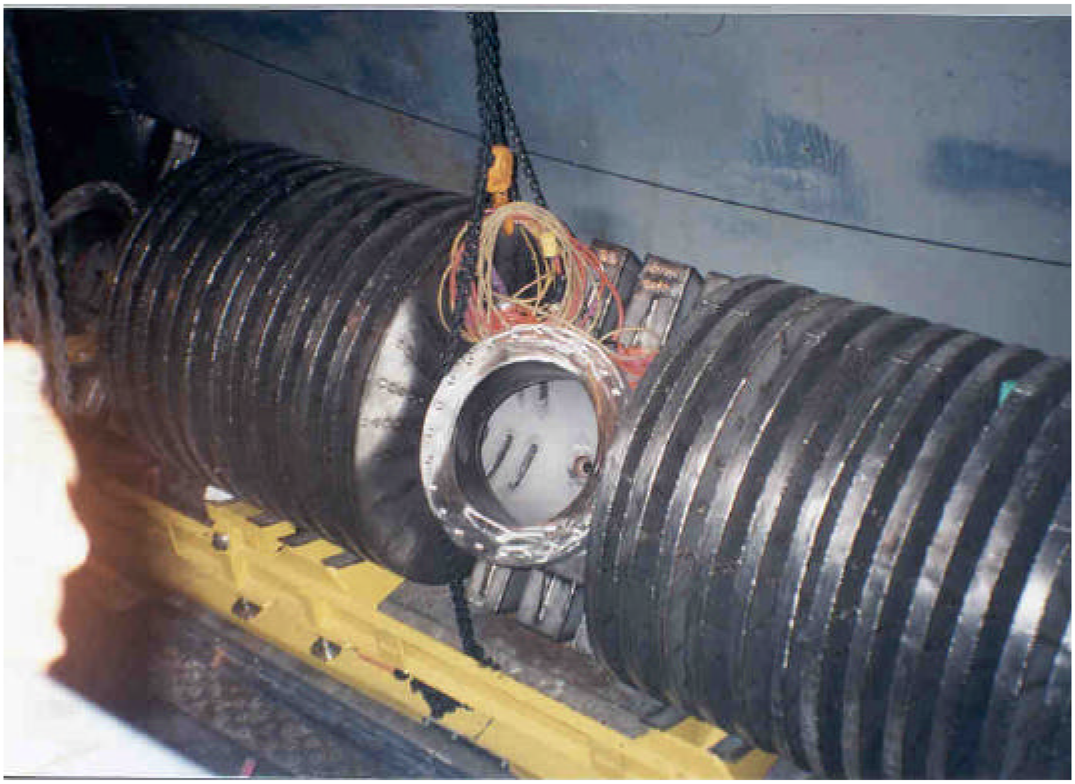


**Figure 5-1. PCI Stacked Disk Strainer being installed at Pilgrim Nuclear Power Plant.**

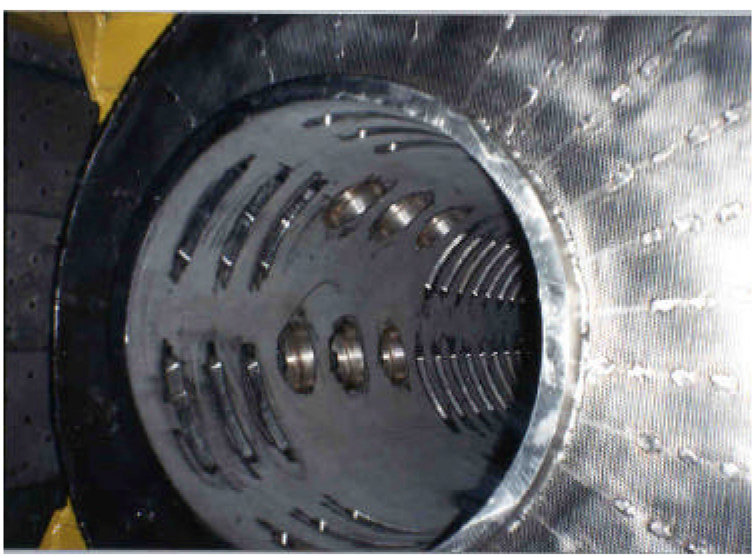


**Figure 5-2. The Core Tube used in the PCI Stacked Disk Strainers. Core tube provides structural support and also makes the approach flow uniform.**

