PWR CONTAINMENT SUMP EVALUATION METHODOLOGY

DRAFT

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Acknowledgments

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Executive Summary

In response to Generic Safety Issue 191 (GSI-191), "Potential of PWR Sump Blockage Post-LOCA," Nuclear Energy Institute and the industry formed the PWR Sump Performance Task Force. The primary purpose of the Task Force was to interface with the U.S. Nuclear Regulatory Commission as the issue developed and to champion creation of a methodology document which could be used as a guideline for PWR operators to address the issue. Much of the previous testing and evaluations supporting the Utility Reference Guide (URG) for the BWRs was used as appropriate. However, it was determined early on that a standard "cookbook" could not be created for PWRs for several reasons. PWRs vary greatly in containment size, floor layout, sump configuration, required ECCS flows, insulation types and location, and post-LOCA operational requirements. Since it was evident one size would never fit all, the NEI methodology document provides basic guidance on approach and various methods available, but recognizes that the best strategy for each plant could involve any number of methods. Each PWR operator, with his unique knowledge or specific plant design and operation, is best qualified to determine the optimum solution strategy. As such, this document does not prescribe specific combination of methods to the user.

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

Section 1 contains an introduction to the PWR strainer debris issue, including an historical review describing the steps which have led to this point in time. Section 2 is a high level summary of the overall process considerations which will need to be addressed during the evaluation process, while Section 3 describes the typical plant specific data required for the evaluation and the documents impacted during this evaluation. The main thrust of the document is contained in Section 4. This Section contains the specific recommendations for carrying out the various steps for each area of the evaluation process, including debris generation, debris transport and head loss evaluation. In Section 5, downstream effects of the evaluation process will be discussed. Section 6 includes a matrix of Regulatory Guide Requirements and a comparison of how each is addressed within this document. References are contained in section 7.

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Attachments

A - NRC Regulatory Guide 1.82 Draft Revision 3, "Water Sources for Long-term Recirculation Cooling Following a Loss-of-Coolant Accident," U.S. Nuclear Regulatory Commission, February 2003
B - Break Characteristics Model for Debris Generation Following a Design Basis Loss of Coolant Accident
C - Comparison of Transport Factors Obtained from Nodal and CFD Approaches
D - A Review of Head Loss Correlations

1 Introduction

1.1 Issue Description

The postulated rupture of a pipe located inside containment and carrying high-energy fluid is one of the key factors used in development of the licensing, design and operational requirements for nuclear reactors. Although the probability of a high-energy line break in a large pipe is extremely low, it is an event that reactors are designed to withstand, without jeopardizing the health and safety of the public. This design basis accident (DBA) is referred to as a loss-of-coolant-accident (LOCA). For some PWR's, a Main Steam Line Break may need to be included if ECCS is required.

Should such an event ever occur, the high-energy fluid has the potential to damage adjacent equipment and material. This LOCA generated debris, including particulates, fibers, and RMI foils, may be transported and result in debris blockage of the emergency core cooling system (ECCS) and core spray system (CSS) pump suction strainers. This scenario raises concerns that the head loss across the suction screens may exceed the available net positive suction head (NPSH) margin. As a result, the Nuclear Regulatory Commission (NRC) has determined that the potential for Pressurized Water Reactor (PWR) core damage presents a risk significant enough to warrant evaluation by each plant, to ensure sufficient NPSH margin exists in the event of this type of accident.

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

1.2 Historical Overview

In January 1979, the NRC originally declared sump-screen blockage to be an Unresolved Safety Issue, USI A-43 and published the concerns identified in the USI in NUREG-0510, "Identification of Unresolved Safety Issues Relating to Nuclear Power Plants" [Reference 7-1]. 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 derived principally from concerns regarding PWR containment emergency sump performance, these concerns applied to BWR ECCS suction, as well. The BWR residual heat removal (RHR) system performs the low-pressure coolant injection (LPCI) function of the ECCS and the safety-related 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.

Substantial experimental and analytical research was conducted to support the resolution of USI A-43. In 1985, the regulatory analysis results and the technical findings of research related to resolving USI A-43 were reported in NUREG-0869 [Reference 7-2] and NUREG-0897

[Reference 7-3], respectively. The bases for these findings were documented in a series of NRC contractor reports, which are listed in NUREG-0897. In NUREG-0897, the NRC concluded the following:

- The information of an air-core vortex that would result in unacceptable levels of air ingestion that potentially could severely degrade pump performance was a concern. This concern was more applicable to PWRs but was still relevant to BWRs. Hydraulic tests showed that the potential for air ingestion was less severe than previously hypothesized. In addition, under normal flow conditions and in the absence of cavitation effects, pump performance is only slightly degraded when air ingestion is less than two percent.
- The effects of LOCA-generated insulation debris on RHR recirculation requirements depend on:
    1. The types and quantities of insulation
    2. The potential of 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
    5. The impact on available net positive suction head (NPSH)
- The effects of debris blockage on the NPSH margin should be dealt with on a plant-specific basis. Insulation debris transport tests showed that severely damaged or fragmented insulation is readily transported at relatively low velocities (0.2 to 0.5 ft/s). Therefore, the level of damage near the postulated break location became a dominant consideration. The level of damage to insulation was correlated with distance between the insulation and the break, in terms of L/Ds (distance divided by the pipe-break diameter). Data showed that jet load pressures would inflict severe damage to insulation within 3 L/D, 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 as a result of debris ingestion was considered unlikely. If the seal did fail, pump leakage would be restricted.
- Nineteen nuclear power plants were surveyed in 1982 to identify the insulation types used, the quantities and distribution of insulation, the methods of attachment, the components and piping insulated, the variability of plant layouts, and the sump designs and locations. The types of insulation found were categorized into two major groups: reflective metallic insulation (RMI) and fibrous insulations. The 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 blocks. Insulation was, at times, enclosed in an outer shell, jacket or cloth cover.

USI A-43 was declared resolved in 1985. The NRC resolution of USI A-43 was presented to the Commission in October 1985 [Reference 7-4]. The resolution consisted of:

1. 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) [Reference 7-5], Section 6.2.2 and Regulatory Guide (RG) 1.82 Revision 1 [Reference 7-6], "Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident," to reflect the staff's technical findings
3. Issuing Generic Letter (GL) 85-22 [Reference 7-7], "Potential for Loss of Post-LOCA Recirculation Capability Due to Insulation Debris Blockage," to all holders of an operating license or construction permit outlining safety concerns and recommending the use of Regulatory Guide (RG) 1.82, Revision 1 as guidance for conducting 10 Code of Federal Regulations (CFR) 50.59 analyses [Reference 7.8]

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 debris blockage effects. As a result, the analysis conclusion was that the issue should be resolved on a plant-specific basis. The staff recommended that RG 1.82, Revision 1, be used as guidance for the evaluation 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 [Reference 7.6].

After 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 dated September 30, 1992, "Partial Blockage of Suppression Pool Strainers at a Foreign BWR," [Reference 7-9]. In this event, a spurious opening of a safety valve, while the reactor was pressurized, discharged steam into the drywell, dislodging mineral wool insulation that subsequently transported to the suppression pool, resulting in suction-strainer blockage and pump cavitation. The Barsbäck-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.

ECCS suction-strainer clogging events also occurred at U.S. plants. These included the following.

- Two events occurred at the Mark III Perry Nuclear Power Plant during 1992 and 1993 [Reference 7-10]. Debris was found on the suppression pool floor and on the RHR suction strainers during a refueling outage inspection. In addition, the buildup of debris on the strainer caused an excessive differential pressure, which deformed the strainers. After the damaged strainers were replaced and the suppression pool was cleaned, the strainers were again found to be fouled by debris such that the pump suction pressure dropped to zero during a test. The debris consisted of glass fibers, corrosion products, and other materials. Fibrous material acted as a filter for suspended particles—a phenomenon not previously recognized by either the NRC or industry.
- An event occurred at Limerick Generating Station Unit in 1995 [Reference 7-11] in which a safety relief valve (SRV) opened while Unit 1 was at 100% power. Subsequently, a thin mat of fibrous material and sludge covering the RHR pump suction strainers in the suppression

pool caused fluctuating motor current and flow, indicating pump cavitation was occurring. Limerick subsequently removed about 635 kg of debris from the pool.

- In 1988 and 1989, the Grand Gulf Nuclear Station experienced strainer blockage events during testing of the RHR pumps. Pump suction pressures fell below the in-service inspection acceptance criteria [Reference 7-10].
- In 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 [Reference 7-12]. This debris had partially blocked the strainers.

Substantial quantities of debris were discovered in suppression pools on other occasions. In other cases, plant inspections have found deteriorated insulation that would render these materials more likely to form debris following a LOCA. In other plant inspections, previously unidentified unqualified coatings that could form debris following a LOCA have been found.

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 containment spray system (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 and/or pressure-reduction capabilities of the plant. The NRC has emphasized the need to minimize the presence of foreign material in the containment [e.g., a strong foreign material exclusion (FME) program].

The string of operational events described above demonstrated the following:

- Larger quantities of debris could reach the ECCS strainers than had been predicted by models and analysis 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 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 ongoing FME programs

The ECCS strainer and foreign material discovery events prompted a review of the strainer blockage issue. As a result, 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 the availability of long-term recirculation of cooling water in BWR plants.

Concerns generated by these strainer-blockage events prompted the NRC to issue Bulletin 93-02 [Reference 7-13], “Debris Plugging of Emergency Core Cooling Suction Strainers,” on May 11, 1993, to both BWR and PWR licensees. Licensees were requested to take the following actions:

- Identify fibrous air filters and other temporary sources of fibrous material in the primary containment not designed to withstand a LOCA.
- Remove the identified material.
- Perform 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 by initiating a detailed plant-specific study in September 1993 using a reference BWR/4 reactor with a Mark l containment. The results were published in NUREG/CR-6224 [Reference 7-14] in 1995. This plant-specific analysis developed analytical models applicable to the reference BWR that considered debris generation, drywell debris transport, suppression-pool debris transport, and strainer blockage. 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. A computer program called BLOCKAGE was developed to calculate debris generation, debris transport, fiber/particulate debris bed head losses and the effect of the debris on the available ECC NPSH. Probabilistic analyses were performed that focused on evaluating the likelihood of ECCS strainer blockage and blockage-related core damage from large loss of coolant accident (LLOCA) initiators. The final results of the reference plant study, as 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 ten minutes into the event). The study also concluded that determining the adequacy of the 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 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 in 1994. 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, Revision 1. Following this workshop, SKI requested the formation of an international working group to establish an internationally agreed-upon knowledge base for assessing the reliability of emergency core cooling water recirculation systems. The NRC compiled a source book of available knowledge for the Organization for Economic Cooperation and Development (OECD) Nuclear Energy Agency [Reference 7-15].

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 enhanced the capability to prevent or mitigate loss of ECCS following a LOCA as a result of strainer clogging. The purpose of these interim actions was to ensure the reliability of the ECCS so that the staff and industry would have sufficient time to develop a permanent resolution.

To provide time to conduct research to resolve the strainer clogging issue, the NRC first ensured that public health and safety were protected adequately. 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 (EOPs) provided adequate guidance on mitigating a strainer-clogging event.
3. Operators were trained adequately to mitigate a strainer-clogging event.
4. Loose and temporary fibrous materials stored in the containment were removed

The responses to NRC Bulletin 93-02 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 Boiling Water Reactor Owners' Group (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 for BWR plants with the issuance of NRC Bulletin 96-03 [Reference 7-16]. Satisfactory implementation of the requested actions in NRC Bulletin 96-03 ensured that the ECCS can perform its safety function and minimize the need for operator action to mitigate a LOCA.

The NRC issued RG 1.82, Revision 2, in May 1996 [Reference 7-6]. 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 debris-blockage evaluation guidance because operational events, analyses, and research work that have occurred since the issuance of Revision 1 indicated that the previous guidance was not comprehensive enough to evaluate a BWR plant's susceptibility to the detrimental effects caused by suction-strainer debris blockage adequately.

An essential aspect of predicting the potential for BWR strainer clogging was estimating 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). In Revision 2 of RG 1.82, the NRC recommended assuming 100% debris transport unless analyses or experiments justified lower transport fractions. 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, which are documented in NUREG/CR-6369 [Reference 7-17], provide reasonable engineering insights that can be used to evaluate the adequacy of the debris-transport factors used in plant-specific strainer-blockage analyses.

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 to install:

1. A large-capacity passive strainer designed with sufficient capacity to ensure that debris loadings equivalent to a scenario calculated in accordance with RG 1.82, Revision 2 do not cause a loss of NPSH for the ECCS.
2. A self-cleaning strainer that automatically prevents strainer clogging by providing continuous cleaning of the strainer surface with a scraper blade or brush.
3. 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 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 designs and one self-cleaning design. The BWROG then developed topical report NEDO-32686 [Reference 7-18], “Utility Resolution Guidance (URG) for ECCS Suction Strainer Blockage,” in November 1996, to provide utilities with:

1. Guidance on evaluation of the potential ECCS strainer clogging issue for their plant
2. A technically sound, standard industry approach to resolution of the issue
3. Guidance that is consistent with the requested actions in NRC Bulletin 96-03 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 the data needed to develop the URG and to qualify plant-specific strainer designs. The URG included substantial portions of this data.

The NRC reviewed the URG and issued its Safety Evaluation Report (SER) on August 20, 1998 [Reference 7-19]. 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 of debris (e.g., fibrous insulation, paint, reflective metallic insulation, dirt, corrosion products, etc.) and characteristics of the debris (size, shape, etc). The analyst should 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 the resolution options and detailed guidance on performing plant specific analyses to estimate potential worst-case debris loadings on ECCS suction strainers during a LOCA. However, the URG lacked complete guidance and/or adequate supporting analysis in several areas. Because insufficient detail and supporting justification on the "resolution options" are 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.

The NRC staff issued GL 97-04 [Reference 7-20], "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 (DBA) 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 inadequate NPSH. Some licensees discovered that they needed to have their licensing basis 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 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 GL 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 the NPSH margin. These concerns were confirmed by the review of the industry submittals [Reference 7-21]. Crediting containment overpressure in the NPSH margin requires supporting 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 are 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 exchangers, and power conversion systems. Because the NPSH is strongly dependent on the accident scenarios evaluated, the minimum pressure is determined conservatively for the purpose of granting an overpressure credit. Since there is substantial uncertainty associated with the strainer clogging issue, the staff did not recommend licensing basis changes as a "resolution option."

The NRC issued GL 98-04 [Reference 7-22], "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. GL 98-04 alerted addressees of additional strainer-blockage concerns, including problems associated with the following:

1. The material condition of Service Level 1 protective coatings inside the containment
2. Foreign material found inside operating nuclear power plant containments
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 safety functions.

The BWR industry addressed the requirements of NRC Bulletin 96-03 [Reference 7-16] by installing large capacity passive strainers in each plant with sufficient capacity to ensure that debris loadings equivalent to a scenario calculated in accordance with 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: Limerick (BWR/4 Mark II), Dresden (BWR/3 Mark l), Duane Arnold (BWR/4 Mark l), and Grand Gulf (BWR/6 Mark III).

The research and regulatory developments associated with the resolution of the strainer-blockage issue for the U.S. BWR plants were summarized in the Los Alamos National Laboratory report LA-UR-01-1595 [Reference 7-23]. This report contains a more thorough history of events and developments than was just presented here. The report also includes brief summaries of the various experiments and analyses conducted to support the issue resolution.

As a result of research findings related to resolving the BWR ECCS strainer blockage safety issue, the NRC conducted further research into the PWR sump-screen blockage issue to determine if further action was needed beyond the original resolution of USI A-43. The Generic Safety Issue (GSI)-191, "PWR Sump Blockage," study was established to determine if the transport and accumulation of debris in a containment following a LOCA would impede the operation of the ECCS in operating PWRs.

A parametric evaluation [Reference 7-24] was performed as part of the GSI-191 study to demonstrate the credibility of recirculation-sump clogging for operating PWRs. Each of the 69 domestic PWRs was modeled in the evaluation using a mixture of generic and plant-specific data. The minimum amount of debris accumulation on the sump screen needed to exceed the required NPSH margin for the ECCS and CSS pumps was determined for each of the 69 representative models. Further, both completed and ongoing GSL-191 PWR research and existing BWR research were used to support the development of these models and the input to these models. The evaluation considered small, medium, and large LOCAs using both favorable and unfavorable assumptions, relative to the plant, for a number of parameters. The results of the parametric evaluation formed a credible technical basis for making the determination that sump blockage was a credible concern.

However, the parametric evaluation had a number of limitations. The most notable were attributed to the extremely limited plant-specific data available for the study. The need for more accurate plant-specific assessments of the adequacy of the recirculation function of the ECCS and CSS to be performed for each operating PWR was clearly indicated. In February 2003, the NRC issued a draft of RG 1.82 Revision 3 [Reference 7-6]. This regulatory guide is being revised to enhance the debris blockage evaluation for PWRs. A copy of the draft revision is included in Attachment A.

1.3 GSI-191 Related NUREGs

There are a number of NUREGs which have been issued dealing with safety issue GSI-191. A summary of the NUREGs discussed in the previous section is given below.

1. NUREG-0510, “Identification of Unresolved Safety Issues Relating to Nuclear Power Plants,” January 1979

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

3. NUREG-0869, “USI A-43 Regulatory Analysis,” October 1985

4. NUREG-0897, “Containment Emergency Sump Performance,” October 1985

5. NUREG/CR-6224, “Parametric Study of the Potential for BWR ECCS Strainer Blockage due to LOCA Generated Debris,” October 1995

6. NUREG/CR-6369

   Volume 1: “Drywell Debris Transport Study,” September 1999
   Volume 2: “Drywell Debris Transport Study: Experimental Work,” September 1999
   Volume 3: “Drywell Debris Transport Study: Computational Work,” September 1999

7. NUREG/CR-6762

   Volume 1: “GSI-191 Technical Assessment: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance,” August 2002
   Volume 2: “GSI-191 Technical Assessment: Summary and Analysis of U. S. Pressurized Water Reactor Industry Survey Responses and Responses to GL 97-04,” August 2002
   Volume 3: “GSI-191 Technical Assessment: Development of Debris Generation Quantities In Support of the Parametric Evaluation,” August 2002
   Volume 4: “GSI-191 Technical Assessment: Development of Debris Transport Fractions In Support of the Parametric Evaluation,” August 2002

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

9. NUREG/CR-6772 dated August 2002, "GSI-191: Separate-Effects Characterization of Debris Transport in Water," August 2002

10. NUREG/CR-6773 dated December 2002, "GSI-191: Integrated Debris-Transport Tests in Water Using Simulated Containment Floor Geometries," December 2002

1.4 Fundamental Assumptions

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

The major assumptions are:

1. Application of Single Failure

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

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

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

3. Application of Risk-Informed Considerations

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

4. Validity of Supporting Data

   Data employed in the development of the evaluation methodology or applied directly through the evaluation methodology may not have been produced under a 10CFR50, Appendix B program. Such data will be carefully evaluated through a validation and verification process that may include analytical methods such as comparison to theoretical predictions or to other similar but independent empirical results.

1.5 Definitions

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

Zone of Influence (ZOI) - One acceptable method for estimating the amount of debris generated in a LOCA is to use the 'zone of influence'. The zone of influence represents the zone where a given HELB will generate debris which may be transported to the sump. The shape of the ZOI for each postulated break location will be spherical for double-ended breaks and hemispherical for single-ended breaks unless robust barriers are present, as described below. The size of the ZOI will be defined in terms of pipe diameters and will be determined based on the pressure contained by the piping and the destruction pressure of the insulation surrounding the break site. Three recommended methods for determining the ZOI are:

- A spherical ZOI with L/D of 12.

- The size of the spherical ZOI can be calculated based on the insulation with the lowest destruction pressure, and all insulation contained within the ZOI is assumed to be damaged such that it becomes debris, regardless of insulation type.

- For each insulation type, a separate spherical ZOI may be calculated.

The destruction pressure for each type of insulation is addressed as follows. The pipe break radial offset may be accommodated for in the calculation of the spherical ZOI size. Similarly pipe restraints may be accommodated for in the calculation of the spherical ZOI size.

The spherical ZOI should be adjusted to appropriately account for robust barriers. Robust barriers consist of structures and equipment that are impervious to jet impingement and prevent further expansion of the break jet. If a robust barrier is encountered by a break jet, the ZOI created will have a spherical boundary with the exception of the volume beyond the robust barrier. The radius of the spherical boundary will be redefined such that the volume encompassed by the ZOI is equal to that encompassed by the spherical ZOI that would be created if the robust barrier were not present. Pure reflection of break jets will not be considered. The use of the spherical ZOI is intended to address any jet reflection effects. Likewise, the effects of pipe whip and traveling jets are addressed by the spherical ZOI.

Debris – The remains of broken or dislodged materials (for example, insulation, coatings, tape, and dust) generated by the action of high-energy fluid released from a postulated break in a high-energy line inside containment.

Latent Debris – Dirt, dust, paint chips, fibers, shredded pieces of paper, plastic, tape, or adhesive labels, and fines or shards of thermal insulation, fireproof barrier, or other materials that are present in the containment prior to a postulated break in a high-energy line inside containment.

Encapsulated Insulation - Encapsulated insulation is insulation covered on all surfaces by metal sheets. Examples of encapsulated insulation include RMI and calcium silicate cassettes.

Jacketed Insulation - Jacketed insulation is insulation that is covered on the outside of the pipe by a wide variety of materials. Examples of jacketed material include solid fiberglass and calcium silicate wrapped with aluminum foil.

Wrapped Insulation - Insulation that is covered on the outside by non-metallic wrapping. Typically, the wrapping is an epoxy impregnated fiberglass mesh that is either fastened to the insulation by tie wraps or has been glued to the insulation.

2 Evaluation Process

2.1 Overview

The purpose of this section is to give the user a complete picture of what is involved in this evaluation process. Each section contains some useful information, but does not provide the details. The basis and details necessary to complete the evaluation are found in Section 4.

2.2 Initiating Events

All design basis initiating events that require ECCS operation in the recirculation mode to successfully mitigate that design basis event should be considered during evaluation. LOCA is the principal initiating event for which sump function is necessary to comply with the evaluation criteria of 10CFR50.46. This is reasonable since LOCA events are significant due to their combination of the requirement to cool the core with the potential for release of significant radionuclides. Other design basis events, such as Main Steam Line Break, which necessitate recirculation flow from the containment sump, should be evaluated using methods, assumptions, and inputs typical for those analyses.

Debris generated during a HELB will need to be calculated for postulated breaks of different sizes, locations and other properties sufficient to provide assurance that the most severe postulated LOCAs are considered. In addition, some PWRs may require recirculation from the sump for licensing basis events other than LOCAs. As a result, plants should review their licensing basis to include potential break locations in the main steam and main feedwater lines as well to determine the most limiting conditions for sump operation.

A sufficient number of breaks in each high-pressure system that relies on recirculation should be considered in order to bound variations in debris generation by the size, quantity, and type of debris. As a minimum, the following postulated break locations should be considered.

- Breaks in the hot leg, cold leg, intermediate leg, and depending on the plant licensing basis, main steam and feedwater lines with the largest amount of potential debris within the postulated zone of influence
- Large breaks with two or more different types of debris, including breaks with the most variety of debris within the expected zone of influence
- Breaks in areas with the most direct path to the sump
- Medium and large breaks with the largest ratio of potential particulate debris to insulation (by weight)
- Breaks that generate an amount of fibrous debris that, after being transported to the sump screen, creates a minimum uniform thin bed (1/8 inch layer of fiber) to filter particulate debris.

2.3 Debris Types

The Nuclear Energy Institute (NEI) has developed guidance for assessing plant debris conditions for a variety of debris types (Reference 7-25). Potential debris types include, but should not be limited to, insulation material (fibrous, ceramic, and metallic), unqualified coatings, and foreign materials. Jet forces may impact all insulation (fibrous, calcium silicate, reflective metallic, and others as applicable), painted surfaces, fire barrier materials, and fibrous, cloth, plastic, or particulate materials within the zone of influence and should be considered debris sources. For breaks postulated in the vicinity of the pressure vessel, the potential for debris generation from the packing materials commonly used in the penetrations and the insulation installed on the pressure vessel should be considered. Particulate debris generated from pipe rupture jets stripping off paint or coatings and eroding concrete at the point of impact should also be considered.

2.3.1 Insulation

There are numerous types of insulation used in PWR containments. The most common of these include NUKON, Calcium Silicate, Armaflex, Reflective Metal Insulation (RMI), TempMat, Min-K, Kaowool, Koolphen-K, Fiberfrax, FiberMat, Unibestos block and Asbestos.

The following data should be obtained to evaluate the insulation's impact on the sump screen NPSH. This data should be available from plant records or recorded in walkdown records.

- Insulation type
- For RMI, whether the insulation is aluminum or stainless steel
- Insulation thickness/pipe size
- Length of insulation
- Type of fastening (jacketing or wrapping, if used)
- Jacketing construction details (spot welded or reinforced jacketing)
- General condition of the jacketing or wrapping
- Method used to band the insulation
- Number of bands used

Note that plant programs which control and document the use and location of various types of insulation inside containment may be able to be used as an alternate or supplemental source of information in lieu of performing walkdowns.

Walkdown documentation of the above should, as a minimum, include the following.

- A marked-up set of drawings and/or a spreadsheet showing the information above
- Location of temporary equipment left inside containment
- Video records – this may be photographs, or use of video cameras

2.3.2 Coatings

Coatings have also been identified as a key source of potential sump screen blockage. As part of the response to Generic Letter 98-04, all PWR facilities have maintained that "acceptable" or "DBA qualified" coatings will not significantly add to the coatings debris generated for this issue. The NRC has reviewed and accepted the responses to this Generic Letter for all PWR licensees. As a result, the coatings of interest include those coatings not identified as "acceptable" or "DBA qualified," and those which are "acceptable" or "DBA qualified," but are observed to be degraded during any plant walkdowns.

As general guidance, below is a list containing common coating types used in PWR containments which are "acceptable" or "DBA qualified". This list should be verified on a plant specific basis prior to use.

"Acceptable" or "DBA Qualified" Coatings
Commonly Used In PWR Containments

Concrete Substrate	Steel Substrate
Surfacer, epoxy phenolic topcoat	Inorganic zinc primer, epoxy phenolic topcoat
Surfacer, epoxy topcoat	Inorganic zinc primer, epoxy topcoat
Epoxy phenolic primer, epoxy phenolic topcoat	Epoxy phenolic primer, epoxy phenolic topcoat
Epoxy primer, epoxy topcoat	Epoxy primer, epoxy topcoat
	Inorganic zinc primer

The following list shows typical systems, structures or components to which coatings may be applied but can not be classified as "acceptable" or "DBA qualified". This list is to be used as guidance only and is not meant as an all inclusive list. It should also be noted that the coatings' review should be applicable to the general containment volume, not limited to the area within the crane wall or areas affected by a non-isolable primary system break, since debris from non-qualified coatings may result from exposure to post accident conditions.

Systems, Structures and Components With Original Vendor
Coatings Applied
Which Are Not "Acceptable" or "DBA Qualified"

Accumulator Tanks	Seismic Platforms and Tie Rods
Reactor Coolant System Supports	Reactor Internals Lifting Rig
Manipulator Crane	Head Lifting Rig
Valves	Transmitters and Small Instruments
Electrical Cabinets	Heat Exchanger Supports
Reactor Coolant Pump	Reactor Coolant Pump Motor and Motor Stand
Transducers	Mounting Brackets

The following data should be obtained to evaluate the coating's impact on the sump screen NPSH. This data should be available from plant records or recorded in walkdown records.

- Location of "acceptable" and "DBA Qualified" coatings, as well as unqualified or non-qualified coatings
- Type of safety related coating system applied in the area of the sump where debris will be transported to the sump by the re-circulating flow. If multiple systems are applied in one

area, the lightest (one with lowest specific gravity) can be assumed to be applied to the entire area, or exact documentation for all coatings systems used can be obtained for evaluation purposes.

- To the extent possible, the area of the safety related coating system
- To the extent possible, the thickness of the safety related coating system
- To the extent possible, the type (alkyd, epoxy, etc.), area, and thickness of unqualified coatings

Walkdown documentation of the above should, as a minimum, include the following.

- Marked-up set of containment drawings and/or a spreadsheet showing the information above
- Video records – this may be photographs, or use of video cameras

Note that plant coating programs which document the periodic containment coating assessments, evaluations of deficient coating conditions, and routine containment coating maintenance may also be used as an alternate or supplemental source of information in supporting the walkdown.

2.3.3 Foreign Materials

The potential for other foreign materials in containment during plant operation which may impact head loss across the Emergency Core Cooling sump screens should also be considered. This may include items such as thermal insulation other than piping insulation, ropes, fire hoses, wire ties, tape, ventilation system filters, permanent tags or stickers on plant equipment, rust flakes from unpainted steel surfaces, corrosion products, dust/dirt, and latent individual fibers. Debris generated by the resulting containment environment (thermal and chemical) also needs to be considered. Examples of this type of debris are coatings forming chips and particulates, or formation of chemical debris (precipitates) caused by chemical reactions in the pool.

Foreign materials left inside containment may also become transportable following the accident and add to the debris loading of the sump screen. Containment walkdowns should identify foreign material that may be transportable to the sump by a LOCA or containment spray washdown. The individuals involved with the walkdown of foreign materials should be familiar with containment decontamination and/or outage housekeeping activities. Discussions regarding the walkdown plans and results with personnel responsible for the plant foreign materials exclusion program and appropriate system engineers are also recommended.

As general guidance, below is a common list of types of foreign materials which should be considered as debris sources. These items may be included under plant housekeeping/foreign materials exclusion programs. If not, it is recommended that they be added to the appropriate program.

- Tape (electrician's tape, duct tape, masking tape, non-slip tape used on ladders, etc.)
- Equipment labels (paper or plastic labels, stickers, signs, etc.)
- Construction and maintenance debris (rags, face shields, bags, packaging, gasket material, sealant materials, ear plugs, sawdust, etc.)

- Temporary equipment (scaffolding, ladders, insulation material, lead shielding blankets, toolboxes, etc.)

In addition to the above, dirt, dust and lint should be characterized in support of quantifying this debris source. The walkdown will not be able to directly measure this type of debris. However, the following guidance is recommended to enable quantification of this debris.

- Record through notes and/or photographs areas where buildup of dirt, dust and lint are greater than what is found in general areas of containment
- If areas of buildup are identified, visually inspect the buildup to determine its nature (dirt, dust, lint, sand, etc.), and record any observations on the nature of the buildup. Collect a sample of the buildup in plastic bags, if possible. Care should be taken to ensure all health physics procedures are followed for any samples collected.

Documentation of the above should, as a minimum, include the following.

- Location of foreign materials inside containment
- Type of foreign materials inside containment (see above for examples)
- To the extent practical, characterize the specific gravity and size of the foreign materials

2.4 Debris Generation

2.4.1 Debris Generation by Break

Consistent with the requirements of 10 CFR 50.46, debris generation should be calculated for a number of postulated LOCAs of different sizes, locations, and other properties sufficient to provide assurance that the most severe postulated LOCAs are evaluated. Some PWRs may require recirculation from the sump for licensing basis events other than LOCAs. Therefore, plants should review the licensing basis and include potential break locations in the main steam and main feedwater lines as well in determining the most limiting conditions for sump operation.

An acceptable method for estimating the amount of debris generated by a postulated LOCA is to use the zone of influence. Examples of this approach are provided in NUREG/CR-6224, Boiling Water Reactor Owners' Group (BWROG) Utility Resolution Guidance (NEDO-32686), and the staff's Safety Evaluation on the BWROG's response to NRC Bulletin 96-03. In addition, the following guidelines should be used for establishing the amount of debris used in the evaluation.

- The size and shape of the zone of influence should be supported by analysis or experiments for the break and potential debris.
- The volume of debris contained within the zone of influence should be used to estimate the amount of debris generated by a postulated break.
- The size distribution of debris created in the zone of influence should be determined by analysis or experiments.
- The shock wave generated during the postulated pipe break and the subsequent jet should be the basis for estimating the amount of debris generated and the size distribution of the debris generated within the zone of influence.

All insulation (e.g., fibrous, calcium silicate, reflective metallic), painted surfaces, fire barrier materials, and fibrous, cloth, plastic, or particulate materials within the zone of influence should be considered debris sources. Analytical models or experiments should be used to predict the size of the postulated debris. For breaks postulated in the vicinity of the pressure vessel, the potential for debris generation from the packing materials commonly used in the penetrations and the insulation installed on the pressure vessel should be considered. Particulate debris generated from pipe rupture jets stripping off paint or coatings and eroding concrete at the point of impact should also be considered.

The cleanliness of the containment during plant operation should be considered when estimating the amount and type of debris available to block the ECC sump screens. The potential for such material (e.g., thermal insulation other than piping insulation, termed latent debris, includes ropes, fire hoses, wire ties, tape, ventilation system filters, permanent tags or stickers on plant equipment, rust flakes from unpainted steel surfaces, corrosion products, dust/dirt, latent individual fibers) to impact head loss across the ECC sump screens should also be considered.

2.4.2 Debris Generation by Washdown

Debris generation that is due to continued degradation of insulation and other debris when subjected to turbulence caused by cascading water flows from upper regions of the containments or near the break overflow region should be considered in the analyses. Various types of insulation may become debris sources due to washdown effects from containment spray. Jacketed insulation should be evaluated as a debris source. Unjacketed and/or unencapsulated insulation may also be susceptible to damage. Encapsulated insulation materials not within the ZOI are resistant to containment spray action and therefore are not a debris source. Containment spray impingement on insulation materials has a low stagnation pressure. Based on the experimental results in NUREG/CR-3170, the encapsulation on even the weakest of insulation blankets would not be susceptible to damage from containment spray. RMI is not affected by washdown effects as it is not soluble or easily penetrable by water. Calcium silicate with metal encapsulation will not become a debris source from the action of containment sprays.

Pumped break flow washdown is not considered to be a credible debris generation mechanism as the jet resulting from RCS depressurization will cause significantly more damage to insulation and will result in the distribution of the resulting debris about the containment away from the postulated break location.

2.4.3 Debris Generation Due to Containment Environment

In addition to debris generated by jet forces from the pipe rupture and washdown effects, debris created by the resulting containment environment (thermal and chemical) should be considered in the analyses. Examples of this type of debris would be disbondment of coatings in the form of chips and particulates or formation of chemical debris (precipitates) caused by chemical reactions in the pool.

2.5 Debris Transport

Once the sources, types, and quantities of debris are defined, the amount of debris transported to the sump screens needs to be established. The calculation of debris quantities transported from debris sources to the sump screen should consider all modes of debris transport. These include airborne transport, containment spray washdown transport, and containment sump pool transport.

An acceptable analytical approach to predict debris transport within the sump pool is to use computational fluid dynamics (CFD) simulations in combination with the experimental debris transport data. Examples of this approach are provided in NUREG/CR-6772 [Reference 7-26] and NUREG/CR-6773 [Reference 7-27]. A second approach described in detail later in this document is the nodal approach.

There are numerous debris characteristics requiring consideration during the transport evaluation. The debris transport analyses should consider each type of insulation (e.g., fibrous, calcium silicate, reflective metallic) and debris size (e.g., particulates, fibrous fine, large pieces of fibrous insulation). The analysis should consider the potential for further decomposition of the debris as it is transported to the sump screen. Bulk flow velocity from recirculation operations, LOCA-related hydrodynamic phenomena, and other hydrodynamic forces (e.g., local turbulence effects or pool mixing) should be considered for both debris transport and ECC sump screen velocity computations.

Intervening structures in the flow path may be considered credited for removing heavier debris that has been shown analytically or experimentally to travel by sliding along the containment floor (curbs, walls, etc.). All debris (e.g., fine fibrous, particulates) that is assumed or demonstrated to suspend indefinitely or to sink very slowly should be considered to reach the sump screen. The time to switch over to sump recirculation and the operation of containment spray should be considered in the evaluation of debris transport to the sump screen.

In lieu of performing debris transport analyses, it may be assumed that 100 percent of debris generation by specific break can be assumed to be transported to the sump screen.

2.6 Head Loss

Once the debris quantities at the sump screens are known, the head loss across the sump screen is calculated. The debris volume at the screen should be used to estimate the rate of accumulation of debris on the ECC sump screen. The head loss model starts with a clean screen and a pool containing a homogenous mixture and concentration of debris (i.e., fibrous, particulate, etc.). Inputs requiring consideration for the head loss evaluation across the debris bed include the thermal/hydraulic conditions as well as the types, total quantities and characteristics of debris generated in the containment and transported to the sump screen. Characteristics of the sump screen, such as surface area and opening size, also impact the head loss evaluation. The estimated clean sump screen head loss is then added to the calculated head loss across the debris bed to obtain the total head loss across the sump screen. The total screen head loss is then used to assess the effect of the head loss on the NPSH margin.

Upon switchover of suction from the refueling water storage tank (RWST) to the recirculation sump, the debris is transported to the sump and accumulates on the sump screen. Initially, some portion of the debris whose size is smaller than the screen mesh size (or hole size of the perforated plate) passes through the sump screen and debris bed. Fibers will quickly start to form a fiber mat in the cases where there is no RMI debris transported to the sump screen. As the fiber mat forms it will start trapping particulate debris reaching the sump screen. With sufficient fibers reaching the screen, a uniform fiber mat bed may be formed at which time the head loss across the debris will start increasing. The head loss across the debris bed will continue to rise as more debris is deposited on the screen, reaching steady state when all of the available debris is deposited on the screen.

Consideration of ECC sump screen submergence (full or partial) at the time of switchover to ECCS should be taken into consideration when calculating the available (wetted) screen area. Unless otherwise shown analytically or experimentally, debris should be assumed to be uniformly distributed over the available sump screen surface. Debris mass should be calculated based on the amount of debris estimated to reach or to be in the ECC sump. See Revision 1 of NUREG-0897, NUREG/CR-3616 [Reference 7-28], and NUREG/CR-6224 for details.

For fully submerged sump screens, the NPSH available to the ECC pumps should be determined using the conditions specified in the plant's licensing basis. For partially submerged sumps, NPSH margin may not be the only failure criterion considered.

For partially submerged sumps, credit should only be given to the portion of the sump screen that is expected to be submerged at the beginning of recirculation. Estimates of head loss caused by debris blockage should be developed from empirical data based on the sump screen design (e.g., surface area and geometry), postulated combinations of debris (i.e., amount, size distribution, type), and approach velocity. Because debris beds that form on sump screens can trap debris that would pass through an unobstructed sump screen opening, any head loss correlation should conservatively account for filtration of particulates by the debris bed, including particulates that would pass through an unobstructed sump screen.

Consistent with the requirements of 10 CFR 50.46, head loss should be calculated for the debris beds formed of different combinations of fibers and particulate mixtures (e.g., minimum uniform thin-bed of fibers supporting layer of particulate debris) based on assumptions and criteria described in Regulatory Positions 1.3.2 and 1.3.3.

2.7 NPSH Comparison

An NPSH comparison between the existing NPSH design margin and the head loss calculated due to the debris bed across the sump screen should then be made. A new design basis margin should be calculated and documented based on the existing design basis NPSH available minus the NPSH head loss due to the debris bed. Should the margin be sufficient to withstand the additional head loss, no additional plant actions are required.