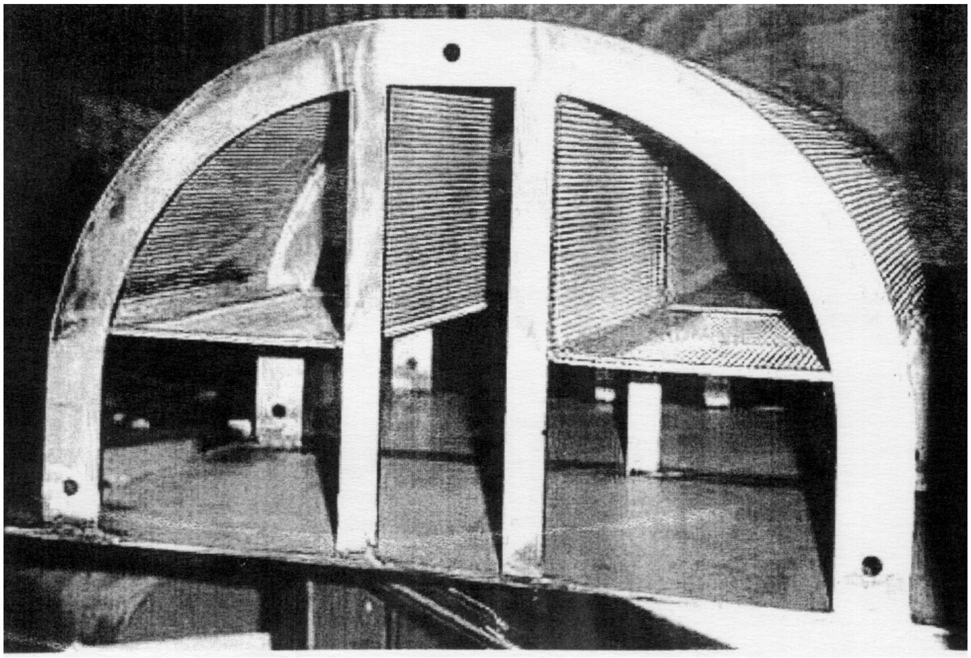


**Figure 5-3. Individual Panel of Mark III strainer installed at Grand Gulf Nuclear Power Plant.**

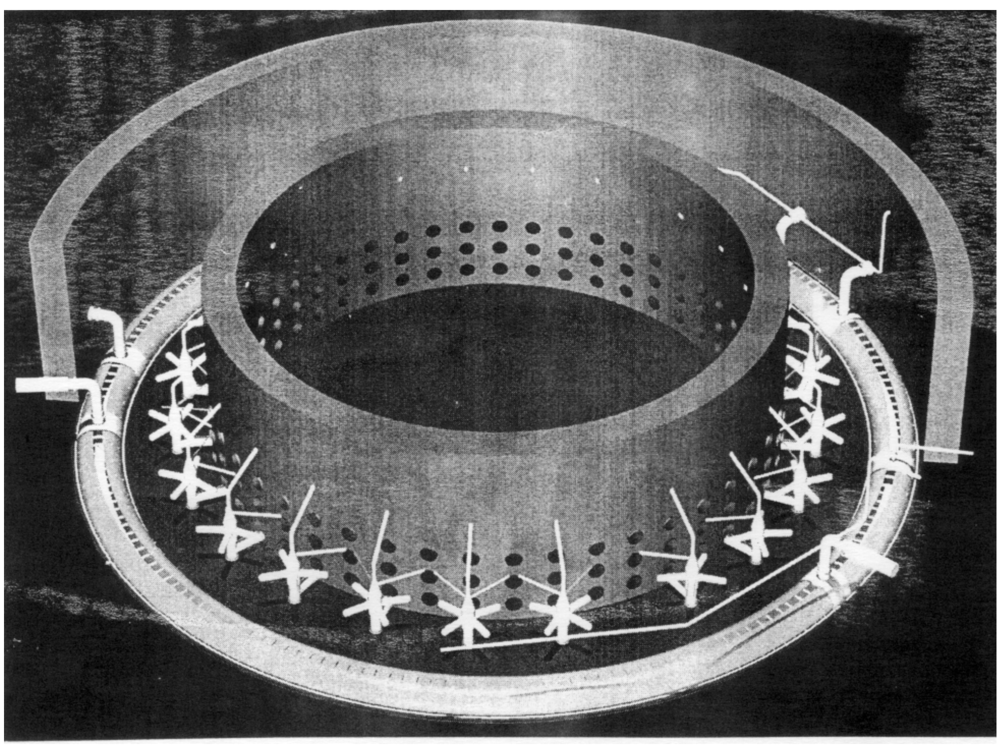


**Figure 5-4. Pictorial Illustration of the Mark III strainer as installed in the Suppression Pool.**

The replacement strainer testing and qualification programs were also discussed as part of Section 3 of this report. Sections 3.1.2 through 3.1.5 provided NRC review of the test programs and important conclusions. The NRC review found that the hydraulic performance testing program(s) used by the individual vendors or licensees met the following the objectives:

- The debris sizes used in the test program were prototypical of the debris expected to reach the strainers following a LOCA. Furthermore, the debris sizes compared favorably with those previously used in NRC test programs.

- The test procedures used to measure head loss across the strainers were reasonable, although in some cases the testing was terminated before steady state head loss was reached.

- Direct application of the head loss data obtained for the prototype strainers in the plant submittals is probably not likely because the plant-specific designs varied significantly from the test prototypes.

NRC notes two deficiencies of the test programs:

- In some cases, the debris loads used in the test programs did not cover the entire range over which the strainers may be applied. For example, limited, if any, head loss data is available for special debris such as aluminum RMI. This made strainer head loss estimation difficult.

- The strainer-specific head loss correlation(s) often lacked the appropriate theoretical or analytical support and therefore may not be extrapolated outside their original range of testing.

In spite of these reservations, NRC found that use of the data obtained from the test program(s) in plant specific calculations was reasonable provided the vendor or the licensee uses the data within the original range of testing or provides a theoretical basis for extrapolating the data to other strainer designs or debris loads.

### 5.2 Overview of Industry Implementation

From the beginning, it was recognized both by NRC and the BWROG that none of the passive strainer designs are standardized designs (i.e., one-size fits all type of strainers). Further, it was recognized that additional analyses would have to play an important role in sizing the strainer. As a result, considerable effort was devoted in the BWROG URG to provide detailed guidance on performing plant-specific analyses to estimate potential for debris loads on the ECCS Suction strainers following a LOCA, taking into consideration the guidance provided in the RG 1.82, Rev. 2.

Every single operating US BWR plant replaced the old semi-conical type strainers installed on Low Pressure Core Injection (LPCI) and Low Pressure Core Spray (LPCS) pump suctions. The industry addressed the requirements of NRC Bulletin 96-03 by installing large capacity passive strainers in each plant (i.e., NRC Option 1) with sufficient capacity. There were however a few plants that installed the replacement strainer before the BWROG URG and the URG SER were issued. The supporting analyses for these plants deviated in some cases significantly from the approved URG methodologies.

The NRC closely followed plant implementations through active participation in the industry meetings, review of plant-specific submittals, and by performing onsite audits of four nuclear power plants. Participation in the industry meetings facilitated exchange of information with the BWROG and individual licensees, and provided a means for NRC to clarify specific elements of the regulatory guidance (e.g., thin-bed head loss issue). The participation also helped the NRC staff to keep abreast with the methods used by the licensees and major uncertainties in some of the assumptions in sizing the strainers.

### 5.2.1 NRC Review of Plant Specific Submittals

Plant-specific submittals were provided by some licensees as part of licensing amendment requests, consistent with the requirements of 10 CFR 50.90 and 10 CFR 50.59. Most of the licensing amendments were related to licensee intent to use higher containment overpressure credit in the NPSH calculations.

Prior to the completion of the staff's review of the URG, some submittals were provided for NRC review during the strainer sizing and design phase to minimize the replacement project risk. A list of plants that provided replacement strainer details for NRC review are as follows: Browns Ferry – Units 2 and 3; Brunswick – Units 1 and 2; Cooper; Hatch – Units 1 and 2; Hope Creek –Units 1 and 2; LaSalle – Units 1 and 2; Limerick – Units 1 and 2; Peach Bottom – Units 2 and 3; Pilgrim –Unit 1; and Quad Cities – Units 1 and 2.

The sizes of strainers installed at some of the operating BWR plants are listed below in Table 5-1. As evident the replacement strainers are in general very large compared to pre-NRCB 96-03 strainers. The flow velocities at the plate for the replacement strainers ranged between about 0.1 ft/s and 0.001 ft/s.

**Table 5-1. The strainer design details of some of the plants reviewed by NRC**

| Plant Name | System | Strainer Flow (GPM) | Fiber Debris Mass (lbm) | Sludge Mass (lbm) | Strainer Screen Area ($ft^2$) | Strainer Circum-scribed Area ($ft^2$) | Strainer Approach Velocity (ft/s) |
|---|---|---|---|---|---|---|---|
| Duane Arnold | RHR | 9600 | 255 | 357 | 388 | 47.43 | 0.002 |
| | CS | 3100 | 146 | 204 | 310 | 35.47 | 0.003 |
| Hatch-1 | All | 5300 | 156 | 129 | 186 | 32.92 | 0.003 |
| Oyster Creek | All | 6133 | 189 | 98 | 475 | 63.49 | 0.011 |
| River Bend | All | 6400 | 1338 | 201 | 606 | 63.24 | 0.007 |
| Cooper | RHR | 9349 | 22 | 132 | 423 | 52.11 | 0.007 |
| | CS | 6135 | 38 | 226 | 236 | 34.20 | 0.002 |
| Fermi-2 | RHR | 10000 | 33 | 163 | 387 | 47.26 | 0.005 |
| | CS | 6350 | 21 | 103 | 387 | 47.60 | 0.008 |
| Susquehanna-1, 2 | RHR | 5000 | 103 | 1235 | 204 | 32.94 | 0.000 |
| | CS | 3175 | 41 | 489 | 131 | 21.57 | 0.001 |
| Nine Mile Point-2 | RHR | 8200 | 15 | 8 | 353 | 48.18 | 0.099 |
| | CS | 7800 | 15 | 8 | 353 | 48.45 | 0.098 |
| Browns Ferry | All | 13542 | 4 | 205 | 298 | 42.67 | 0.003 |

NRC reviewed each plant submittal(s). Based on the review of the plant submittals it was the NRC's conclusion that the industry addressed the requirements of NRC Bulletin 96-03 by installing large capacity passive strainers in each plant (i.e., NRC Option 1). The strainers had sufficient capacity to accommodate the debris loads postulated to reach the strainer following a worst-case large break LOCA.

The NRC found that in most cases the licensees had voluntarily used conservative assumptions in sizing and designing the replacement strainers. This voluntary conservatism was in addition to conservatism built-in to the URG guidance. In the case of Quad Cities, the NRC concluded that the debris generation and transport methods used to size the strainer were not consistent with the NRC or URG guidance. The confirmatory analyses performed by the NRC found that this inconsistency was a reflection of the fact that the licensee designed the strainer before the BWROG URG was issued but that the strainer itself is adequately sized to provide sufficient NPSH margin through out the accident.

### 5.2.2 Onsite Plant Audits

Four BWR plants were chosen for detail onsite audit by NRC staff; these plants are Limerick (BWR/4 Mark II), Dresden (BWR/3 Mark I), Duane Arnold (BWR/4 Mark I), and Grand Gulf (BWR/6 Mark III). The primary objective of the audit was to independently confirm the adequacy of the strainer size and to independently evaluate performance of the replacement strainers under LOCA conditions. In addition, the audit also focused on reviewing the supporting documentation to identify any concerns regarding the licensee's strainer design criteria and strainer performance analyses. In particular, the review of licensee strainer design analyses did the following:

1. Evaluated how the licensee estimated the quantity of debris used for sizing the strainer, that is, determined if the methodologies used for selecting the breaks were consistent with RG 1.82, Rev. 2, and provided reasonable estimates for debris generation and transport.

2. Evaluated the licensee’s proposed strainer design criteria and strainer performance.

During the plant audit, NRC staff and its contractors undertook a detailed review of the documentation provided by the licensee. As necessary, the staff performed several independent calculations. The type of analyses performed by the staff during the audit included:

1) Debris Generation Calculations. Wherever possible and/or necessary, the NRC staff used the reactor piping layout drawings to independently map the zone of influence (ZOI) and estimate the quantity of debris contained within the ZOI.

2) Debris Loading Evaluations. In every case, the staff independently calculated the debris loads expected on the strainer following a LOCA and how these loadings compared with the licensee estimates. The comparison provided a measure of the margin-of-conservatism in the licensee calculations.

3) Strainer Head Loss and NPSH Evaluations. NRC staff used a modified version of the BLOCKAGE computer code to estimate head losses corresponding to various postulated ECCS responses (e.g., single-failure criterion). These head loss estimates were compared with the licensee estimates to draw conclusions regarding strainer performance.

In addition, NRC staff paid close attention to judge the effectiveness of the licensee foreign materials exclusion (FME) program. The results of the technical analyses are summarized in the audit reports. These TERs were:

- LA-CP-00-18, “On-Site Audit of the Grand Gulf Nuclear Station Emergency Core Cooling System Strainer-Blockage Resolution,” January 3, 2000.

- LA-UR-01-738, "On-Site Audit of the Dresden Nuclear Power Plant Emergency Core Cooling System Strainer Blockage Resolution,” Undated.

- LA-UR-00-426, "On-Site Audit of the Limerick Nuclear Power Plant Emergency Core Cooling System Strainer Blockage Resolution," January 21, 2000.

- LA-CP-99-346, "On-Site Audit of the Duane Arnold Energy Center Emergency Core Cooling System Strainer Blockage Resolution," December 1999.

Table 5-2 provides a brief summary of the issue resolution for the audited plants. More detailed discussions on each plant are provided below.

**Table 5-2. Issue Resolution Summary for Audited Plants**

| Plant | Design | Insulation Types Located in the Drywell | Plant Resolution | Resolution Basis | NRC Audit Findings |
|---|---|---|---|---|---|
| Grand Gulf Nuclear Station | BWR/6 Mark III | RMI* Kaowool Calcium-Silicate Fiberglass | Increased existing strainer surface area from 170 $ft^2$ to 6253 $ft^2$ by installing passive large-capacity suction strainers. | Licensee based analyses on URG supported by ¼ scale testing. | Licensee conservatively estimated debris generation, transport, and strainer head loss. NRC estimated head-losses substantially less than licensee estimate. |
| Limerick | BWR/4 Mark II | NUKON * Min-K RMI** | Increased existing strainer surface area from 269 $ft^2$ to 2715 $ft^2$ by installing passive large-capacity suction strainers. | Licensee based analyses on URG. Head-loss estimate less than 4 ft-water and NPSH margin of 12 ft-water. | Licensee conservatively estimated debris generation, transport, and strainer head loss. NRC estimated head-loss less than 2 ft-water. |
| Duane Arnold | BWR/4 Mark I | NUKON * Calcium-Silicate** RMI** Lead Wool** | Increased existing strainer surface area from 38 $ft^2$ to 1359 $ft^2$ by installing passive large-capacity suction strainers. | Licensee based analyses on URG and GE head loss correlation. | Licensee used NRC-approved methods to estimate debris generation and transport, and estimated conservative strainer head loss. |
| Dresden | BWR/3 Mark I | RMI* NUKON Calcium-Silicate Asbestos** Amaflex** | Increased existing strainer surface area from 18.8 $ft^2$ to 475 $ft^2$ by installing passive large-capacity suction strainers. | Licensee based analyses on URG and plant specific alternate methods. | NRC determined licensee strainers adequately sized, although inconsistencies and deviations from URG found in licensee analyses. |

* Majority of total insulation of this type.
** Insulation screened out of analysis due to location, e.g., inside biological shield.