2.8 Margin Recovery

Efforts to improve the NPSH margin available may focus on numerous areas. These include the evaluation methodology used to determine the margin, housekeeping practices to reduce debris amounts, and the type of potential modifications considered. Detailed analyses which include the use of CFD models for debris transport will lessen the calculated debris quantities reaching the sump screens. Time dependent analyses for water level, ECCS flow rates, and/or post-LOCA pool water temperatures may be required to reduce conservatism if the head loss is unacceptable. Removal of problematic insulation may improve margins. Identification of, and taking credit for, debris interceptors will also minimize debris amounts reaching the sump screens. Modifications can look at a number of variables to improve margins, including screen orientation, and surface area adding an extra disk or two providing ample margin yet requiring minimal space). Detailed discussions of these methodologies are provided in Sections 4.2 through 4.5.

3 Plant Data

3.1 Design/Licensing Bases

As stated previously, debris generated during a HELB will need to be calculated for postulated breaks of different sizes, locations and other properties sufficient to provide assurance that the most severe postulated Design Basis LOCAs are considered. In addition, some PWRs may require recirculation from the sump for licensing basis events other than LOCAs. As a result, plants should review their licensing basis to include potential break locations in the main steam and main feedwater lines as well to determine the most limiting conditions for sump operation.

Information regarding the plant design basis and licensing commitments for the sump should be reviewed. This information includes, but is not limited to, the following:

- Containment sump design considerations - List the design requirements of the containment sump. Locate, retrieve and review existing containment pool height, pool temperature and sump NPSH calculations and the basis for those calculations. Locate and retrieve sump civil and structural drawings.
- Licensing basis for the sump - Identify, locate, extract and list the licensing basis requirements and commitments for the containment sump. Note that, depending upon plant-specific designs, design basis transients other than LOCA may require recirculation from the containment sump, particularly for containment spray for postulated non-LOCA (secondary system) events.
- Historical debris sources - Identify sources of debris that have been identified in the operating history of the plant. Examples of these include, but are not limited to, coatings failures and foreign materials (electrician's tape, etc.) found inside containment during operations.
- Transport calculations - Locate, retrieve and review calculations of local fluid velocities, debris considered in the calculations and hydraulic characteristics of that debris.
- Sump blockage considerations - Locate, retrieve and review previous evaluations of sump blockage potential. This may be included in the topic immediately above.

3.2 Physical Configuration Data

The information regarding debris sources/locations at a plant needs to be assembled and reviewed in order to provide a clear understanding of the debris blockage issue for the ECCS sump screens. Information concerning insulation, coatings and foreign materials should be assembled to the extent possible. See NEI-02-01 for additional guidance (Reference 7-25). This information will exist to varying degrees for each plant. There are numerous records which may be used to identify documentation containing pertinent data for evaluation of this issue. It is recommended that the following information be assembled as a minimum to determine what information is available versus what information may need to be obtained via a walkdown.

Records of insulation installation

- Types of insulation used inside containment

- Insulation locations
- Insulation installation method (banded, encapsulated, etc)
- Insulation inspection records
- Insulation design changes since original installation

Records of coatings used inside containment

- Types of coatings applied
- Coatings locations
- Coating QA program requirements
- Coating application specifications
- Coating inspection records
- Coating applied to purchased equipment

Documents containing this data which should be obtained include the following:

- Piping and Instrumentation Drawings
- Piping Layout Drawings
- Cable Tray Layout Drawings
- Piping Isometrics
- Insulation Specifications
- Plant Housekeeping/Foreign Materials Exclusion Programs
- Work Orders For Insulation Repair and Modifications
- Historic Insulation Inspections and Surveys
- Historic Coatings Inspections and Surveys
- Sump Blockage Calculations
- Review Of Design Basis Events Requiring Recirculation From The Containment Sump
- "Exempt" or "Unqualified" Coatings Log

3.3 EOPs

Evaluation of the sump blockage issue may result in impacting plant Emergency Operating Procedures (EOPs) depending on each site specific resolution for the issue. EOPs which have the potential to be impacted include the following:

(Later)

4 Analysis Methodology

4.1 Introduction

<u>Scoping Process</u>
Prior to beginning the formal analysis process, one may want to consider a scoping evaluation or preliminary assessment to determine how vulnerable the emergency sump is to post-LOCA debris and to decide the best course of action. The scoping evaluation should look at the sensitivity of the debris sources with respect to head loss as well as the sensitivity of the strainer area with respect to head loss. The objective of the scoping process is to (1) identify the general strainer clogging conditions, (2) identify the controlling issues such as debris type and mixtures as well as strainer area, and (3) identify limitations such as changes in debris material and changes in strainer area.

The scoping process should begin with reviewing the design inputs that would support the debris generation analysis, the debris transport analysis, and the head loss analysis. The following are examples of inputs that should be reviewed. The following is not necessarily all inclusive as these may differ depending upon plant specifics.

ECCS Parameters

- Recirculation flow rate through the emergency sump
- Containment spray flow rate and setpoints
- Minimum and Maximum post-LOCA pool height (including height at switchover to recirculation)
- Minimum and Maximum post-LOCA pool temperature
- ECCS Pump/Containment Spray Pump NPSH Margin

Debris Sources

- Known debris types (insulation, latent debris, coatings, FME, etc.)
- Quantities, locations and thickness of debris within containment
- Insulation Specifications
- Coatings Specifications

Design Drawings

- Isometrics of High-Energy piping inside containment
- Structural and/or arrangement drawings of containment (elevation, plan and section views)
- Sump screen drawings and calculations

The next step is to develop a preliminary debris generation analysis using conservative estimates of types, quantities and sizes of debris that could be generated by a hypothetical high-energy pipe break inside containment. It should be noted that this step is not a detailed analysis and the level of effort should be limited to a review the containment drawings and insulation information to determine the principal locations and the approximate distribution of insulation material. In addition, insulation materials that are known to produce large head loss values and combination of these materials should be considered in the review of containment. Using this information, a single compartment with in containment would then be selected. The insulation quantities within this compartment would then be determined in detail with the assumption that all thermal insulation and coatings within this compartment are encompassed within the Zone of Influence (ZOI), i.e., destroyed by a postulated large-break LOCA.

Other items to also consider are ablated concrete and miscellaneous latent debris sources (dirt, dust, fibers, equipment tags, electrical tape, etc.). These items are discussed in further detail in the "Debris Generation" section of this document.

The third step would be to develop plant-specific debris transport logic trees based on the generic guidance provided in NUREG/CR-6762 Volume 4. The debris transport logic tree will account for transport during the blowdown phase, the washdown phase, and the recirculation phase. The debris transport logic trees will provide conservative engineering estimates of the debris fractions along each of the potential transport paths from the initial break location to the recirculation sump.

The debris transport logic trees should quantify the transport fractions of the Blowdown Transport, the Containment Spray Transport and the Recirculation Transport. These items are discussed in detail in the "Airborne/Washdown Debris Transport" section and the "Sump Pool Debris Transport" section of this document. Again this step should not be considered a detailed analysis.

The fourth step would be to determine the sump screen head loss due to the LOCA-generated debris accumulated on the sump screens using the quantity determined to be destroyed and transported in the steps above. The overall sump screen head loss depends on the composition of the debris mixture that is determined to reach the sumps, the debris size, its characteristics, and also the mechanical construction of the sumps and any trash racks and vortex suppression structures.

The NUREG/CR-6224 head loss correlations should be used for this analysis. They have been extensively validated for a variety of flow conditions and experimental facilities, types and quantities of fibrous insulation debris, and types and quantities of particulate matter debris. Specifically, this analysis will provide appropriate average values for the coefficients in the head loss equation based on specific quantities of each debris type (fiber, IOZ, rust, dirt/dust, paint chips) and the specific physical characteristics of each debris type (density and typical size). The thickness of the resulting debris layer on the screens should be determined. This analysis is discussed in further detail in the "Head loss" section of this document.

This preliminary evaluation will provide estimates of debris generation, debris transport and sump screen head loss. The total screen head loss would then be compared to the existing

ECCS, RHR and containment spray pump NPSH margins. The susceptibility of the sumps to air ingestion or vortexing should also be addressed based on the containment floor water level.

In the end, this scoping evaluation should help determine the next step of action. If the resulting head loss across the predicted debris bed is close to being acceptable with respect to the NPSH required, then the next step may be to focus on a detailed debris generation analysis, a detailed transport analysis, and a detailed head loss analysis. However, if the resulting head loss across the predicted debris bed is very large when compared with the NPSH required, then debris/insulation changes and/or strainer changes should be the focus of the next step.

If plant modifications appear to be required, it would be appropriated at this time to begin the plant Design Change process and develop a cost benefit analysis following the plant procedures for the design change options. There are cost limitations and physical limitations for both insulation changes and strainer changes. In many cases there will be a balance in the changes in the debris sources and changes in the strainer area.

4.2 Debris Generation

4.2.1 General Considerations

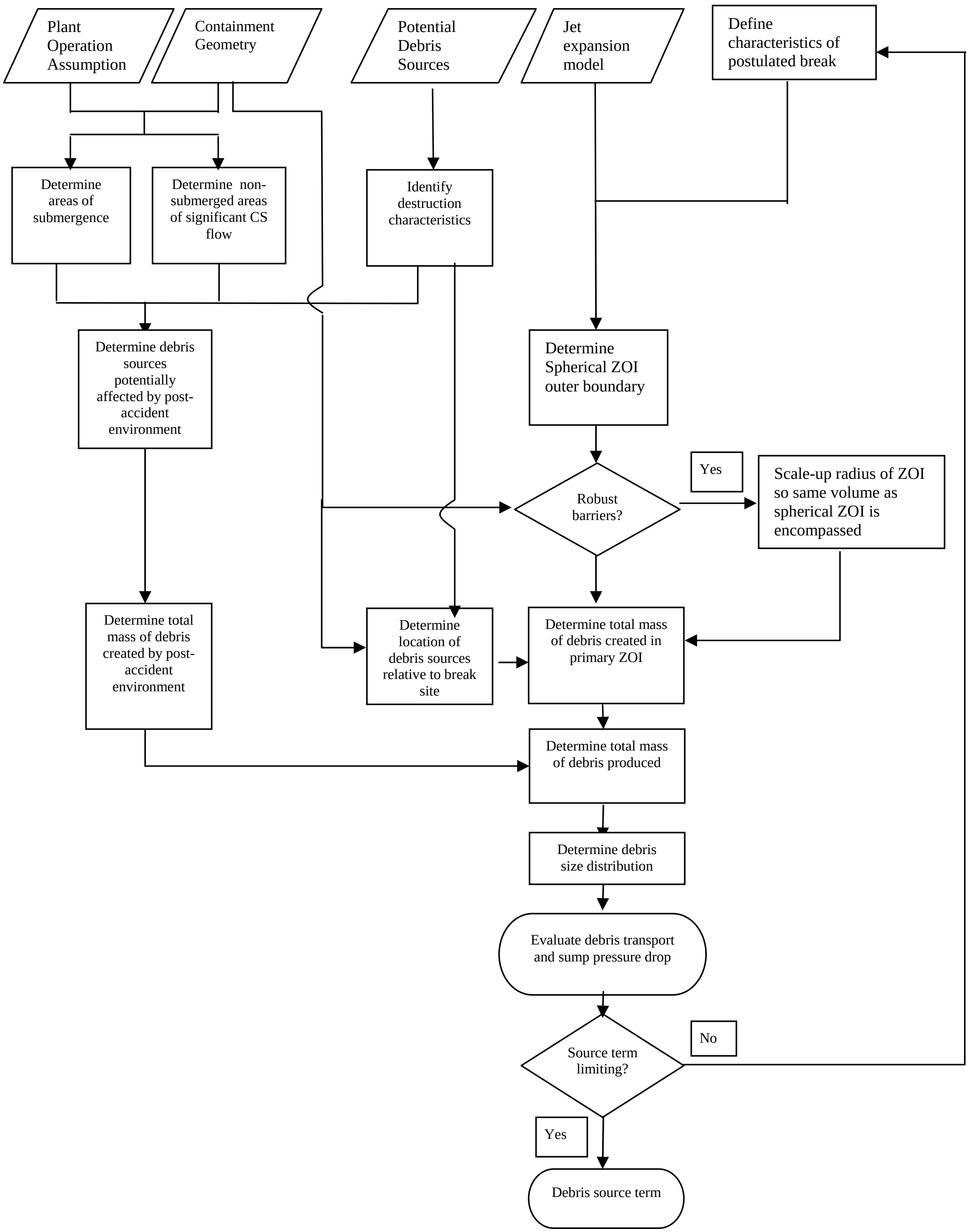
This section provides guidance on evaluating debris generation to be used in assessing post-accident containment sump performance through:

- Identification of an appropriate piping breach
- Identification of an appropriate resulting Zone of Influence (ZOI) in which materials (insulation, protective coatings, other materials) are reduced to debris
- Additional debris generation due to action of containment spray and submergence

The debris generation evaluated here is then used as input to an evaluation of the transport characteristics of that debris and its subsequent transport to the containment sump.

A logic diagram, highlighting options that may be taken in performing the debris generation evaluation, is given in Figure 4.2.1-1. The diagram highlights the major steps in evaluating debris generation. Note under the title, “Break Definition,” one may also insert Medium and Small LOCAs.

Figure 4.2.1-1 Flow Chart Describing Debris Generation



4.2.1.1 Plant Conditions

4.2.1.1.1 Containment Geometry

Use the results of containment condition assessment performed using NE-02-01 [Reference 7-25] to inventory the containment geometry information pertinent to the sump performance evaluation. In accomplishing this, it is recommended that the following tasks be performed:

- Identify all robust barriers located inside containment. Robust barriers are defined as structures and equipment that are impervious to jet impingement and prevent further expansion of the break jet.
- Record layout of high-energy piping.
- Determine the major paths for containment spray flow and assess the areas covered by the containment sprays.
- Determine the containment spray flow paths to the sump.
- Determine areas where submergence occurs. It is recommended that this be accomplished by first determining the maximum possible sump depth. Next, all areas of the containment below that depth are considered submergence areas.

4.2.1.1.2 Debris Sources

Use containment walkdown results to inventory the potential debris sources inside containment.

Identify and document the types, quantities, and locations of insulation materials.

Identify and document the types, quantities, and locations of both DBA-qualified and non-DBA-qualified coatings (for pre-ANSI-101.2 plants, acceptable and non-acceptable coatings).

Determine the types, quantities, and locations of latent debris sources. Plant surveys to date indicate that latent debris volume may be taken as 150 pounds upper bound.

4.2.1.1.3 Plant System Operation Assumptions

The operation of plant systems will have an impact on the sump performance evaluation. The following may be used to define the plant system operations for the debris generation evaluation:

The following assumptions are recommended for use throughout the evaluation:

- All containment spray trains are functional.
- Containment spray actuation occurs with Engineered Safeguard Features (ESF) pump start signals following a LOCA.
- All ECCS trains are functional.

- Loss of offsite power occurs coincident with event initiation (taken to be consistent with limiting single failure assumption for Design Basis Analysis calculations).

It is recommended that assumptions listed above be compared to documented vendor-specific and plant-specific accident sequences and environmental conditions. Where supported by plant-specific and vendor specific documentation, the plant-specific accident sequences and environmental conditions may be used.

It is suggested that NUREG/CR-6670 [Reference 7-29] be consulted for additional information that may be used to supplement and augment plant-specific and vendor-specific accident sequences and environmental conditions for debris generation.

4.2.2 Break Characteristics and Locations

4.2.2.1 Pipe Break Sizes

The debris generation for postulated large, medium and small piping breaks is to be considered. The debris generation for each of the breaks is calculated for each break size in an interactive manner to determine the worst possible accident break size, location and accident sequence to evaluate a limiting source term for transport to the containment sump.

The timing of events in the postulated accident (such as spray washdown, transport, pool level, accident progression, and head loss) account for the break size used to for the purpose of debris generation.

Note that the pipe break size will determine the selection of the pipe break characteristics to be used to evaluate debris generation.

4.2.2.2 Pipe Break Characteristics

Table 4.2.2.2-1 identifies and gives a brief discussion of the recommended options a plant might choose with regard to identifying the characteristics of a postulated pipe break to be used to evaluate debris generation. The options provide results that range from extremely conservative to realistic. Note that the more realistic the pipe break characteristics selected by the plant, the greater the effort needed to quantify the use of that option. The plant may choose the pipe breach option it determines appropriate for its specific design and condition.

4.2.2.3 Pipe Runs to Consider

The break location with the limiting consequences for sump function should be used for the plant evaluation. Since debris generation and debris transport should be included in the identification of the limiting break location, the identification of that location will be an iterative process. As a minimum, breaks in the following lines should be considered:

- Hot leg, cold leg, intermediate (crossover) leg and surge line
- Piping attached to the reactor coolant system. Examples include, but are not limited to Charging Lines and/or RHR lines upstream of the isolation valves.

Some plant designs require plants to eventually recirculate coolant from the sump for pipe ruptures other than a LOCA. Two such events are main feedwater breaks and steam line breaks. If this is true for the plant under consideration, then these lines must also be considered for debris generation.

4.2.2.4 Selection of Break Locations

For Options 2, 3 and 4 identified under Section 4.2.2.2, Pipe Break Characteristics, the volume of debris generated is evaluated by assuming a pipe break anywhere that would produce the largest amount of debris volume or destroy material which has higher HL characteristics. The volume of debris generated by the fluid released by the postulated break from the materials in the Zone Of Influence is calculated. Basis, however, is to determine break location providing worst case debris generation, whether it be simple debris volume or debris type which has the greatest effect on headloss.

4.2.2.5 Other Considerations

- Look for and evaluate breaks with the most direct flow path to the containment sump. Confirmation of the direct flow path between the break location and the containment sump from may be accomplished by using containment layout drawings.

- Locations of large breaks that generate two or more different types of debris. These locations are determined by considering the location of materials (insulation, coatings, etc,) inside containment relative to the break location and Zone of Influence. The location of materials inside containment should have been identified during the application of NEI-02-01.

- Medium and large breaks with the largest potential particulate debris to insulation ratio by weight.

- Locations for which postulated breaks generate an amount of fibrous debris that, after transport to the sump screen, creates a minimum uniform thin bed (1/8-inch layer of fiber) to filter particulate debris.

Evaluate the probability of failure and the predicted mode of failure for each of the possible break locations. If the probability of rupture for a given location is extremely low, or a small failure is expected to occur instead of a full double-ended break, the dynamic effects associated with a rupture at that break site may be excluded from consideration.

Table 4.2.2.2-1 Pipe Break Characteristics

Option	Pipe Break Characteristics	Pipe Break Size	Discussion
1	Assume that the postulated break affects the entire volume inside crane wall (This is not a break characteristic, but rather a consequence of the break.)	Debris generation is evaluated independent of pipe break size since the full containment volume inside the crane wall is affected by the break.	This approach: • Takes the entire volume of the containment to be affected by the postulated break. • Removes break size from consideration. • Provides for all debris sources inside containment to be considered in the total volume of debris generated. • Provides for the evaluation of an extremely conservative the region that would be affected by the energy release from the postulated break.
2	Complete severing of the pipe	Break area is equal to the total cross sectional area of both sides of the pipe. However, the break area is reduced if flow is terminated from one side of the break	This approach provides for the generation of a very conservative region of the containment that would be affected by the energy release from the postulated break, consistent with a double-ended rupture of piping. This approach would use a ZOI of either: • A sphere with a radius 12 times the crossection of the break • Material specific ZOI's, dependent upon the destruction pressure of materials inside containment.

3	Fracture Mechanics-Based Break	The following generic break flow areas are used for primary coolant piping: B&W: 83 in^2 CE: 40 in^2 Westinghouse: 40 in^2 Flow areas from plant-specific fracture mechanics analyses, multiplied by 10^3, may also be used for surge line and other piping, if such analyses have been performed for the plant.	This approach takes advantage of the inherent toughness of PWR piping design. Fracture Mechanics methods are applied to identify a stable leakage flaw flow area, and an associated multiplier on that flow area is applied to define a break size for use in evaluating debris generation. Break sizes calculated with this approach are typically less than the break size resulting from a complete severing of the pipe. Fracture mechanics approaches have typically been applied to piping that has been qualified as LBB pipe and may be applied, if desired, to additional non-LBB piping at the discretion of the plant owner. This approach provides for a more realistic, but still conservative evaluation of the region of that would be affected by the energy release from the postulated break. A hemispherical ZOI is used for this approach.
4	Leak Before Break (LBB) Methods	Twice the flow area of a stable through-wall flaw that yields a 10-gpm leak is used.	LBB methods require the use of fracture mechanics methods to define a through-wall crack that yields 10-gpm leak. LBB methods require that a crack twice the length of the 10gpm leak be shown to be stable (won't instantaneously grow). Twice the length yields twice the flow area of the 10 gpm through wall flaw. The flow area is, in turn, used to evaluate the flow rate through the flaw which, in turn, is used to evaluate debris generation. This approach provides for a realistic evaluation of the region of containment that would be affected by the energy release from the postulated break.
5	RCP Seal LOCA	Total flow is limited by the maximum seal leakage for the RCP pump being considered.	Consider the geometry of the discharge of the leakage flow path when evaluating debris generation associated with the postulated RCP seal LOCA. Specifically, consider the orientation of the leakage flow relative to its release into containment.

4.2.3 Zone of Influence Definition

4.2.3.1 Zone of Influence Geometry

The Zone of Influence (ZOI) is the volume about the break in which the fluid escaping from the break has sufficient energy to generate debris from insulation, coatings, etc. Table 4.2.3.1-1 identifies and gives a brief discussion of the recommended options a plant might choose with regard to identifying a ZOI to be used to evaluate debris generation. The options identified provide for the evaluation of ZOI's that range from a physical representation of a jet to a conservative approximation that the entire volume within the crane wall becomes a potential source of debris. Note that the use of directionally dependent ZOI's should require a greater effort to support their use. The plant should choose the ZOI option it determines appropriate for its specific design and condition.

4.2.3.2 Robust barriers

Robust barriers (structures that prevent further expansion of the break jet in a given direction) should be included in the evaluation.

- If a break jet encounters a robust barrier, the ZOI created will have a spherical boundary with the exception of the volume beyond the robust barrier.

- The radius of the spherical boundary can be redefined such that the volume encompassed by the ZOI is equal to that encompassed by the spherical ZOI that would be created if the robust barrier were not present.

- Pure reflection of break jets should not be included in the evaluation. The use of a spherical ZOI is intended to bound any jet reflection effects.

- Likewise, the effects of pipe whip and traveling jets are bounded by the spherical ZOI.

4.2.3.3 Thermal Hydraulic Conditions

- LOCA Definitions

- The following break sizes are defined for the purposes of performing this evaluation:

  - Large LOCA – Greater than six inches
  - Medium LOCA – From two inches to six inches
  - Small LOCA – Less than two inches

  Plant-specific definitions of the various categories may supercede these definitions.

- For the postulated break location, determine the following information:

- ➢ System fluid conditions (pressure and temperature of the RCS coolant)

- ➢ Size of break, based on the size of the pipe and results of piping analyses. See Attachment B for breach size as determined through the application of fracture mechanics.

- ➢ Locations and geometry of equipment and structures surrounding the break site

- ➢ Destruction pressures of materials surrounding the break site that are potential contributors to the debris source term

- Define the jet impingement pressure(s) of interest, based on the destruction pressures of materials surrounding the break site. Three methods recommended for defining the jet impingement are:

  - ➢ Use a ZOI of a sphere of a radius 12 times the diameter of the cross sectional diameter of the postulated broken pipe (Ref. 7-39) and, assume that all debris sources within the ZOI become debris.

  - ➢ Identify the types of potential debris in the area of containment surrounding the break site. Determine which potential debris source has the lowest destruction pressure. Use this destruction pressure to as the jet impingement pressure of interest.

  - ➢ Identify the types of potential debris in the area of containment surrounding the break site. Consider multiple jet impingement pressures, with each equal to the destruction pressure of one of the potential debris sources being considered.

- If using destruction pressures to evaluate debris generation:

  - ➢ Use the break size and geometry, the system fluid conditions, and the containment thermodynamic state as initial conditions to calculate the jet expansion and equivalent static impingement force as described in Chapter 7 of ANSI/ANS-58.2-1988 [Reference 7-30].

  - ➢ Using the volume of the expanded jet calculated from the preceding step, calculate the diameter of an equivalent sphere that would have the same volume as that jet. This spherical volume is the ZOI.

  - ➢ Consider both transient and steady state break flow in calculating the volume of the ZOI.

- Determine where the outer boundary of the sphere or hemisphere would exist inside containment.

- Evaluate the effects of robust barriers (defined as structures and equipment that are impervious to jet impingement and prevent further expansion of the break jet)

- Use the locations and geometry of equipment and structures surrounding the break site to determine if robust barriers are present.

- Calculate the portion of the spherical ZOI that would be intercepted by the robust barriers.

  - If a break jet encounters a robust barrier, the ZOI created should have a spherical boundary with the exception of the volume beyond the robust barrier.

  - Debris generation in any part of the ideal spherical ZOI that would be located beyond the robust barriers is not considered.

  - The overall volume of the ZOI is not reduced. Re-calculate the radius of the spherical boundary such that the volume encompassed by the ZOI is equal to that encompassed by the spherical ZOI that would be created if the robust barrier were not present.

  - Note that increasing the radius of the outer boundary of the ZOI could cause additional robust barriers to be encountered. Thus, multiple re-calculations of the outer boundary of the ZOI may be necessary.

- If multiple jet impingement pressures are being considered, repeat the process of determining the outer boundary of the ZOI for each pressure of interest.

Table 4.2.3.1-1: ZOI Geometry

Option	ZOI Geometry	Discussion
1	Entire volume within crane wall	This assumes that a postulated pipe break generated debris from all insulation and coatings within the crane wall. This approach provides for the postulated generation of a maximum volume of debris.
2	Sphere having a diameter of 12 times the cross sectional diameter of the severed pipe	This geometry is used with a complete severing of the pipe being evaluated. Sphere having a radius of 12 times the crossectional diameter of the severed pipe . A constant sphere having a radius of 12 times the diameter of the pipe provides for maximum ZOI area.
3	Spheres of various diameters, depending upon the destruction pressure of the material being considered as a debris source	This geometry is used with a complete severing of the pipe being evaluated. Accounting for the destruction pressure of materials being considered can reduce the volume of debris generated from robust materials.
4	Hemispherical shape having a diameter of 12 times the equivalent diameter of the break flow area.	This geometry is used with a postulated hole in piping taken from the stable leakage flaw flow area calculated using fracture mechanics methods. This takes the postulated hole to be circular. Hemispherical shape having a radius equal to 12 times the cross sectional diameter of the hole size. This assumes the postulated hole to be circular. A constant hemisphere having a radius equal to 12 times the diameter of the hole size calculated using fracture mechanics methods provides for a maximum ZOI volume, which in turn, maximizes the debris from robust and non-robust insulation types.
5	Hemispheres of various diameters, depending upon the destruction pressure of the material being considered as a debris source	This geometry is used with a postulated hole in piping taken from the stable leakage flaw flow area calculated using fracture mechanics methods. This takes the postulated hole to be circular. Accounting for the destruction pressure of materials being considered can reduce the volume of debris generated from robust materials. The use of a hemispherical ZOI suggests that debris generation is dependent upon the break orientation. The break orientation may affect the volume of debris generated and should be considered in calculating the volume of debris resulting from the break.

6	ANSI/ANS-58.2-1988 Jet Model	This geometry is used with a postulated hole in piping taken from the stable leakage flaw flow area calculated using fracture mechanics methods. This takes the postulated hole to be circular. This model predicts geometry of a jet and its associated static pressure as the jet expands. The use of the model gives a direction to the destruction caused by the jet. Thus, orientation of the break becomes important, as only those items in the path of the expanding jet are considered "targets" for debris generation.

4.2.4 Debris Quantity Calculation

4.2.4.1 Potential Debris ZOI

The following is a recommended process for calculating the amount of debris generated within the ZOI. The boundaries of the ZOI are calculated using one of the methods described in Section 4.2.3.

- For each potential debris source of interest, calculate the amount of material that is located inside the ZOI. All material located in this area can contribute to the debris source term.

- For breaks postulated in the vicinity of the pressure vessel, consider packing materials used in penetrations as a potential source of debris. Review the design and test packages for these materials to determine if they should be included as a debris source for break locations located near the pressure vessel.

- Use the debris characteristics in Section 4.2.5 to assign a debris size distribution to each debris type.

- Catalog the results for each debris type.

4.2.4.2 Post-Accident Environment

4.2.4.2.1 Containment Spray Washdown

Containment spray action has the potential to cause debris generation from some materials used inside containment. The recommended procedure to determine the quantity of debris generated by this mechanism is as follows:

- Use containment walkdown data to identify the potential debris sources located throughout containment.

- Catalog the type, location, and quantity of each potential debris source.

Evaluate the debris production from each of the potential sources. It is recommended that the following considerations be made when performing the evaluation:

- RMI is not affected by washdown effects since it is not soluble or easily penetrable by water and therefore will not become a debris source from the action of containment sprays.

- Calcium Silicate with metal encapsulation will not become a debris source from the action of containment sprays.

- DBA-qualified coatings will not become a debris source from the action of containment sprays.

- Non-DBA-qualified coatings will become debris sources. Section 4.2.5.4 contains information regarding the failure of these materials.

- Encapsulated insulation materials not within the ZOI are resistant to containment spray action and therefore are not a debris source.

- Jacketed insulation that could be subjected to containment spray should be evaluated as a debris source. If the jacketing is overlapped or butted end-to-end, deterioration of insulation due to containment sprays is mitigated: the configuration of the jacketing, however, should be confirmed by walkdown. If the jacketing is not overlapped or butted end-to-end, debris generation due to erosion may occur. It is recommended that the volume of insulation that will be treated as debris be calculated using four times the width of the gap between two adjacent jackets, and the thickness of the insulation at that location. It is also recommended that the debris generated due to this method be treated as fines or individual fibers.

- Unjacketed and/or unencapsulated insulation may be susceptible to damage as a result of containment sprays. These types of materials are typically used in fire barrier applications. If this type of insulation is known to be subject to erosion, and the material is subjected to containment spray, then it is recommended that the entire volume of the material be treated as a debris source. It is also recommended that the debris generated due to this method be treated as fines or individual fibers.

- Various other types of materials in containment contribute to the debris source term. Section 4.2.5 contains detailed information regarding these materials.

4.2.4.2.2 Pumped Break Flow

This is not considered to be a credible debris generation mechanism as the jet resulting from RCS depressurization will cause significantly more damage to insulation and will result in the distribution of the resulting debris about the containment away from the postulated break location.

4.2.4.2.3 Submergence

Submergence has the potential to cause debris generation from some materials used inside containment. The recommended procedure to determine the quantity of debris generated by this mechanism is as follows:

- Determine what areas inside containment will be submerged in the post-accident environment.

- Submerged areas that are either isolated from the sump, or for which fluid in the area does not equal or exceed the transport threshold velocity of debris contained within that area, may be excluded from the evaluation. Debris generated in these areas is not transportable to the sump.

- For areas that have transport paths to the containment floor or sump, the following procedure should be used:

  - Determine the maximum water height above the containment floor, based on the plant operation assumptions recommended above.

  - Assume all areas below the maximum water height are fully submerged (all surfaces are exposed to water – credit should not be taken for air pockets).

  - Determine other areas inside containment that could be submerged. Possible areas include cable trays and the refueling canal.

  Note that it is possible that some areas may be continuously draining yet remain filled with water because of continuous water input from containment sprays.

- Use condition assessment and containment walkdown data to identify the potential debris sources located in areas subject to submergence.

- Catalog the type, location, and quantity of each potential debris source.

- Evaluate the consequential debris production due to submergence from each of the potential types, particularly if the debris generated by fluid escaping from the break remains in the flow path to the containment sump. Base the debris production amount on the debris characteristics presented in Section 4.2.4. It is recommended that the following considerations be made when performing the evaluation:

  - RMI is not affected by submergence effects since it is not soluble or easily penetrable by water and therefore should not become a debris source from the action of containment sprays.

  - Encapsulated insulation materials are resistant to submergence effects and therefore are not a debris source.

  - Jacketed insulation that could be subjected to submergence should be evaluated as a debris source. If the jacketing is overlapped or butted end-to-end, deterioration of insulation due to submergence is mitigated: the configuration of the jacketing, however, should be confirmed by walkdown. If the jacketing is not overlapped or butted end-to-end, debris generation due to submergence and limited erosion may occur. It is recommended that the volume of insulation that will be treated as debris be calculated using four times the width of the gap between two adjacent jackets, and the thickness of the insulation at that location. It is also recommended that the debris generated due to this method be treated as fines or individual fibers.

- Unjacketed and/or unencapsulated insulation may be susceptible to damage as a result of submergence. These types of materials are typically used in fire barrier applications. If this type of insulation is known to be subject to erosion, and the material is subjected to immersion, then it is recommended that the entire volume of the material be treated as a debris source. It is also recommended that the debris generated due to this method be treated as fines or individual fibers.

- DBA-qualified coatings tested in immersion will not become a debris source from either the action of containment sprays or post-accident submergence.

- Non-DBA-qualified coatings, and DBA-qualified coatings not tested in immersion, are potential debris sources. Section 4.2.5.4 contains information regarding the failure of these materials.

- Various other types of materials in containment contribute to the debris source term when submerged. Section 4.2.5 contains detailed information regarding these materials.

4.2.4.3 Total Debris Source Term

The total debris source team is determined by summing the volume of:

- The individual debris types produced in the ZOI
- The individual debris types produced in the post-accident environment
- The volume of latent containment debris evaluated for the plant

The total debris source term is used in the remainder of the sump performance evaluation: debris transport to the containment sump, debris accumulation and head loss across the containment sump screen.

If the results of the evaluation using a particular debris source do not represent the worst case with respect to debris generation, debris transport or debris accumulation and sump screen pressure drop, the postulated break should be changed and a new source term calculated.

4.2.5 Debris Characteristics

This section provides data to be used with the logic and procedures presented above to conservatively predict the characteristics of debris generated as a result of a LOCA.

4.2.5.1 Fibrous Insulation

Physical characteristics of fibrous materials (except Calcium Silicate, which is addressed in Section 4.2.5.2) are identified in Table 4.2.5.1-1. Not all generated fibrous debris needs to be assumed to be of a size that is transportable. The specifics of transportability will be discussed in the Debris Transport section.

Fire barrier materials are addressed separately in Section 4.2.5.6.

For some plant sites, it may be desirable to use a bounding, simplifying assumption for the debris size distribution. It would always be acceptable to conservatively assume that all debris is generated into fine particles. It is also acceptable to assume a more conservative (biased toward smaller pieces) distribution than that presented in Table 4.2.5.1-1.

Plants should also review their design documentation for additional information regarding debris generation characteristics of insulation used in their plant. For example, the NRC has previously reviewed and issued a SER on NUKON insulation and its consequential effect on ECCS operation post-accident [Reference 7-31].

4.2.5.2 Cal-Sil Insulation

Calcium silicate insulation typically has a higher destruction pressure than most types of fibrous insulation. NRC confirmatory analyses performed to support resolution of strainer issues for BWRs indicate a destruction pressure of 150 psi for calcium silicate insulation with an aluminum jacket. However, calcium silicate destruction tests performed by Ontario Power Generation indicate that the destruction pressures can be less than 24 psi, depending on the orientation of the longitudinal cladding seams.

The destruction pressures for calcium silicate are given in Table 4.2.5.2-1.

If credit for orientation of cladding seams is to be taken:

- Data from the licensee’s walkdown program should be used to determine the orientation of seams relative to the postulated break. Probabilistic methods are not be used with regard to seam orientation.

- Assumptions according to Table 4.2.5.2-1 are recommended to determine the destruction pressure of the Cal-Sil insulation. The values are based on the Ontario Power Generation jet impact tests.

- The licensee should implement sufficient procedures and configuration controls to assure that future modifications or repairs to insulation will either not invalidate the debris generation evaluation, or will initiate a review of the debris generation evaluation to evaluate the effect of the modifications or repairs on the volume of debris generated.

The suggested method for determining calcium silicate debris generation is:

- Identify seam orientation of jacketing for each pipe section located within the ZOI based on the lowest calcium silicate destruction pressure.

- Use the stagnation pressure vs. radius information to determine the impingement pressure on each pipe section. The pipe section should be defined as the length of pipe that is covered by one piece of jacketing.

- If $p_0 > p_{dest}$, assume all calcium silicate insulation on the pipe section in question fails.

As an alternative, a conservatively low destruction pressure can be assumed for all sections of pipe that are potentially located within the primary ZOI. When calcium silicate insulation is damaged, a number of types of debris can be generated. The recommended debris size distribution is given in Table 4.2.5.2-1.

4.2.5.3 Reflective Metallic Insulation (RMI)

RMI debris is assumed generated within the ZOI. Typically, RMI is installed in pre-fabricated cassettes that conform to the piece of equipment being insulated. Break jet impingement can dislodge RMI and possibly destroy cassettes, creating smaller pieces of debris. The following information should be used to evaluate the potential for debris generation from RMI cassettes:

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

RMI destruction regimes are defined as:

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

The destruction pressures for RMI are given in Table 4.2.5.3-1. The recommended debris size distribution is given in Reference 7-32.

4.2.5.4 Coatings

All coatings need to be identified as DBA-qualified/Acceptable or non-DBA qualified/Unacceptable. Guidance on evaluating coatings is given in Reference 7-33.

4.2.5.4.1 Coatings Within the ZOI

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

- The type(s) of coating systems within the ZOI should be identified and documented. If multiple coating systems have been applied to surfaces within the ZOI, the properties of the coating system which produces post-accident debris most detrimental to the containment sump should be used in subsequent transport and sump clogging analyses. Representative physical characteristics of the failed coating materials within the ZOI are shown in Table 4.2.5.4.2-1.

4.2.5.4.2 Coatings Outside the ZOI

- DBA-qualified coatings outside the ZOI, when properly maintained, do not fail and therefore do not contribute to the debris source term.

- Non-DBA-qualified coatings outside the ZOI may disbond from the substrate and contribute to the debris source term.
  - Non-DBA-qualified coatings that are potential debris sources include coatings on equipment permanently stored in containment or temporarily left in containment after an outage.
  - In the absence of vendor-generated or plant-specific data, all non-DBA-qualified coatings should be assumed to fail and therefore be considered in the debris source term.
  - Vendor or plant-specific data or experience may support using less than complete (100%) failure of non-DBA-qualified coatings in the debris source term. Additionally, an industry research project is being conducted by EPRI PSE in 2003/2004 concerning the failure of OEM non-DBA-qualified/Unacceptable coatings in the PWR DBA environment to provide additional data on this topic.

- The type(s) of coating systems outside of the ZOI should be identified and documented. If individual non-DBA-qualified coating systems used outside of the ZOI are not identified, the properties of the non-DBA-qualified coating system which produces post-accident debris most detrimental to the containment sump should be used in subsequent transport and sump clogging analyses. Representative physical characteristics of failed coating materials outside of the ZOI are shown in Table 4.2.5.4.2-1.