### 5.2.2.1 Limerick Plant Audit Summary

Plant Resolution Approach and Description

Limerick Generating Station Units 1 and 2 are BWR/5 plants with Mark II containments. The replacement strainers were installed in Unit 1 during the 1998 spring outage and in Unit 2 during the spring outage in 1999. Limerick Units 1 and 2 are very similar in layout, insulation, and ECCS design. The NRC on-site audit focused primarily on reviewing documents related to design and installation of replacement strainers at Unit 1.

Limerick Units predominantly use NUKON™ mats[1] to insulate the primary piping. Limited quantities of Min-K® blankets[2] are used around the pipe-whip restraints. The plant estimated that 3900 $ft^3$ of NUKON™ and between 40 and 100 $ft^3$ of Min-K (and other miscellaneous fiberglass) insulation is present in the containment. The NUKON™ insulation is protected by stainless-steel jackets with normal J-hooks. The Min-K insulation is protected by steel jackets that are welded on all sides to provide additional structural strength. The reactor pressure vessel is insulated by Mirror™ brand reflective metallic insulation (RMI) cassettes.[3] However, the plant screened out RMI insulation from the analyses because there are no postulated breaks within the biological shields that could generate and transport debris. Therefore, for the purpose of this audit, the insulation of primary concern at this plant is of fibrous composition (NUKON™).

Before 1998, Limerick Unit 1 used truncated-cone strainers with 1/16-in. perforations[4] to protect against plugging of core-spray nozzles and ECCS pump seals and bearings. The net surface area of the strainers was 269 $ft^2$. Total, licensing-basis, run-out, ECCS flow through the strainers is 59,900 GPM. The BLOCKAGE computer code was used to analyze the potential for loss of ECCS flow resulting from blockage of the old (pre-NRCB 96-03) strainers. It was found that an insulation volume of only 100 $ft^3$ was sufficient to induce frictional losses that exceed the NPSH margin (14.1 ft of water for the LPCI system and 10 ft of water for the LPCS system) within 10 min after a LOCA. This fact highlighted the need to replace the strainers at Limerick Unit 1.

The plant's resolution of the potential strainer-blockage issue was the installation of passive, large-capacity suction strainers designed and manufactured by ABB Combustion Engineering (ABB). The replacement strainers have a combined surface area of 2715 $ft^2$ (an increase of approximately 1100% compared with the old design). Table 5-3 provides geometric details of the strainers installed at Limerick Unit 1. The plant estimated the debris loading on the strainers following a postulated LOCA using methodologies discussed by the BWROG URG document. Estimates for quantities of fibrous debris generated were evaluated on a plant-specific basis using Method 2 of the URG, and all of the generated debris was assumed to be transported to the strainer (i.e., a transport factor of 1.0). The quantity of sludge used to size the strainer (2000 lb.) was chosen to bound the sum of suppression-pool sludge and other particulate debris, including qualified paint chips, foreign material, dust and dirt, rust from unpainted structures, and unqualified or indeterminate coatings. The FME Program and the Suppression Pool Cleanliness Program (SPCP) were implemented to limit the quantities of foreign materials and suppression pool sludge (e.g., clothing or plastic sheet) in the drywell.

---

[1] NUKON is a trademark insulation manufactured and marketed by Performance Contracting, Inc. (PCI). It is a low-density (2/3 $lbm/ft^3$) fiberglass mat.

[2] Min-K is a trademark fibrous-ceramic insulation. At Limerick, Min-K blankets were steel jackets.

[3] Mirror is trademark insulation manufactured and installed by Transco, Inc. It contains 2.5-mm stainless-steel foils enclosed in a welded stainless-steel cassette.

[4] The strainer plate has 5/8-in. perforations. However, the wire mesh around the plate has 1/16-in. square holes.

Strainers were designed to handle the limiting single failure that would result in a loss of one LPCI pump and two LPCS pumps for injection into the core. The strainers also were designed such that sufficient NPSH margin exists to accommodate any uncertainties in the estimation of debris volume or head loss. Estimates of available NPSH were based on an assumed wetwell pressure of 14.7 psia (equivalent to no containment overpressure) and a suppression pool temperature of 212°F.

Audit Conclusions

The licensee employed conservative methods to estimate the quantity of insulation debris generated in the drywell and transported to the ECCS suction strainer. The licensee's assumptions for non-insulation debris also appear reasonable. Similarly, the licensee calculation of the resulting head loss is conservative and is consistent with independent calculations performed by the Los Alamos staff using BLOCKAGE. The most likely head loss across the RHR-pump strainers as a result of debris-layer buildup will not exceed 2 ft-water compared with an available NPSH margin of 12 ft-water. The licensee head-loss estimate of 4 ft-water was obtained based on conservative estimates for debris loadings.

**Table 5-3. Geometric Details of the Limerick Strainers**

| Specification | LPCI | Core Spray |
|---|---|---|
| | | |
| ***System Totals*** | | |
| Pumps | 4 | 4 |
| Flow Rate (GPM) | 11,000 | 3,950 |
| Modules Per Pump | 4 | 2 |
| Total Modules | 16 | 8 |
| Circumscribed Area Per Pump | 186 $ft^2$ | 78.5 $ft^2$ |
| Holding Volume Per Pump | 85 $ft^3$ | 30 $ft^3$ |
| Surface Area Per Pump | 475 $ft^2$ | 203 $ft^2$ |
| Velocity at Screen | 0.052 ft/s | 0.043 ft/s |
| Load Factor Per Pump* | 0.18 | 0.07 |
| ***After Single Failure*** | | |
| Remaining Pumps | 3 | 2 |
| Modules on Remaining Pumps | 12 | 4 |
| Total Circumscribed Area | 560 $ft^2$ | 157 $ft^2$ |
| Total Holding Volume | 255 $ft^3$ | 60 $ft^3$ |
| Total Surface Area | 1425 $ft^2$ | 400 $ft^2$ |
| Load Factor Per Pump* | 0.27 | 0.10 |
| *Load Factor is the ratio of the debris value present on the strainer attached to one pump to the total debris volume present on all strainers. | | |

### 5.2.2.2 Dresden Plant Audit Summary

<u>Plant Resolution Approach and Description</u>

Dresden Units 2 and 3 are BWR/4 plants with Mark I containments. Dresden Units 2 and 3 are similar in layout and ECCS design, including the dimensions of the replacement strainers. Both units primarily use reflective metallic insulation (RMI) for insulating primary piping. The on-site audit reviewed documents related to the design and installation of replacement strainers at both units.

Dresden Units 2 and 3 predominantly use 2.5-mil stainless steel, 2-mil stainless steel, and 6-mil aluminum RMI cassettes[5] for insulating the primary piping and reactor vessel. Limited quantities of NUKON™ mats are used around special components and certain piping segments. The plant estimates that between 90 and 100 $ft^3$ of NUKON™ insulation is present in the drywells of Units 2 and 3. Most of the NUKON™ insulation is protected by stainless-steel jackets with normal J-hooks. The flued head penetrations are insulated with asbestos (14 $ft^3$ per flued head penetration) and a small quantity of non-encapsulated NUKON™ (1.93 and 2.67 $ft^3$ in Units 2 and 3, respectively). Amaflex closed-cell foam insulation was used on the chilled water pipes. Additionally in Unit 3, small quantities of calcium-silicate insulation (8.24 $ft^3$) are used on the reactor water clean-up (RWCU) pipes located in the mid-regions of the drywell. Using qualitative rationale, the licensee eliminated Amaflex foam insulation and asbestos from the analyses.

The Dresden Units 2 and 3 ECCS configuration includes an ECCS ring header circumscribing the torus with connecting piping to four inlet penetrations. In the torus, each connecting line is fitted with a flanged surface for mating to the ECCS strainer flange. The original pre- NRCB 96-03 suction strainers were truncated cone strainers. The base of the strainer where it mates the flange was about 18.3 in. in diameter and gradually decreased to 14.5 in. in diameter over its 10-in. length. The net surface area of each strainer was 4.7 $ft^2$. The design flows for the LPCI and LPCS pumps are 5000 and 4500 GPM, respectively, for the short term and 2500 and 4500 GPM for the long term (t > 10 min). This results in a design net ECCS flow of 29,000 GPM for the short term and 19,000 GPM for the long term. During the short term, the licensing-basis flow is different from the design-basis flow because of considerations such as single failure. Total, licensing-basis, ECCS flow through the four strainers combined during the short term is 32,200 GPM. This flow corresponds to an assumed failure of the LPCI Loop Select Logic (SF-LSL), which causes all four LPCI pumps to inject into a broken reactor recirculation loop at 5150 GPM each[6] and core decay heat removal to be achieved by two LPCS pumps operating at 5800 GPM each. The Dresden licensee's NPSH margin estimates were obtained subject to the following assumptions: (a) the operator would throttle the ECCS flow after 10 min and (b) the wetwell would be at a pressure higher than the atmospheric pressure by up to 9 psig during the short term and 2.5 psig over the long term.

The plant's resolution of the potential strainer-blockage issue is installation of passive, large-capacity stacked-disk suction strainers designed and manufactured by PCI. The geometrical details of the replacement strainers are listed in Table 5-4. The replacement strainers have a combined surface area of 475 $ft^2$ (an increase of approximately 2500% compared with the pre-NRCB 96-03 design). The plant estimated the debris loading on the strainer following a LOCA using methods and calculations developed and performed by its contractors. In many instances, these methods varied significantly from those discussed by the BWROG) in the URG document. Estimates for quantities of fibrous debris generated were evaluated on a plant-specific basis using Method 2 of the URG. No debris generation calculations were performed for RMI. Instead, the analyses assumed that sufficient RMI debris would be generated to form a "saturation bed" around the strainer. The quantity of sludge used to size the strainer was 370 lb. based on a conservative interpretation of "actual plant measurements." [7] Reportedly, this quantity

[5] RMI cassette construction consists of metallic foils of a certain type and thickness encapsulated by 304 stainless steel sheaths that are approximately 0.028 in. thick. The actual type and thickness of the foils varies depending on the manufacturer. Diamond Power Specialty Company (DPSC) uses 2.5-mil stainless steel and 6-mil aluminum foils, whereas Transco Products, Inc. (TPI) uses 2-mil stainless steel.

[6] This flow is not equal to the LPCI pump run-out flow. Instead, the Dresden licensee estimated fractional losses in the LPCI piping and Recirculation line. These losses then were coupled with pump curves to estimate the actual flow out the break assuming free release into the drywell.

[7] This value of 370 lb was based on one worst-case measurement with large uncertainties. The licensee believes that the actual sludge volume would be significantly lower than this value.

corresponds to sludge generated during one power cycle; in other words, the licensee has committed to clean up the suppression pool during every outage. Other particulate debris included in the design basis included qualified paint chips, rust from unpainted structures, dust and dirt, and unqualified or indeterminate coatings. The FME Program and the SPCP were implemented to limit the quantities of foreign materials and suppression pool sludge (e.g., clothing or plastic sheet) in the drywell.

Audit Conclusions

Based on the audit it is concluded that the Dresden strainer is adequately sized to handle the debris loading expected to reach the strainer following a LOCA. However, the audit noted several inconsistencies and errors in the licensee evaluations and documentation provided for review. For example, the licensee's technical approach for estimating debris loading following a LOCA is not consistent with the URG or the staff's SER on the URG in two areas: (1) the Dresden suppression pool transport calculations do not follow NRC/URG guidance and (2) the Dresden head loss estimates do not follow NRC/URG guidance. In addition, NRC concluded that Dresden NPSH evaluations had several inconsistencies.

**Table 5-4. Geometric Details of Dresden Strainers**

| *Specification* | Licensing Basis | Actual |
|---|---|---|
| ***Short Term (Unthrottled with SF-LSL)*** | | |
| Number of Strainers | 3 | 4 |
| Flow Rate (GPM) | 32,200 | 32,200 |
| Flow Rate per Strainer (GPM) | 10733. | 8050 |
| Total Circumscribed Area ($ft^2$) | 115 | 143 |
| Total Holding Volume ($ft^3$) | 19.2 | 25.6 |
| Total Surface Area ($ft^2$) | 356 | 475 |
| Velocity at Screen (ft/s) | 0.201 | 0.151 |
| Circumscribed Velocity(ft/s)* | 0.625 | 0.469 |
| ***Long Term (Throttled with SF-LSL)*** | | |
| Flow Rate (GPM) | 19,000 | 19,000 |
| Velocity at the Plate (ft/s) | 0.11 | 0.089 |
| Circumscribed Velocity (ft/s)* | 0.37 | 0.277 |

*Circumscribed velocity is calculated using a circumscribed area without the area of the ends as suggested by BWROG URG. This maximizes the velocity and the RMI "saturated bed thickness.'