Table 4.2.5.4.2-1: Representative Characteristics of Failed Coating Materials within and outside the ZOI

For Use in Transport and Head Loss Analyses

Generic Coating Material	Material Density (lbs/ft^3)	Characteristic Size µm	Characteristic Size ft
Inorganic Zinc (IOZ)	350	$10^{(1)}$	3.28E-05
Epoxy and Epoxy Phenolic Coating Chip (outside ZOI)	94	$25^{(2)}$	8.20E-05
Epoxy and Epoxy Phenolic Coating Particles (in ZOI)	94	$10^{(1)}$	3.28E-05
Alkyd Coating	98	$10^{(1)}$	3.28E-05

Note 1: Spherical Particle Diameter
Note 2: Flat Plate Thickness

Discussion of Values Presented in Table 4.2.5.4.2-1

The following types of coatings are commonly found within PWR containments: Inorganic Zinc (IOZ), Epoxy, Epoxy Phenolic and Alkyd. The densities for epoxy, epoxy phenolic and alkyd coating shown in Table 4.2.5.4.2-1 are based on specific gravities presented in the "Performance of Containment Coatings During a Loss of Coolant Accident" [Reference 7-34]. The specific gravity for IOZ is reported in CRC [Reference 7-35] as 5.6. A specific gravity of 5.6 corresponds to a nominal density of 350 lbs/ft^3. This value is lower than the 437 lbs/ft^3 reported by Carboline for the zinc dust used in the formulation of CarboZinc 11 [Reference7-36]. As such, the nominal density value of 350 lbs/ft^3 is conservative since lower density values imply higher volumes and thus higher head losses.

Coatings within the ZOI will be ablated by the break jets [Reference 7-37]. In the absence of specific experimental details about the debris particle size distribution for IOZ, alkyds, epoxy and epoxy phenolic coating debris generated by high pressure water/steam jets in the ZOI, a diameter of 10 µm has been selected as the characteristic size of coating debris generated within the ZOI. The 10 µm characteristic diameter is the nominal diameter of unbound zinc particles and also the alkyd pigment particles of failed coatings [Reference 7-38]. Epoxy and epoxy phenolic coatings outside the ZOI will fail as chips [Reference 7-38]. A typical lower bound for epoxy and epoxy phenolic coating chip thickness is 1 mil (25.4 µm) [Reference 7-34]. 10 µm diameters are shown as the characteristic size of IOZ and alkyd coating debris outside of the ZOI [Reference 7-38].

4.2.5.5 Tape and Stickers

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

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

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

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

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

4.2.5.6 Fire Barrier Materials

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

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

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

For materials that are unique to fire barrier applications and do not have supporting test data, assume a destruction pressure equal to that of low-density fiberglass. Available destruction information for fire barrier and other materials that might be found inside typical PWR containments are given in Table 4.2.5.6-1.

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

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

Specific Fire Barrier Materials include:

- Marinite board which may be included in the debris is generated within the ZOI. According to NUREG/CR-6772, large amount of plastic deformation is necessary to break Marinite Board apart. Therefore, Marinite board is assumed destroyed within the ZOI but left intact outside the ZOI. All destroyed Marinite board can be assumed to be broken into large chunks.

- Kaowool blanket and mineral wool debris are destroyed in the ZOI. Assume same destruction data for fiberglass or NUKON.

- RTV foam debris is assumed to be destroyed within the ZOI. As with some other types of fire barrier, destruction information is needed for RTV/silicone foam insulation.

4.2.5.7 Miscellaneous Debris Sources

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

Dust and dirt includes miscellaneous particulates that are present in the containment. Potential origins for this material include activities performed during outages and foreign particulates brought into containment during outages. Plant-specific walkdown results can be used to determine a conservative amount of dust and dirt to be included in the debris source term.

Several plants took latent debris samples while performing insulation walkdowns. The results were tabulated and compared. The general conclusion was that a plant with typical containment cleanliness procedures would result in no more that 3 lbs of debris per 10,000 square feet of horizontal surface area. This would support the use of an upper bound of 150lbs of latent debris as a generic value, if site specific samples are not taken. Lower values could be justified with site specific information.

- Concrete located sufficiently close to the break will produce particulate debris. It is appropriate for the licensee to assume all concrete debris is in the form of fine particulates. The quantity of concrete debris produced should be evaluated on a break-specific and plant-specific basis.

Other miscellaneous debris sources that are to be evaluated on a plant specific basis are listed below. For each potential debris type considered, debris generation resulting from jet impingement and washdown effects is to be considered.

- Fabric equipment covers
- Fire hoses
- Ropes
- Ventilation system filters
- Cloth
- Wire ties
- Plastic sheeting
- Rust from unpainted surfaces
- Scaffolding
- Auxiliary equipment left inside containment
- Caulking
- Mastic or filler materials
- Fibrous material from lead blankets
- Radiation protection signage
- Operations tags

Table 4.2.5.1-1: Damage Characteristics of Common Fibrous Insulation Materials inside PWR Containments

Material Category / Type	Destruction Pressure (psi)	Debris Size Distribution	Comments
1. Fiberglass - Generic a. Unjacketed b. Encapsulated c. Steel-jacketed	Assume same as NUKON.	Assume same as NUKON.	Assume equal destruction pressure to that of NUKON. Account for encapsulation/ jacketing configuration.
2. Fiberglass – NUKON a. Jacketed, with modified “Sure-Hold” bands, Camloc strikers and latches b. Jacketed, with standard bands c. Unjacketed	a. 190 psi b. 10 psi c. 10 psi	NUREG/CR-6772 characterizes NUKON fibers	See Reference 7-30 for additional information regarding destruction pressure.
3. Fiberglass – Temp-Mat a. Unjacketed, with stainless steel wire retainer b. Other configurations	a. 17 b. Conservatively use data from 3(a), above	Assume same as NUKON.	Use destruction pressure for NUKON. Account for encapsulation/jacketing configuration.
4. Fiberglass – Transco	NUREG/CR 6369 - the debris transport tests at CESI - used Transco blankets. Document has been requested.	Assume same as NUKON.	Assume equal destruction pressure to that of NUKON. Account for encapsulation/ jacketing configuration.
5. Mineral Wool	NEA/CNSI/R (95) 11 has information on Mineral Wool. There is some concern of the applicability of this information. Consider using a bounding assumption.	Assume same as NUKON However, it is unclear if fiberglass and mineral wool exhibit similar destruction characteristics.	Using existing data with caution.
6. Miscellaneous Fibrous a. Asbestos b. Min-K – not fiber – this is a micorporous insulation NUREG/CR-6762 indicates it is fibrous c. Unibestos	a. Data needed. b. < 4 psi c. Data needed.	b. SEM of Min-K shows amorphous globs in fiber bed.	Some forms of Calcium Silicate use asbestos fibers as reinforcement. Calcium Silicate is still the insulation type subject to destruction. Therefore, for this insulation, the asbestos reinforcement should not be considered separately.

Table 4.2.5.2-1: Damage Characteristics of Calcium Silicate Insulation inside PWR Containments

Material Description	Destruction Pressure (psi)	Debris Size Distribution	Comments
Metal-jacketed Aluminum cladding, stainless steel bands	51 (seam at 0°) >24 (seam at 45°) >64 (seam at 180°) NRC SER on the BWR URG suggests 20 psi as a generic value.	Debris Fines: 75% < 1 in.: 10% 1-3 in.: 10% > 3 in.: 5%	Debris destruction pressures determined in NUREG/CR-6762, Vol.3 are based on Ontario Power Generation tests. Debris distribution determined based on data from Ontario Power Generation tests. These data apply only to the type of calcium silicate tested. NEA/CNSI/R (95) 11 has a table on Newtherm – a European variant of Calcium Silicate. Considering the differences in strength between aluminum and stainless steel, it is suggested that the destruction pressure and debris size distribution evaluated for aluminum cladded calcium silicate may be conservatively applied to stainless steel cladded calcium silicate.

Table 4.2.5.3-1: Damage Characteristics of Common Reflective Metallic Insulation inside PWR Containments

Material Description	Destruction Pressure (psi)	Debris Size Distribution	Comments
Stainless steel a. Transco b. Diamond Power MIRROR (with "Sure-Hold" bands, Camloc strikers and latches) c. Diamond Power MIRROR (with standard banding d. Darchem DARMET	a. 190 psi b. 150 psi c. 4 psi d. 190 psi	See Reference 7-32 for size distribution	

Table 4.2.5.6-1: Damage Characteristics of Common Fire Barrier and Other Insulation inside PWR Containments

Material Description	Destruction Pressure (psi)	Debris Size Distribution	Comments
1. 3M Interam	Assume same destruction data as for NUKON (representative of low-density fiberglass).	Assume same destruction data as for NUKON (representative of low-density fiberglass).	Account for encapsulation/ jacketing configuration.
2. Fiberglass blanket	Conservatively assume destruction data for fiberglass or Temp-Mat.	Conservatively assume destruction data for fiberglass or Temp-Mat.	Account for encapsulation/ jacketing configuration.
3. Kaowool	Assume same destruction data as for NUKON (representative of low-density fiberglass).	Assume same destruction data as for NUKON (representative of low-density fiberglass).	Account for encapsulation/ jacketing configuration.
4. Marinite board	Conservatively assume destruction data for fiberglass or Temp-Mat.	Conservatively assume destruction data for fiberglass or Temp-Mat.	Assumes conservatively low destruction pressure.
5. Silicone foam	Conservatively assume destruction data for fiberglass or Temp-Mat.	Assume debris, regardless of size, floats.	Assumes conservatively low destruction pressure.
6. Koolphen (closed cell phenolic)	4 psi (From the BWROG URG)	Limited Data Debris observed to float	NUREG/CR-6762 Volume 2 does not identify Koolphen as an insulation that is used in U.S. PWR containments.

4.3 Airborne/Washdown Debris Transport

4.3.1 Introduction

The section on Debris Generation discussed and provided guidance on evaluating the amount and kind of debris that might be generated from insulation, protective coatings, and materials inside containment subjected to flows and environmental conditions resulting from a postulated high-energy pipe break inside the containment. In addition to debris generation, the effluent from the postulated pipe break also provides the initial mechanism to transport and distribute that debris about the containment. Although the escaping effluent might deposit some of the debris directly on the containment floor, much of the debris would be carried about the containment by the released effluent. This transport mechanism during the "blowdown" phase is called airborne debris transport.

If the postulated break is sufficiently large, the released effluent would pressurize the containment sufficiently to activate the containment spray system. The transport of debris about the containment would then also be driven by the drainage of containment spray water from the spray headers to the containment sump. This transport mechanism is called washdown debris transport.

Both airborne and washdown debris transport occur above the water pool on the containment floor. Evaluation of airborne and washdown debris transport should provide an assessment of the type of debris that might enter the pool, and where and when that debris will enter the pool. Irrespective of the time of arrival, once in the pool, debris is then evaluated for transport to and potential blockage of the containment sump screen.

4.3.2 Transport Mechanisms

Airborne and wash-down debris transport within a PWR containment is dependent upon both the physical processes and phenomena associated with the postulated break being evaluated, and the particular design features of the containment being evaluated. It is important to account for these event- and design-specific dependencies in evaluating these mechanisms of debris transport.

4.3.2.1 Accident Characterization

The size of the break is the most important aspect of the accident scenario in regard to debris transport inside the containment. For Loss of Coolant Accidents (LOCA's), break sizes are usually segregated as a small, medium, or large LOCA.

The break size influences the debris transport in a number of ways:

- The break size determines the dynamics within the containment of the resultant primary system depressurization. The depressurization of the Reactor Coolant System (RCS), typically referred to as the blowdown phase of the event, determines transport velocities and flow qualities (ratio of steam and water in the break flow) within the containment, which in turn affects the mechanisms for debris transport about the containment and debris deposition onto structures.

- The size of the break also affects the timing of the accident sequence (the completion of the blowdown phase, the duration of ECCS injection phase, and the time when the recirculation from the containment sump is initiated). The injection phase corresponds to the ECCS injecting the Refueling Water Storage Tank (RWST) inventory into the RCS. The injected water flowing out the postulated break establishes the pool on the containment floor. The recirculation phase refers to long-term ECCS recirculation from the containment floor sump into the RCS, out of the postulated break and back into the pool.

- The size of the postulated break also determines whether the containment sprays activate. For large breaks, the containment spray system actuates almost immediately, whereas for a smaller break, the resulting increase in containment pressure may not be sufficient to cause the containment sprays to initiate.

- The size of the break determines the pumping flow rate from the sump in that the pump flow rate would be limited by the rate of flow from the break after the vessel inventory was replaced.

The location of the break, along with the general design of the containment, determines the patterns of flow and debris movement throughout the containment during the blowdown phase. The break location affects flow dynamics, how and where debris impacts structures, and whether debris would be transported away from the sump or toward the sump. The location of the break relative to the piping insulation would affect the type of debris being generated and transported about the containment. The location of the break also affects the sump-pool flow dynamics near the recirculation sump.

4.3.2.2 Plant Feature Characterization

A number of features of a PWR containment are important to the post-accident transport of debris. The most significant containment feature is the relatively large containment free volume. The containment spray system is also important.

For a PWR containment, the direction of the breakflow some distance from the break would tend to be up toward the large free volume of the containment dome and away from the ECCS sump screens. The breakflow will also carry smaller debris resulting from the postulated break into this region. Thus, for PWR plants, substantial quantities of debris would be carried away from the lower regions of the containment and toward the higher regions of the containment. Containment sprays, however, tend to wash the debris down toward the containment floor.

The flow carrying debris upward in the containment may be directed through relatively narrow passageways in some containment designs, such as a steam generator cubicle. This provides an opportunity for portions of the debris entrained within the flow to impact and be deposited on structures and surfaces within the flow path. Other structural features, such as gratings, piping and beams, may also capture debris as it is carried past those structural features.

After the airborne debris is dispersed throughout the containment, the design of the containment spray system and of the drainage paths for the sprayed water determine the washdown of a portion of that debris to the containment pool. The spray droplets tend to sweep remaining airborne debris out of the containment atmosphere. The falling droplets then wash debris off surfaces (structures, equipment, walls, floors, cable trays, etc.). As the drainage works its way downward, entrained debris will move along with the flow. However, not all debris will be washed off surfaces and entrained. Also, this washdown process occurs only on those regions of the containment that are subjected to the sprays.

A PWR containment is generally designed to readily drain the spray water to the sump, to minimize water holdup and maximize sump water levels. However, the refueling pool may hold up substantial quantities of water if the pool drains are not open or are blocked by debris. Thus, the design of the refueling pools, including the pool drainage system, should be considered when evaluating washdown debris transport.

The locations where spray drainage enters the sump pool relative to the location of the containment sump are also important. Debris that is deposited into the pool well away from the containment sump may be less likely to transport to the sump screen than debris deposited near the sump. Debris transport within the sump pool depends on a number of plant features, including the lower compartment geometry that defines the shape and depth of the sump pool, such as the open floor area, ledges, structures, and obstacles within the pool. In addition, the relative locations of the containment sump, the postulated LOCA break, and the drainage paths from the upper regions of containment to the sump pool are important to determining pool turbulence, which, in turn, influences whether debris can settle in the pool.

4.3.2.3 Debris Characterization

Transport of debris is dependent on the characteristics of the debris formed including the types of debris (insulation type, coatings, dust, etc.), the size distribution and form of the debris. Each type of debris has its own set of physical properties, such as density; specific surface area; buoyancy when dry, partially wet, or fully saturated; and settling velocity in water. The size and form of the debris depends on the method of debris formation, e.g., jet impingement, erosion, aging, operational, etc. The size and form of the debris determines the susceptibility of that debris to be transported about containment towards the containment sump as well as being held up by objects, such as gratings, in the flow path. For example, fibrous debris may consist of individual fibers or large sections of an insulation blanket and all sizes between these two extremes.

4.3.3 Suggested Debris Transport Approach

4.3.3.1 Summary of BWR Drywell Debris Transport Study (DDTS)

During the evaluation and resolution of BWR ECCS strainer blockage concerns, the NRC initiated a study to investigate the transport and capture characteristics of debris in BWR drywells. The debris-transport processes associated with the drywell were relatively complex and involved debris transport during both the reactor blowdown phase through entrainment in steam/gas flows and the post-blowdown phase by water flowing out of the break and/or containment sprays. It also addressed characteristics of debris erosion caused by air and water flows.

Because of its complexity, the problem was broken into several individual steps. Each step was 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.

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

A simplified logic-chart method was chosen to integrate the problem subcomponents into a comprehensive study. The logic chart subdivides the problem into five independent steps: (1) break type, (2) debris classification, (3) debris distribution after blowdown, (4) erosion and washdown, and (5) sedimentation in the drywell floor pool. A separate logic chart was generated for each scenario and 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 were tabulated.

4.3.3.2 Guidance - Use of Logic Charts for Airborne Debris Transport

It is suggested that the simplified logic-chart method be applied to evaluate the PWR debris transport processes. The application of this approach is similar to that implemented in the BWR DDTS. Specifically:

- Construct simplified logic-charts as a first step to evaluate debris transport.
- Each logic-chart should address:
    - A specific accident scenario; large break LOCA, medium break LOCA, small break LOCA, or Main Steamline Break, if applicable, and,
    - A specific debris source; low density fiber glass insulation, reflective metallic insulation, etc.

An example of a simplified logic-chart for a typical PWR is given in Figure 4.3.3.2-1. The sample logic-chart was prepared for a specific event (large break LOCA) and a specific type of debris source. Additional detail may be added to the chart, as determined appropriate for the specific plant and scenario conditions.

Using the simplified logic-chart, knowledge of the containment flow path characteristics, knowledge of debris airborne transport characteristics, and engineering judgment, distribution of airborne debris transport for a given accident scenario and debris type is then evaluated. Starting with the initial 100% debris volume generated by the LOCA at the left of Figure 4.3.3.2-1, the first task is to determine the debris size classification (e.g., small, medium and large) and to estimate percentages for each size. This will depend on the insulation type in the break zone of influence (ZOI) and the type of postulated break. The next step is to estimate the percentages of each debris size that may be transported during the blowdown phase to various regions of the containment. Airborne transport and retention by containment features is discussed below. Each branch of the logic chart under the Spray Washdown/Erosion heading determines the percentages of captured debris that remain on the containment structures after being subjected to the various washdown flows (i.e., containment spray, condensate drainage and break flow). Similarly, each branch under the Recirculation Phase Transport heading estimates the percentage of the debris which settles to the floor and remains there and what percentage would be transported. Multiplication of the percentages along any set of branches determines the percent debris at given final locations, in particular, the sump.

4.3.3.3 Debris Transport by Washdown

If the accident scenario results in the actuation of the containment spray system, a fraction of the debris deposited throughout the containment by means of airborne transport may be subject to potential washdown by the containment spray flow and the drainage of the spray water to the sump pool. While flow rates are considerably smaller, the draining of condensate on walls and structures within the containment also provides a mechanism for moving debris from upper levels of containment into the containment pool. Debris on surfaces that is exposed to direct impingement of containment spray is much more likely to transport with the flow of water than debris on a surface that is only wetted by condensation.

Debris entrained in spray water drainage is not easy to characterize. If the drainage flow is large and moves rapidly (> 0.2 ft/sec), even reflective metallic insulation is subject to transport with the water. However, at some locations inside the containment, the drainage flow may be slow and shallow enough for the debris to remain in place.

As water drains from the upper containment to the lower containment, flowing water may impact and splatter on each successively lower elevation. The impact of this flow on the transport of debris beyond the main flow of the drain path, thereby capturing the debris at the lower elevations, should be considered. Also, the potential for erosion of larger debris due to the action of the falling water, generating additional fine easily transportable debris, should be evaluated.

4.3.3.4 Guidance

Knowledge of the containment spray design is required to evaluate washdown. Typically, by design, about 70 per cent of containment spray is directed to the operating deck. This value should be confirmed on a plant specific basis. Also, the volume or mass flow rate delivered by the containment spray system is needed to determine the flow rates on the operating deck.

Knowledge of the drainage system for the containment is also needed. Specifically, features that affect the draining of water from the upper containment to the lower containment should be confirmed. These features include but are not limited to:

- The slope of the operation deck
- Drain paths such as the gap between decks and the containment shell
- The location and design of drains
- The location and design of grating
- The location and design of curbs (holes in the curbs or specific drain paths)
- The location and design of gates in doorways restricting access to portions of the containment

Using the designed containment spray distribution (coverage) and the geometry of the operating deck (or first level floor structure that will experience direct containment spray) estimate the following:

- The distribution of water delivered by the containment spray system to the operating deck (or first level floor structure that will experience direct containment spray).

- The location and rate of drainage from the operating deck (or first level floor structure that will experience direct containment spray) down to each successive floor until the flow reaches the pool.

These flow distribution estimates may be aided by considering the open areas that can receive direct spray relative to the total spray area and by considering the relative length of edges on openings at a given floor level that can spill sheet flow to the next lower level. The distribution of drainage flow rates are needed to assess both the potential for washdown from the various containment elevations, and as an input into the pool transport evaluation.

Debris retention during washdown is estimated for the debris deposited on each surface, i.e., retention is the fraction of debris that remains on each surface after spray washdown is complete. These estimates are based on experimental data and engineering judgment.

- For surfaces that would be exposed to only condensate, nearly all deposited fine and small debris likely would remain there. A value of 90 per cent retention is suggested as a most likely value, with a value of 75 per cent suggested as a minimum retention value.

- For surfaces exposed directly to spray flow, a majority of the fine and small debris will transport with the flow. A value of 25 per cent retention is suggested as a most likely value, with a value of 0 per cent (no retention) as a minimum retention value.

- Large and intact debris may not be washed down to the sump pool because of the screens or gratings across the floor drains and the size of those drains. Credit for retaining this debris away from the sump depends upon the containment design.
- For surfaces not exposed to direct spray, but receive accumulated spray inventory as it drains to the lower containment, the fraction of debris retained is based on engineering judgment and estimated water flow rates and patterns.

From the above, it is apparent that debris transport by washdown draws heavily on engineering judgment. Therefore, it is suggested that the basis for that judgment be clearly documented when identifying a "most likely" value.

Erosion of insulation into smaller size debris due to containment spray is evaluated based on the location of the material relative to containment sprays, the location of the material relative to the drainage of spray flow from upper containment to lower containment, and on engineering judgment. Debris erosion due to containment spray is limited by the time that containment sprays are active (operating). However, like debris retention, debris erosion washdown draws heavily on engineering judgment. Therefore, it is suggested that the basis for that judgment be clearly documented when identifying a "most likely" value.

4.3.3.5 Discussion

The use of logic-charts provides for the clear identification of engineering judgment in assessing debris transport. For example, the transport of debris into upper containments due to break flow depends upon both the containment geometry and the break location. Engineering judgment, along with knowledge of the containment flow paths and the location of the postulated break, may be used to estimate the airborne distribution of debris about the containment due to the blowdown phase of the event.

Flowpaths about the containment are obtained from as-built drawings and confirmed by walkdowns. The dimensions of obstacles in the flowpaths should be noted as they provide surfaces for debris to adhere. This reduces the transport of debris due to blowdown. The mechanical adhesion of debris along containment flowpaths should be considered when assessing debris transport due to washdown.

The use of engineering judgment should provide for conservatism in the values used to assess debris transport during the blowdown phase of the transient. A more realistic assessment of blowdown debris transport may be made using velocities in the flow paths of the containment. These velocities may be calculated with the use a multi-node containment analysis code and other appropriate models. Compared to engineering judgment, the use of a multi-node containment model or other appropriate models will provide both a more rigorous and a more realistic assessment of the airborne transport of debris.

4.3.3.6 Debris Retention by Containment Features

The US NRC has performed debris transport evaluations for a volunteer PWR. Although currently unpublished as a body of work, some information is available from this work and may be used to assess debris retention for all PWR containments.

The volunteer plant has some amount of Low Density Fiberglass (LDFG) insulation. The LDFG debris for the volunteer plant analysis was subdivided into four categories; the transport of each category of debris was treated separately. The four categories and their properties are shown in Table 4.3.3.6-1.

The primary difference between the two categories of smaller debris and the two categories of larger debris was whether the debris was likely to pass through a grating. Fines were distinguished from the small pieces because the fines would tend to remain in suspension in the sump pool under even relatively quiescent conditions, whereas the small pieces would tend to sink. Further, the fines tend to transport more like an aerosol in the containment air/steam flows and settle slower when airflow turbulence drops off, compared to the small pieces.

The distinguishing difference between the large and intact debris was whether the blanket covering was still protecting the LDFG insulation. The primary reason for this distinction was whether the containment sprays could erode the insulation material further. Estimates were made for a distribution among the four categories based on available data and previously accepted engineering judgments.

Table 4.3.3.6-2 lists debris retention properties from an integrated effects debris transport test conducted in support of BWR sump strainer blockage resolution [Reference 7-17]. The components (gratings, I-beams, pipes and turns and bends in the containment) are typical of both BWR and PWR containments. Therefore, this data may be used in assessing debris deposition in PWR containments as a result of the blowdown phase of the transient.

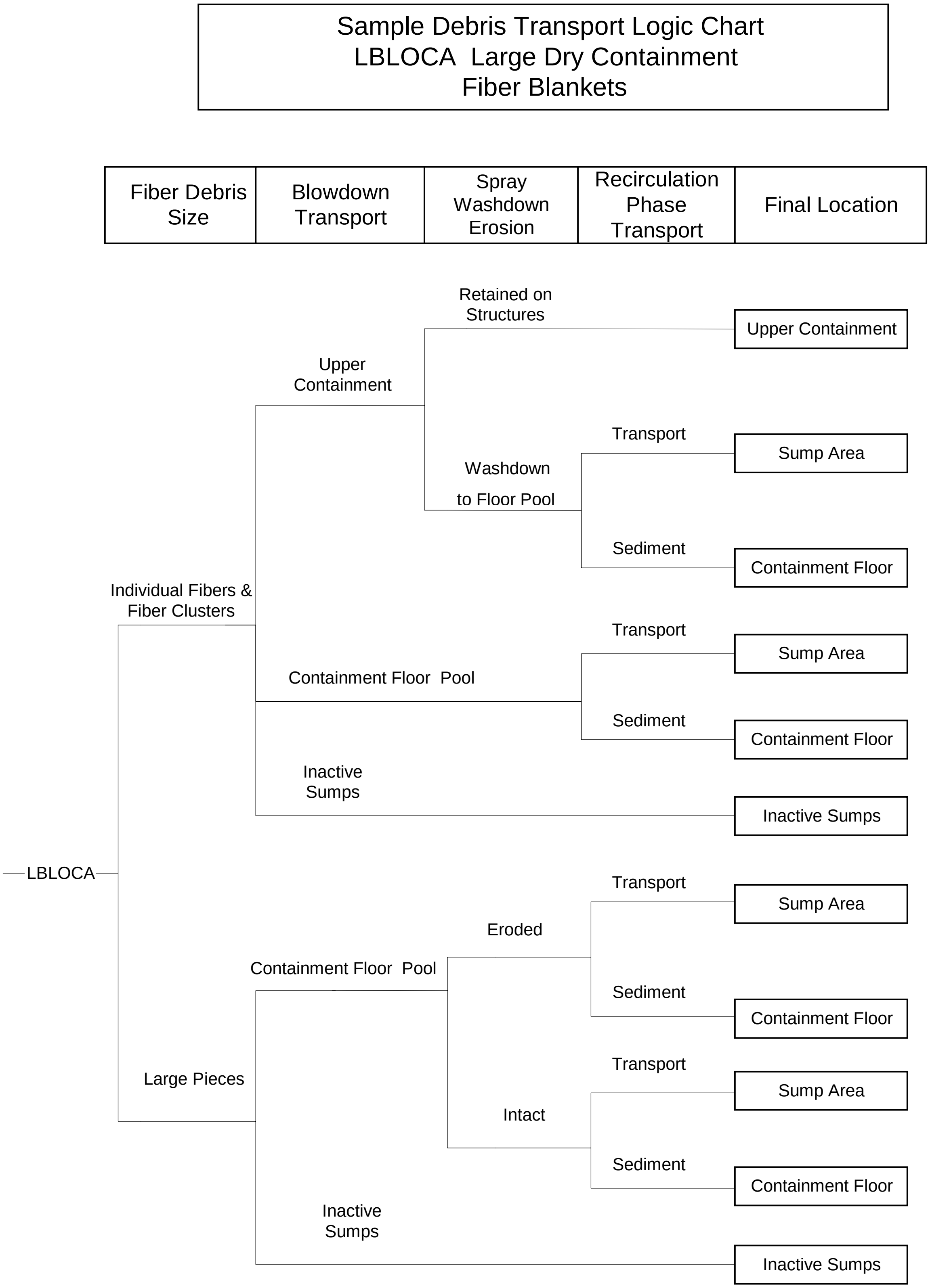


Figure 4.3.3.2-1: Example of a Simplified Logic-Chart for a Typical PWR

Table 4.3.3.6-1: Debris Size Categories and Their Capture and Retention Properties

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

Source: NUREG/CR-6808, Table 4-15 [Reference 7-39]

Table 4.3.3.6-2: Small Fibrous Debris Capture Fractions During Blowdown	
Structure Type	**Debris Capture**
I-Beams and Pipes (Prototypical Assembly)	9%
Gratings	
V Shaped Grating	28%
Split Grating	24%
90º Bend in Flow	17%

Source: Reference 7-17 and NUREG/CR-6808, Table 4-7 [Reference 7-39]

The retention factors given in the table above are cumulative. For example, start with 100% of a debris volume. If the blowdown flow was ducted through two 90º bends, the total amount of debris remaining in the flow would be evaluated as 83% after the first bend. After the second bend, the amount of debris remaining in the flow would be 68.9% of the initial amount (17% of the 83% would be deposited in the second 90º bend).

Other intervening structures would be evaluated in a similar manner.

4.4 Sump Pool Debris Transport

4.4.1 Introduction

The postulated break of a high energy line inside containment of a PWR will result in the generation of debris from insulation on the pipe in the region of the break, and as a result of the action of the released effluent impinging on adjacent surfaces (coatings and concrete). There is also some amount of resident debris in the containment. Some debris is deposited at the containment floor elevation due to the blowdown portion of the postulated event. Still other debris can be transported into the pool due to the runoff of condensation on vertical walls and due to the action of containment spray collecting at upper elevations of containment and draining to the pool of water collected on the containment floor. This generated and resident debris accumulates in the containment pool post accident.

Upon drain-down of the Refueling Water Storage Tank (RWST), the Emergency Core Cooling System (ECCS) and Containment Spray System (CSS) are realigned to draw suction from the containment pool via the containment sump. Upon initiating the recirculation flow path, a portion of the debris already in the pool, and the debris being transported to the pool, may be transported to and collect on the sump screen. If debris is loaded onto the containment sump screen in sufficient quantity, it may cause an unacceptably large pressure drop to the flow passing through the sump screen. In this case, the ECCS and CSS pumps could have insufficient net positive suction head (NPSH) to operate as designed.

This section provides guidance on the evaluation of debris transport in the containment pool.

4.4.2 Transport Mechanisms

Transport of debris within the post-accident pool of a PWR containment is dependent upon both the physical processes and phenomena associated with the postulated event being evaluated, and by the particular design features of the containment being evaluated. These debris transport processes range from debris deposited on the containment floor during blowdown that would subsequently be carried by the spread of water as the containment begins to fill, to debris that later transports into an established sump pool from the upper reaches of the containment by the draining of containment spray water.

Finer debris (such as individual fibers, particulates) that remains suspended will be simply transported to the recirculation sump. Nonbuoyant larger size debris (insulation blankets, large pieces etc.) will sink to the floor, but could be transported by sliding or tumbling along the floor, if velocities are high enough. Truly buoyant debris will also reach the recirculation sump screen.

4.4.2.1 Accident Characterization

The features of the postulated PWR accident scenario that are important to evaluating debris transport in the water pool formed on the containment floor include:

- The characteristics of the debris within the pool (including type, density and size of debris, location where the debris enters the pool and the timing associated with delivering the debris to the pool)
- The postulated break (location, orientation, and flow rate)
- Effect of containment sprays (drainage locations and flow rate)
- The containment (recirculation) sump (location, geometry, flow rate, and the activation time)
- Containment pool (geometric shape, depth, and temperature)

The transport of debris within the containment pool may be thought of as occurring in two distinct phases.

- The first phase of pool transport occurs as the containment fills and a pool forms. Debris deposited onto the sump floor as a result of the postulated break may be transported with the water forming the pool on the containment floor. Initially shallow but gradually increasing water levels and initially fast but gradually slowing water velocities characterize this initial phase. Under these conditions, debris may be transported from its initial deposition location.

- The second phase of pool transport phase occurs after the ECCS has switched over to recirculation and the pool is at or near quasi-steady-state flow conditions. In this phase, debris may move from its deposited location in the pool following the fill-up. In addition, more debris may enter the pool because of containment spray inventory draining to the containment floor.

The movement of water through the containment pool is unique to each postulated accident sequence and for each plant. The geometry of the containment is plant specific and affects the dynamic behavior of water movement in the pool. The containment pool is supplied water from both the pipe break and by containment spray water (if sprays were activated by the postulated event) draining from upper elevations of containment. The break location, the orientation of the break, and the rate of flow from the break may also affect flow patterns in the pool. Similarly, the elevation of the break and obstacles in the path of the break flow may affect the turbulence level and mixing of the pool in the immediate vicinity of the break flow entering the containment pool, possibly causing disintegration of some debris sources and the disruption of debris settling.

Containment spray drain patterns are plant specific. Typical drain paths for containment spray to the containment floor are:

- Through the refueling pool drains
- Through floor drains
- Through stairwells and elevator shafts

- Through an annular circumferential gap between the containment liner and the various floors or decks in containment
- Openings to the upper containment, such as a steam generator shaft
- Direct spray onto the pool surface (this is a plant specific design feature)

The location that the spray drain flows enter the pool may have a significant affect on debris transport within the pool.

The locations of the incoming water relative to the location of the recirculation sump would be especially important. The relative locations determine the flow patterns, which in turn determine whether or how many significant quiescent regions would exist in the pool. Debris within quiescent regions could remain in those regions indefinitely. For example, if incoming water entered the containment pool well away from the recirculation sump inlet, then the water flow could sweep a majority of the pool, thereby enhancing debris transport. Conversely, incoming water could enter near the recirculation inlet so that much of the containment pool was relatively quiescent. Debris would be much more likely to remain suspended in the turbulent regions of the pool than in the more quiescent regions. In addition, it is known that pool turbulence can affect the further disintegration of certain types of debris, e.g., fibrous or calcium silicate insulation debris.

The depth of the pool affects debris transport. The deeper the pool, the slower the water flows towards the containment sump. The lower the water velocities, the less it may transport debris to the sump screen. The water inventory released to the containment, and the water hold-up inside containment (for example, on films on surfaces and in the containment atmosphere) govern the depth of the pool. The depth of the containment pool at time of ECCS switchover from injection from the RWST to recirculation from the containment sump may also depend upon timing associated with the event.

The temperature-driven properties of water are also important to debris transport. Temperature (and to a lesser degree, pressure) determine the density and viscosity of water and the rate at which water penetrates dry insulation debris. Density and viscosity affect the hydraulic drag exerted by flowing water on debris, which, in turn, affects the transport of debris within the sump pool. The pool temperature also affects the rate at which water penetrates the inner spaces of fibrous debris, thereby releasing the trapped air. This, in turn, affects the buoyancy of the debris. When fibrous debris is dropped in colder water, it can float for an extended period of time, whereas when similar debris is dropped in heated water, the debris tends to sink in a reasonably short period of time.

4.4.2.2 Plant Features

Containment geometry that impact flow patterns and therefore also impact debris transport include:

- Compartmentalization of the containment
- Free-flowing annuli
- Flow restrictions (such as doorways and chain-link gates)

- Obstacles (such as curbs, the Pressurizer Relief Tank or other components located inside containment that would also be in the path of flow to the sump)

For a given accident scenario, the containment geometry may provide for regions of relatively high flow velocity, areas of relatively low flow velocity, and possibly essentially stagnant areas (for example, in dead-ended compartments). Debris may transport more readily in the high-velocity regions, less readily in low-velocity regions, and not at all in dead-ended compartments.

The shape of the containment pool can contribute to rotational flows (eddies), where debris can be trapped within the eddy. The flow would accelerate through narrow pathways, such as an entrance into an interior compartment, and then decelerate beyond the entrance as the flow expands, thereby likely creating regions of rotational flow. Debris that did not transport to the sump screen might have been trapped effectively within a quiescent region, such as an inner compartment that does not receive significant flow, or trapped effectively inside an eddy, or stopped behind an obstacle. The existence of a vortex suppressor in the recirculation sump pit or inlet screening structure could influence how flow approaches the sump.

Obstacles to debris transport on the floor of the sump pool include installed equipment and curbs placed along the floor in front of the sump screen to catch debris. Another example of an obstacle is a raised concrete pad or platform, which may stop tumbling debris from reaching the screen unless the local flow velocities were sufficient to lift the debris over or around it. The location, extent, and height of a curb would be important. An example of a miscellaneous structure that could affect debris transport is a closed chain-link gate at a walkway between compartments.

Drainage from the containment sprays ultimately moves from the upper containment levels into the sump pool. The drainage pattern is plant-specific and likely would involve a number of features, including refueling pool drains, floor drains, stairwells, elevator shafts, an annular circumferential gap, or openings to the upper containment, such as a steam generator shaft. In some plants, a train of containment sprays may spray directly into the sump pool. The pattern of the spray drainage and the containment spray flow rate could affect the complexity of the flows within the pool and the subsequent transport of debris within the pool.

Plant features that affect the water level also affect debris transport. These features include the volumes of water injected into the RCS and containment during the injection phase of the accident (for example, accumulator volumes and RWST volumes). Containment features that may potentially hold water in the upper elevations of the containment, or in volumes apart from the containment pool, would reduce pool depth. For example, if the refueling pool drains were to become blocked by debris, the water retained in the refueling pool would effectively reduce the pool depth.

The location and design of the recirculation sump affects the transport of debris in the containment pool. The approach velocities of the water entering the recirculation sump screen depend on the area of the screen and the pumping flow rate. The turbulence near the sump screen affects the formation of the debris bed, and the level of turbulence would be related directly to the proximity of the sump to the break. Should the break be located near the sump screen, turbulence associated with the falling water could remove previously deposited debris from the screen and the turbulence could negate the effectiveness of debris curbs placed in front of the screens. Conversely, a sump distanced from a break or sheltered from a break by compartment walls would not experience much direct agitation from the break stream.

Some recirculation sump designs have the entire sump screen submerged during operation in the ECCS recirculation phase. Some sump designs have the sump screen partially exposed during the part or all of the accident scenario. Submergence of the screen may influence the failure criteria for the recirculation sumps:

- A submerged screen could result higher debris-bed head loss exceeding the available NPSH margin.
- A non-submerged sump screen could result in a debris-bed head loss exceeding the available hydrostatic head (approximately half of the sump pool depth).

The volume of the recirculation sump pit may affect debris transport during the containment pool fill-up transport phase. As the pit fills with water, the fast moving shallow flow of water across the sump floor would move debris toward the sump screen, while filling the sump. Therefore, the larger the pit, the greater the potential for debris transport toward the screen during the initial filling phase.

4.4.2.3 Physical Processes/Phenomena

There are a number of processes and phenomena that affect the transport of debris within the containment pool.

Hydraulic Processes

Hydraulic processes include the entry of water onto the containment floor, the establishment of a pool, the pumping of water from the recirculation sump, and the flow through an established pool.

Following a LOCA, liquid from the break drains to the containment floor, either directly or after flowing off of containment structures, with most of the flow entering the sump in the vicinity of the break. If the containment spray system activates, the flow from these sprays also drains to the containment floor, but its entry occurs at multiple locations. Initially, water falling from a significant height onto the containment floor would spread out in a sheeting type of flow characterized as very shallow but fast-moving. For containments with the recirculation sump as the lowest point in the containment, the water will preferentially flow toward the sump (lowest elevation).

After sufficient water is on the floor to begin building the containment pool with high velocity flows filling the pool, a hydraulic jump may form and likely begin to move back toward the source of the water until the source becomes fully engulfed by the pool. Pool formation hydraulics are dynamic and transient in nature, and have the potential for moving debris across the containment floor.

When the ECCS switches over to the recirculation mode and the ECCS pumps draw suction from the recirculation sump, the flow rates in the pool gradually approach steady state conditions. Flow patterns formed in the pool may be expected to generally exhibit characteristics of three-dimensional flow. If the pool is sufficiently shallow, the flow patterns may become more two-dimensional in nature.

Depending upon the specific containment design, pool behavior may include accelerated flow through narrow passageways followed by decelerated flow, rotational flow (vortices), regions of relatively quiescent flow (sometimes referred to as inactive or dead zones), flow around and over obstacles, vertical mixing flows, and boundary layer flow. Flow characteristics along the flow paths in the pool may also be characterized by bulk flow terms, such as the bulk flow velocity.

4.4.2.4 Debris Transport Processes

The transport processes that could be important for evaluating containment pool debris transport can generally be grouped into debris entry processes, debris pool transport processes, debris entrapment processes, and debris transformation processes.

Debris may be carried into the containment pool by either airborne flows or waterborne flows. During the blowdown portion of the accident scenario, RCS depressurization flows would carry debris into the containment floor where some of that debris may be deposited onto the containment floor before the containment pool is established. At the end of blowdown, little, if any, additional debris would be moved by airflow to the sump. Following the blowdown period, flow from condensate and containment spray (if activated) would wash debris deposited in the upper elevations of the containment to the lower elevation. The entry of the debris into the containment pool is, therefore, time dependent: some early blowdown-deposited debris, followed by a somewhat continuous transport due to containment sprays. (Note: if containment sprays are terminated, this also terminates the washdown of debris from the upper elevations of containment to the containment pool.) Condensate drainage may transport debris deposited on vertical walls; however, the flow rate is low.

Once the containment pool is established, suspended debris moves with the water flow. Fine debris, such as individual fibers or light particles (e.g., calcium silicate), essentially remain suspended at relatively low levels of pool turbulence throughout the entire accident scenario. Larger debris may be suspended in more turbulent regions of the pool (e.g., under the break). Debris not completely water saturated may also remain suspended in the pool. Truly buoyant debris, such as some of the forms of foam insulation, would float on the water surface unless the pool turbulence was sufficient to pull the debris beneath the surface.

Depending upon its prior exposure to water, fibrous insulation debris entering the containment pool may be dry or fully or partially saturated with water. If the debris is fully saturated (i.e., contains trapped air), then the debris will readily sink to the containment floor. If the debris is not fully saturated (i.e., contains trapped air), then the debris may still be buoyant. The time required for water to saturate a piece of debris depends on the type of insulation, the size of the piece of debris and the temperature of the water. The space between the fibers of fibrous debris usually fills with water rapidly when the water is hot (sump-pool temperatures).

Nonbuoyant debris, such as saturated fibrous debris, would settle to the floor of the containment pool, except in regions of high turbulence (velocity), if the terminal settling velocity is high enough. If local flow velocities were sufficiently high, sunken debris may be transported along the floor with the water flow. Test data provides the flow velocities (referred to as incipient velocities) needed to start debris in motion (referred to as "incipient motion) and the flow velocities (bulk velocities) needed to cause the debris to transport in bulk motion.

Debris moving across the containment pool floor may encounter obstacles that stop further movement to the recirculation sump. These obstacles include equipment and curbs placed in front of the recirculation sump to trap debris. Typical equipment obstacles are the supports for equipment located at the containment pool level. These supports are frequently large raised concrete pads. Debris trapped against one of these obstacles could be lifted over the obstacle when the flow velocities are sufficiently fast. Test data also provides lift velocities for various debris sources. This lifting action also applies to debris that would arrive at the curb or base of the recirculation sump screen, where that debris could be lifted (or rolled) up onto the screen.

Some debris could become entangled on equipment, where it may held independent of flow velocity (for example, debris could become entangled in a chain-link gate. Some debris may move into a location where the local flow was insufficient to transport the debris further, such as in quiescent flow regions associated with rotational flow or a compartment off of the main flow. When flow decelerates and slows with a widening flow cross section, the resulting velocity may be insufficient to keep the debris in suspension. Similarly, it is also possible that trapped debris can become re-entrained into the main flow.

Debris inside the containment pool is either transported to the to the recirculation sump screens, become trapped along the way to the screens, or settles out on the containment floor. Debris that reaches the sump screen is expected to remain on the screen.

Debris may undergo a transformation. Generally, this transformation takes the form of either the agglomeration of small debris into larger debris, or the disintegration (also referred to as erosion) of larger debris into finer debris.

- In general, agglomeration would make debris less transportable and disintegration would make debris more transportable.
- Disintegration causes very fine debris to be formed that is likely to remain suspended in the water even at relatively low levels of turbulence. Disintegration increases the potential for transport of additional debris to sump screens. The rate of debris disintegration depends mostly on the turbulence to which the debris was subjected. Most of the disintegration likely would occur due to debris thrashing around in the turbulence associated with the break flow plummeting into the sump pool.

If the fluid velocity is sufficiently large, debris disintegration may occur (particularly near the postulated break location where the churning action of the water falling from the break may cause fiberglass and other insulation to disintegrate into smaller pieces.

4.4.2.5 Debris Characteristics

Transport of debris in the containment pool depends upon the characteristics of the debris formed. These characteristics include the type and the size of the debris. There are several kinds of insulation material in use in PWR containments. These are generally grouped as fibrous insulation, RMI insulation, and particulate insulation (e.g., calcium silicate). In addition, there are other types of debris, such as failed coatings, dust, and miscellaneous operational materials. Pieces of debris would be varied in size; for example, fibrous debris would range from individual fibers to nearly intact pillows. Debris from failed coatings would range from very small particles to substantially large chips. Debris transport depends greatly on the type and size of the debris.

Each type of debris has its own set of physical properties, including properties that determine whether it would sink in the containment pool. Debris buoyancy depends upon the density of each piece of debris:

- The density of each constituent of the debris (e.g., the solid density of an individual fiber)
- The density of the insulation as fabricated or as installed, which for fibrous insulation includes the air space between the fibers
- The density of a piece of insulation debris, which could differ significantly from the as-fabricated density
- The density of the debris after it becomes saturated with water

In addition, the time required for a piece of debris to saturate with water could be important because this would determine how long and how far the debris could float before sinking to the floor. An intact pillow of fibrous insulation could retain sufficient air for the pillow to transport all the way to the recirculation sump screen. The debris settling velocity (the rate at which debris settles vertically in water) could become important if the pool were sufficiently deep.

The flow velocities needed to initiate specific debris transport motions are also debris transport characteristics. These motions include tumbling/sliding across the floor, lifting the debris over an obstacle, and retaining the debris on the sump screen when it arrives there. These velocities have been measured for selected debris types and sizes and for both incipient and bulk motion. The lift velocity also depends on the height of the obstacle.

The characteristics associated with debris disintegration are also important. The byproduct of the disintegration is usually very fine debris that remains suspended and therefore transports readily to the sump screen.

4.4.3 Guidance

4.4.3.1 Debris Transport During Containment Pool Formation

Detailed movement of debris during pool formation is difficult, at best, to evaluate analytically. For the purposes of this evaluation, the following assumptions are to be made:

1. The break flow uniformly distributes debris about the floor of the compartment that the break is postulated to occur. If the containment design is open (no robust barriers), then the

debris may be distributed uniformly about the containment floor. Knowledge of the plant design and engineering judgment are used to assess this debris distribution within the containment due to the postulated break.

2. By inspection of the containment design, engineering judgment is to be used to assess the movement of debris about the containment floor.

4.4.3.2 Debris Disintegration

Debris disintegration will not be addressed directly. Rather, this will be addressed through a sensitivity evaluation of the amount of readily transported debris considered in the pool transport evaluation.

4.4.3.3 Containment Pool Velocity Calculation

To determine the transportability of debris, the velocity distribution of the liquid within the containment pool must be calculated. Two methods of performing this calculation are presented.

4.4.3.3.1 Nodal Network Approach (Open Channel Flow):

The flow across the containment floor is treated as a collection of open channel flow paths. Using an electrical circuit analogy, the bulk velocity of liquid moving across the containment floor in discrete paths or channels is calculated using a nodal network.

The procedure for accomplishing this is as follows:

- The containment is segregated into discrete flow paths.
  - Each flow path should have relatively constant hydraulic characteristics along the path length
  - A "node" is defined as the junction of two or more flow paths.
  - Flow paths are connected or joined by nodes.
  - The sump represents a terminal or "sink" node in the network.
  - The break represents a supply or "source" node in the network.
  - The source node may be moved to represent different break locations.
  - Depending upon flow paths from the upper containment to the sump floor region, other supply or "source" nodes may be identified and located in the network.
  - It is suggested that abrupt changes in hydraulic characteristics (specifically, abrupt changes in flow area) be treated by creating two flow paths connected by a node at the abrupt hydraulic change.

- Using reference manuals (such as I'delchek) for loss coefficients and standard hydraulic practices, the hydraulic characteristics of each flow path are evaluated.
  - Characteristic hydraulic length
  - Characteristic hydraulic flow area
  - Hydraulic loss coefficients for the entrance and exit of flow path in the network
  - Select an appropriate correlation to represent the frictional losses associated with each characteristic hydraulic length. The correlation will be determined by surface roughness, etc.

- Several options exist for solving the hydraulic network to calculate bulk fluid velocities.
  - First, a nodal network code may be applied to calculate bulk velocities
  - Second, the network equations may be entered into an engineering calculation software package, such as TkSolver® and the software allowed to operate on the system of equations to obtain a solution.
  - A third solution is to enter the equations into a spreadsheet and solve them in an iterative manner until the results converge to a pre-determined acceptance limit.

- A sensitivity evaluation on fluid velocities and associated debris transport should be performed with the nodal network by varying the hydraulic parameters of the network. Based on the uncertainties typically associated with hydraulic loss coefficients and friction pressure drop correlations, a variation of ± 20% on the hydraulic parameters input to the fluid velocity calculation is recommended.

This approach provides for the calculation of the bulk fluid velocity in each flow path about the containment floor. Once the velocities in the network are calculated, an assessment of debris transport may be made for the nominal network bulk velocities for the containment design being considered.

Advantages and Disadvantages of Network Approach

The main advantage is that no special computer codes are needed and the analysis can be performed with basic knowledge of hydraulics. However, there are many disadvantages which should be considered. The network analysis can not predict turbulence intensities, flow separations and eddies. Turbulence will keep particles in suspension, while eddy regions may result in significant velocity gradients and shear affecting degradation of particles. Selection of flow paths is uncertain and changing flow areas along the paths are unknown. Neglecting vertical velocity profile (3-D) effects may also mean ignoring localized high velocity regions within a flow path such as at a constriction. Further, including wash-down flows along the walls from sprays (resulting in spatially varied flows along some flow paths) would be difficult. Hence, the CFD approach may be more appropriate for complex containment geometries involving several inflows to the containment and containment pool.

4.4.3.3.1.1 Example of Hydraulic Network Formulation

The assumptions important to the method are:

- The containment recirculation sump is modeled as a point sink.
- The various inflows to the sump floor are modeled as point sources.
- The total volumetric flowrate, Q, is set equal to the demand from the ECCS and CSS under recirculation conditions
- Steady-state flow conditions (inflow=outflow) are assumed
- One-dimensional flow between nodes is assumed.

A summary of the method is:

- Gather information needed to define flow network

  - Detailed containment drawings including structures and equipment
  - Containment water depth at time of switch-over to ECCS / CSS recirculation mode
  - Flow demand from ECCS and CSS

- Define nodes and flow paths of network based on containment geometry and postulated break locations

  - Nodes should typically model discrete areas of interest on the containment floor and may include a sink or a source.

  - The node resolution should be based on the geometry of the containment. Areas of rapidly accelerating or decelerating flows such as those near sinks or sources, or flow transitions, should typically have a higher resolution than other areas.

- Perform network analysis

  The resistance network can be analyzed to determine the flow distribution through each branch. Standard electrical circuit analysis methods are applicable, using the following analogies.

voltage	hydrostatic pressure
current	flow rate
current source	flow source
resistor	flowpath
node	node

For this type of analysis, the pressure drop calculation is analogous to Ohm's law:

$$\text{Pressure Drop, } \Delta P = R\,(Q^2) = R' \left(\dot{m}\right)^2$$

where:

Q = Volume flow rate along a flow path

$\dot{m}$ = Mass flow rate along a flow path

$$R = \left(\frac{\gamma}{2gA^2}\right)\left(K + \frac{fL}{D}\right)$$

$$R' = \frac{R}{\rho^2}$$

K= form loss coefficient

f·L/D= friction loss coefficient

Q= Volume Rate of Flow along a Flow Path

γ= specific weight of liquid

ρ= density of liquid

f = Darcy-Weisbach friction factor

L= Length of flow path

D= 4 x Hydraulic Radius (D_h)

D_h= A/P

A= Cross-sectional Flow Area

P= Wetted Perimeter

Values for friction factor and form loss coefficients are available from sources such as Chanson [Reference 7-40] and Montes [Reference 7-41]. Since the loss coefficients may dependent on Reynolds number which in turn depends on flow velocity, it is recommended that values for hydraulic coefficients be chosen based on estimated flow velocities.

Once the resistance of each flow path has been determined, the flow network can be reduced to an equivalent resistance. Since the mass flowrate through the network is defined by the plant parameters and an equivalent resistance has been calculated, the total pressure drop through the network can be calculated using the equation above.

The flow distribution through the network (mass flow rate from which volume flow rate can be calculated for each flow path) can be calculated using circuit analysis principles. Once the flow distribution has been determined, the average flow velocity along each flow path can be calculated, since

$$V = Q / A$$

Note that the calculations of flow velocities depend on the assumed flow areas.

For analysis of some flow transitions, the use of Bernoulli's equation might be preferable to the circuit analysis method. For open-channel flow Bernoulli's equation between two points 1 and 2 in a transition is written as:

$$y_1 + z_1 + \frac{V_1^2}{2 \cdot g} \quad = \quad y_2 + z_2 + \frac{V_2^2}{2 \cdot g}\left(1 + K + \frac{f \cdot L}{D}\right)$$

where "y" represents the water depth and "z" represents the floor elevation.

The loss coefficients can then be re-defined based on the results of the initial calculation. The process is then repeated until the results converge within a pre-selected acceptance limit.

At that point it is necessary to check the flow network to determine if super critical flow conditions are predicted to occur. Open-channel super critical flow is analogous to sonic flow in piping systems, and is defined as when the fluid speed exceeds the wave speed of the fluid. Super critical flow is indicated when the Froude number is greater than 1. The Froude number is defined as:

$$\mathrm{Fr} = \frac{V}{(g \cdot y)^{0.5}}$$

If super critical flow conditions are calculated, change over to sub-critical conditions downstream may be possible and it is necessary to re-evaluate the flow network to investigate possibility of a hydraulic jump. An analysis that may be performed for super critical flow is described in detail in Montes.

4.4.3.3.2 Computational Fluid Dynamics (CFD) Approach

Once the containment recirculation pumps are activated and the ECCS flow is drawn from the recirculation sump, detailed flow patterns in the containment pool can be obtained using state-of-the-art computational fluid dynamics (CFD). The flow is quasi-steady or steady at this stage of the ECCS operation. Several commercially available CFD programs (software) can be used for the flow simulation and analysis, which essentially solve the full set of the conservation of mass and momentum equations (Navier-Stokes equations) as well as turbulence equations for each of the computational elements in the domain of interest. Thus, fully three dimensional (3D) flow patterns can be obtained, which in turn can be used to predict the various flow paths to the recirculation sump(s), including detailed 3D velocities for the debris transport analysis.

4.4.3.3.2.1 Selection of CFD Software and CAD Package

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

- Solves the full set of Navier-Stokes equations
- Turbulence closure options, such the typical k- ε equations with the standard wall function
- Incompressible fluid flow solution
- Modern mesh generator
- Modern preprocessor for specifying fluid property and boundary conditions, such as non-slip walls, inflows, outflows etc.
- Modern postprocessor or compatibility with independent modern postprocessor for analyzing CFD results

The CAD package used for preparing the 3D geometry of the containment sump should be capable of performing 3D solid modeling and have a compatible interface with the selected CFD software, i.e. the CAD files should be imported by the CFD mesh generator.

4.4.3.3.2.2 Building the CAD Model

The 3D geometric model of the containment pool should cover the entire volume that forms the pool after a LOCA, i.e., all the open space from the containment floor (and the containment sump floor) to the potential maximum water level, including a short length (at least five diameters) of the suction pipes from the recirculation sump(s). A detailed review of the containment civil and mechanical pipe drawings, and any available photographs, should be made to identify major flow obstructions, such as structures, equipment, pipes etc. that will be submerged in the pool. Obstructions less than 6 inches in diameter or the equivalent may be omitted.

If available, use an existing electronic 3D solid model (file) of the containment as a basis for the geometric model. If a CAD file is unavailable or is not used, the containment geometry and details of obstructions as in Item 2.1 should be obtained from as built drawings and/or a containment walkdown.

4.4.3.3.2.3 Building the CFD Model

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

<u>Specification of Material Properties and Boundary Conditions</u>:
The computational meshes are read into the selected CFD package and preprocessing of the CFD model is performed. Preprocessing includes the following:

- Specify the properties of water in the containment pool

- Specify boundary conditions. The types of boundary conditions associated with the containment pool flow simulations are “non-slip” walls for solid surfaces, a zero-stress lid for the water surface, inflows for the break and core spray flow and outflows for the suction pipes of the recirculation sump(s). It may be conservative to assume that the break flow falls freely by gravity onto the water surface from the break location without interruption by any structures. Knowledge of plant specific spray flow path(s) should be obtained to determine the proper location(s) and method for introducing spray flow into the pool. The water surface may be treated either as a zero-stress rigid lid or a free surface, depending on the capability of the CFD software used. Outflow or pressure is generally specified at the recirculation sump suction pipe outlet.

- Specify the accuracy of discretization schemes. Generally, a second order accuracy for discretization schemes should be used in the CFD analyses.

4.4.3.3.2.4 CFD Analysis

A converged CFD solution should be obtained by running the CFD model for a sufficient time. If the velocity components, turbulent kinetic energy and turbulent energy dissipation rate do not change appreciably with subsequent iterations, it is an indication that a converged solution has been achieved. The generally acceptable convergence criterion is that the residuals of these pertinent flow parameters should be less than 10 [Reference 7-43]. Other equivalent criteria may be used if properly justified.

4.4.3.3.2.5 CFD Results for Debris Transport

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

For a given type and size of debris, plot velocity magnitude contours for the minimum bulk transport velocity (from available experimental data, see Table 4.4.3.4.2.5-1) at a selected elevation(s) within the containment pool using the CFD software’s built-in post-processor or an independent post-processor. Conservative results are obtained if the elevation selected for analysis gives the maximum area under the bulk velocity contour. The area within the velocity magnitude contour connected to the recirculation sump is determined, and it may be conservatively assumed that debris in this area (of the given type and size being analyzed) will be transported to the sump screen.

- The effects of turbulence level may be taken into account by assessing whether debris particles or fibers will stay suspended due to the instantaneous vertical velocity component being equal to or greater than the settling velocity of the debris particles. The maximum instantaneous vertical velocity is calculated by adding the fluctuating vertical velocity to the (CFD) computed mean (time average) vertical velocity. The fluctuating velocity is determined from the computed turbulent kinetic energy, k. Contours within which the instantaneous vertical velocity component is equal to or greater than the settling velocities of different type and size of debris being analyzed may be used to assess if this debris may become or stay suspended.

- Velocity vectors and flow streamlines may also be used to assist the analysis of debris transport

4.4.3.3.2.6 Example of a CFD Simulation

The Basic Assumptions are:

A fictitious PWR containment is shown in Figure 4.4.3.4.2.6-1. The flow patterns are calculated with FLUENT software. The containment has a diameter of about 100 ft and has structures in the pool as shown. There are two recirculation pumps with suction pipes of diameter one foot. It is assumed that spray flow enters the water surface from a 6 inch annular gap on the outsider perimeter and two rectangular stair wells (shown in solid color). It is assumed that the break jet (shown as a small circle of solid color) has a diameter of 10 inch when it free falls from its break location. Flow conditions being simulated are as follows:

- Water depth: 3.5 ft
- Break flow: 2,000 gpm
- Containment spray flow: 1,000 gpm (60% of the spray flow is assumed to enter into the water surface from the annular gap)
- Two recirculation pumps are in operation with 1,500 gpm each
- Fluid medium is water

<u>Model Setup</u>
A total of 1.2 million hexagonal computational meshes were generated as shown in Figure 4.4.3.4.2.6-1. It can be seen that meshes are clustered around the LOCA break, spray flow inlets (the annular gap and two stairwells), recirculation pump intake and the structures. The boundary conditions are shown in Figure 4.4.3.4.2.6-1.

<u>CFD Calculation Results</u>
Figure 4.4.3.4.2.6-2 plots streamlines of the flow field that illustrates the general flow patterns in the containment. These streamlines are colored by velocity magnitudes. Figure 4.4.3.4.2.6-3 shows two velocity magnitude contours (0.25 ft/s in blue and 0.5 ft/s in red). These contours are used to calculate the areas within which the debris with the corresponding bulk transport velocities are assumed to be transported to the sump screens.

Figure 4.4.3.4.2.6-1. Containment Geometry and Computational Meshes

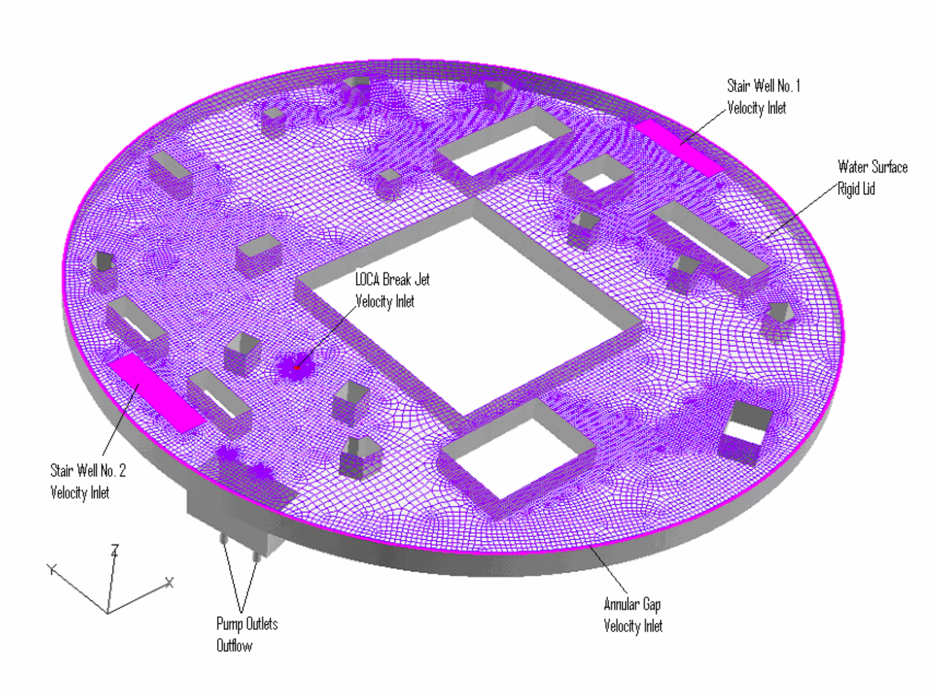


Figure 4.4.3.4.2.6-2. Streamlines Illustrating Flow Patterns

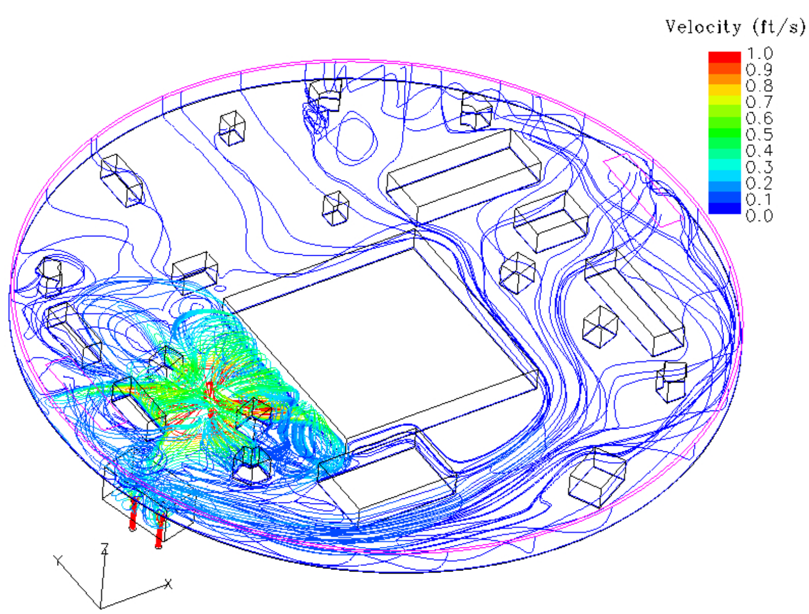
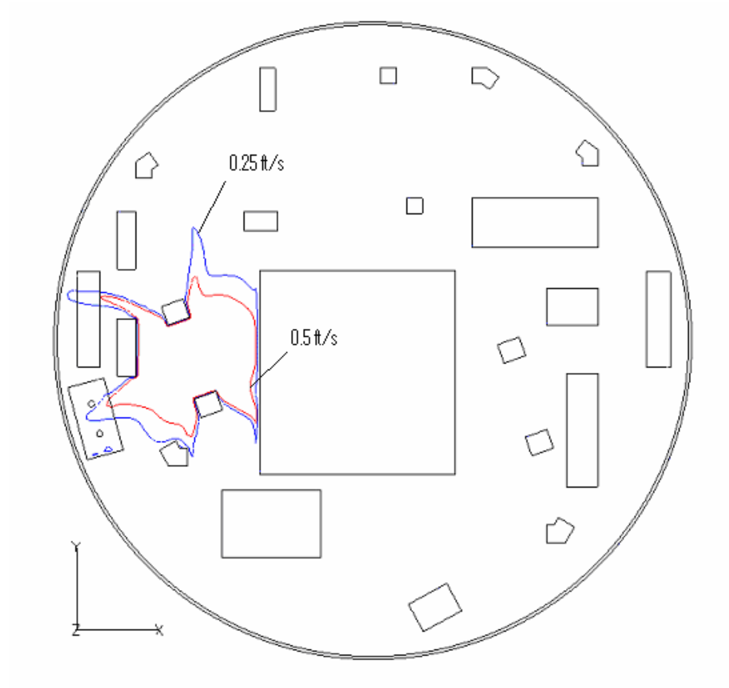


Figure 4.4.3.4.2.6-3. Velocity Magnitude Contours near the Containment Floor



4.4.4 Debris Transport Assessment

4.4.4.1 Transport within Containment Pool

Using Network Analysis Results

The bulk or average velocities calculated from the network analysis are compared to the transport data listed in the attached table.

- If the calculated fluid velocity is below the incipient transport velocity of the debris type being evaluated, that debris type will not transport and may be excluded from further consideration of sump blockage. Note that both the debris material and the debris geometry (size) determine the debris type.

- If the calculated fluid velocity is less than the bulk transport velocity to transport the debris type, compare the transport time to the terminal (settling) velocity of the debris type and its distance from the sump to assess if it will settle prior to reaching the sump screen. Note that, typically, a linear velocity equal to about 7 times the settling velocity of the largest particle in the slurry of debris is required to maintain the particles in suspension [Reference 7-42].

- If the debris type settles, check if the local fluid velocity is higher than the incipient velocity sufficient to transport the debris type to the sump by tumbling or sliding along the containment floor.

Using CFD Analysis Results
The debris transport assessment using CFD analysis is discussed earlier with the post processing of CFD results under the CFD approach.

4.4.4.2 Transport Over Curbs and through Screens in the Flow Path to the Sump

Curbs provide an obstacle to debris types that would slide or tumble to the sump screen on the floor of the containment. For the debris type to continue to be transported to the sump, the local fluid velocity at the curb must be equal to or greater than the Lift-over Curb Velocity in the attached table to lift the debris type over the curb.

- Screens in the flow path can capture both suspended debris types and debris types tumbling or sliding along the containment floor.

- The volume of debris type captured by either curbs or screens in the flow path is not considered for sump screen blockage. However, the debris loading on intermediate screens in the flow path must be evaluated to determine if the resulting blockage may divert or hold up flow from the sump. This is accomplished by first evaluating the amount of the various types of debris that might be collected by the intermediate screen. The pressure drop across the intermediate screen is then calculated using the same method as applied to the sump screen.

4.4.4.3 Evaluate Potential for Debris Disintegration

If the calculated fluid velocity is greater that the incipient transport velocity and the debris are fibrous, the debris will likely be subject to disintegration. Using the calculated fluid velocity and engineering judgment estimate the rate at which disintegration occurs.

If the calculated fluid velocity is less than the incipient transport velocity, fibrous debris is not likely to be subject to disintegration and may be neglected.

Debris types are to be considered in the debris loading on the sump screen if:
The calculated fluid velocity is sufficiently large to transport the debris type to the sump without the debris type settling and the debris type can pass through intermediate screens in the flow path, or,
The calculated fluid velocity is sufficiently large to lift a debris type that is calculated to slide or tumble along the floor over a curb that is in the flow path.

Table 4.4.3.4.2.5-1- Debris Transport Reference Table

Material Category / Type	Incipient Transport Velocity (ft/sec)	Bulk Transport Velocity (ft/sec)	Lift-Over-Curb Velocity (ft/sec)	Terminal Settling Velocity (ft/sec)	Comment	Reference Document
A. Fibrous Insulation						
1. Fiberglass - Generic	Same as NUKON	Same as NUKON	Same as NUKON	Same as NUKON	Since no data for “generic fiberglass” is available, it is recommended that the data for NUKON be used to represent low-density fiberglass.	
2. Fiberglass – NUKON Microscopic Density = 175 lb/ft^3 Macroscopic Density = 2.4 lb/ft^3	0.06 (Size Classes 3 and 4)	0.09 (Size Classes 3 and 4)	0.22 (2-in. curb) 0.25 (6-in. curb) (Size Classes 3 and 4)	0.41 (6-in.) 0.40 (4-in.) 0.15 (1-in.)	The NUKON manufacturer created debris by using air jets. NUREG/CR-6224 indicates that individual fibers and small groups of fibers settle at speeds less than 0.06 ft/sec	NUREG/CR-6772 NUREG/CR-6224, Table 4-8
3. High Density Fiberglass	0.2 (shreds) 0.3 (4 x 4 x 1 in. and 4 x 1 x 1 in.) 0.9 (whole pillow)	1.1 (lowest value for all sizes tested)	See comment	See comment	No data for lift over curb or settling velocity. Recommend that the data for NUKON be used.	NUREG-0897, Rev. 1
4. Fiberglass – Temp-Mat Macroscopic Density = 11.3 lb/ft^3	See comment.	See comment.	See comment.	See comment.	No data specifically for Temp-Mat. Conservatively use data for NUKON (NUKON has a lighter macroscopic density and lower damage pressure).	NUREG-6808, Section 3.2.1.2

Material Category / Type	Incipient Transport Velocity (ft/sec)	Bulk Transport Velocity (ft/sec)	Lift-Over-Curb Velocity (ft/sec)	Terminal Settling Velocity (ft/sec)	Comment	Reference Document
5. Fiberglass – Transco (Thermal Wrap®) a. Shredded b. 4-in. x 6-in. pieces c. Various Sizes – Transco Tests	a. 0.07 b. 0.12 c. Not Identified	a. 0.11 b. 0.16 c. 0.12-0.4 (15° C, size + type dependent)	a. 0.22 (2-in. curb) b. 0.25 (6-in. curb) c. Not identified	a. 0.13 b. Not Tested c. 0.09 – 0.51 (91° C, size dependent)	• Most limiting transport velocities were taken from NUREG/CR-6772. • Transco tested various sizes of debris for transport velocities. • Submersion of floating samples occurs within seconds for high temperatures (~90° C). • Settling velocity weakly dependent on temperature (higher velocities for higher temps)	a. NUREG/CR-6772 b. NUREG/CR-6772 c. Transco documents: ITR-92-03N, ITR-93-02N
6. Mineral Wool a. 4-in. x 4-in. x 1-in. b. Shreds	a. 0.4 b. 0.3	a. 1.4 b. See second comment	a. See second comment b. See second comment	a. See second comment b. See second comment	• Mineral Wool floats unless forced to sink. • No data specifically for Mineral Wool. Conservatively use data for NUKON.	NUREG/CR-2982 and NUREG-0897
7. Miscellaneous Fibrous a. Asbestos b. Unibestos	a. See comment b. See comment	a. See comment b. See comment	a. See comment b. See comment	a. See comment b. See comment	No data specifically for asbestos or Unibestos. Conservatively use data for NUKON (has a lighter macroscopic density).	
B. Calcium Silicate Insulation						
Generic – Chunks with dust + fibers	0.10 (dust + fibers) 0.25 (small chunks) 0.30 (larger chunks)	0.35	Not tested: see comment on dissolution	Not tested: see comment on dissolution	Tests performed at ~20° C. Chunks were almost fully dissolved after immersion in near-boiling water for 20 min. 10 g pieces lost 50 to 75% of weight after immersion in 80° C water for 20 min.	NUREG/CR-6772

Material Category / Type	Incipient Transport Velocity (ft/sec)	Bulk Transport Velocity (ft/sec)	Lift-Over-Curb Velocity (ft/sec)	Terminal Settling Velocity (ft/sec)	Comment	Reference Document
C. Reflective Metallic Insulation						
1. Stainless Steel a. Fragments – 0.5-in. x 0.5-in. b. Fragments – 2-in. x 2-in. c. Cassette – Half Assembly d. Covers – Inside and Outside e. Fragments – Various Sizes	a. 0.20 b. 0.20 c. 1.0 d. 0.7 e. Use values from (a) and (b) above	a. 0.22 b. 0.22 c. 1.0 d. 0.8 e. Use values from (a) and (b) above	a. 0.30 b. 0.30 (2-in. curb) >1.0 (6-in. curb) c. Use values from (b) above d. Use values from (b) above e. Use values from (b) above	a. 0.37 b. 0.48 c. Use values from (b) above d. Use values from (b) above e. 0.3-0.4 (size dependent)	• The lowest transport velocities from NUREG/CR-6772 were used. • Approx. 2/3 of RMI remained suspended in "chugging" tests (SEA document)	a. NUREG/CR-6772 b. NUREG/CR-6772 c. NUREG/CR-3616 d. NUREG/CR-3616 e. SEA 95-970-01-A:2
2. Aluminum Fragments – 2-in. x 2-in.	0.20	0.30	Use value from 1(b), stainless steel, above	0.11	Use of Lift-over curb velocity for stainless steel is based on similar behavior for incipient transport velocity and bulk transport velocity.	NUREG/CR-6772
D Fire Barrier						
1. 3M Interam	Same as NUKON	Same as NUKON -	Same as NUKON	Same as NUKON	With no data for 3M Interam available, recommend that data for low-density fiberglass be conservatively used.	
2. Fiberglass blanket	Same as NUKON	Same as NUKON	Same as NUKON	Same as NUKON	Since no data for "generic fiberglass" is available, it is recommended that the data for NUKON be used to represent low-density fiberglass.	
3. Kaowool a. Shredded b. 4-in. x 6-in.	a. 0.09 b. 0.12	a. 0.19 b. 0.16	a. 0.25 b. 0.25 (2-in. or 6-in. curb for both debris types)	a. 0.21 b. Use value from (a) above	Based on similarity of other hydraulic transport characteristics, suggest using same settling velocity for shredded and cut Kaowool.	NUREG/CR-6772

Material Category / Type	Incipient Transport Velocity (ft/sec)	Bulk Transport Velocity (ft/sec)	Lift-Over-Curb Velocity (ft/sec)	Terminal Settling Velocity (ft/sec)	Comment	Reference Document
4. Marinite board a. 1-in. x 1-in. b. 4-in. x 4-in. Three values for density: Marinite-23 = 23 lb/ft^3 Marinite-36 = 36 lb/ft^3 Marinite-65 = 65 lb/ft^3	a. 0.77 b. 0.77	a. 0.79 b. >= 0.99	a. Not Tested b. Not Tested	a. 0.59 – 0.63 b. 0.42 – 0.60		NUREG/CR-6772
5. Silicone foam	--	--	--	--	Floats – Readily transports at any velocity	NUREG/CR-6772
E Other						
1. Koolphen (closed cell phenolic)	See comment.	See comment.	See comment.	See comment.	Suggest using data for NUKON.	
2. Min-K (microporous)	See comment.	See comment.	See comment.	See comment.	Suggest using data for NUKON.	
3. Lead Wool Macroscopic Density = 10-15 lb/ft^3	See comment.	See comment.	See comment.	See comment.	Lead would settle and not transport. Suggest using data for NUKON for fabric cover. Confirm site use of lead wool blankets. (May not be used.)	
4. Dust / Dirt Density = 156 lb/ft^3	See comment.	See comment.	See comment.	See comment.	Although the density is large, suggest using data for calcium silicate.	
5. Sludge (Iron) Density = 324 lb/ft^3	N/A	N/A	N/A	N/A	No credible source of iron sludge identified for PWR's.	
F Coating						
1. Epoxy – Generic Density = 90 lb/ft^3 (Nominal)	0.31	0.40	0.55 (2-in. curb)	0.15	0.55 ft/sec results in some transport over debris curb Tests conducted in ambient temperature water	NUREG/CR-6772
2. Alkyd – Generic Density = 94 lb/ft^3 (Nominal)	See comment.	See comment.	See comment.	See comment.	Conservatively use data for epoxy coatings (has a lighter nominal density).	

Material Category / Type	Incipient Transport Velocity (ft/sec)	Bulk Transport Velocity (ft/sec)	Lift-Over-Curb Velocity (ft/sec)	Terminal Settling Velocity (ft/sec)	Comment	Reference Document
3. Inorganic Zinc – Generic Density = 156 lb/ft (intact) = 437 lb/ft3 (detached, Carboline) = 350 lb/ft3 (detached, CRC)	See comment.	See comment.	See comment.	See comment.	Conservatively use data for epoxy coatings (has a lighter nominal density).	

4.5 Headloss

4.5.1 Introduction/Scope

As of September 2003, there are several key uncertainties associated with the calculations of head losses across a debris bed. As the NRC provides further clarifications on regulatory matters and releases new technical information, it may be necessary to review the new information and perhaps modify or enhance the methodology for calculating the head loss across a debris bed.

The methodology presented within this chapter details how to calculate the head loss from a debris bed that could be formed on an ECCS sump screen. As stated previously, the total sump screen head loss is a combination of the clean sump screen head loss plus the head loss across the debris bed.