### 5.2.2.3 Duane Arnold Plant Audit Summary

Plant Resolution Approach and Description

Duane Arnold Energy Center (DAEC) is a single BWR/4 unit with Mark I containment. Duane Arnold was the Reference plant used in the NUREG/CR-6224 study that formed the basis for BWR strainer blockage issue resolution. Replacement ECCS suction strainers were installed at the DAEC unit in

1997. The NRC staff performed an on-site audit at DAEC of the analyses that formed the basis for the design and installation of replacement strainers.

The DAEC plant predominantly uses NUKON™ mats to insulate the primary piping. Limited quantities of 2.5-mil s/s reflective metallic insulation (RMI) cassettes and calcium-silicate insulation (encapsulated in aluminum jackets) were used around some of the piping located inside the drywell. Stainless steel jackets with normal J-hooks protected the NUKON™ insulation. RMI cassettes insulate the reactor pressure vessel. However, the plant screened out RMI insulation from the analyses because (a) there are no postulated breaks within the biological shields that could generate and transport debris from the RMI located on the reactor vessel[8], and (b) the RMI located on the process piping will be replaced by fiber-glass insulation gradually. The calcium-silicate insulation was screened out because it is located in the higher regions of the containment where potential for generation of large quantities of insulation is negligible. Therefore, for the purpose of this audit, the insulation of primary concern at this plant is of fibrous composition (NUKON™).

Before 1998, DAEC used truncated-cone strainers with 1/8-in. perforations to protect against plugging of core-spray nozzles and ECCS pump seals and bearings. The net surface area of the strainers was 38 $ft^2$. Total, licensing-basis, run-out, ECCS flow through the strainers is 35,000 GPM. NUREG/CR-6224 analyzed the potential for loss of ECCS flow resulting from blockage of the pre-NRCB 96-03 strainers. It was found that an insulation volume of only 2 $ft^3$ (in combination with suppression pool sludge) was sufficient to induce frictional losses that exceed the NPSH margin within 10 min after a LOCA. This finding formed the basis for issuance of NRCB 96-03 and the development Revision 2 to the RG 1.82.

The plant's resolution of the potential strainer-blockage issue is (a) installation of passive, large-capacity suction strainers designed and manufactured by GE and (b) suppression pool cleaning to minimize the amount of sludge. The replacement strainers have a combined surface area of 1359 $ft^2$ (an increase of approximately 2600% compared with the old design). The plant estimated the debris loading on the strainer following a postulated LOCA using methodologies discussed by the BWROG in the URG document. Estimates for quantities of fibrous debris generated were evaluated on a plant-specific basis using Method 2 of the URG. The total volume of insulation debris transported to the suppression pool was estimated using the URG drywell transport factor of 0.28 (i.e., 28% of the volume of the generated debris would be transported to the suppression pool as a result of blowdown and washdown). No credit was taken for settling of the debris in the suppression pool. The quantity of sludge used to size the strainer (500 lbm) was chosen to bound the sludge generation rates measured by the licensee. Additional sources of particulate debris were considered in the strainer sizing analyses. These debris included qualified-paint chips, foreign material, dust and dirt, rust from unpainted structures, and unqualified- or indeterminate-coatings. The FME Program and the SPCP were implemented to limit the quantities of foreign materials (e.g., clothing or plastic sheet) and suppression pool sludge.

Strainers were designed to handle the limiting single failure that resulted in loss of one LPCI train (or two LPCI pumps) for injection into the core. Table 5-5 provides a listing of the important geometrical parameters of the replacement strainers. A sensitivity analysis was performed to assure that a slight variation in the debris quantity does not significantly affect NPSH margin. Estimates of NPSH margin were based on an assumed suppression pool temperature of 202 F over long-term. The NRC had previously approved a containment overpressure credit of 2.5 psig in calculating core spray NPSH margin.

Audit Conclusions

[8] Even if trace quantities of RMI do get transported, their effect on ECCS performance would be bounded by the fibrous debris impact.

The licensee employed NRC approved methods to estimate the quantity of insulation debris generated in the drywell and transported to the ECCS suction strainer. The licensee's assumptions for non-insulation debris also are reasonable and conservative. Similarly, the licensee calculation of resulting head loss is conservative and is consistent with independent calculations performed by the staff, using BLOCKAGE.

Overall, it is concluded that DAEC strainer replacement strategy is sound and their analyses provide reasonable assurance that ECCS strainers are adequately sized to support long-term ECCS operation following a LOCA. Any uncertainties in licensee analyses are compensated by the conservatism factored in by the licensee. The most important conservatism is that the licensee did not take credit for settling of debris in the suppression pool.

**Table 5-5. Geometric Details of Duane Arnold Strainers**

| PARAMETER | RHR#1 | RHR#2 | CS #3 | CS #4 |
|---|---|---|---|---|
| Outer Diameter (in.) | 45 | 45 | 45 | 45 |
| Active Length (in.) | 49 | 49 | 37 | 37 |
| Flange Diameter (in.) | 24 | 24 | 24 | 24 |
| Plate Area (Effective) | 388.7 | 388.7 | 290.9 | 290.9 |
| Circumscribed Area ($ft^2$) | 59.0 | 59.0 | 47.2 | 47.2 |
| Gap Volume ($ft^3$) | 27.4 | 27.4 | 20.5 | 20.5 |

### 5.2.2.4 Grand Gulf Plant Audit Summary

<u>Plant Resolution Approach and Description</u>

Grand Gulf Nuclear Station (GGNS) is a BWR/6 plant with Mark-III containment. The replacement strainers were installed at GGNS during the 1998 outage. NRC staff performed an on-site audit at Grand Gulf of the analyses that formed the basis for the design and installation of the replacement. Included in the audit were the licensee's (Mississippi Power and Light Company) implementations of programs related to the general issue of ECCS strainer blockage, such as the FME and SPCP programs.