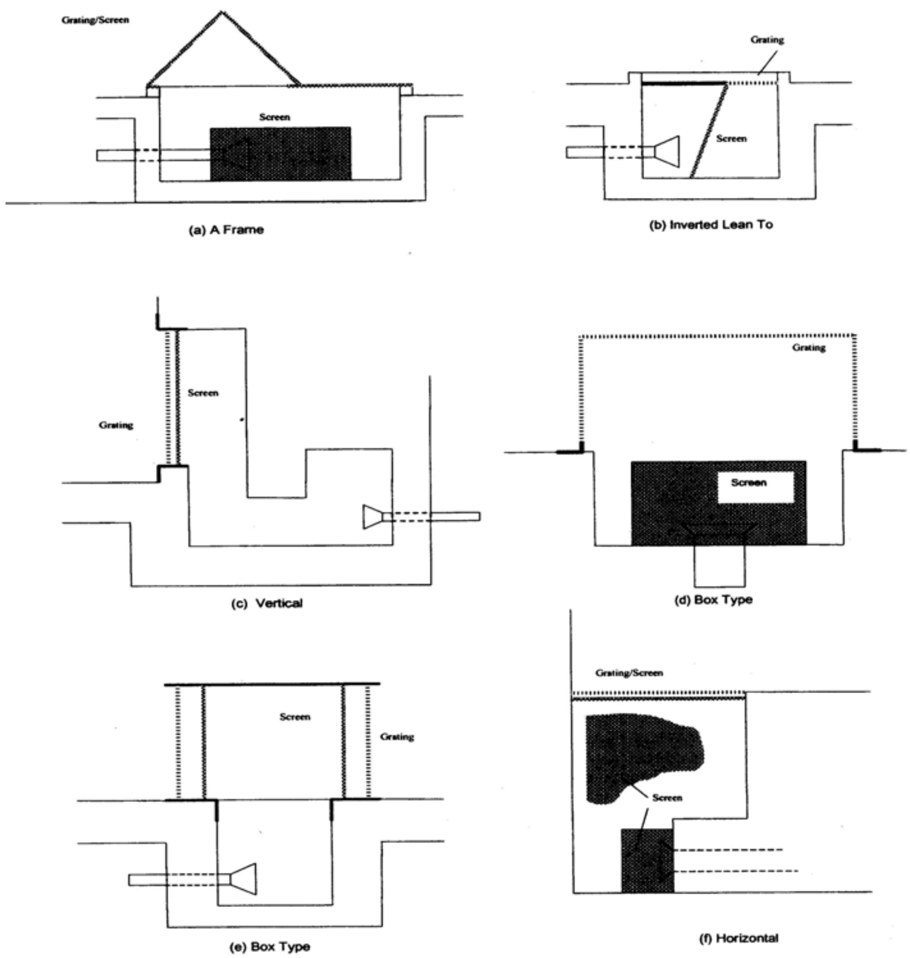
In addition to the thermal/hydraulic conditions, the types, total quantities and characteristics of debris that are generated in the containment and transported to the sump screen are the primary design inputs for this methodology. This methodology will provide the user with a head loss value (feet-of-water) for the debris bed on the sump screen. The user then has to add the estimated clean sump screen head loss to obtain the total head loss across the sump screen. The total screen head loss is then used to assess the effect of the head loss on the NPSH margin.

4.5.2 Inputs Into Head Loss Evaluation

4.5.2.1 Sump Screen Design

The sump screen design is an important consideration in the evaluation of debris head loss. Plant drawings should provide details as to the screen construction, the orientation and the mesh size (or hole size and pitch for perforated plates). Typical PWR sump screen configurations are illustrated in Figure 4.5.2.1-1. Newer designs typically have more surface area and alternate geometries.

Figure 4.5.2.1-1. Typical PWR Sump Screen Configurations



Derived from plant drawings, the sump screen area (A) is the total area of the sump screen (without any correction for the solid area of the mesh or wire screen) over which debris accumulates. For flat screens, the sump screen is simply the total circumscribed area of the screen or perforated plate. For alternate geometry, particularly in the case of star or stacked disc designs, the sump screen surface area available for debris deposition will start off with the total available surface area and evolve to the circumscribed area as debris fills in the voids and gaps between the ridges and disks.

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

The debris transport analysis may conclude that large flexible debris such as step-out mats and plastic sheets could reach the sump screen. In this event, the surface area to be used in the head loss analysis should be the total sump screen surface area less the area of the large flexible debris.

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

The Clean Strainer Head Loss (CSHL) is the head loss of the sump screen assembly in a clean, unfouled condition. The CSHL is a required input for the overall head loss evaluation and is highly dependent on plant-specific sump screen construction details and thermal hydraulic conditions.

Calculating the head loss of the sump screen assembly in a clean condition involves calculating the head loss across the screen itself taking submergence of the screen into consideration. The CSHL will mainly depend on the screen mesh size (or hole size and pitch for perforated plates), the flow through the screen, and the water temperature using standard methods of fluid mechanics.

In some cases the head losses due to the attendant support structures, mechanical configuration of the bracing and other structures in the sump (such as vortex suppressors) cannot be neglected. Sump screen head loss information is available from the manufacturer of the raw screen material itself. Note that existing plant calculations often document CSHL.

4.5.2.2 Thermal-Hydraulic Conditions

4.5.2.2.1 Recirculation Pool Water Level

For conservatism, the minimum water level of the recirculation pool should be used for estimating the head loss across the debris bed accumulated on a screen. The minimum level will yield the smallest surface area (thus potentially greater head loss) for those screens that are not completely submerged in the pool as well as the lowest available NPSH to the ECCS pumps. Time dependent water level calculations may be required to reduce conservatism should the head loss calculated with the lowest water level be unacceptable.

4.5.2.2.2 ECCS Flow Rate

For conservatism, the highest flow rate (Q) should be used in calculating the head loss across a screen. In this regard, pump run-out flows should be used to compute the maximum flow rates. Some plants, however, use their ECCS design flows for head loss calculations. For multiple sump screens, the flow rate used in the head loss calculation is the flow through each of the screens. Calculating sump screen performance based on time-dependent ECCS flow rates is also an option, especially when excessive conservatism cannot be tolerated.

4.5.2.2.3 Temperature

The recirculation sump water temperature should be documented in the plant design basis calculations and is a key parameter in the head loss calculation. The head loss through a debris bed is directly proportional to the viscosity of the water. Viscosity, in turn, is inversely proportional to the temperature. As such, the higher the water temperatures, the lower the head loss across the debris bed due to decreased water viscosity. Therefore, when calculating the debris-bed head loss, it is conservative to use the lowest water temperature calculated for the period from start of recirculation through the end of ECCS operation. Calculating sump screen performance based on time-dependent post-LOCA pool water temperature is also an option when excessive conservatism cannot be tolerated.

Note that the recommendation above for debris bed water temperature is just the opposite of the usual recommendation for NPSH evaluations, in which it is generally more conservative to use the highest water temperature, the sump water vapor pressure being higher.

4.5.2.2.4 Chemical Considerations

(Later)

4.5.2.3 Debris Types, Quantities and Characteristics

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

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

In a homogeneous debris bed, the densities and size characteristics of the individual constituents are necessary to determine the porosity of the debris bed. In general, lower bound values for the median characteristic sizes of the debris are adopted. This is conservative for head loss calculations because the specific surface is inversely proportional to the characteristic size of the debris particle. The smaller the characteristic size of the particles within the debris bed, the higher the pressure drop will be across the bed.

Sections 4.5.2.4 through 4.5.2.6 describe the characteristics of common fibrous, coatings and particulate debris. For convenience, tables within this section provide recommended values of some debris characteristics necessary for the head loss computations. Plant-specific data can supersede these where necessary and appropriate.

4.5.2.4 Thermal Insulation Material Debris Characteristics

This class of insulation includes low-density fiberglass (~2.4 lbm/ft^3), medium-density fiberglass, and preformed fiberglass, as well as fiber felt materials. It also includes microporous insulation such as MinK, and Microtherm, as well as Calcium Silicate insulation.

There are four principal types of thermal insulation in PWR containments:

Fibrous Insulation (including Asbestos)
Granular Insulation (Calcium Silicate & Microporous)
Cellular Insulation
Reflective Metal Insulation (RMI)

Table 4.5.2.4-1 depicts characteristic the characteristic densities and sizes for thermal insulation materials that have been identified as potential debris in nuclear containments. Some are listed by trade names and some by generic names, whereas others are listed as a system and still others as simply an insulation material.

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

The NRC refers to the insulation fillers in NUKON, Thermal Wrap, and Knaupf-ET as "Low Density Fiber Glass" (LDFG). The LDFG materials are soft, loose and contain minimal binders. There is extensive test data for LDFG. There are also some glass fiber felt mat insulation materials and these include Temp-Mat® and Insulbatte® insulations, both made by JPS Corp., as well as some by other trade names such as AlphaMat® by Alpha Inc. Again, these are relatively soft and loose. Other fibrous materials include ceramic felt mat insulation, two of which are Kaowool® and Cerawool®, both by Thermal Ceramics, Inc.

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

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

Granular insulation materials include calcium silicate and microporous insulation. All the calcium silicate insulation in North America has been manufactured without the use of asbestos since about 1972. Produced by various manufacturers over the years, today all calcium silicate is manufactured by IIG, a joint venture between Calsilite Corp. and Johns-Manville Corp., at three factories. The only microporous insulation manufactured in North America is MinK®, manufactured by Thermal Ceramics, Inc. today but by Johns-Manville for many years. Microtherm, manufactured in the UK, is also available in North America.

The only **cellular insulation** in Table 4.5.2.4-1 is cellular glass. Most of what has been installed in US nuclear plants has been manufactured by Pittsburgh Corning Corporation and is known by its trade name, Foamglas®. This is an inorganic, rigid, and brittle cellular insulation typically used in containments on chilled water lines. However, for reference, there are numerous other types of cellular insulations available which are organic compounds. These include melamine, polystyrene, polyisocyanurate, phenolic, polyimide, polyolefin, flexible elastomeric, and polyurethane foams. There are numerous trade names by which these are known. The best known is Dow Chemical's Styrofoam, which is polystyrene foam insulation. Cellular insulation may be ignored in head loss calculations, since it floats and has no impact in this regard.

Table 4.5.2.4-1: Mass Insulation Material Debris Characteristics

Debris Name	Insulation Material Description	As-Fabricated Density (lbs/ft^3)	Material Density (lbm/ft^3)	Characteristic Size	
				μm	inch
PCI's NUKON® Blankets	Removable / reusable blankets with woven glass fiber cloth covering fibrous glass insulating board (referred to by the NRC as a "LDFG")	2.4[3, 7]	159[7]	7.0 fiber diameter	28E-05[3,7]
Fiberglass – preformed pipe	Knaupf fibrous glass wool preformed into cylindrical shapes	4.0 +/- 10%[2] or	159[2]	7.5 fiber diameter	30E-05[2]
Fiberglass – preformed pipe	Owens-Corning fibrous glass wool preformed into cylindrical shapes	3.5 to 5.5[7]	159[7]	8.25 fiber diameter	33E-03[7]
Fiberglass – pipe and tank wrap	Fibrous glass wool wrap, using perpendicularly oriented fibers, adhered to an All Service Jacketing (ASJ) facing (made by Knaupf, Owens-Corning, & others)	3.0 +/- 10%	159[2]	6.75 fiber diameter	27E-05[2]
Transco's Thermal Wrap® Blankets	Removable / reusable blankets with woven glass fiber cloth covering fibrous glass insulation)	2.4[2, 14]	159[2]	5.5 fiber diameter	22E-05[2]
Knaupf	Knaupf ET Panel (LDFG similar to Nukon)	2.4	159	5.5 fiber diameter	22E-05
Temp-Mat® and Insulbatte®	Glass fibers needled into a felt mat; these are trade names of insulation products made by JPS Corp.	11.8[4]	162[4]	9.0 fiber diameter	36E-05 max. average[13]
Cellular Glass	Foamglas® is the trade name for this cellular glass product made by Pittsburgh Corning Corporation	6.1 to 9.8 (mean value of 7.5)[15]	156[15]	NA	0.05 to 0.08 pore size[15]; grain size unknown
Kaowool®	Needled insulation mat made from ceramic fibers; Kaowool is a trade name for a family of ceramic fiber products made by Thermal Ceramics, Inc.	3 to 12[6]	160 to 161[16]	2.7 to 3.0[16] fiber diameter	10.8 to 12.0E-05
Cerawool®	Needled insulation mat made from ceramic fibers; Cerawool is a trade name for a family of ceramic fiber products made by Thermal Ceramics, Inc.	3 to 12[6]	156 to 158[16]	3.2 to 3.5[16] fiber diameter	12.8 to 14.0E-05
Mineral Wool	Generic name for families of products made by Rock Wool Mfg., Roxul, Fibrex, IIG, and others	4, 6, 8, and 10[8] pcf are standard	90[8]	5 to 7[8] fiber diameter	20 to 28 E-05
MinK®	Trade name of microporous insulation products made by Thermal Ceramics, Inc. from fumed silica, glass fibers, and quartz fibers	8 to 16 pcf[17]	NA	< 0.1[18]	< 4E-06
Calcium Silicate	Manufactured by IIG in three locations (2 use diatomaceous earth, 1 uses expanded perlite)	14.5[9]	144[10]	40 μm mean particle size (2 to 100 μm range)[10]	1.60E-03
Microtherm	Microporous Insulation	5 to 12 pcf	NA	<0.2	<4.0E-06
Asbestos	Structural fiber used in Cal-Sil type ins.	7 to 10	153	1 to 8	4 to 32E-05

References for Table 4.5.2.4-1:

1 Thermal Insulation Handbook, by William C. Turner and John F. Malloy, Robert E. Krieger Publishing Company, Inc.,1981.
2 Phone conversation with Scott Miller, Knaupf Fiberglass on July 7, 2003.
3 Telephone conversation with Gregg Hunter, Performance Contracting, Inc., July 9, 2003.
4 Product literature provided by JPS Glass Fabrics on Insulbatte® and Tempmat@ insulation products (www.jpsglass.com).
5 Phone conversation with Joan Kirby, JPS Glass Fabrics on July 7, 2003.
6 Product literature provided by Thermal Ceramics, Inc. on Kaowool Blanket Products (www.thermalceramics.com).
7 E-mail from Chris Crall, Owens Corning Corporation, July 7, 2003.
8 Telephone conversation with Chris Bullock, Rock Wool Manufacturing, July 7, 2003.
9 Telephone conversation with Jeremy Haslam of IIG, Inc., July 7, 2003.
10 Certificate of Analysis from Tech-Flo, supplier of Perlite Filteraids, provided by IIG, Inc.
11 Product literature provided by Thermal Ceramics, Inc. on Min-K Insulation (www.thermalceramics.com).
12 Product literature provided by Microtherm, Ltd. (http://www.microtherm.uk.com).
13 Military Specification MIL-I-16411F, Section 3.3.
14 Telephone conversation with Mike Sollie, Transco Products, Inc., July 9, 2003.
15 Telephone conversation with Tim Bovard, Pittsburgh Corning Corp., July 10, 2003.
16 E-mail from Garrick Ackart, Thermal Ceramics, Inc., July 10, 2003
17 Telephone conversation with Frank Duchon, Thermal Ceramics, Inc., July 10, 2003.
18 Microporous Theory, Technical Notes on MinK, Document Number TN01301, provided by Thermal Ceramics, Inc.

4.5.2.5 Failed Coatings Debris Characteristics

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

Unless replaced by plant-specific information of higher value, Table 4.5.2.5-1 lists the bulk density and the characteristic size and shape for various types of coatings debris, and these can be used for the evaluation. The actual size distributions of these materials in a post-LOCA environment are not known. Thus, the table lists particle sizes that are conservative (i.e. small) for head loss evaluations. Plant-specific data, if available, can supersede these data.

The following types of coatings are commonly found within PWR containments: Inorganic Zinc (IOZ), Epoxy, Epoxy-Phenolic and Alkyd. The densities for the epoxy, epoxy-phenolic and alkyd coatings listed in Table 4.5.2.5-1 are based on specific gravities presented in the “Performance of Containment Coatings During a Loss of Coolant Accident” [Reference 7-34]. The specific gravity for IOZ is 437 lbm/ft^3 as reported by Carboline for the zinc dust used in the formulation of CarboZinc-11 [Reference 7-36].

Break jets will ablate coatings within the ZOI [Reference 7-37]. In the absence of specific experimental details about the debris particle size distribution for IOZ, alkyds, epoxy and epoxy-phenolic coating debris generated by high pressure water/steam jets in the ZOI, a diameter of 10 µm has been selected as the characteristic size of coating debris generated within the ZOI. The 10 µm characteristic diameter is the nominal diameter of unbound zinc particles and also the alkyd pigment particles of failed coatings [Reference 7-38]. Epoxy and epoxy-phenolic coatings outside the ZOI are assumed to fail as chips [Reference 7-38]. A typical lower bound for epoxy and epoxy-phenolic coating chip thickness is 1-mil (25.4 µm). A ten-micron (10 µm) diameter is shown as the characteristic size of IOZ and alkyd coating debris outside of the ZOI [Reference 7-38].

Table 4.5.2.5-1: Coating Debris Characteristics

Generic Coating Material	Material Density (lbs/ft^3)	Characteristic Size µm	Characteristic Size Ft
Inorganic Zinc (IOZ)	350	10(1)	3.28E-05(1)
Epoxy and Epoxy Phenolic Coating Chip (outside ZOI)	94	25(2)	8.20E-05(2)
Epoxy and Epoxy Phenolic Coating Particles (in ZOI)	94	10(1)	3.28E-05(1)
Alkyd Coating	98	10(1)	3.28E-05(1)

Note 1: Spherical Particle Diameter
Note 2: Flat Plate Thickness

4.5.2.6 Miscellaneous Debris Characteristics

Rust flakes, dirt/dust, concrete debris, etc. are commonly encountered miscellaneous sources of debris. The characteristics of several types of miscellaneous debris are depicted in Table 4.5.2.6-1. To evaluate the impact of miscellaneous debris upon the sump screen head loss, the types and quantities (mass, surface area, or volume, as appropriate) of each type of debris must be specified in the design input.

Rust flakes are considered as iron oxide particulate material with a microscopic density of 324 lbm/ft^3 [Reference 7-14]. Based on Reference 2.24, the lower bound value of epoxy paint chip thickness may also be adopted for rust flake thickness. In this regard, an equivalent thickness of 1-mil (25.4 μm) could be adopted for the characteristic size of rust flakes. However, considering that rust flakes readily disperse in turbulent water, a fine-particle size of ~10μm is conservative, and based on BWR test experience, should be used.

In the absence of specific information, a microscopic density of 156 lbm/ft^3 [Reference 7-34] is adopted for dirt/dust particles. Based on typical diameter of dust particles [Reference 7-44], a diameter of 10 μm is suggested.

Concrete debris that is ablated in the ZOI (as well as latent concrete debris that is washed down by the containment sprays) is assumed to be fine particulate, with a size of ~10 μm for head loss analysis. In practice, silica sand components of the concrete can easily reach ~1/32″-diameter or greater, so this is conservative. The appropriate density of concrete debris is being determined.

Latent fiber debris is not well characterized. Research is ongoing at LANL in this regard, who is doing an SEM-characterization of the debris. Utilities should plan to do plant-specific confirmatory analysis in this regard.

Plastic sheets, if present, could potentially end up in the containment pool and be transported to the strainer. This reduces the effective surface area, because if a plastic tarp were to cover a portion of the strainer, that portion would become inactive due to the impermeable plastic layer. While this possibility may have to be evaluated on a plant-specific basis, the FME Programs currently in place may preclude the need for this consideration.

Equipment tags, both paper and plastic, may be numerous in some containment buildings. The characteristics and properties would have to be specified on a plant-specific basis. Generally, BWR test experience shows that these would have a very minor impact on the sump screen head loss.

The quantities of all materials present in containment and listed in Table 4.5.2.6-1 must be specified as design input from the debris generation analysis in order for them to be considered in the head loss analysis.

Table 4.5.2.6-1: Miscellaneous Debris Characteristics

Debris Material	Material Density (lbm/ft^3)	Characteristic Size	
		μm	ft
Rust	324	10(2)	3.28E-05(2)
Dirt/Dust	156	10(2)	3.28E-05(2)
Concrete	TBD	10(2)	3.28E-05(2)
Latent Fiber	TBD	TBD(4)	TBD
Plastic Sheets	N/A	N/A	Area TBD
Equipment Tags	TBD	N/A	TBD

Note 2: Spherical Particle Diameter
Note 3: Flat Plate Thickness
Note 4: Packaged Density and Fiber Density must be determined.

4.5.3 Head Loss Methodology

The head loss model starts with a clean screen and a pool containing a homogenous mixture and concentration of debris (i.e., fibrous, particulate, etc.). Upon switchover of suction from the refueling water storage tank (RWST) to the recirculation sump, the debris is transported to the sump and accumulates on the sump screen. Initially, some portion of the debris whose size is smaller than the screen mesh size (or hole size of the perforated plate) passes through the sump screen and debris bed. Fibers will quickly start to form a fiber mat in the cases where there is no RMI debris transported to the sump screen. As the fiber mat forms it will start trapping particulate debris reaching the sump screen. With sufficient fibers reaching the screen, a uniform fiber mat bed could be formed at which time the head loss across the debris will start increasing. The head loss across the debris bed will continue to rise as more debris is deposited on the screen, reaching steady state when all of the available debris is deposited on the screen.

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

Some analysts may have NPSH calculations computed over the duration of the accident, have time dependent post-LOCA pool temperatures, and the ECCS flow rates may reduce over time by shutting down pumps. In these cases the analyst may want to compute the head loss as a function of time. The head loss methodology herein is amenable to calculating the time dependent debris head loss. This would also hold true for any plant using overpressure (if approved) in their time dependent HL calculations.

Additionally the head loss methodology herein is also amenable to calculating head losses based on time dependent debris loadings if time dependent debris loading on the sump screen is computed. One method to estimate the time dependent debris loading on the sump screen is to adopt the general assumption that at the time of starting the recirculation phase all debris is uniformly suspended in the pool. Using this assumption the rate of debris accumulation on the screen will simply be proportional to the debris transported by the flow.

4.5.3.1 General Theoretical/Empirical Formulas

4.5.3.1.1 Fibrous Debris Beds with Particulate

For general use with fiber and particulate debris beds, the NUREG/CR-6224 correlation is recommended for determination of the head loss. Attachment D provides a discussion of factors associated with estimating debris head losses and presents several debris head loss correlations developed over the last few years.

The NUREG/CR-6224 head loss correlation is described in detail in Appendix B to that report and is a semi-theoretical head loss model. The correlation is based on the theoretical and experimental research for the head loss across a variety of porous and fibrous media carried out since the 1940s. The NUREG/CR-6224 head loss correlation has been extensively validated for a variety of flow conditions, water temperatures, experimental facilities, types and quantities of fibrous insulation debris, and types and quantities of particulate matter debris. The types of fibrous insulation material tested include NUKON™ and Temp-Mat®. The particulate matter debris tested includes iron oxide particles from 1 to 300 μm in characteristic size, inorganic zinc, and paint chips. In all cases, the NUREG/CR-6224 head loss correlation has bounded the experimental results.

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

$$\Delta H = \Lambda \left[3.5\, S_v^2\, \alpha_m^{1.5} (1+57\, \alpha_m^3)\, \mu\, U + 0.66\, S_v\, \alpha_m/(1-\alpha_m)\, \rho\, U^2 \right] \Delta L_m \quad (4.5.3.1\text{-}1)$$

where,

ΔH is the head loss
S_v is the specific surface to volume ratio of the debris
μ is the dynamic viscosity of water
U is the fluid approach velocity
ρ is the density of water
α_m is the mixed debris bed solidity (one minus the porosity)

ΔL_m is the actual mixed debris bed thickness
Λ is a conversion factor –
$\Lambda = 1$ for SI units, and
$\Lambda = 4.1528\text{x}10^{-5}$ (ft-water/inch)/(lbm/$ft^2 sec^2$) for English units.

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

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

where,

Q is the total volumetric flow rate through the screen, and
A is the screen surface area.

The screen surface area, A, is the submerged (wetted) surface area of the screen as described in Section 4.5.2.1 above. As noted previously, the available surface area may change with time, particularly in the case of star or stacked disc designs. For these alternate geometry screens such as stacked disks or star strainers, given sufficient debris reaching the screen, the surface area may eventually evolve to the circumscribed area. At the limit, the head loss for alternate geometry screens may be calculated using the circumscribed area and the debris load equal to the total debris load transported to the screen less the quantity of debris required to fill in the volumes/gaps of the alternate geometry screen.

The mixed debris bed solidity (α_m) is given by:

$$\alpha_m = \left(1 + \frac{\rho_f}{\rho_p}\eta\right)\alpha_o c \qquad (4.5.3.1.1\text{-}2)$$

where,

α_o is the solidity of the original fiber blanket (i.e. the “as fabricated” solidity)
$\eta = m_p/m_f$, the particulate to fiber mass ratio in the debris bed
ρ_f is the fiber density
ρ_p is the average particulate material density
c is the head-loss-induced volumetric compression of the debris.

For debris deposition on a flat surface of a constant size, the compression (c) relates the actual debris bed thickness, ΔL_m, and the theoretical fibrous debris bed thickness, ΔL_o, via the relation

$$c = \frac{\Delta L_o}{\Delta L_m} \qquad (4.5.3.1.1\text{-}3)$$

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

$$c = 1.3 * K * (\Delta H / \Delta L_o)^{0.38} \qquad (4.5.3.1.1\text{-}4)$$

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

For very large pressure gradients, the compression has to be limited such that a maximum solidity is not exceeded. In the NUREG/CR-6224, this maximum solidity is defined to be:

$$\alpha_m = 65\ \text{lb/ft}^3/\rho_p \qquad (4.5.3.1.1\text{-}5)$$

which is equivalent to having a debris layer with a density of 65 lb/ft^3. Note that 65 lb/ft^3 is the macroscopic, or bulk density of a granular media such as sand or gravel and clay [Reference 7-39].

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

Cylindrically-shaped debris: $S_v = 4/\text{diam}$

Spherically-shaped debris: $S_v = 6/\text{diam}$

Flakes (flat-plates): $S_v = 2/\text{thick}$

where 'diam' is the diameter of the fiber or spherical particle, and 'thick' is the thickness of the flake/chip. Other debris not listed above would have its surface-to-volume ratio calculated similarly based on one of the above characteristic shapes. The following is a method for calculating the average surface to volume ratio for two different types of debris constituents [Reference 7-45].

$$S_v = \text{SQRT}\ [(S_{V1}^2 * v_1 + S_{V2}^2 * v_2)/(v_1 + v_2)], \qquad (4.5.3.1.1\text{-}6)$$

where v_1 and v_2 are the microscopic volumes of constituents '1' and '2,' respectively.

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

$$S_v = SQRT\ [\ \ ((S_{Vn}^2 * v_n)/\ \ (v_n)], \qquad (4.5.3.1.1\text{-}7)$$

where the subscript 'n' refers to the nth constituent.

Summarizing the computation process:

- Fiber and particulate debris are handled with the general form of the NUREG/CR-6224 correlation, Equation 4.5.3.1.1-1.
- Material properties are necessary – see Section 4.2 (Debris Generation) for material properties of material commonly encountered in PWRs.
- Knowing the debris quantities that are calculated to reach the sump screen, the mass ratio of particulates-to-fiber (η), the fiber density (ρ_f), and the average particulate density (ρ_p) are determined.
- A compression factor [c] must be specified, with a value of 2.0 being a reasonable first approximation.
- The mixed bed solidity (α_m) is next calculated from Equation 4.5.3.1.1-2.
- An overall, average value of S_v must be determined for the fiber, each of the particulates and then an average for the overall debris mixture by Equation 4.5.3.1.1-7. If multiple fiber types are present, then each type should be included in the averaging process.
- The water properties (ρ and μ) are specified at the sump temperature at the time the head loss across the debris bed is calculated. Alternatively a conservative approach would be to calculate the head loss using the lowest sump water temperature calculated over the entire time frame that the ECCS needs to function.
- The approach velocity will be known from the sump screen area and the ECCS flows through the screen.
- Substitution of all of the above information into Equation 4.5.3.1.1-1, in combination with iterative solution of Equations 4.5.3.1.1-3 and 4.5.3.1.1-4, yields the sump screen head loss and the actual debris-bed thickness, ΔL_m.

The head loss across a debris bed consisting of fibrous debris (no particulates) can be calculated with the general form of the NUREG/CR-6224 correlation, Equation 3-1, where the mass ratio of particulates-to-fiber (η) is set to zero. Given the presence of particulates from dirt/dust and possibly unqualified coatings, it would be unusual to have to analyze pure fiber bed head loss for a PWR. However, this case has application when interpreting experimental results, so it is included for completeness.

4.5.3.1.2 RMI Debris Beds

The head loss for a RMI debris bed on the sump screen surface depends mainly on the accumulation at the sump screen and the type and size distribution of RMI debris. The key parameter needed to evaluate pure RMI head loss is the surface area of the RMI bed on the screen. The commonly accepted empirical correlation for RMI [Reference 7-39] is:

$$\Delta H = [1.56E\text{-}05/(K_t)^2]\ U^2 A_{foil}/A \qquad (4.5.3.1.2\text{-}1)$$

where,

K_t is the interfoil gap thickness (ft)

ΔH is the head loss, (feet-of-water)
U is the sump screen approach velocity, (ft/sec)

A_{foil} is the RMI foil surface area, (ft^2)

A_c is the sump screen surface area, (ft^2).

The NRC concluded [Reference 7-39] that a value of K_t of 0.012 in the above general equation bounds the available RMI head loss data reasonably well. Substituting this value of K_t into Equation 4.5.3.1.2-1, one obtains:

$$\Delta H = 0.108\ U^2 A_{foil}/A \qquad (4.5.3.1.2\text{-}2)$$

Equation 4.5.3.1.2-2 accounts for experimental uncertainties, repeatability variations, and debris size and material types. As such, Equation 4.5.3.1.2-2 is the RMI correlation adopted to predict the head loss across a pure RMI debris bed for PWR sump screens. Attachment D provides for further discussion of RMI head loss correlations.

4.5.3.1.3 Mixed Debris Beds (RMI, Fiber and Particulates)

A mixed debris bed of RMI, fiber and particulates is handled by superposition [Reference 7-39]. First, the fiber-and-particulate head loss is determined using the methodology of Section 4.5.3.1.1. Next, the RMI head loss is determined using the methodology of Section 4.5.3.1.2. These two head losses are then added to estimate the total head loss of a RMI, fiber, and particulate bed.

The superposition of RMI and fiber may be overly conservative for cases where relatively large amounts of RMI and small amounts of fiber (e.g. latent fiber) are estimated to be transported to the sump screen. Experiments have shown that fiber can become caught either within the voids of the RMI bed or at the surface of the RMI bed (which can have a significantly larger surface area and a lower approach velocity than the sump screen itself). For plants that are essentially all RMI, a relatively small amount of latent fiber could provide the quantity necessary to develop a thin bed and cause unacceptable results when added algebraically to the RMI head loss.

4.5.3.1.4 Calcium Silicate Insulation

Later

4.5.3.1.5 Microporous Insulation

Microporous insulation (e.g. Cal-Sil, MinK, Micortherm, etc.) has been used in PWRs. The analyst is cautioned to ensure that the applicable material properties are used, especially in the case of Cal-Sil since there could be significant variations in material properties from those suggested in the debris generation section. Attachment D provides additional background as to insights gained in the very limited series of head loss experiments available for review through September 2003. Additional head loss data for Cal-Sil is anticipated to be released by the NRC in the near future.

<u>Microporous and Fiber Debris</u>

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

The computation of the head loss of mixed microporous and fiber debris beds (where the microporous to fiber mass ratio is less than 20 percent) is the same as described for a fiber and particulate bed [Section 4.5.3.1.1). The currently available experimental database does not support a correlation for estimating the head loss across a debris bed composed of microporous and fibrous insulation where the microporous to fiber mass ratio is more than 20 percent.

The alternatives currently available for accessing the sump screen performance in the event the debris generation and transport analysis yields the formation of a debris bed on the screen composed of microporous and fibrous insulation where the microporous to fiber mass ratio is more than 20 percent includes:

- Removal of microporous insulation until the debris generation and transport analysis yields a debris mix of composed of microporous and fibrous insulation where the microporous to fiber mass ratio is less than 20 percent
- Use of a head loss correlation other than NUREG/CR-6224 (See Attachment D for potentially applicable head loss correlations.)

- Conduct of head loss experiments using plant specific debris mix, sump screen configuration, and thermal hydraulic conditions

<u>Microporous Debris Only</u>

Based on results from a very limited series of experiments, debris from microporous insulation (Cal-Sil) by itself has been shown to induce significant head losses. These tests determined that the NUREG/CR-6224 correlation is unreliable for predicting the head loss of microporous insulation debris alone. The currently available experimental database does not support a correlation for estimating the head loss across a debris bed composed solely of microporous insulation debris.

The alternatives currently available for assessing sump screen performance for a debris bed on the screen composed of only microporous insulation includes:

- Removal of all microporous insulation
- Use of a head loss correlation other than NUREG/CR-6224 (See Attachment D for potentially applicable head loss correlations.)
- Conduct of head loss experiments using plant specific debris mix, sump screen configuration, and thermal hydraulic conditions

<u>Microporous and RMI Debris</u>

Reference 7-46 suggests that the head loss for an RMI and calcium silicate debris bed will be relatively low, with increased head loss as the quantity of CalSil debris quantities increases. The expectation is that the same would occur for all types of microporous and RMI debris beds. Mixtures of microporous, RMI, fiber, and other debris should be treated the same as mixed debris bed treatment of 4.5.3.1.3 with the limitations noted in 4.5.3.1.4 (a) and (b) above.

4.5.3.2 Methodology Application Considerations

4.5.3.2.1 Total Sump Screen Head loss

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

$$TSHL = CSHL + DBHL$$

4.5.3.2.2 Evaluation of Breaks with Different Combinations of Debris

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

4.5.3.2.3 Thin Fibrous Beds

For conditions of fiber and particulate present in the post-LOCA suppression pool, as the fiber-bed is deposited on the screen particulate material will be trapped by the fiber, increasingly so as the fiber bed thickens. Once a fiber bed of approximately one-eighth inch thickness is formed, if there is sufficient particulates a low permeability granular layer of debris on top of the fiber bed will be formed. The head loss associated with the accumulation of mostly particulate debris on thin fibrous beds can be quite high, and surprisingly enough, greater than the head losses associated with much larger quantities of fiber and much thicker beds of debris. This apparently counter-intuitive head loss phenomenon is known as the Thin Bed Effect (TBE). Attachment D provides for further discussions on the TBE.

It only takes a small quantity of fiber to facilitate TBE occurrence and it is difficult to make a defensible case that no fiber whatsoever are present in the containment, hence the possibility of forming a thin fibrous bed should be evaluated. Additionally, given the uncertainties of debris generation and transport calculations, the total quantities of fiber calculated to reach the sump screens may be on the high side, hence the impact of a smaller quantity of fiber reaching the sump screen should be examined – the transport of only the fiber necessary to for a thin bed being the limiting case. This methodology recommends that the head losses given a one-eighth inch fiber bed be calculated as a sensitivity analysis.

To analyze a thin fiber bed, a fiber quantity sufficient to form a bed one-eighth inch thick is assumed to be present and deposited on the sump screen. The estimation of the head loss computations is the same as described for fiber and particulate bed (Section 4.5.3.1.1) using the full value of particulate matter transported to the sump screen. It should be noted that the particulate layer is characterized by a very high sludge-to-fiber ratio, hence a limiting value for the compression is used.

4.5.3.2.4 Sump Screen Submergence

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

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

4.5.3.3 Methodology Limitations and Other Considerations

4.5.3.3.1 Debris Interceptors

Debris interceptors (trash racks, curbs, etc.) can be designed to be located anywhere along the containment floor and may prevent debris movement toward or at the sump. Debris interceptors may also be unintentional, such as gates into high radiation areas, and should be identified and their impact evaluated. Debris accumulation at these points should be evaluated for flow restriction, specifically those structures whose height exceeds the minimum anticipated post-LOCA pool water depth. Excessive debris accumulation on debris interceptors could restrict the flow of water to the sump and affect the water level in the sump. Any reduction in sump water level should be addressed in NPSH evaluations as well as considered in air ingestion and sump submergence evaluations. Local debris trapping along the containment floor should be addressed in debris transport evaluations. If local head loss calculations are required for intervening structures along the flow path, these can be performed in similar manner to those for the sump screen, with appropriate consideration of the local geometry.

4.5.3.3.2 Flat Screen Assumption

The NUREG/CR-6224 correlation adopted in this methodology was developed mainly using data obtained in a closed loop that contained a vertical pipe section which housed a horizontally mounted flat screen. The flat screens yielded conservative data for the development of the NUREG/CR-6224 correlation because all debris is forced onto a relatively small screen in a small-scale test apparatus. In the case of alternate design screens (stacked disc, star, etc.) direct application of the NUREG/CR-6224 will yield overly conservative results [Reference 7-14]. For these alternate geometry screens, independent head loss correlations should be developed based on actual design configurations, debris loads, and test data to reduce conservatism.

4.5.3.3.3 Non-Uniform Deposition on Sump Screen Surfaces

PWR sump screens can have vertical and inclined orientation. On a vertical screen, there is greater chance for non-uniform deposition of debris, which will usually lead to lower head losses because of thin spots in the debris bed. Body forces also tend to shear the bed from the screen, also a mitigating factor. For these reasons, using the uniform deposition assumption for vertical screens is a conservative approach. Similar statements can be made for curved surfaces such as horizontally oriented, cylindrical strainer designs, since body forces in the debris bed essentially act in the opposite direction to the suction forces over a significant portion of the strainer area. An inclined, flat surface is less limiting than a horizontal surface, therefore, the uniform deposition again should be slightly conservative.

4.5.3.3.4 Very Thin Fiber Beds

The NUREG/CR-6224 head loss correlation was developed and validated for debris that is uniformly distributed on the screen surface. However, experiments have shown that very thin fibrous beds (with a thickness of less than one-eighth inch) are characterized by large scale non-uniformities on the screen and negligible head losses. For fibrous debris bed less than one-eighth inch thick, the NUREG/CR-6224 head loss correlation significantly over predicts the experimentally determined head loss and should not be used. Instead, it is appropriate to consider the head loss across fibrous debris beds less than one-eighth inch to be negligible.

4.5.3.3.5 Long-Term Effects

The effects of long-term flow of water through a debris bed are not well understood at this time. Most of the head loss experiments have been conducted with durations from a few minutes to twenty-four hours at most. No experiments to date have been conducted for the time period that ECCS recirculation is expected to be maintained, i.e. mission duration. Reference 7-39 suggests that over a long period of time the debris constituents tend to deteriorate and the bed becomes less porous, hence an increased pressure drop. Debris bed degradation is anticipated to occur over a period of several hours hence active accident management may allow mitigation of the long term effects. Absent applicable experimental data no long-term effects are included in the correlations presented herein.

4.5.3.3.6 Vortexing

The possibility of air ingestion by vortexing needs to be evaluated in all sump performance assessments. General guidelines for determining the susceptibility of vortexing can be found in Reference 7-6 based on the determination of the Froude number for the sump inlet arrangement. The lack of air ingestion by vortexing for a particular sump and screen/strainer configuration can also be determined experimentally.

4.5.3.3.7 Structural Effects on the Sump Screen

A total head loss of even one foot of water will cause a significant mechanical load on the sump screen, hence the mechanical effect of the pressure drop across the sump screen should be evaluated to ensure that the screen is capable of withstanding this force without collapse or other damage.