Grand Gulf Unit 1 predominantly uses Mirror™-brand RMI cassettes[9] to insulate reactor-system piping. Smaller inventories of Kaowool[10], calcium silicate[11] (Cal-Sil), and fiberglass are also present. The plant estimated that 676 $ft^3$ of Kaowool (including miscellaneous fiberglass) and 908 $ft^3$ of Cal-Sil insulation are present in the total containment inventory. Aluminum jackets protect the Cal-Sil insulation. Some of the fiberglass is also encased in a metal jacket. The plant conducted extensive quarter-scale pool-transport testing for their complete replacement strainer design and small-scale testing for a segment of the design. No simulated RMI debris was observed to accumulate or remain attached on the strainer under design approach velocities, so RMI was screened out of their debris-generation, debris-transport, and head-loss

[9] Mirror is a trademark insulation manufactured and installed by Diamond Power Speciality Company. It contains 2.5-mm stainless-steel foils enclosed in a welded stainless-steel cassette.
[10] Kaowool is a spun mineral-fiber material with a manufactured density in the range of 7.4 to 8.4 $lbm/ft^3$ that is formed in blankets supported with wire mesh.
[11] Calcium silicate is a formed particulate material with fiber binding and a manufactured density in the range of 13 $lbm/ft^3$ that is encased in a metal covering.

calculations. Therefore, the primary concern is estimating the combined effects of damaged fibrous (Kaowool and fiberglass) and damaged particulate (Cal-Sil) insulation.

Before 1998, Grand Gulf Unit 1 used truncated-cone strainers with 3/32-in perforations on a 5/32-in pitch to protect against plugging of core-spray nozzles and damage of ECCS-pump seals and bearings. The net surface area of the strainers was 170 $ft^2$, and each strainer was 40-in long, 23.25 in at the base and 6 in at the top. Total, licensing-basis, run-out, ECCS flow is 44,895 GPM.

The plant's resolution of the potential strainer-blockage issue was the installation of passive, large-capacity suction strainers designed and manufactured by Enercon Services, Inc. The replacement strainers have a combined surface area of 6,253 $ft^2$ (an increase of approximately 3700% compared with the old design). This very large strainer is located on the suppression-pool floor. It serves as a common header for all six emergency core cooling systems (RHR-A, RHR-B, RHR-C, HPCS, LPCS, RCIC), so that any combination of operating systems can draw recirculation water through the same large screen area.

The plant estimated debris loading on the strainer following a postulated LOCA using methodologies discussed by the BWROG in the URG document. Estimates for quantities of insulation debris generated were evaluated following the intent of Method 1 in the URG. The quantity of sludge used to size the strainer (500 lbm) was chosen to bound the estimated generation rate. URG guidance was used to estimate quantities of other particulate debris including qualified paint chips, foreign material, dust and dirt, rust from unpainted structures, and unqualified or indeterminate coatings. The FME and SPCP programs were implemented to limit the quantities of foreign materials (e.g., clothing or plastic sheet) and suppression pool sludge in the drywell.

Audit Conclusions

The licensee employed conservative methods to estimate the quantity of insulation debris generated in the drywell and transported to the ECCS suction strainer. The licensee's assumptions for non-insulation debris also appear reasonable. Similarly, the licensee calculation of resulting head loss is conservative and is significantly larger than the independent estimates by the staff.

### 5.3. Outstanding Issues

As of the date of this report, two head loss issues remain partially unresolved. The first of these issues is determination of the head losses for mixed fiber and RMI debris beds. The second issue is the long-term head loss, i.e., the head loss well beyond the times at which the tests were terminated.

#### 5.3.1 Head Losses for Mixed Fiber and RMI Debris Beds

While substantial data has been collected on mixed debris beds formed of a combination of fiber/sludge and RMI debris, a comprehensive methodology has not been completed. The primary reason for this situation is due to the general complexity and variability of these types of beds. The complexity includes such considerations as the flow resistant past RMI debris, the tortuosity of the flow, and the debris type, size, and shape. The variability includes the variety of strainer designs (size, shape, area, gap volume), bed morphology (thickness, porosity, formation, and compression), and accident conditions (approach velocity, temperature, water chemistry). A methodology that works for one set of tests, may not necessarily work for another. Further research will be required to develop a comprehensive methodology that adequately covers the complexity and variability of the problem.

For the conditions tested in the ARL tests (see Section 2.1.2.3), the RMI head loss tests demonstrated that introduction of prototypical RMI debris, in combination with fibrous debris and sludge, does not cause significantly different head losses than those observed with only fiber and sludge loadings. In fact, the most significant finding was that when RMI debris was mixed with fibrous debris and sludge, the head losses appeared to decrease when compared to similar conditions without RMI debris. The trend where the addition of RMI to fibrous bed reduced the head loss was not apparent in the tests without sludge. For the limited thicknesses and debris distributions tested, the mixed layers of RMI and fibrous insulation debris on the strainer produced higher head losses than did the layered (stratified) debris. When RMI debris was tested alone (no fibrous debris), the head losses were relatively small compared to the head losses of fibrous beds. Caution must be used in generalizing these specific conclusions and in applying the data to actual plant specific analyses since the number of experiments was limited, data scatter was significant, and not all prototypical situations were explored.

Limited data from other test programs conducted by the industry indicated that the head loss contribution due to the addition of RMI to a fiber/sludge bed could be significant in some situations. Selected PCI tests (see Section 3.1.4) evaluated the impact of adding RMI debris to a fibrous/sludge debris bed. Comparing two tests where the test parameters were essentially identical with the exception of the addition of RMI debris in one of the two tests, clearly demonstrated that the addition of the RMI increased the head loss significantly for higher flow rates.

The BWROG URG originally stated that head loss for mixed beds can be evaluated by ignoring RMI altogether and estimating the head loss resulting from the other debris. But the staff concluded that the BWROG generalized statement does not hold true in all situations. It must be further cautioned that data collected for the flat test strainer likely will not be directly applicable to the advanced complex-geometry strainers employed by the strainer replacement program. On the basis of the staff's analysis, the staff believes this issue should be resolved on a plant-specific basis. Licensees should ensure that their strainer vendor review the debris combinations of interest for their plant and ensures that the vendor data supports the head loss used in their plant-specific analysis. Subsequent to the NRC's review, the BWROG agreed to the NRC position that this may not be true in all situations, thereby agreeing to resolve the mixed bed issue on a plant-specific basis.

### 5.3.2 Long-Term Head Loss

Head loss test procedures have generally continued the measurement of the pressure drop across the debris bed, following the establishment of that bed, until the head loss became relatively stable. The time required to reach 'steady-state' has generally been on the order of tens of minutes. Occasionally tests were continued for a few hours. But some limited long-term testing has been conducted where the tests were continued for several days to examine the long-term effects of acidity on the debris bed. These tests have been described in ARL Test Report: 72-92/M670F, "Extended Head Loss Testing in Alkaline Water of Thermal Insulation used in Nuclear Containments," dated May 1992 and in a paper presented to the OECD/NEA Workshop on Sump Screen Clogging held in May 1999, entitled "Tests for Long Term Head Loss Across Fiberglass Insulation Debris Using Warm, Alkaline Water."