4.5.3.3.8 Debris Bypass

For situations where the quantity of fibrous debris is insufficient to form a homogeneous bed (Section 4.5.3.3.4 above) there is the potential for a significant portion of fine particulates transported to the sump screen during a LOCA, (e.g. ablated concrete particles, dirt, dust, rust, etc.) to pass through the screen and be introduced into the ECCS. The impact of debris ingested should be addressed as part of ECCS reliability assurance.

4.5.4 Sample Calculations

The following examples demonstrate the use of the head loss equations with typical debris sources and plant conditions.

4.5.4.1 Fiber and Particulate Debris Bed

Flow Conditions:

Obtained from plant design documents.

ECCS Flow Rate (Q)	=	14000	gpm
Temperature (T)	=	170	°F
Fluid Density (ρ)	=	60.80	lb/ft^3
Fluid Viscosity (μ)	=	2.51E-04	lb/ft/sec

Screen Parameters:

Obtained from screen design drawings and ECCS flow rate.

Effective Surface Area (A)	=	300	ft^2
Screen Approach Velocity (U)`	=	0.104	ft/s

Debris Types/Quantities:

Obtained from debris generation and transport analysis.

NUKON Fiber	=	200	ft^3
Dirt-Dust	=	85	lbs
Qual-Epoxy	=	85	lbs
Rust	=	50	lbs

Debris Characteristics:

- NUKON

Theoretical Packing Density (ρ_f)	=	2.4	lbs/ft^3	
Fiber Diameter (D)	=	2.33×10^{-5}	ft	
Surface to Volume Ratio (S_v)	=	1.72×10^{5}	ft^{-1}	$\Leftarrow 4 / 2.33 \times 10^{-5}\ ft^3$
Mass of Fiber (m_f)	=	480	lbs	$\Leftarrow 200\ ft^3 \times 2.4\ lbs/ft^3$
Fiber Density	=	175	lbs/ft^3	
Fiber Volume	=	2.74	ft^3	$\Leftarrow 480\ lbs / 175\ lbs/ft^3$

- Dirt/Dust

Particle Density	= 156	lbs/ft^3	
Particle Diameter (D)	= 3.28×10^{-5}	ft	
Surface to Volume Ratio (S_v)	= 1.83×10^{5}	ft^{-1}	$\Leftarrow 6 / 3.28 \times 10^{-5}\ ft^3$
Particle Volume	= 0.54	ft^3	$\Leftarrow$ 85 lbs / 156 lbs/ft^3

- Rust

Particle Density	= 324	lbs/ft^3	
Particle Diameter (D)	= 3.28×10^{-5}	ft	
Surface to Volume Ratio (S_v)	= 1.83×10^{5}	ft^{-1}	$\Leftarrow 6 / 3.28 \times 10^{-5}\ ft^3$
Particle Volume	= 0.15	ft^3	$\Leftarrow$ 50 lbs / 324 lbs/ft^3

- Qualified Epoxy

Particle Density	= 94	lbs/ft^3	
Particle Diameter (D)	= 3.28×10^{-5}	ft	
Surface to Volume Ratio (S_v)	= 1.83×10^{5}	ft^{-1}	$\Leftarrow 6 / 3.28 \times 10^{-5}\ ft^3$
Particle Volume	= 0.90	ft^3	$\Leftarrow$ 85 lbs / 94 lbs/ft^3

- Average Particulate

Total Particle Volume	= 1.60	ft^3
Total Particle Mass	= 220	lbs
Ave Particle Density	= 137.20	lbs/ft^3
Ave Surface to Volume Ratio (S_v)	= 1.83×10^{5}	ft^{-1}

- Average Debris

Total Particle Volume	= 1.60	ft^3
Ave Surface to Volume Ratio (S_v)	= 1.83×10^{5}	ft^{-1}
Total Fiber Volume	= 2.74	ft^3
Surface to Volume Ratio (S_v)	= 1.72×10^{5}	ft^{-1}

Ave Debris Surface to Volume Ratio (S_v) = 1.76×10^{5} ft^{-1}

Debris Bed Equations:

- Theoretical Debris Bed Thickness (ΔL_o)
  Total Volume of Fiber divided by Screen Area = 8.00 in

- Particulate to Fiber Mass Ratio (η)
  Mass of Particles divided by Mass of Fiber = 0.458

- Actual Bed Thickness (ΔL_m) = 8.0
  Assume a value and iterate until Equations 3-3 and 3-4 converge on the same number

Eq. 4.5.3.1.1-1: Head Loss Across Debris Bed (ΔH) = 3.56 ft

Eq. 4.5.3.1.1-2: Mixed Debris Bed Solidity (α_m) = 0.022

Eq. 4.5.3.1.1-3: Head Loss Volumetric Compression (c) = 1.00

Eq. 4.5.3.1.1-4: Head Loss Volumetric Compression (c) = 1.00

Equations 4.5.3.1.1-3 and 4.5.3.1.1-4 have converged within ~1% of each other, therefore, the head loss is 3.56 feet of water.

The mixed debris bed solidity should be less than 0.20, therefore OK.

4.5.4.2 Fiber Debris Bed

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

4.5.4.3 RMI Debris Bed

Flow Conditions:

Obtained from plant design documents.

ECCS Flow Rate (Q)	= 14000	gpm
Temperature (T)	= 170	°F
Fluid Density (ρ)	= 60.80	lb/ft^3

Fluid Viscosity (μ) = 2.51E-04 lb/ft/sec

Screen Parameters:

Obtained from screen design drawings and ECCS flow rate.

Effective Surface Area (A) = 300 ft^2
Screen Approach Velocity (U)` = 0.104 ft/s

Debris Types/Quantities:

Obtained from debris generation and transport analysis.

2.5 mil SS RMI = 25000 ft^2

Debris Bed Equations:

The head loss correlation for RMI is taken from Section 4.5.3.1.2

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

where,

ΔH = the head loss across the RMI bed (ft-water),
U = the approach velocity to the screen (ft/s),
A_{foil} = the surface area of the RMI foils (ft^2 – nominal), and
A_c = the strainer circumscribed area (ft^2).

Substituting the above plant specific parameters,

$$\Delta H = 0.108\, (0.104)^2\, (25000 / 300)$$

$$= 0.097 \text{ ft-water} \cong 0.10 \text{ ft } H_2O$$

4.5.4.4 Mixed Debris Beds (RMI, Fiber, and Particulates)

The head loss of a mixed fiber, particulate, and RMI debris bed is the addition of the fiber-and-particulate head loss to the RMI head loss. For example, if the quantities of debris were as in the totals of Sections 4.5.4.1 and 4.5.4.2, then the total mixed RMI and fibrous debris bed head loss would be:

ΔH_{RMI} = 0.10 ft-water

$\Delta H_{\text{Fiber + Particulate}}$ = 3.56 ft-water

hence,

$\Delta H_{\text{RMI+ Fiber + Particulate}}$ = 3.66 ft-water

4.5.4.5 Calcium Silicate

(Later)

4.5.4.6 Microporous Insulation

As noted in 4.5.3.1.5 above, the currently available experimental data can only support the head loss calculations of microporous insulation debris in the presence of fibrous debris provided the mass ratio of microporous insulation-to-fiber is less than 20 percent. In these cases the microporous insulation debris is treated as a particulate and the equations and methods for fibrous and particulate head loss are used (see example of Section 4.5.4.1 above).

4.5.4.7 Additional Calculations

When performing a sump screen head loss analysis, the analyst may find that additional calculations may be necessary to evaluate the effects of varying debris loads on the screen, to assess the sensitivity of the results to the transport factors, or develop an acceptable screen size based on a given debris load.

4.5.4.7.1 Sensitivity Analysis

Sensitivity calculations are typically performed to evaluate the uncertainty in the debris generation and transport quantities on the debris head loss. This methodology recommends that the analyst should typically vary the debris loading plus or minus 10 percent, 25 percent or 50 percent and evaluate the impact on the calculated head loss. Additionally, for the reasons discussed in Section 4.5.3.2.2 and as suggested in draft Revision 3 of RG 1.82, this methodology recommends that the head loss for a one-eighth inch thick fiber debris bed (including particulates) be calculated.

4.5.4.7.2 Determination of Requisite Sump Screen Size

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

The key assumption in the head loss correlations provided is homogeneous debris accumulation on a flat plate. As noted in Section 4.5.3.3.3, different screen orientations and configurations can provide different debris accumulation profiles and take advantage of uneven debris distribution and flow redistribution. In these cases, the head loss correlations provided in this methodology may yield overly conservative results. As such, adjustments to the head loss correlation could be made based on experimental test data applicable to the actual sump screen orientation and configuration.

5 Downstream Effects

(Later)

6 Regulatory Guide Requirements Comparison

(Later)

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Attachment A

Water Sources for Long Term Recirculation Cooling Following a Loss-of-Coolant Accident

U.S. NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REGULATORY RESEARCH

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Division 1
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DRAFT REGULATORY GUIDE

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DRAFT REGULATORY GUIDE DG-1107

(Proposed Revision 3 to Regulatory Guide 1.82)

WATER SOURCES FOR LONG-TERM RECIRCULATION COOLING FOLLOWING A LOSS-OF-COOLANT ACCIDENT

A. INTRODUCTION

General Design Criteria 35, "Emergency Core Cooling"; 36, "Inspection of Emergency Core Cooling System"; 37, "Testing of Emergency Core Cooling System"; 38, "Containment Heat Removal"; 39, "Inspection of Containment Heat Removal System"; and 40, "Testing of Containment Heat Removal System," of Appendix A, "General Design Criteria for Nuclear Power Plants," to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," require that systems be provided to perform specific functions, e.g., emergency core cooling, containment heat removal, and containment atmosphere clean up following a postulated design basis accident. These systems must be designed to permit appropriate periodic inspection and testing to ensure their integrity and operability. General Design Criterion 1, "Quality Standards and Records," of Appendix A to 10 CFR Part 50 requires that structures, systems, and components important to safety be designed, fabricated, erected, and tested to quality standards commensurate with the importance of the safety functions to be performed.

This guide is being revised to describe methods acceptable to the NRC staff for implementing these requirements with respect to the sumps and suppression pools performing the functions of water sources for emergency core cooling, containment heat removal, or containment atmosphere clean up. The guide also provides guidelines for evaluating the adequacy of the availability of the sump and suppression pool for long-term recirculation cooling following a loss-of-coolant accident (LOCA). This guide applies to light-water-cooled reactors. Additional information is provided in NRC Bulletin 96-03, "Potential Plugging of Emergency Core Cooling Suction Strainers By Debris in Boiling Water Reactors"; NRC Bulletin 95-02, "Unexpected Clogging of a Residual Heat Removal Pump Strainer While Operating in Suppression Pool

This regulatory guide is being issued in draft form to involve the public in the early stages of the development of a regulatory position in this area. It has not received complete staff review or approval and does not represent an official NRC staff position.

Public comments are being solicited on this draft guide (including any implementation schedule) and its associated regulatory analysis or value/impact statement. Comments should be accompanied by appropriate supporting data. Written comments may be submitted to the Rules and Directives Branch, Office of Administration, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001. Comments may be submitted electronically or downloaded through the NRC's interactive web site at <WWW.NRC.GOV> through Rulemaking. Copies of comments received may be examined at the NRC Public Document Room, 11555 Rockville Pike, Rockville, MD. Comments will be most helpful if received by **April 30, 2003.**

Requests for single copies of draft or active regulatory guides (which may be reproduced) or for placement on an automatic distribution list for single copies of future draft guides in specific divisions should be made to the U.S. Nuclear Regulatory Commission, Washington, DC 20555, Attention: Reproduction and Distribution Services Section, or by fax to (301)415-2289; or by email to DISTRIBUTION@NRC.GOV. Electronic copies of this draft regulatory guide are available through the NRC's interactive web site (see above); the NRC's web site <WWW.NRC.GOV> in the Electronic Reading Room under Document Collections, Regulatory Guides; and in the NRC's ADAMS Documents at the same web site, under Accession Number ML030550431.

Cooling Mode"; NRC Bulletin 93-02, "Debris Plugging of Emergency Core Cooling Suction Strainers"; Supplement 1 to NRC Bulletin 93-02, "Debris Plugging of Emergency Core Cooling Suction Strainers"; Generic Letter 85-22, "Potential for Loss of Post LOCA Recirculation Capability Due to Insulation Debris Blockage"; and Generic Letter 97-04, "Assurance of Sufficient Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal Pumps."

This regulatory guide is being revised to enhance the debris blockage evaluation guidance for pressurized water reactors. Research after the issuance of Revision 2 indicated that the previous guidance was not comprehensive enough to adequately evaluate a pressurized water reactor (PWR) plant's susceptibility to the detrimental effects caused by debris accumulation on debris interceptors (e.g., trash racks and sump screens). The sections pertaining to PWRs have been changed, and minor changes have been made to the sections on boiling water reactors (BWRs) to make them consistent with current staff positions as described in the Safety Evaluation on the Boiling Water Reactor Owners Group's response to NRC Bulletin 96-03 (1998).

This regulatory guide is also being revised to include guidance previously provided in Regulatory Guide 1.1, "Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal Pumps." The provisions of Regulatory Guide 1.1 have been updated to reflect the results of the NRC's review of responses to Generic Letter 97-04, "Assurance of Sufficient Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal Pumps," dated October 7, 1997.

Regulatory guides are issued to describe and make available to the public such information as methods acceptable to the NRC staff for implementing specific parts of the NRC's regulations, techniques used by the staff in evaluating specific problems or postulated accidents, and guidance to applicants. Regulatory guides are not substitutes for regulations, and compliance with regulatory guides is not required. Regulatory guides are issued in draft form for public comment to involve the public in developing the regulatory positions. Draft regulatory guides have not received complete staff review; they therefore do not represent official NRC staff positions.

The information collections contained in this draft regulatory guide are covered by the requirements of 10 CFR Part 50, which were approved by the Office of Management and Budget (OMB), approval number 3150-3011. The NRC may not conduct or sponsor, and a person is not required to respond to, a request for information or an information collection requirement unless the requesting document displays a currently valid OMB control number.

B. DISCUSSION

GENERAL

The primary safety concerns regarding long-term recirculation cooling following a LOCA are (1) LOCA-generated and pre-LOCA debris materials transported to the debris interceptors (i.e., trash racks, debris screens, suction strainers) resulting in adverse blockage effects, (2) post-LOCA hydraulic effects, particularly air ingestion, and (3) the combined effects of items (1) and (2) on long-term recirculation pumping operability (i.e., effect on net positive suction head (NPSH) available at the pump inlet).

Debris resulting from a LOCA, together with debris that exists before a LOCA, could block the emergency core cooling (ECC) debris interceptors and result in degradation or loss of NPSH margin. Such debris can be divided into the following categories: (1) debris that is generated by the LOCA and is transported by blowdown forces (e.g., insulation, paint), (2) debris that is generated or transported by washdown, and (3) other debris that existed before a LOCA (e.g., corrosion material, sludge in a BWR suppression pool) and that may become suspended in the containment sump or suppression pool. Debris can be further subdivided into (1) debris that has a high density and could sink but is still subject to fluid transport if local recirculation flow velocities are high enough, (2) debris that has an effective specific gravity of 1.0 and tends to be suspended or sink slowly but will nonetheless be transported by very low velocities or local fluid turbulence phenomena, and (3) debris that will float indefinitely by virtue of low density and will be transported to and possibly through the debris interceptors. Debris generation, early debris transport, long-term debris transport, and attendant blockage of debris interceptors must be evaluated to ensure that the ability of the emergency core cooling system (ECCS) to provide long-term post-LOCA core cooling is not jeopardized. All potential debris sources should be evaluated, including but not limited to, the fire barrier material, insulation materials (e.g., fibrous, ceramic, and metallic), filters, corrosion material, and paints or coatings. Relevant information for such evaluations is provided in the Regulatory Position and in Appendix A to this guide. Additional information relative to the above concerns may be found in Revision 1 of NUREG-0897, NUREG/CR-2758, NUREG/CR-2759, NUREG/CR-2760, NUREG/CR-2761, NUREG/CR-2772, NUREG/CR-2791, NUREG/CR-2792, NUREG/CR-2982, NUREG/CR-3170, NUREG/CR-3394, NUREG/CR-3616, NUREG/CR-6224, NUREG/CR-6369, NUREG/CR-6762, NUREG/CR-6772, NUREG/CR-6773, NRC Information Notice 94-57, NRC Information Notice 95-06, NRC Information Notice 95-47, Regulatory Guide 1.1, Safety Evaluation on NRC Bulletin 96-03, NEDO-32686, and Generic Letter 97-04. A current knowledge base describing results of research on the BWR suction-strainer and PWR sump screen blockage is provided in NUREG/CR-6808.

This regulatory guide provides separate guidance for PWR and BWR plants based on the design features of currently operating reactors. Advanced PWR or BWR designs may employ design features which this regulatory guide only associates with the opposite reactor design (e.g., an advanced PWR design which employs an in-containment refueling water storage tank that is similar to the suppression pool of a current BWR design, or an advanced BWR design which employs a large dry containment that is similar to a current PWR design). Therefore, for advanced PWR and BWR designs, the guidance provided in both the PWR and BWR sections of this regulatory guide should be considered that is appropriate and consistent with the plant's design features.

PRESSURIZED WATER REACTORS

In PWRs, the containment emergency sumps provide for the collection of reactor coolant and chemically reactive spray solutions following a LOCA; thus, the sumps serve as water sources to support long-term recirculation for the functions of residual heat removal, emergency core cooling, and containment atmosphere cleanup. These water sources, the related pump inlets, and the piping between the sources and inlets are important safety components. The sumps servicing the ECCS and the containment spray systems (CSS) are referred to in this guide as ECC sumps. Features and relationships of the ECC sumps pertinent to this guide are shown in Figure 1. In operating PWRs, the ECC sump designs may vary from this figure (e.g., in some plants sump screens may be located below the floor level). A more comprehensive description of various ECC sump designs is included in NUREG/CR-6762.

The design of PWR sumps and their outlets includes consideration of the avoidance of air ingestion and other undesirable hydraulic effects (e.g., circulatory flow patterns, outlets leading to high head losses). The location and size of the sump outlets within ECC sumps is important in order to minimize air ingestion since ingestion is a function of submergence level and velocity in the outlet piping. It has been experimentally determined for PWRs that air ingestion can be minimized or eliminated if the sump hydraulic design considerations provided in Appendix A to this guide are followed. Revision 1 of NUREG-0897, NUREG/CR-2758, NUREG/CR-2761, and NUREG/CR-2792 provide additional technical information relevant to sump ECC hydraulic performance and design guidelines.

In order for a centrifugal pump to perform its safety function there must be adequate margin between the available net positive suction head (NPSH) and the required NPSH. Failure to provide and maintain adequate NPSH margin for the emergency core cooling system pumps could result in cavitation and their subsequent failure to deliver the amount of water assumed in design basis LOCA calculations. Failure to provide and maintain adequate NPSH for the containment heat removal pumps could result in pressurization of the containment above the design pressure and an increase in the offsite and control room radiological doses.

The available NPSH is a function of the static head of water above the pump suction, the pressure of the atmosphere above the sump water surface, and the temperature of the pumped water at the suction of the pump.

Predicted performance of the emergency core cooling and the containment heat removal pumps should be independent of the calculated increases in containment pressure caused by postulated LOCAs in order to ensure reliable operation under a variety of possible accident conditions. For example, if proper operation of the emergency core cooling system or the containment heat removal system depends on containment pressure above a specified minimum amount, then operation of these systems at a containment pressure less than this amount (resulting, for example, from impaired containment integrity or operation of the containment heat removal systems at too high a rate) could significantly affect the ability of this system to accomplish its safety functions. However, for some operating reactors, some credit for containment accident pressure may be necessary. This should be minimized to the extent possible.

The American National Standard for Centrifugal Pumps for Nomenclature, Definitions, Application and Operation, ANSI/HI 1.1-1.5- 1994 specifies a method of accounting for the decrease in required NPSH with an increase in temperature of the pumped fluid. This method is subject to restrictions specified in the standard dealing with experience with the specific pump, the amount of air dissolved in the fluid and the transient nature of the pressure and temperature of the pumped fluid. The staff considers it prudent to not take credit for the reduction in required NPSH due to the temperature of the pumped fluid because of the uncertainty in these factors.

Although it is possible to perform static NPSH calculations, transient calculations provide more information, ensure that the most conservative conditions are chosen, and ensure a consistent result.

Placement of the ECC sumps at the lowest level practical ensures maximum use of available recirculation coolant. Areas within the containment in which coolant could accumulate during the containment spray period are provided, as necessary, with drains or flow paths to the sumps to prevent coolant holdup. It is also a concern that these drains or flow paths may themselves be blocked either totally or partially, diverting water away from the active sump region. This guide does not address the design of such drains or flow paths. Because debris can migrate to the sump via these drains or paths, they are best terminated in a manner that will prevent debris from being transported to and accumulating on or within the ECC sumps.

Containment drainage sumps are used to collect and monitor normal leakage flow for leakage detection systems within containments. They are separated from the ECC sumps and are located at an elevation lower than the ECC sumps to minimize inadvertent spillover into the ECC sumps from minor leaks or spills within containment. The floor adjacent to the ECC sumps would normally slope downward, away from the ECC sumps, toward the drainage collection sumps. This downward slope away from the ECC sumps will minimize the transport and collection of debris against the debris interceptors. High-density debris may be swept along the floor by the flow toward the trash rack. A debris curb upstream of and in close proximity to the rack will decrease the amount of such debris reaching the trash rack and debris screens. Debris blockage of the sump screen may also be mitigated by placement of an active device or system that will take some action to prevent debris, which could block restrictions or damage components in the systems served by the ECC pumps, from entering the ECC pump suction lines, remove debris from the sump screen and flow stream upstream of the ECC pumps, or mitigate any detrimental effects of debris accumulation. Examples of active mitigation systems are listed in Appendix B.

It is necessary to protect sump outlets with sump screens and trash racks of sufficient strength to withstand the vibratory motion of seismic events, to resist jet loads and impact loads that could be imposed by missiles that may be generated by the initial LOCA, and to withstand the differential pressure loads imposed by the accumulation of debris. Considerations for selecting materials for the debris interceptors include long periods of inactivity, i.e., no submergence, and periods of operation involving partial or full submergence in a fluid that may contain chemically reactive materials. Isolation of the ECC sumps from high-energy pipe lines is an important consideration in protection against missiles, and it is necessary to shield the screens and racks adequately from impacts of ruptured high-energy piping and associated jet loads from the break. When the screen and rack structures are oriented vertically or nearly vertically, the adverse effects from large pieces of debris (e.g., partially torn insulation blankets or damaged reflective metallic insulation cassettes) collecting on them will be reduced. Consistent with the plant licensing basis single-failure criterion, redundant ECC sumps and sump outlets should be separated to the extent practical to reduce the possibility that a single event could render both sumps inoperative.

It is generally expected that the water surface will be above the top of the debris interceptor structure after completion of the safety injection, and before the ECC sumps become operational. However, the uncertainties about the extent of water coverage on the structure, the amount of floating debris that may accumulate, and the potential for early clogging do not favor the use of a horizontal top interceptor. Therefore, in the computation of available interceptor surface area, no credit may be taken for any horizontal interceptor surface unless plant evaluations that adequately account for inherent water source uncertainties demonstrate that the horizontal surface will be submerged at the time of recirculation. For certain sump designs, it is preferable that the top of the interceptor structure is a solid cover plate that will provide additional protection from LOCA-generated loads and is designed to provide for the venting of any trapped air. It is possible that ECC sumps in some plants may not be submerged completely under water at the time of recirculation, either because of unique sump designs or uncertainties in water level estimates. Such partially submerged sumps may be subject to failure criteria other than NPSH margin as discussed in NUREG/CR-6762. In the case of partially submerged sumps, credit should only be given to the portion of the sump screen that is expected to be submerged at the beginning of recirculation.

All debris that is transportable to the trash rack, the debris screen, and the outlets need to be analyzed for head loss effects. Debris that is small enough to pass through the trash rack and the debris screen needs to be analyzed for head loss effects together with the fibrous debris bed that may filter small particulates. Blockage of trash rack, sump screen, and sump outlet is a function of the types, combinations, sizes, shapes, and quantities of insulation debris that can be transported to these components. A vertical or nearly vertical inner debris screen located above the containment floor level would minimize the deposition or settling of debris on screen surfaces and thus help to ensure the greatest possible free flow through the fine inner debris screen. Similarly, locating the sump screens and trash racks above the containment floor level, preferably on a pedestal, minimizes the potential for debris buildup. NUREG/CR-6773 provides test results for transport of various types, sizes, and shapes of debris.

The size of openings in the screens is dependent on the physical restrictions that may exist in the systems that are supplied with coolant from the ECC sump. The size of the mesh of the fine debris screen is determined by considering a number of factors, including the size of the openings in the containment spray nozzles, coolant channel openings in the core fuel assemblies, the presence of fuel assembly inlet debris screens, the minimum dimension within the flow-path (e.g., high pressure safety injection (HPSI) throttle valves), and such pump design characteristics as seals, bearings, and impeller running clearances.

As noted above, degraded pumping can be caused by a number of factors, including plant design and layout. In particular, debris blockage effects on debris interceptor and sump outlet configurations and post-LOCA hydraulic conditions (e.g., air ingestion) must be considered in a combined manner. Small amounts of air ingestion, i.e., 2% or less, will not lead to severe pumping degradation if the "required" NPSH from the pump manufacturer’s curves is increased based on the calculated air ingestion. Thus it is important to use the combined results of all post-LOCA effects to estimate NPSH margin as calculated for the pump inlet. Appendix A to this guide provides information for estimating NPSH margins in PWR sump designs where estimated levels of air ingestion are low (2% or less). Revision 1 of NUREG-0837 and NUREG/CR-2792 provide additional technical findings relevant to NPSH effects on pumps performing the functions of residual heat removal, emergency core cooling, and containment atmosphere cleanup. When air ingestion is 2% or less, compensation for its effects may be achieved without redesign if the "available" NPSH is greater than the "required" NPSH plus a margin based on the percentage of air ingestion. If air ingestion is not small, redesign of one or more of the recirculation loop components may be required to achieve satisfactory design.

To ensure the operability and structural integrity of the trash racks and screens, access openings are necessary to permit inspection of the ECC sump structures and outlets. Inservice inspection of racks, screens, vortex suppressors, and sump outlets, including visual examination for evidence of structural degradation or corrosion, should be performed on a regular basis at every refueling period downtime. Inspection of the ECC sump components late in the refueling period will ensure the absence of construction trash in the ECC sump area.

BOILING WATER REACTORS

In BWRs, the suppression pool, in conjunction with the primary containment, downcomers, and vents, serves as the water source for effecting long-term recirculation cooling. This source, the related pump suction inlets, and the piping between them are important safety components. Features and relationships of the suppression pool pertinent to this guide are shown in Figure 2. Concerns with the performance of the suppression pool hydraulics and ECC pump suction strainers include consideration of air ingestion effects, blockage of suction strainers (by debris), and the combined effects of these items on the operability of the ECC pumps (e.g., the impact on NPSH available at the pump inlets). Revision 1 of NUREG-0897 and NUREG/CR-2772 provide data on the performance and air ingestion characteristics of BWR suction strainer configurations.

In order for a centrifugal pump to perform its safety function there must be adequate margin between the available and the required net positive suction head (NPSH). Failure to provide and maintain adequate NPSH of the emergency core cooling system pumps could result in cavitation and their subsequent failure to deliver the amount of water assumed in design basis LOCA calculations. For those BWRs that credit containment spray systems in the safety analyses, failure to provide and maintain adequate NPSH of the containment heat removal pumps could result in overpressurization of the containment and an increase in the offsite and control room radiological dose.

Since the safety of a nuclear power plant depends on the expected performance of the centrifugal pumps in the emergency core cooling system and the containment heat removal system, it is important to maintain adequate margin between the available and required NPSH under all potential conditions.

The available NPSH is a function of the static head of water above the pump suction, the pressure of the atmosphere above the water level, and the temperature of the pumped fluid at the suction of the pump.

Predicted performance of the emergency core cooling and the containment heat removal pumps should be independent of the calculated increases in containment pressure caused by postulated LOCAs in order to ensure reliable operation under a variety of possible accident conditions. For example, if proper operation of the emergency core cooling system or the containment heat removal system depends on containment pressure above a specified minimum amount, then operation of these systems at a containment pressure less than this amount (resulting, for example, from impaired containment integrity or operation of the containment heat removal systems at too high a rate) could significantly affect the ability of this system to accomplish its safety functions. However, for some operating reactors, credit for containment accident pressure may be necessary. This should be minimized to the extent possible.

The American National Standard for Centrifugal Pumps for Nomenclature, Definitions, Application and Operation, ANSI/HI 1.1-1.5- 1994 specifies a method of accounting for the decrease in required NPSH with an increase in temperature of the pumped fluid. This method is subject to restrictions specified in the standard dealing with experience with the specific pump, the amount of air dissolved in the fluid and the transient nature of the pressure and temperature of the pumped fluid. The staff has considered it prudent to not take credit for the reduction in required NPSH due to the temperature of the pumped fluid because of the uncertainty in these factors.

Although it is possible to perform static NPSH calculations, transient calculations provide more information and ensure that the most conservative conditions have been used.

It is desirable to consider the use of debris interceptors (i.e., suction strainers) in BWR designs to protect the pump inlets and NPSH margins. The debris interceptor can be a passive suction strainer or an active suction strainer or active strainer system. A passive suction strainer is a device that prevents debris, which may block restrictions in the systems served by the ECC pumps or damage components, from entering the ECC pump suction line by accumulating debris on a porous surface. An example of a passive suction strainer is a truncated-cone-shaped, perforated plate strainer. An active suction strainer or an active strainer system is a device or system that will take some action to prevent debris, which may block restrictions in the systems served by the ECC pumps or damage components, from entering the ECC pump suction lines, remove debris from the flow stream upstream of the ECC pumps, or mitigate any detrimental effects of debris accumulation. Examples of active mitigation systems are listed in Appendix B.

Suppression pool debris transport analysis should include the effects of LOCA progression because LOCAs of different sizes will affect the duration of LOCA-related hydrodynamic phenomena (e.g., condensation oscillation, chugging). The LOCA-related hydrodynamic phenomena and long-term recirculation hydrodynamic conditions will affect the transport of debris in the suppression pool.

Debris that is transported to the suppression pool during a LOCA, or that is present in the suppression pool prior to a LOCA (NRC Information Notices 94-57, 95-06, and 95-47) could block or damage the suction strainers and needs to be analyzed for head loss effects. This head loss analysis should include filtering of particulate debris by the accumulated debris bed. The head loss characteristics of a debris bed will be a function of the types and quantities of the debris, suction strainer approach velocities, and LOCA-related hydrodynamic phenomena in the suppression pool.

C. REGULATORY POSITION

1. PRESSURIZED WATER REACTORS

1.1 Features Needed To Minimize the Potential for Loss of NPSH

The ECC sumps, which are the source of water for such functions as emergency core cooling and containment heat removal following a LOCA, should contain an appropriate combination of the following features and actions to ensure the availability of the ECC sumps for long-term cooling. The adequacy of the combinations of the features and actions taken should be evaluated using the criteria and assumptions in Regulatory Position 1.3.

1.1.1 ECC Sumps, Debris Interceptors, and Debris Screens

1.1.1.1 A minimum of two sumps should be provided, each with sufficient capacity to service one of the redundant trains of the ECCS and CSS.

1.1.1.2 To the extent practical, the redundant sumps should be physically separated by structural barriers from each other and from high-energy piping systems to preclude damage to the components of both sumps (e.g., trash racks, sump screens, and sump outlets) by whipping pipes or high-velocity jets of water or steam.

1.1.1.3 The sumps should be located on the lowest floor elevation in the containment exclusive of the reactor vessel cavity. The sump outlets should be protected by at least two vertical or nearly vertical debris interceptors: (1) a fine inner debris screen and (2) a coarse outer trash rack to prevent large debris from reaching the debris screen. A curb should be provided upstream of the trash racks to prevent high-density debris from being swept along the floor into the sump.

1.1.1.4 The floor in the vicinity of the ECC sump should slope gradually downward away from the sump to reduce the fraction of debris that might reach the sump screen.

1.1.1.5 All drains from the upper regions of the containment should terminate in such a manner that direct streams of water, which may contain entrained debris, will not directly impinge on the debris interceptors or discharge in the close proximity of the sump. The drains and other narrow pathways that connect compartments with potential break locations to the ECC sump should be designed to ensure that they would not become blocked by the debris; this is to ensure that water required for an adequate NPSH margin could not be held up or diverted from the sump.

1.1.1.6 The strength of the trash racks should be adequate to protect the debris screens from missiles and other large debris. Trash racks and sump screens should be capable of withstanding the loads imposed by expanding jets, missiles, the accumulation of debris, and pressure differentials caused by post-LOCA blockage under design-basis flow conditions.

1.1.1.7 The top of the debris interceptor structures should be a solid cover plate that is designed to be fully submerged after a LOCA and completion of the ECC injection. It should be designed to ensure the venting of air trapped underneath the cover.

1.1.1.8 The debris interceptors should be designed to withstand the vibratory motion of seismic events without loss of structural integrity.

1.1.1.9 Materials for debris interceptors and sump screens should be selected to avoid degradation during periods of both inactivity and operation and should have a low sensitivity to such adverse effects as stress-assisted corrosion that may be induced by the chemically reactive spray during LOCA conditions.

1.1.1.10 The debris interceptor structures should include access openings to facilitate inspection of these structures, any vortex suppressors, and the sump outlets.

1.1.1.11 A sump screen design (i.e., size and shape) should be chosen that will avoid the loss of NPSH from debris blockage during the period that the ECCS is required to operate in order to maintain long-term cooling or maximize the time before loss of NPSH caused by debris blockage when used with an active mitigation system (see Regulatory Position 2.1.5).

1.1.1.12 The diameter of the circular opening or the length of the diagonal that connects the opposite corners for rectangular openings in the sump screen should be smaller than the minimum restrictions found in systems served by the ECC sumps. The minimum restriction should take into account the operability of the systems served. For example, spray nozzle clearances, coolant channel openings in the core fuel assemblies, the presence of fuel assembly inlet debris screens, minimum dimension within the HPSI throttle valve flow-path, and such pump design characteristics as seals, bearings, and impeller running clearances will need to be considered in the design to ensure long-term pump operability.

1.1.1.13 The ECCS pumps should be assessed to determine their susceptibility to degradation from debris ingestion and abrasive effects, and actions should be taken to minimize the potential for degradation of long-term recirculation pumping capacity.

1.1.1.14 ECC pump suction inlets should be designed to prevent degradation of pump performance through air ingestion and other adverse hydraulic effects (e.g., circulatory flow patterns, high intake head losses).

1.1.1.15 All drains from the upper regions of the containment building should terminate in such a manner that direct streams of water, which may contain entrained debris, will not discharge downstream of the sump screen.

1.1.2 Minimizing Debris

The debris (see Regulatory Position 1.3.2) that could accumulate on the sump screen should be minimized.

1.1.2.1 Cleanliness programs should be initiated to clean the containment on a regular basis, and plant procedures should be established for control and removal of foreign materials from the containment.

1.1.2.2 Procedures should be established for using alternative water sources to be activated when unacceptable head loss renders the sump inoperable. The valves needed to align the ECCS with an alternative water source should be periodically inspected and maintained.

1.1.3 Instrumentation

If relying on operator actions to mitigate the consequences of the accumulation of debris on the ECC sump screens, safety-related instrumentation that provides operators with an indication and audible warning of impending loss of NPSH for ECCS pumps should be available in the control room.

1.1.4 Active Sump Screen System

An active device or system (see examples in Appendix B) may be provided to prevent the accumulation of debris on a sump screen or to mitigate the consequences of accumulation of debris on a sump screen. An active system should be able to prevent debris that may block restrictions found in the systems served by the ECC pumps from entering the system. The operation of the active component or system should not adversely affect the operation of other ECC components or systems. Performance characteristics of an active sump screen system should be supported by appropriate test data that addresses head loss performance.

1.2 Evaluation of Alternative Water Sources

In order to demonstrate that a combination of the features and actions listed above are adequate to ensure long-term cooling and that the five criteria of 10 CFR 50.46(b) will be met following a LOCA, an evaluation using the criteria and assumptions in Regulatory Position 1.3 should be conducted. If a licensee is relying on operator actions to prevent the accumulation of debris on ECC sump screens or to mitigate the consequences of the accumulation of debris on the ECC sump screens, an evaluation should be performed to ensure that the operator has adequate indications, training, time, and system capabilities to perform the actions required. Procedures should be established for using alternative water sources to be activated when unacceptable head loss renders the sump inoperable. The valves needed to align the ECCS with an alternative water source should be periodically inspected and maintained.

1.3 Evaluation of Long-Term Recirculation Capability

The following techniques, assumptions, and criteria should be used in a deterministic, plant-specific evaluation to ensure that any implementation of a combination of the features and actions listed in Regulatory Position 1.1 are adequate to ensure a reliable water source for long-term recirculation following a LOCA. The assumptions and criteria listed below can also be used to develop test conditions for sump screens.

Evaluation and confirmation of (1) sump hydraulic performance (e.g., geometric effects and air ingestion), (2) debris effects (e.g., debris transport, interceptor blockage, and head loss), and (3) the combined impact on NPSH available at the pump inlet should be performed to ensure that long-term recirculation cooling can be accomplished following a LOCA. Such an evaluation should arrive at a determination of NPSH margin calculated at the pump inlet. An assessment should also be made of the susceptibility to debris blockage of the containment drainage flow paths to the recirculation sump; this is to protect against reduction in available NPSH if substantial amounts of water are held up or diverted away from the sump. An assessment should be made of the susceptibility of the flow restrictions in the ECCS and CSS recirculation flow paths downstream of the sump screens, and of the recirculation pump seal and bearing assembly design to failure from particulate ingestion and abrasive effects to protect against degradation of long-term recirculation pumping capacity.

1.3.1 Net Positive Suction Head of ECCS and Containment Heat Removal Pumps

1.3.1.1 Emergency core cooling and containment heat removal systems should be designed so that sufficient available NPSH is provided to the system pumps assuming no increase in containment pressure from that present prior to the postulated LOCAs. (See Regulatory Position 1.3.1.2).

1.3.1.2 For certain operating reactors for which the design cannot be practicably altered, compliance with Regulatory Position 1.3.1.1 may not be possible. In these cases, no more containment pressure should be included in the determination of available NPSH than is required to preclude pump cavitation. Calculation of available containment pressure should underestimate the expected containment pressure when determining available NPSH for this situation. Calculation of sump temperature should overestimate the expected temperature when determining available NPSH.

1.3.1.3 For certain operating reactors for which the design cannot be practically altered, if credit is taken for operation of an ECCS or containment heat removal pump in cavitation, prototypical pump tests must be performed along with post-test examination of the pump to demonstrate that pump performance will not be degraded such that the pump continues to meet all the performance criteria assumed in the safety analyses. The time period in the safety analyses during which the pump may be assumed to operate while cavitating should not be longer than the time demonstrated by the performance tests.

1.3.1.4 The decay and residual heat produced following accident initiation should be included in the determination of the water temperature. The uncertainty in the determination of the decay heat should be included in this calculation. The residual heat should be calculated with margin.

1.3.1.5 The hot channel correction factor specified in the American National Standard for Centrifugal Pumps for Nomenclature, Definitions, Application and Operation, ANSI/HI 1.1-1.5-1994, should not be used in determining the margin between the available and required NPSH for emergency core cooling system and containment heat removal system pumps.

1.3.1.6 The calculation of available NPSH should minimize the static head of water above the pump suction (i.e., the level of water on the containment floor). The amount of water in enclosed areas which cannot be readily returned to the sump should not be included in the calculated height of water on the containment floor.

1.3.1.7 The calculation of pipe and fitting resistance and the calculation of the nominal screen resistance without blockage by debris should be done in a recognized, defensible method or determined from applicable experimental data.

1.3.1.8 Sump screen flow resistance due to blockage by LOCA-generated debris or foreign material in the containment which is transported to the suction intake screens should be determined using the Regulatory Position 1.3.4.

1.3.1.9 Calculation of available NPSH should be performed as a function of time until it is clear that the available NPSH will not decrease further.

1.3.2 Debris Sources and Generation

1.3.2.1 Consistent with the requirements of 10 CFR 50.46, debris generation should be calculated for a number of postulated LOCAs of different sizes, locations, and other properties sufficient to provide assurance that the most severe postulated LOCAs are calculated. Some PWRs may require recirculation from the sump for licensing basis events other than LOCAs. Therefore, plants should review the licensing basis and include potential break locations in the main steam and main feedwater lines as well in determining the most limiting conditions for sump operation.

1.3.2.2 An acceptable method for estimating the amount of debris generated by a postulated LOCA is to use the zone of influence. Examples of this approach are provided in NUREG/CR-6224 and Boiling Water Reactor Owners' Group (BWROG)Utility Resolution Guidance (NEDO-32686 and the staff's Safety Evaluation on the BWROG's response to NRC Bulletin 96-03). A representation of zone of influence for commonly used insulation materials is shown in Figure 3.

- The size and shape of the zone of influence should be supported by analysis or experiments for the break and potential debris.

- The volume of debris contained within the zone of influence should be used to estimate the amount of debris generated by a postulated break.

- The size distribution of debris created in the zone of influence should be determined by analysis or experiments.

- The shock wave generated during postulated pipe break and the subsequent jet should be the basis for estimating the amount of debris generated and the size or size distribution of the debris generated within the zone of influence.

1.3.2.3 A sufficient number of breaks in each high-pressure system that relies on recirculation should be considered to reasonably bound variations in debris generation by the size, quantity, and type of debris. As a minimum, the following postulated break locations should be considered.

- Breaks in the hot leg, cold leg, intermediate leg, and, depending on the plant licensing basis, main steam and main feedwater lines with the largest amount of potential debris within the postulated zone of influence,
- Large breaks with two or more different types of debris, including the breaks with the most variety of debris, within the expected zone of influence,
- Breaks in areas with the most direct path to the sump,
- Medium and large breaks with the largest potential particulate debris to insulation ratio by weight, and
- Breaks that generate an amount of fibrous debris that, after its transport to the sump screen, creates a minimum uniform thin bed (1/8-inch layer of fiber) to filter particulate debris.

1.3.2.4 All insulation (e.g., fibrous, calcium silicate, reflective metallic), painted surfaces, fire barrier materials, and fibrous, cloth, plastic, or particulate materials within the zone of influence should be considered debris sources. Analytical models or experiments should be used to predict the size of the postulated debris. For breaks postulated in the vicinity of the pressure vessel, the potential for debris generation from the packing materials commonly used in the penetrations and the insulation installed on the pressure vessel should be considered. Particulate debris generated from pipe rupture jets stripping off paint or coatings and eroding concrete at the point of impact should also be considered.

1.3.2.5 The cleanliness of the containment during plant operation should be considered when estimating the amount and type of debris available to block the ECC sump screens. The potential for such material (e.g., thermal insulation other than piping insulation, ropes, fire hoses, wire ties, tape, ventilation system filters, permanent tags or stickers on plant equipment, rust flakes from unpainted steel surfaces, corrosion products, dust/dirt, latent individual fibers) to impact head loss across the ECC sump screens should also be considered.

1.3.2.6 In addition to debris generated by jet forces from the pipe rupture, debris created by the resulting containment environment (thermal and chemical) should be considered in the analyses. Examples of this type of debris would be disbondment of coatings in the form of chips and particulates or formation of chemical debris (precipitates) caused by chemical reactions in the pool.

1.3.2.7 Debris generation that is due to continued degradation of insulation and other debris when subjected to turbulence caused by cascading water flows from upper regions of the containments or near the break overflow region should be considered in the analyses.

1.3.3 Debris Transport

1.3.3.1 The calculation of debris quantities transported from debris sources to the sump screen should consider all modes of debris transport including airborne debris transport, containment spray washdown debris transport, and containment sump pool debris transport.

1.3.3.2 The debris transport analyses should consider each type of insulation (e.g., fibrous, calcium silicate, reflective metallic) and debris size (e.g., particulates, fibrous fine, large pieces of fibrous insulation). The analysis should also consider potential for further decomposition of the debris as it is transported to the sump screen.

1.3.3.3 Bulk flow velocity from recirculation operations, LOCA-related hydrodynamic phenomena, and other hydrodynamic forces (e.g., local turbulence effects or pool mixing) should be considered for both debris transport and ECC sump screen velocity computations.

1.3.3.4 An acceptable analytical approach to predict debris transport within the sump pool is to use computational fluid dynamics (CFD) simulations in combination with the experimental debris transport data. Examples of this approach are provided in NUREG/CR-6772 and NUREG/CR-6773.

1.3.3.5 Curbs can be credited for removing heavier debris that has been shown analytically or experimentally to travel by sliding along the containment floor and that cannot be lifted off the floor within the calculated water velocity range.

1.3.3.6 All debris (e.g., fine fibrous, particulates) that is assumed or demonstrated to suspend indefinitely or to sink very slowly should be considered to reach the sump screen.

1.3.3.7 The time to switch over to sump recirculation and the operation of containment spray should be considered in the evaluation of debris transport to the sump screen.

1.3.3.8 In lieu of performing debris transport analyses, it should be assumed that all debris will be transported to the sump screen.

1.3.4 Debris Accumulation and Head Loss

1.3.4.1 ECC sump screen blockage should be evaluated based on the amount of debris estimated using the assumptions and criteria described in Regulatory Position 1.3.2 and on the debris transported to the ECC sump per Regulatory Position 1.3.3. This volume of debris should be used to estimate the rate of accumulation of debris on the ECC sump screen.

1.3.4.2 Consideration of ECC sump screen submergence (full or partial) at the time of switchover to ECCS should be given in calculating the available (wetted) screen area. Unless otherwise shown analytically or experimentally, debris should be assumed to be uniformly distributed over the available sump screen surface. Debris mass should be calculated based on the amount of debris estimated to reach or to be in the ECC sump. (See Revision 1 of NUREG-0897, NUREG/CR-3616, and NUREG/CR-6224.)

1.3.4.3 For fully submerged sump screens, the NPSH available to the ECC pumps should be determined using the conditions specified in the plant's licensing basis.

1.3.4.4 For partially submerged sumps, NPSH margin may not be the only failure criterion as discussed in Appendix A. For partially submerged sumps, credit should only be given to the portion of the sump screen that is expected to be submerged at the beginning of recirculation.

1.3.4.5 Estimates of head loss caused by debris blockage should be developed from empirical data based on the sump screen design (e.g., surface area and geometry), postulated combinations of debris (i.e., amount, size distribution, type), and approach velocity. Because debris beds that form on sump screens can trap debris that would pass through an unobstructed sump screen opening, any head loss correlation should conservatively account for filtration of particulates by the debris bed, including particulates that would pass through an unobstructed sump screen.

1.3.4.6 Consistent with the requirements of 10 CFR 50.46, head loss should be calculated for the debris beds formed of different combinations of fibers and particulate mixtures (e.g., minimum uniform thin-bed of fibers supporting layer of particulate debris) based on assumptions and criteria described in Regulatory Positions 1.3.2 and 1.3.3.

2. BOILING WATER REACTORS

2.1 Features Needed To Minimize the Potential for Loss of NPSH

The suppression pool, which is the source of water for such functions as emergency core cooling and containment heat removal following a LOCA, in conjunction with the vents and downcomers between the drywell and the wetwell, should contain an appropriate combination of the following features and actions to ensure the availability of the suppression pool for long-term cooling. The adequacy of the combinations of the features and actions taken should be evaluated using the criteria and assumptions in Regulatory Position 2.2.

2.1.1 Net Positive Suction Head of ECCS and Containment Heat Removal Pumps

2.1.1.1 Emergency core cooling and containment heat removal systems should be designed so that sufficient available NPSH is provided to the system pumps assuming no increase in containment pressure from that present prior to the postulated LOCAs. (See Regulatory Position 2.1.1.2).

2.1.1.2 For certain operating reactors for which the design cannot be practicably altered, compliance with Regulatory Position 2.1.1.1 may not be possible. In these cases, no more containment pressure should be included in the determination of available NPSH than is necessary. Calculation of containment pressure should underestimate the expected containment pressure when determining available NPSH for this situation. Calculation of suppression pool water temperature should overestimate the expected temperature when determining available NPSH.

2.1.1.3 For certain operating reactors for which the design cannot be practically altered, if credit is taken for operation of an ECCS or containment heat removal pump in cavitation, prototypical pump tests and post-test examination of the pump must demonstrate that pump performance will not be degraded such that the pump continues to meet all the performance criteria assumed in the safety analyses. The time period in the safety analyses during which the pump may be assumed to operate while cavitating should not be longer than the time demonstrated by the performance tests.

2.1.1.4 The decay and residual heat produced following accident initiation should be included in the determination of the water temperature. The uncertainty in the determination of the decay heat should be included in this calculation. The residual heat should be calculated with margin.

2.1.1.5 The hot channel correction factor specified in the American National Standard for Centrifugal Pumps for Nomenclature, Definitions, Application and Operation, ANSI/HI 1.1-1.5-1994 should not be used in determining the margin between the available and required NPSH for emergency core cooling system and containment heat removal system pumps during recirculation following a LOCA.

2.1.1.6 The level of water in suppression pools should be the minimum value given in the technical specifications reduced by the drawdown due to suppression pool water in the drywell and the sprays.

2.1.1.7 The calculation of pipe and fitting resistance and the calculation of the nominal screen resistance without blockage by debris should be done in a recognized, defensible method or determined from applicable experimental data.

2.1.1.8 Suction strainer screen flow resistance due to blockage by LOCA-generated debris or foreign material in the containment which is transported to the suction intake screens should be determined using the methods given in this Regulatory Position 2.3.3.

2.1.1.9 Calculation of available NPSH should be performed as a function of time until it is clear that the available NPSH will not decrease further.

2.1.2 Passive Strainer

The inlet of pumps performing the above functions should be protected by a suction strainer placed upstream of the pumps; this is to prevent the ingestion of debris that may block restrictions in the systems served by the ECC pumps or damage components. The following items should be considered in the design and implementation of a passive strainer.

2.1.2.1 A suction strainer design (i.e., size and shape) should be chosen that will avoid the loss of NPSH from debris blockage during the period that the ECCS is required to operate in order to maintain long-term cooling or maximize the time before loss of NPSH caused by debris blockage when used with an active mitigation system (see Regulatory Position 2.1.5).

2.1.2.2 The size of openings in the suppression pool suction strainers should be based on the minimum restrictions found in systems served by the suppression pool. The minimum restriction should take into account the operability of the systems served. For example, spray nozzle clearances, coolant channel openings in the core fuel assemblies, the presence of fuel assembly inlet debris screens, and such pump design characteristics as seals, bearings, and impeller running clearances should be considered in the design to ensure long-term pump operability. The ECCS pumps should be assessed to determine their susceptibility to degradation from debris ingestion and abrasive effects; actions should be taken to minimize the potential for degradation of long-term recirculation pumping capacity.

2.1.2.3 ECC pump suction inlets should be designed to prevent degradation of pump performance through air ingestion and other adverse hydraulic effects (e.g., circulatory flow patterns, high intake head losses).

2.1.2.4 All drains from the upper regions of the containment should terminate in such a manner that direct streams of water, which may contain entrained debris, will not impinge on the suppression pool suction strainers.

2.1.2.5 The strength of the suction strainers should be adequate to protect the debris screen from missiles and other large debris. The strainers and the associated structural support should be adequate to withstand loads imposed by missiles, debris accumulation, and hydrodynamic loads induced by suppression pool dynamics. To the extent practical, the strainers should be located outside the zone of influence of the vents, downcomers, or spargers to minimize hydrodynamic loads. The strainer design, vis-a-vis the hydrodynamic loads, should be validated analytically or experimentally.

2.1.2.6 The suction strainers should be designed to withstand the vibratory motion of seismic events without loss of structural integrity.

2.1.2.7 Material for suction strainers should be selected to avoid degradation during periods of inactivity and normal operations.

2.1.3 Minimizing Debris

The amount of potential debris (see Regulatory Position 2.3.1) that could clog the ECC suction strainers should be minimized. This may be accomplished by:

2.1.3.1 Containment cleanliness programs should be instituted to clean the suppression pool on a regular basis and plant procedures should be established for control and removal of foreign materials from containment.

2.1.3.2 Debris interceptors in the drywell in the vicinity of the downcomers or vents may serve effectively in reducing debris transport to the suppression pool. In addition to meeting Regulatory Position 2.1.2, debris interceptors between the drywell and wetwell should not reduce the suppression capability of the containment.

2.1.4 Instrumentation

If relying on operator actions to mitigate the consequences of the accumulation of debris on the suction strainers, safety-related instrumentation that provides operators with an indication and audible warning of impending loss of NPSH for ECCS pumps should be available in the control room.

2.1.5 Active Strainers

An active component or system (see Appendix B) may be provided to prevent the accumulation of debris on a suction strainer or to mitigate the consequences of accumulation of debris on a suction strainer. An active system should be able to prevent debris that may block restrictions found in the systems served by the ECC pumps from entering the system. The operation of the active component or system should not adversely affect the operation of other ECC components or systems. The use of active strainers should be validated by adequate testing.

2.1.6 Inservice Inspection

Inservice inspection requirements should be established that include (1) inspection during every refueling outage to ensure the cleanliness of the suppression pool, (2) a visual examination for evidence of structural degradation or corrosion of the suction strainers and strainer system, and (3) an inspection of the wetwell and the drywell, including the vents, downcomers, and deflectors, for the identification and removal of debris or trash that could contribute to the blockage of suppression pool suction strainers.

2.2 Evaluation of Alternative Water Sources

In order to demonstrate that a combination of the features and actions listed above are adequate to ensure long-term cooling and that the five criteria of 10 CFR 50.46(b) will be met following a LOCA, an evaluation using the criteria and assumptions in Regulatory Position 2.3 should be conducted. If a licensee is relying on operator actions to prevent the accumulation of debris on suction strainers or to mitigate the consequences of the accumulation of debris on the suction strainers, an evaluation should be performed to ensure that the operator has adequate indications, training, time, and system capabilities to perform the actions required. Procedures should be established to use alternative water sources. The valves needed to align the ECCS with an alternative water source should be periodically inspected and maintained.

2.3 Evaluation of Long-Term Recirculation Capability

During any evaluation of the susceptibility of a BWR to debris blockage, the considerations and events shown in Figures 4 and 5 should be addressed. The following techniques, assumptions, and criteria should be used in a deterministic evaluation to ensure that any implementation of a combination of the features and actions listed in Regulatory Position 2.1 are adequate to ensure a reliable water source for long-term recirculation after a LOCA. An assessment should be made of the susceptibility to debris blockage of the containment drainage flowpaths to the suppression pool, and flow restrictions in the ECCS and containment spray recirculation flowpaths downstream of the suction strainer to protect against degradation of long-term recirculation pumping capacity. Unless otherwise noted, the techniques, assumptions, and criteria listed below are applicable to an evaluation of passive and active strainers. The assumptions and criteria listed below can also be used to develop test conditions for suction strainers or strainer systems.

2.3.1 Debris Sources and Generation

2.3.1.1 Consistent with the requirements of 10 CFR 50.46, debris generation should be calculated for a number of postulated LOCAs of different sizes, locations, and other properties sufficient to provide assurance that the most severe postulated LOCAs are calculated.

2.3.1.2 An acceptable method for determining the shape of the zone of influence of a break is described in NUREG/CR-6224 and Boiling Water Reactor Owners' Group Utility Resolution Guidance. The volume contained within the zone of influence should be used to estimate the amount of debris generated by a postulated break. The distance of the zone of influence from the break should be supported by analysis or experiments for the break and potential debris. The shock wave generated during postulated pipe break and the subsequent jet should be the basis for estimating the amount of debris generated and the size or size distribution of the debris generated within the zone of influence.

2.3.1.3 All sources of fibrous materials in the containment such as fire protection materials, thermal insulation, or filters that are present during operation should be identified.

2.3.1.4 All insulation, painted surfaces, and fibrous, cloth, plastic, or particulate materials within the zone of influence should be considered debris sources. Analytical models or experiments should be used to predict the size of the postulated debris.

2.3.1.5 As a minimum, the following postulated break locations should be considered.

- Breaks on the main steam, feedwater, and recirculation lines with the largest amount of potential debris within the expected zone of influence,
- Large breaks with two or more different types of debris within the expected zone of influence,
- Breaks in areas with the most direct path between the drywell and wetwell,
- Medium and large breaks with the largest potential particulate debris to insulation ratio by weight, and
- Breaks that generate an amount of fibrous debris that, after its transport to the suction strainer, creates a minimum uniform thin bed (1/8-inch layer of fiber) to filter particulate debris.

2.3.1.6 The cleanliness of the suppression pool and containment during plant operation should be considered when estimating the amount and type of debris available to block the suction strainers. The potential for such material (e.g., thermal insulation other than piping insulation, ropes, fire hoses, wire ties, tape, ventilation system filters, permanent tags or stickers on plant equipment, rust flakes from unpainted steel surfaces, corrosion products, dust and dirt, latent individual fibers) to impact head loss across the suction strainer should also be considered.

2.3.1.7 The amount of particulates estimated to be in the pool prior to a LOCA should be considered to be the maximum amount of corrosion products (i.e., sludge) expected to be generated since the last time the pool was cleaned. The size distribution and amount of particulates should be based on plant samples.

2.3.2 Debris Transport

2.3.2.1 It should be assumed that all debris fragments smaller than the clearances in the gratings will be transported to the suppression pool during blowdown. Credit may be taken for filtration of larger pieces of debris by floor gratings and other interdicting structures present in a drywell (NEDO-32686 and NUREG/CR-6369). However, it should be assumed that a fraction of large fragments captured by the gratings would be eroded by the combined effects of cascading break overflow and the drywell spray flow. The fraction of the smaller debris generated and thus transported to the suppression pool during the blowdown, as well as the fraction of the larger debris that may be eroded during the washdown phase, should be determined analytically or experimentally.

2.3.2.2 It should be assumed that LOCA-induced phenomena (i.e., pool swell, chugging, condensation oscillations) will suspend all the debris assumed to be in the suppression pool at the onset of the LOCA.

2.3.2.3 The concentration of debris in the suppression pool should be calculated based on the amount of debris estimated to reach the suppression pool from the drywell and the amount of debris and foreign materials estimated to be in the suppression pool prior to a postulated break.

2.3.2.4 Credit should not be taken for debris settling until LOCA-induced turbulence in the suppression pool has ceased. The debris settling rate for the postulated debris should be validated analytically or experimentally.

2.3.2.5 Bulk suppression pool velocity from recirculation operations, LOCA-related hydrodynamic phenomena, and other hydrodynamic forces (e.g., local turbulence effects or pool mixing) should be considered for both debris transport and suction strainer velocity computations.

2.3.3 Strainer Blockage and Head Loss

2.3.3.1 Strainer blockage should be based on the amount of debris estimated using the assumptions and criteria described in Regulatory Position 2.3.1 and on the debris transported to the wetwell per Regulatory Position 2.3.2. This volume of debris, as well as other materials that could be present in the suppression pool prior to a LOCA, should be used to estimate the rate of accumulation of debris on the strainer surface.

2.3.3.2 The flow rate through the strainer should be used to estimate the rate of accumulation of debris on the strainer surface.

2.3.3.3 The suppression pool suction strainer area used in determining the approach velocity should conservatively account for blockage that may result. Unless otherwise shown analytically or experimentally, debris should be assumed to be uniformly distributed over the available suction strainer surface. Debris mass should be calculated based on the amount of debris estimated to reach or to be in the suppression pool. (See Revision 1 of NUREG-0897, NUREG/CR-3616, and NUREG/CR-6224.)

2.3.3.4 The NPSH available to the ECC pumps should be determined using the conditions specified in the plant’s licensing basis.

2.3.3.5 Estimates of head loss caused by debris blockage should be developed from empirical data based on the strainer design (e.g., surface area and geometry), postulated debris (i.e., amount, size distribution, type), and velocity. Any head loss correlation should conservatively account for filtration of particulates by the debris bed.

2.3.3.6 The performance characteristics of a passive or an active strainer should be supported by appropriate test data that addresses, at a minimum, (1) suppression pool hydrodynamic loads and (2) head loss performance.

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC staff’s plans for using this draft regulatory guide. No backfitting is intended or approved in connection with the issuance of this guide.

This draft guide has been released to encourage public participation in its development. Except in those cases in which an applicant or licensee proposes an acceptable alternative method for complying with the specified portions of the NRC's regulations, the methods to be described in the active guide reflecting public comments will be used in the evaluation of applications for construction permits and operating licenses. The active guide will also serve as guidance for the conduct of reviews under 10 CFR 50.59 that deal with plant modifications installed on primary coolant system piping and components when such modifications may affect the availability of water sources for long-term recirculation (e.g., altering potential sources of debris). The active guide will also be used by the NRC staff to evaluate licensees' compliance with 10 CFR 50.46.

REFERENCES

NRC Generic Letter 85-22, "Potential for Loss of Post-LOCA Recirculation Capability Due to Insulation Debris Blockage," USNRC, December 3, 1985.[1]

NRC Generic Letter 97-04, "Assurance of Sufficient Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal Pumps," USNRC, October 7, 1997.[1]

NEDO-32686, Boiling Water Reactor Owners Group Topical Report, "Utility Resolution Guidance for ECCS Suction Strainer Blockage," General Electric, November 1996.[1]

NRC Bulletin No. 93-02, "Debris Plugging of Emergency Core Cooling Suction Strainers," USNRC, May 11, 1993.[1]

NRC Bulletin No. 93-02, Supplement 1, "Debris Plugging of Emergency Core Cooling Suction Strainers," USNRC, February 18, 1994.[1]

NRC Bulletin No. 95-02, "Unexpected Clogging of a Residual Heat Removal Pump Strainer While Operating in Suppression Pool Cooling Mode," USNRC, October 17, 1995.[1]

NRC Bulletin No. 96-03, "Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling Water Reactors," USNRC, May 6, 1996.[1]

NRC Information Notice 94-57, "Debris in Containment and the Residual Heat Removal System," USNRC, August 12, 1994.[1]

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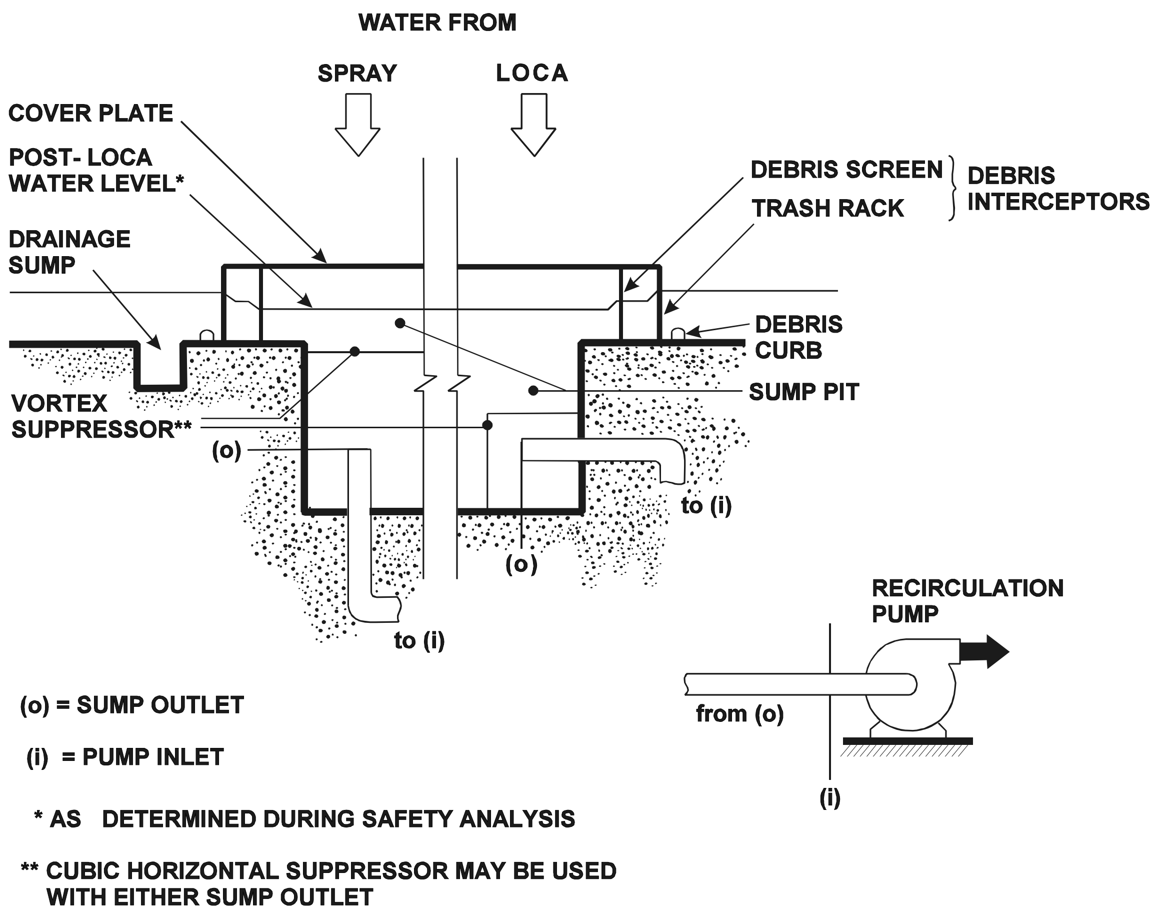
WATER FROM
SPRAY
LOCA
COVER PLATE
POST- LOCA
WATER LEVEL*
DRAINAGE
SUMP
DEBRIS SCREEN
TRASH RACK
DEBRIS
INTERCEPTORS
DEBRIS
CURB
SUMP PIT
VORTEX
SUPPRESSOR**
(o)
to (i)
(o)
to (i)
RECIRCULATION
PUMP
from (o)
(i)
(o) = SUMP OUTLET
(i) = PUMP INLET
* AS DETERMINED DURING SAFETY ANALYSIS
** CUBIC HORIZONTAL SUPPRESSOR MAY BE USED
WITH EITHER SUMP OUTLET

Figure 1.

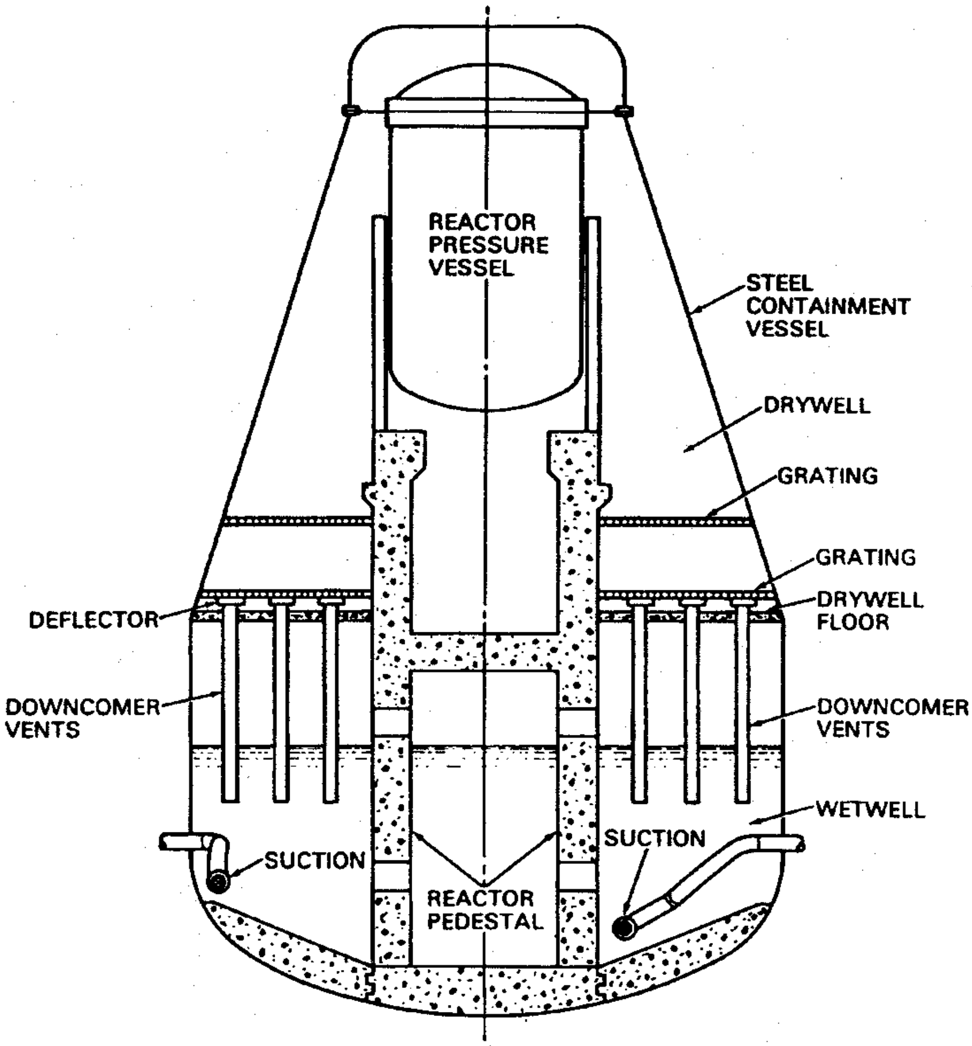
REACTOR
PRESSURE
VESSEL
STEEL
CONTAINMENT
VESSEL
DRYWELL
GRATING
GRATING
DEFLECTOR
DRYWELL
FLOOR
DOWNCOMER
VENTS
DOWNCOMER
VENTS
WETWELL
SUCTION
SUCTION
REACTOR
PEDESTAL

Figure 2.

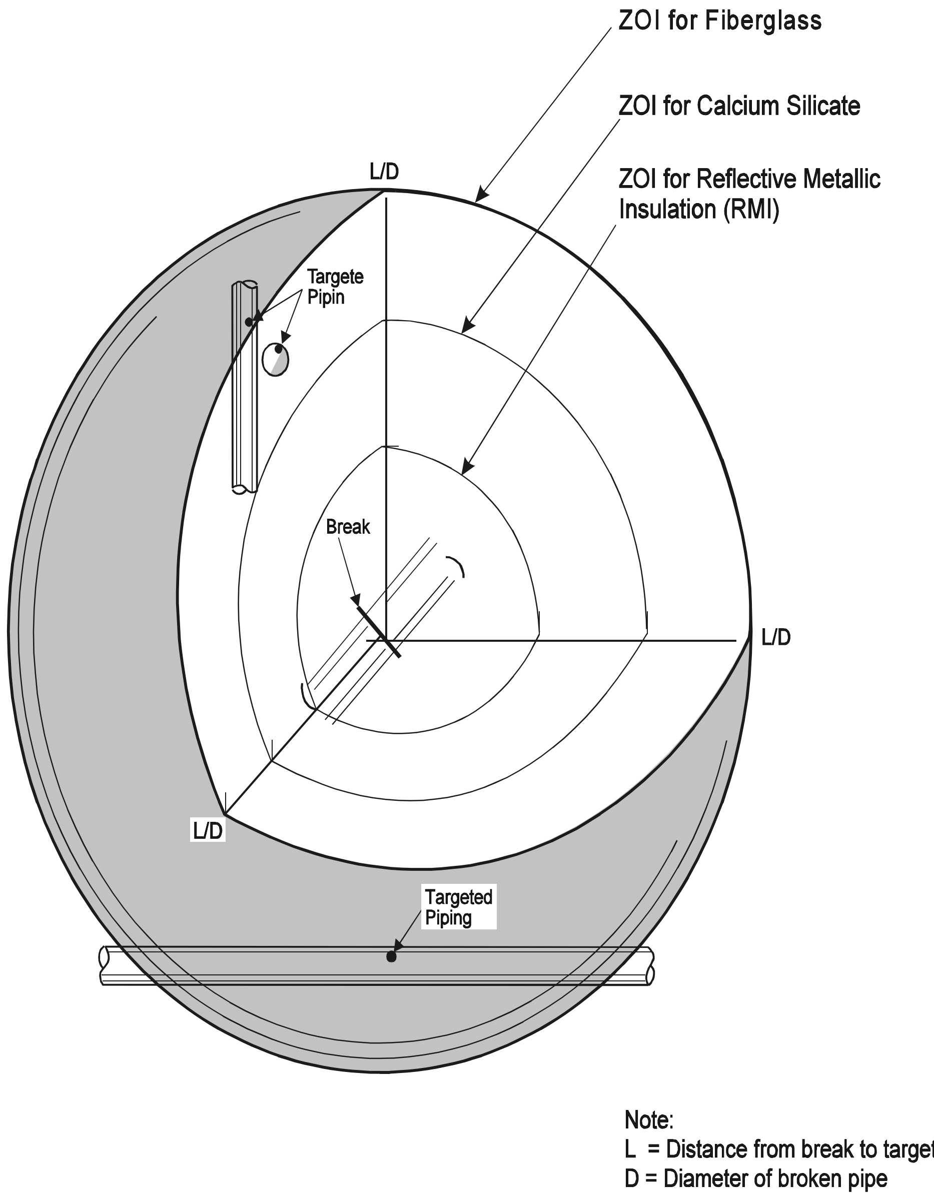

Figure 3. Zone of Influence (ZOI)

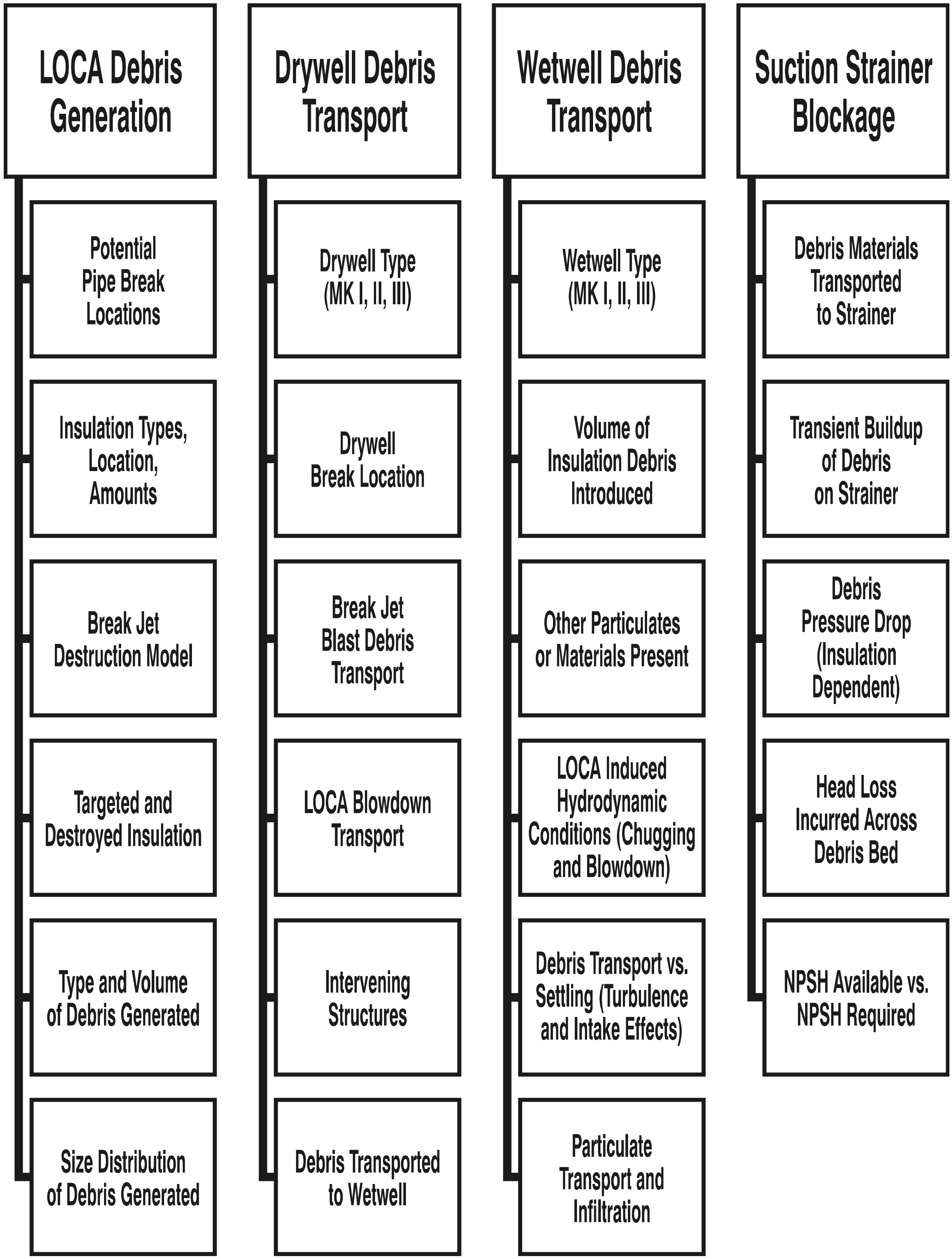

Figure 4. Debris Blockage Considerations

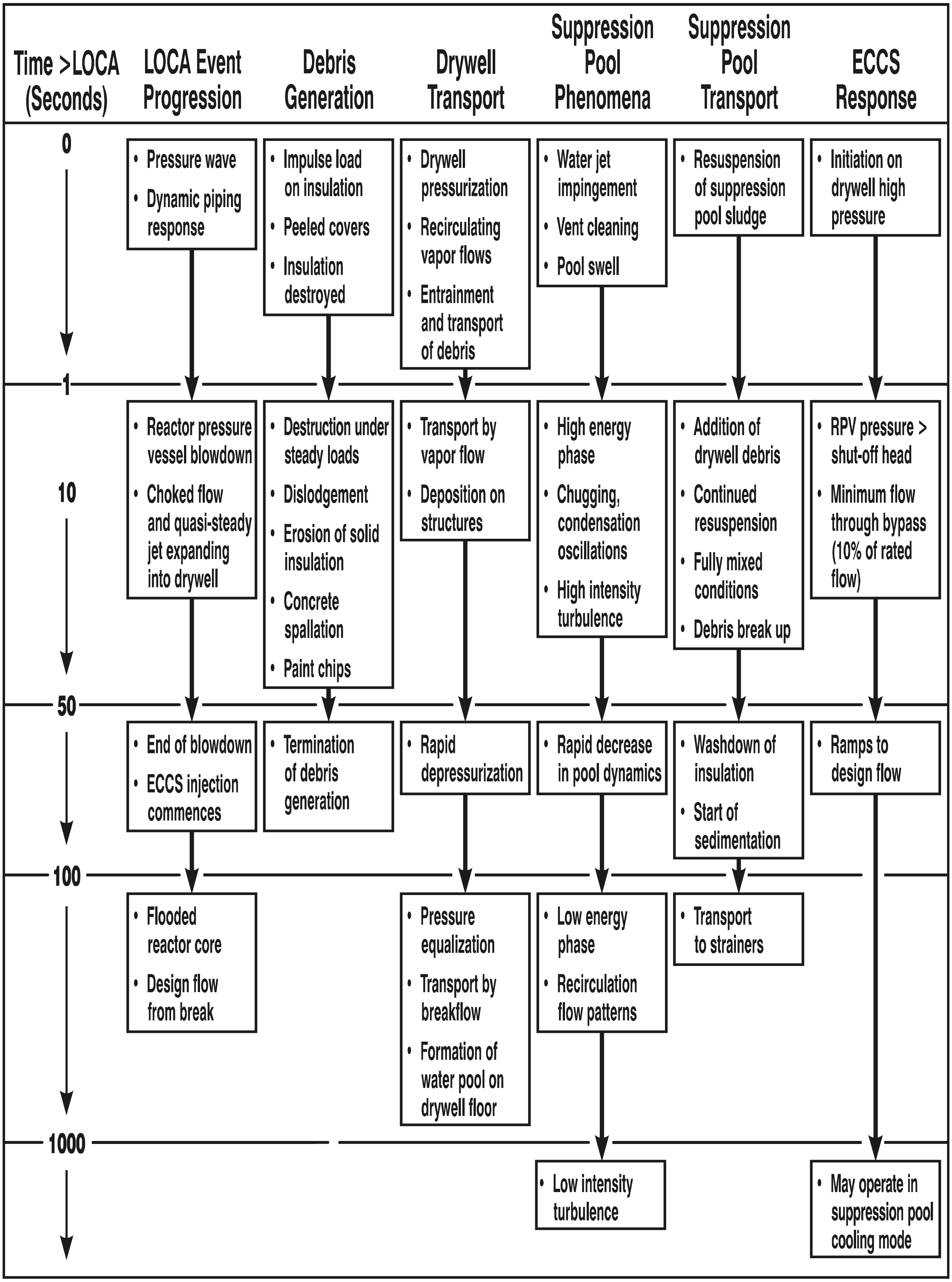

Figure 5. Events That May Effect Debris Blockage

APPENDIX A

GUIDELINES FOR REVIEW OF
WATER SOURCES FOR EMERGENCY CORE COOLING

Water sources for long-term recirculation should be evaluated under possible post-LOCA conditions to determine the adequacy of their design for providing long-term recirculation. Technical evaluations can be subdivided into (1) sump hydraulic performance, (2) LOCA-induced debris effects, and (3) pump performance under adverse conditions. Specific considerations within these categories, and the combination thereof, is shown in Figure A-1. Determination that adequate NPSH margin exists at the pump inlet under all postulated post-LOCA conditions is the final criterion.