The concern of the long term testing was whether or not the structure of a fibrous debris bed remained stable in the long term. Although the long term testing was not extensive enough to conclusively determine the long term debris bed behavior, it appeared that fiberglass in debris beds is subject to dissolution in alkaline solutions. Further, the binder could lose it attachment to the fibers and the bed matrix could break down, so that the bed would become denser. The primary parameters affecting increased long term head loss appear to be water acidity level and temperature.

In the limited testing, the head loss was shown to increase gradually (approximately linear with time) until the test was terminated. The length of the long term tests ranged from 1 to about 11 days. An example of long term head loss is shown in Figure 5-5.

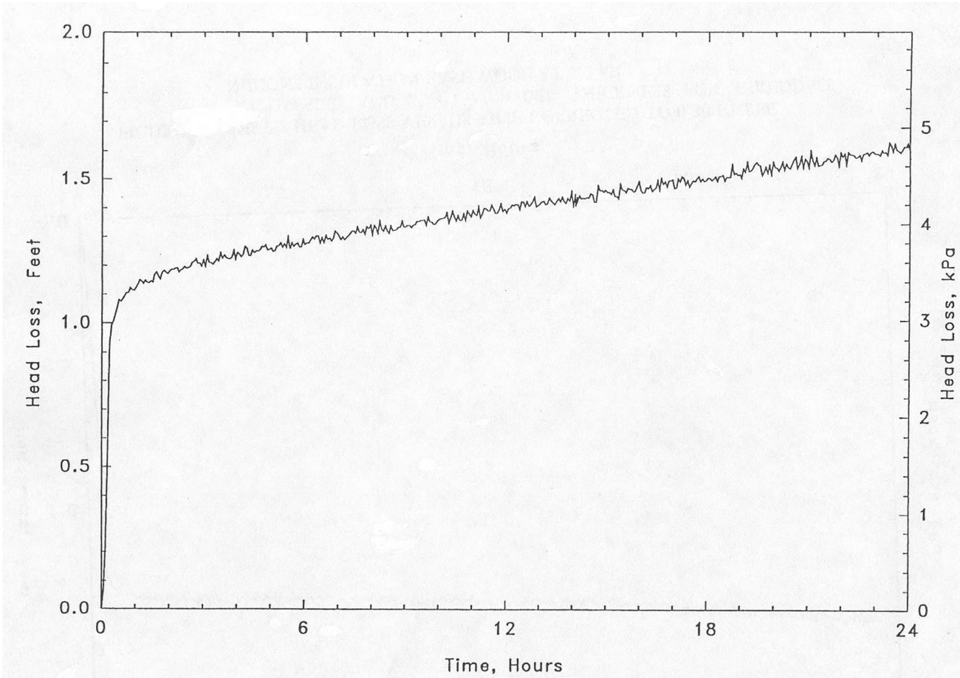



**Figure 5-5. Example of Long Term Head Loss for a NUKONä Debris Bed**

## 5.3 References


NUREG/CR-6224, Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris, G. Zigler, et al., Science and Engineering Associates, Inc., Prepared for Nuclear Regulatory Commission, Sept. 1995.

NEDO-32686, Rev. 0, Utility Resolution Guidance for ECCS Strainer Blockage, General Electric Nuclear Energy Company, Class 1, Nov. 1996.

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 (PWG-1), International Task Group, Committee on the Safety of Nuclear Installations, Organization for Economic Cooperation and development (OECD) Nuclear Energy Agency (NEA), Restricted, February 1996.

PCI-97, Summary Report on Performance of Performance Contracting, Inc., Sure-Flow Suction Strainer with Various Mixes of Simulated Post-LOCA Debris, Revision 1., R. A. Biasca, Performance Contracting, Inc., Sept. 1997.

PCI-NPD-CE03, Tests Conducted at the Fairbanks Morse Pump Company to Determine Head Loss Performance of PCI Bare Sure-Flow Strainer, Tech. Doc. No.:, June 1997.

CDI-96-22, Results of ECCS Sure-Flow Strainer Testing for Performance Contracting, Inc., Rev. 0, AE Kaufman, Continuum Dynamics, Inc., Technical Note No. 96-22, Dec 1996.

SEA-96, A Generalized Correlation for Pressure Drop Across Fibrous Debris Beds, D. V. Rao, Calculation Note, Science and Engineering Associates, Inc., Dec. 1996.

ITS-97, Comparison of Head Loss Model Based on NUREG/CR-6224 with PCI Full-Scale Strainer Test Data, P. Mast and F. Souto, Innovative Technology Solutions Corporation, Presented to US Nuclear Regulatory Commission, Rockville, Md., Feb. 1997.

LA-UR-00-5159, D. V. Rao, "Technical Review of Selected Reports on Performance Contracting, Inc. Sure-Flow Strainer™ Test Data,' Prepared for U. S. Nuclear regulatory Commission, April 27, 2000.

LaSalle-98, "Test Evaluation Report for Test TPP-VL0400-005: LaSalle Strainer Fiber and RMI Debris Tests," Duke Engineering &Services, TPP-VL04 00 –006, June 6, 1998.

LA-CP-99-7, D. V. Rao, "Technical Review of GE LTR NEDC-32721P: Application Methodology for GE Stacked-Disk ECCS Suction Strainer," NRC Technical Evaluation Report, RP12-TER-98-02, Proprietary, December 23, 1998.

LA-CP-00-18, Bruce Letellier, and D. V. Rao, "On-Site Audit of the Grand Gulf Nuclear Station Emergency Core Cooling System Strainer-Blockage Resolution," Los Alamos Technical Evaluation Report, January 3, 2000.

LA-UR-01-738, D. V. Rao and Bruce Letellier, "On-Site Audit of the Dresden Nuclear Power Plant Emergency Core Cooling System Strainer Blockage Resolution," Los Alamos Technical Evaluation Report, Undated.

LA-UR-00-426, D. V. Rao and Bruce Letellier, "On-Site Audit of the Limerick Nuclear Power Plant Emergency Core Cooling System Strainer Blockage Resolution," Los Alamos Technical Evaluation Report, January 21, 2000.

LA-CP-99-346, D. V. Rao and Bruce Letellier, "On-Site Audit of the Duane Arnold Energy Center Emergency Core Cooling System Strainer Blockage Resolution," Los Alamos Technical Evaluation Report, December 1999.

72-92/M670F, James B. Nystrom, "Extended Head Loss Testing in Alkaline Water of Thermal Insulation used in Nuclear Containments," Alden Research Laboratory, Inc., May 1992.

Hart-99, Gordon Hart, "Tests for Long Term Head Loss Across Fiberglass Insulation Debris Using Warm, Alkaline Water," Paper presented to the OECD/NEA Workshop on Sump Screen Clogging, Stockholm, May 10-11, 1999.