SUMP HYDRAULIC PERFORMANCE

Sump hydraulic performance (with respect to air ingestion potential) can be evaluated on the basis of submergence level (or water depth above the PWR sump or BWR suction strainer outlets) and required pumping capacity (or pump inlet velocity). The water depth above the pipe centerline(s) and the inlet pipe velocity (U) can be expressed non-dimensionally as the Froude number:

$$Froude\ \ number = \frac{U}{\sqrt{gs}}$$

where g is the acceleration due to gravity. Extensive experimental results have shown that the hydraulic performance of ECC sumps (particularly the potential for air ingestion) is a strong function of the Froude number. Other nondimensional parameters (e.g., Reynolds number and Weber number) are of secondary importance.

Sump hydraulic performance can be divided into three performance categories:

1. Zero air ingestion, which requires no vortex suppressors or increase of the "required" NPSH above that from the pump manufacturer’s curves.
2. Air ingestion of 2% or less, a conservative level at which degradation of pumping capability is not expected based on an increase of the "required" NPSH.
3. Use of vortex suppressors to reduce air ingestion effects to zero.

For PWRs, zero air ingestion can be ensured by use of the design guidance set forth in Table A-l. Determination of those designs having ingestion levels of 2% or less can be obtained using correlations given in Table A-2 and the attendant sump geometric envelope. Geometric and screen guidelines for PWRs are contained in Tables A-3.1, A-3.2, A-4, and A-5. Table A-6 presents design guidelines for vortex suppressors that have shown the capability to reduce air ingestion to zero. These guidelines (Tables A-l through A-6) were developed from extensive hydraulic tests on full-scale sumps and provide a rapid means of assessing sump hydraulic performance. If the PWR sump design deviates significantly from the design boundaries noted, similar performance data should be obtained for verification of adequate sump hydraulic performance.

For BWRs, full-scale tests of suppression pool suction strainer screen outlet designs for recirculation pumps have shown that air ingestion is zero for Froude numbers less than 0.8 with a minimum submergence of 6 feet, and operation up to a Froude number 1.0 with the same minimum submergence may be possible before air ingestion levels of 2% may occur (NUREG-0897, Rev. 1, and NUREG-2772).

LOCA-INDUCED DEBRIS EFFECTS

Assessment of LOCA debris generation and the determination of possible debris interceptor blockage is complex. The evaluation of this safety question is dependent on the types and quantities of insulation employed, the location of such insulation materials within containment and with respect to the sump or suppression pool strainer location, the estimation of quantities of debris generated by a pipe break, and the migration of such debris to the interceptors. Thus blockage estimates (i.e., generation, transport, and head loss) are specific to the insulation material, the piping layout, and the plant design.

Since break jet forces are the dominant debris generator, the predicted jet envelope will determine the quantities and types of insulation debris. Figure A-2 provides a three-region model that has been developed from analytical and experimental considerations as identified in NUREG-0897, Rev. 1, and NUREG/CR-6224. The destructive results (e.g., volume of insulation and other debris generated, size of debris) of the break jet forces will be considerably different for different types of insulation, different types of installation methods, and distance from the break. Region I represents a total destruction zone; Region II represents a region where high levels of damage are possible depending on insulation type, whether encapsulation is employed, methods of attachment, etc.; and Region III represents a region where dislodgement of insulation in whole, or as-fabricated, segments is likely occur. NUREG-0897, Rev. 1, and NUREG/CR-6224 provide a more detailed discussion of these considerations. NUREG-0897, Rev. 1; NUREG/CR-6224; NUREG/CR-2982, Rev. 1; NUREG/CR-3170; NUREG/CR-3394, Vols. 1 and 2; and NUREG/CR-3616 provide more detailed information relevant to assessing debris generation and transport.

PUMP PERFORMANCE UNDER ADVERSE CONDITIONS

The pump industry historically has determined NPSH requirements for pumps on the basis of a percentage degradation in pumping capacity. The percentage has at times been arbitrary, but generally is in the range of 1% to 3%. A 2% limit on allowed air ingestion is recommended since higher levels have been shown to initiate degradation of pumping capacity.

The 2% by volume limit on sump air ingestion and the NPSH requirements act independently. However, air ingestion levels less than 2% can also affect NPSH requirements. If air ingestion is indicated, correct the NPSH requirement from the pump curves by the relationship:

$$NPSH_{required(\alpha p < 2\%)} = NPSH_{required(liquid)} \times ß$$

where $ß = 1 + 0.50\alpha_p$ and α_p is the air ingestion rate (in percent by volume) at the pump inlet flange.

COMBINED EFFECTS

As shown in Figure A-l, three interdependent effects (i.e., sump or suction strainer performance, debris generation and transport, and pump operation under adverse conditions) require evaluation for determining long-term recirculation capability (i.e., loss of NPSH margin).

CRITERIA FOR EVALUATING SUMP FAILURE

The sump failure criterion applicable to each plant is determined primarily by sump submergence. Figures A-2(a) and A-2(b) illustrate the two basic sump configurations of fully and partially submerged screens. Although only vertical sump configurations are shown here, the same designations are applicable for inclined screen designs. The key distinction between the fully and partially submerged configurations is that partially submerged screens allow equal pressure above both the pit and the pool, which are potentially separated by a debris bed. Fully submerged screens have a complete seal of water between the pump inlet and the containment atmosphere along all water paths passing through the sump screen. The effect of this difference in evaluation of the sump failure criterion is described below.

Fully Submerged Sump Screens

Figure A-2(a) presents a schematic of a sump that is fully submerged at the time of switchover to ECCS. The most likely mode of failure for sumps in this configuration is due to cavitation within the pump housing when head loss caused by debris accumulation exceeds the $NPSH_{Margin}$. For this set of plants (in which sump screens are fully submerged at the time of switchover), the onset of cavitation is determined by comparing plant $NPSH_{Margin}$, which is part of plant's licensing basis, with the screen head loss calculated in the plant evaluations performed per Regulatory Position 1.3. For this case, therefore, the sump failure criterion is assumed to be reached when

$$\text{Head Loss Across the Debris Bed} \geq NPSH_{Margin.}$$

Partially Submerged Sump Screens

Figure A-2(b) presents a schematic of a sump that is partially submerged at the time of switchover. Failure can occur for sumps in this configuration in one of two ways: either by pump cavitation as explained above, or when head loss caused by debris buildup prevents sufficient water from entering the sump. This flow imbalance occurs when water infiltration through a debris bed on the screen can no longer satisfy the volumetric demands of the pump. Because the pit and the pool are at equal atmospheric overpressure, the only force available to move water through a debris bed is the static pressure head in the pool. Numeric simulations confirm that an effective head loss across a debris bed approximately equal to half the pool height is sufficient to prevent adequate water flow. For all partially submerged sump screens, the sump failure criterion is assumed to be reached when

$$\text{Head Loss Across the Debris Bed} \geq NPSH_{Margin} \quad \text{or} \geq \tfrac{1}{2} \text{ of pool height}$$

After switchover to ECCS recirculation, some plants can change their sump configuration from partially submerged to fully submerged. This can occur for a number of reasons including accumulation of containment-spray water, continued melting of ice-condenser reservoirs, and continued addition of RWST inventory to the containment pool. As the pool depth changes during recirculation, the "wetted area" (or submerged area) of the sump screens can also change. The wetted area of the screen determines the average approach velocity of water that may carry debris. Because information about time-dependent pool depths is difficult to obtain, and because the most significant debris transport will occur early in the scenario when the pool is shallow, analysis should preferably be based on the pool depth at the time of switchover to ECCS recirculation.

APPENDIX A REFERENCES

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NUREG/CR-2772, M. Padmanabhan, "Hydraulic Performance of Pump Suction Inlets for Emergency Core Cooling Systems in Boiling Water Reactors" (ARL-398A), USNRC, June 1982.[1]

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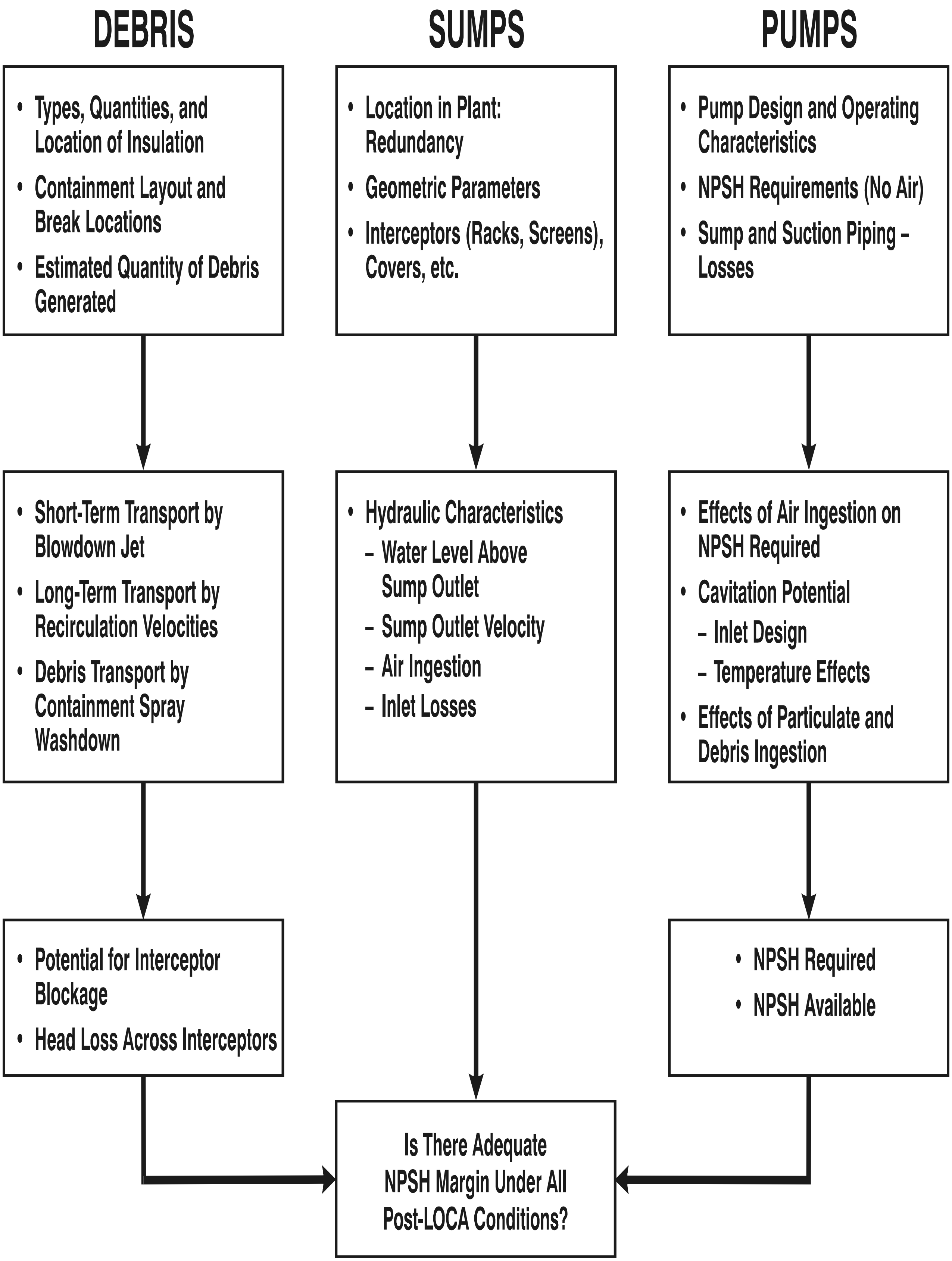
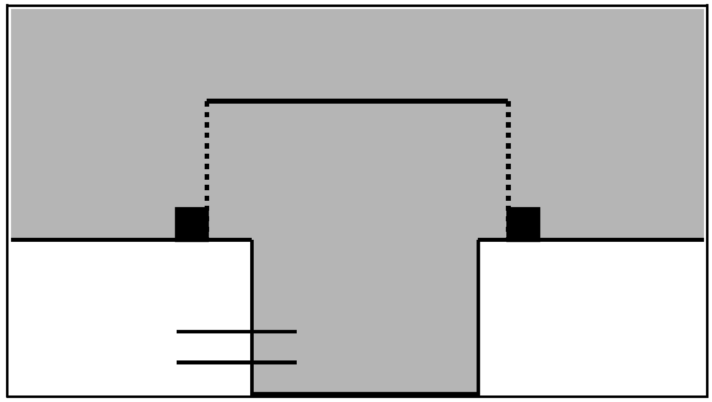
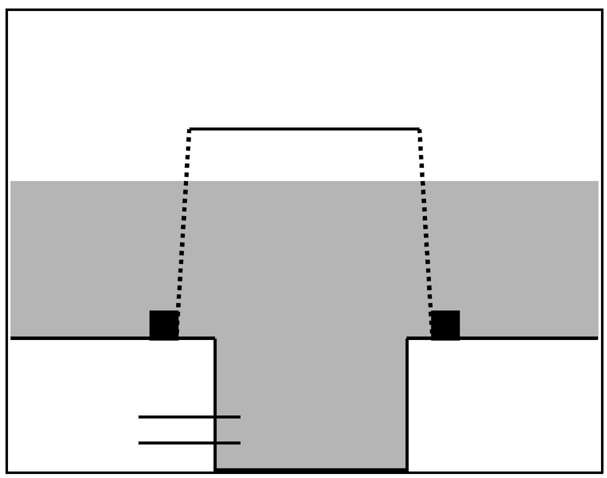


Figure A-1. Technical Considerations Relevant to PWR ECC Sump Performance



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



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

Figure A-2 Sump Screen Schematics

TABLE A-1

PWR HYDRAULIC DESIGN GUIDELINES FOR ZERO AIR INGESTION

Item	Horizontal Outlets	Vertical Outlets
Minimum Submergence, s (ft)	9	9
(m)	2.7	2.7
Maximum Froude Number, Fr	0.25	0.25
Maximum Pipe Velocity, U (ft/s)	4	4
(m/s)	1.2	1.2

NOTE: These guidelines were established using experimental results from NUREG/CR-2772, NUREG/CR-6224, and NUREG/CR-2982 and are based on sumps having a right rectangular shape.

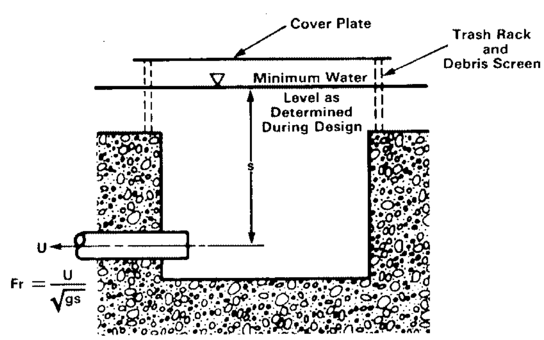


TABLE A-2

PWR HYDRAULIC DESIGN GUIDELINES FOR AIR INGESTION <2%

Air ingestion (α) is empirically calculated as
$\alpha = \alpha_o + (\alpha_1 \times Fr)$
where α_o and α_1 are coefficients derived from test results as given in the table below

Item	Horizontal Outlets		Vertical Outlets	
	Dual	Single	Dual	Single
Coefficient α_o	-2.47	-4.75	-4.75	-9.14
Coefficient α_1	9.38	18.04	18.69	35.95
Minimum Submergence, s(ft)	7.5	8.0	7.5	10.0
(m)	2.3	2.4	2.3	3.1
Maximum Froude Number, Fr	0.5	0.4	0.4	0.3
Maximum Pipe Velocity, U(ft/s)	7.0	6.5	6.0	5.5
(m/s)	2.1	2.0	1.8	1.7
Maximum Screen Face Velocity (blocked and minimum submergence) (ft/s)	3.0	3.0	3.0	3.0
(m/s)	0.9	0.9	0.9	0.9
Maximum Approach Flow Velocity (ft/s)	0.36	0.36	0.36	0.36
(m/s)	0.11	0.11	0.11	0.11
Maximum Sump Outlet Coefficient, C_L	1.2	1.2	1.2	1.2

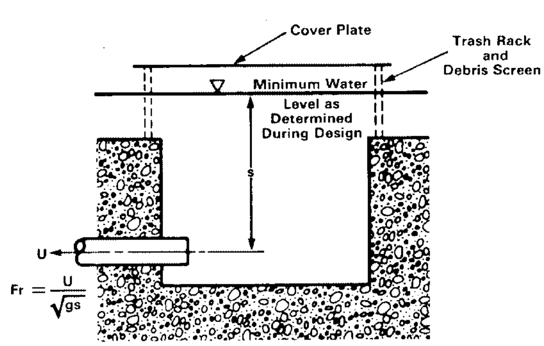


Table A-3.1

PWR GEOMETRIC DESIGN ENVELOP GUIDELINES FOR HORIZONTAL SUCTION OUTLETS

Sump Outlet	Sump Outlet Position*					
	e_y/d	$(B - e_y)/d$	c/d	b/d	f/d	e_x/d
Dual	>1	>3	>1.5	>1	>4	>1.5
Single					-	

* Preferred location.

Note: Dimensions are always measured to pipe centerline

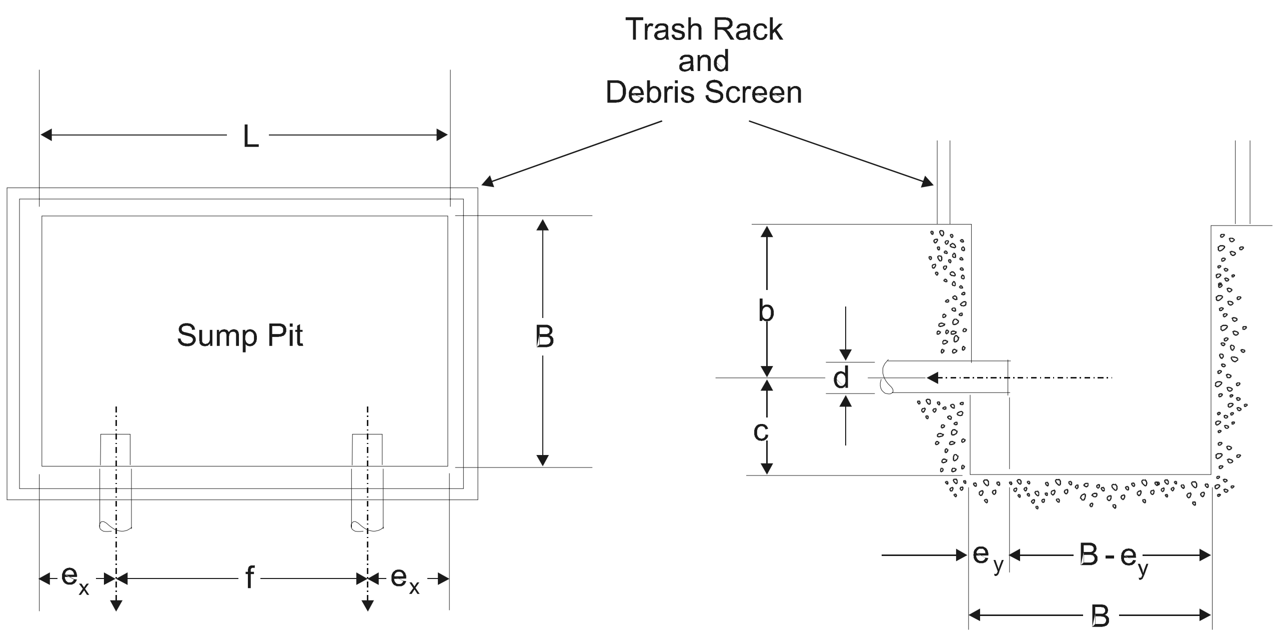


Table A-3.2

PWR GEOMETRIC DESIGN ENVELOP GUIDELINES FOR VERTICAL SUCTION OUTLETS

<table>
<tr><th rowspan="2">Sump Outlet</th><th colspan="6">Sump Outlet Position*</th></tr>
<tr><th>e_y/d</th><th>$(B-e_y)/d$</th><th>c/d</th><th>b/d</th><th>f/d</th><th>e_x/d</th></tr>
<tr><td>Dual</td><td rowspan="2">>1</td><td rowspan="2">>1</td><td>>0</td><td rowspan="2">>1</td><td>>4</td><td rowspan="2">>1.5</td></tr>
<tr><td>Single</td><td>>1.5</td><td>-</td></tr>
</table>

* Preferred location.

Note: Dimensions are always measured to pipe centerline

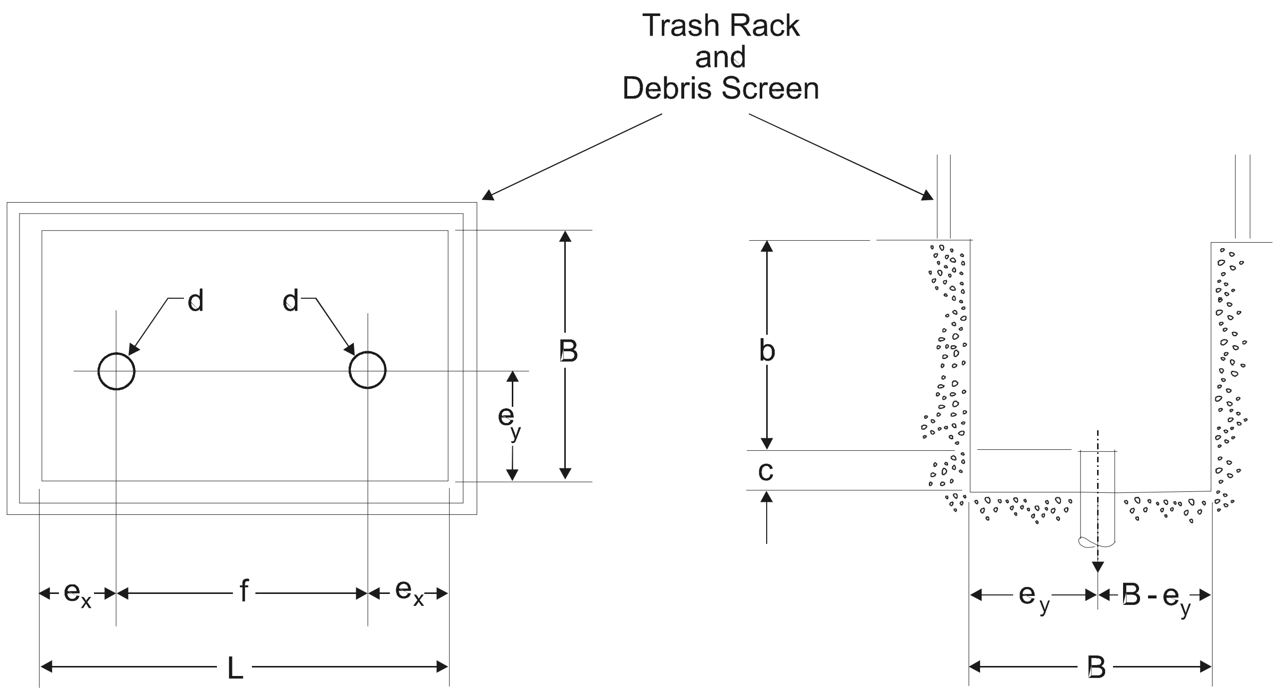


TABLE A-4

ADDITIONAL GUIDELINES RELATED TO SUMP SIZE AND PLACEMENT

1. The clearance between the trash rack and any wall or obstruction of length ℓ equal to or greater than the length of the adjacent screen/grate (B_s or L_s) should be at least 4 feet (1.2 meters).

2. A solid wall or large obstruction may form the boundary of the sump on one side only, i.e., the sump must have three sides open to the approach flow.

3. These additional guidelines should be followed to ensure the validity of the data in Tables A-1, A-2, A-3.1, and A-3.2.

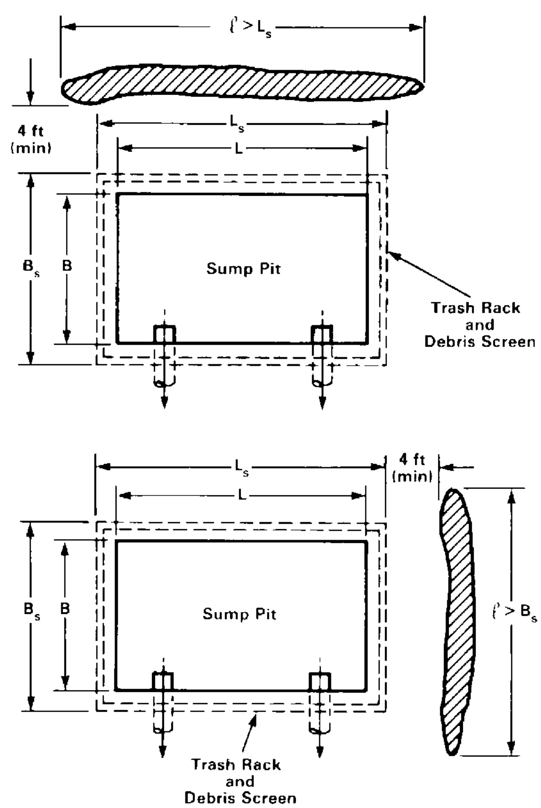


TABLE A-5

PWR DESIGN GUIDELINES FOR INTERCEPTORS AND COVER PLATE

1. Minimum height of interceptors should be 2 feet (0.61 meters).

2. Distance from sump side to screens, g_s, may be any reasonable value.

3. Screen mesh size (see Regulatory Position 1.1.1.12)

4. Trash racks should be vertically or nearly vertically oriented 1- to 1½-inch (25- to 38-mm) standard floor grate or equivalent.

5. The distance between the debris screens and trash racks should be 6 inches (15.2 cm) or less.

6. A solid cover plate should be mounted above the sump and should fully cover the trash rack. The cover plate should be designed to ensure the release of air trapped below the plate (a plate located below the minimum water level is preferable).

NOTE: See NUREG-0897.

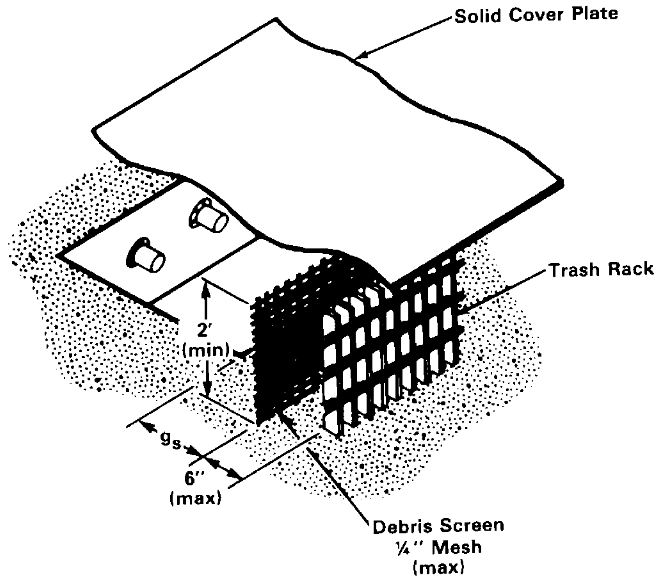


TABLE A-6

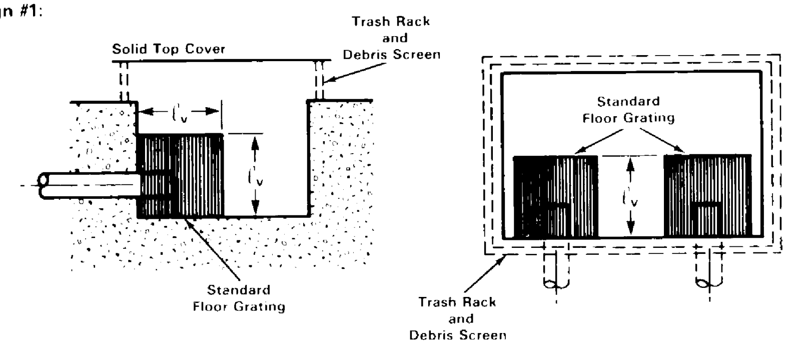
PWR GUIDELINES FOR SELECTED VORTEX SUPPRESSORS

1. Cubic arrangement of standard 1½-inch (30-mm) deep or deeper floor grating (or its equivalent) with a characteristic length, ℓ_v, that is at least 3 pipe diameters and with the top of the cube submerged at least 6 inches (15.2 cm) below the minimum water level. Noncubic designs with ℓ_v > 3 pipe diameters for the horizontal upper grate and satisfying the depth and distances to the minimum water level given for cubic designs are acceptable.

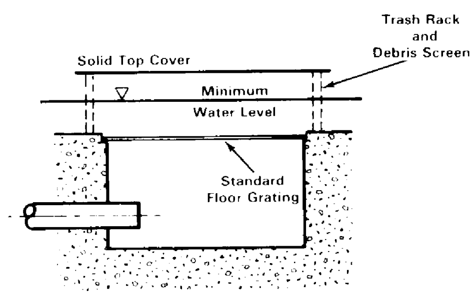
2. Standard 1½-inch (38-mm) or deeper floor grating (or its equivalent) located horizontally over the entire sump and containment floor inside the screens and located below the lip of the sump pit.

NOTE: Tests on these types of vortex suppressors at Alden Research Laboratory have demonstrated their capability to reduce air ingestion to zero even under the most adverse conditions simulated.

Design #1:



Design #2:



APPENDIX B

EXAMPLES OF ACTIVE MITIGATION SYSTEMS

In-Line (or Pipeline) Strainer

A strainer installed in the piping system, upstream of equipment, that will remove harmful objects and particulates from the fluid stream by a backwashing action.

Self-Cleaning Strainer

A strainer that is used upstream of equipment to filter out harmful objects and particulates and is designed to clean itself without the aid of external help.

Strainer Backwashing System

A system designed to dislodge objects and particulates from the surface of a strainer by directing a fluid stream in the opposite direction of the flow through the strainer.

REGULATORY ANALYSIS

A separate regulatory analysis was not prepared for this proposed Revision 3 of Regulatory Guide 1.82 since the revised guidance for pressurized water reactors and minor changes to guidance for boiling water reactors is intended to ensure compliance with the existing applicable regulatory requirements. Therefore a new regulatory analysis is not needed. The regulatory analysis (NUREG-0869, Revision 1, "USI A-43 Regulatory Analysis," October 1985[1]) that was prepared for the resolution of USI A-43, "Containment Emergency Sump Performance," is applicable to this proposed Revision 3 of Regulatory Guide 1-82.

In addition, the pertinent regulatory guidance in Regulatory Guide 1.1, also referred to as NRC Safety Guide (SG) 1, “Net Positive Suction Head For Emergency Core Cooling and Containment Heat Removal System Pumps,” is incorporated into this proposed Revision 3 of Regulatory Guide 1.82. Generic Letter 97-04, “Assurance of Sufficient Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal Pumps,” dated October 7, 1997, requested licensees of nuclear power plants to respond to several questions related to the net positive suction head of the ECCS and containment heat removal system pumps in their power plants. The staff reviewed these responses and wrote letters to the licensee of each power plant providing the staff’s conclusions based on these reviews. Based on its review of GL 97-04 responses, the staff determined that all operating plants satisfy the guidance in SG 1. The criteria used for these reviews were discussed in the generic letter and its regulatory analysis, in meetings with the NRC’s Committee to Review Generic Requirements and Advisory Committee on Reactor Safeguards, and with licensees during the NRC’s review of the generic letter responses. These criteria are now incorporated into this proposed Revision 3 of Regulatory Guide 1.82. The portion of the guidance related to the use of containment pressure for the determination of available NPSH is taken from the guidance in SG 1 which will be deleted when this guidance is incorporated into the proposed Revision 3 of Regulatory Guide 1.82.

[1] Copies are available at current rates from the U.S. Government Printing Office, P.O. Box 37082, Washington, DC 20402-9328 (telephone (202)512-1800); or from the National Technical Information Service by writing NTIS at 5285 Port Royal Road, Springfield, VA 22161; (telephone (703)487-4650; <http://www.ntis.gov/ordernow>. Copies are available for inspection or copying for a fee from the NRC Public Document Room at 11555 Rockville Pike, Rockville, MD; the PDR’s mailing address is USNRC PDR, Washington, DC 20555; telephone (301)415-4737 or (800)397-4209; fax (301)415-3548; email is PDR@NRC.GOV.

Attachment B

Break Characteristics Model for Debris Generation Following a Design Basis Loss of Coolant Accident

Break Characteristics Model for Debris Generation Following a Design Basis Loss of Coolant Accident

October 10, 2003

Prepared by the Nuclear Energy Institute PWR Sump Performance Task Force

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1 Introduction

An important safety concern regarding long-term recirculation cooling following a Loss of Coolant Accident (LOCA) is the transport of debris materials to interceptors (i.e., trash racks, debris screens, suction strainers) inside containment and the potential for debris accumulation to result in adverse blockage effects. Debris resulting from a LOCA, together with pre-existing debris, could block the emergency core cooling system (ECCS) debris interceptors and result in degradation or loss of recirculation flow margin. Potential debris sources can be divided into three categories: (1) debris that is generated by the LOCA and is transported by blowdown forces (e.g., insulation, paint), (2) debris that is generated or transported by washdown, and (3) other debris that existed before a LOCA (dust, sand, etc.). Each debris source is separately evaluated to estimate the quantity and other characteristics necessary to assess the fraction that could be transported to the containment recirculation sump and its combined effect on recirculation flow.

An initial step in evaluating post-accident sump performance is the determination of the amount of debris generated from a postulated breach in the piping system. Current regulatory guidance calls for determination of the quantity and characteristics of debris generated by a postulated LOCA covering a range of break sizes, break locations, and other properties, in a manner that provides assurance that the most severe postulated LOCAs are calculated. Methods for determining debris generation typically utilize a bounding combination of deterministic and mechanistic methods to provide a conservative representation of the destructive behavior of a postulated break. These methods provide a conservative estimation of debris generation based upon models that are not representative of the expected behavior of pipe breaks.

This paper presents a model for use by Pressurized Water Reactor (PWR) plants that provides a more realistic representation of one aspect of debris generation modeling (break size) while maintaining an overall conservative representation of the debris generation potential of postulated breaks. The proposed model utilizes fracture mechanics as the basis for determining a break size that is realistically conservative. This break size is then used in determining the quantity of debris that would be generated from identified break locations.

The fracture mechanics techniques described in this paper are the same techniques that have been used successfully in the support of Leak-Before-Break (LBB) and the application of LBB to postulated leakage cracks in large reactor coolant piping in PWR's. These leakage cracks have leak rates well above the demonstrated PWR leak detection capabilities (typically 10 gpm), while at the same time have been shown to remain stable under all normal and off-normal plant operating conditions.

While the proposed treatment method and LBB applications utilize the same technical basis, the method proposed in support of debris generation differs substantially from an LBB application. LBB applications[1] typically use fracture mechanics to demonstrate that the probability of fluid system piping rupture is extremely low, and using this basis, local dynamic effects are excluded. The proposed fracture mechanic approach continues to include the local dynamic effects (e.g., debris generation) but uses fracture mechanics as a basis for determining the amount of debris that is generated by the postulated break via identification of an effective break area. Therefore, this method credits the demonstrated toughness of PWR piping, yet defines a conservative design input for sump performance evaluations.

The proposed model will be one of the options available for use by PWR licensees as a step in the overall analysis effort necessary to demonstrate compliance with regulatory requirements governing operation of the ECC and Containment Spray Systems (CSS).

[1] Applications utilizing the provisions of General Design Criterion 4 contained in Appendix A to 10 CFR Part 50, that allow the exclusion of local dynamic effects from the design basis for qualified piping systems.

2 Summary of Current Guidance and Need for Revised Approach

Upon initiation of a break in the reactor coolant system of a PWR, the forces released by the break have the potential to dislodge piping thermal insulation and other materials in the vicinity of the break. A portion of this material will be transported to the containment floor by the break flow and by containment sprays. Upon initiation of recirculation flow from the containment sump to the reactor coolant system, some of the debris in the lower containment elevations will be transported to and accumulate on the containment sump screens. The resultant increase in resistance to the flow by the debris accumulating on the containment sump screen has the potential to challenge the capability of the ECCS to provide long-term cooling to the reactor core.

In order to calculate plant response to a postulated event and the potential for significant blockage of the containment sump screens, it is necessary to take into account a wide range of phenomena and processes. These phenomena and processes are highly dependent upon plant design and operation as well as the specifics of the postulated LOCA event. The complexity and multivariate nature of the event progression, coupled with the absence of a comprehensive database addressing the full range of encountered phenomena inevitably leads to a calculation process that accounts for the resulting uncertainties in a conservative manner.

Typically the analyses investigating ECCS operation during the recirculation phase divide the process into three separate phases: (1) Debris Generation, (2) Debris Transport and (3) Debris Accumulation and Headloss. Each phase of the calculation process, while interdependent, involves its own set of phenomena and uncertainties. Known limitations in the knowledge base of these phenomena and associated calculation methods are typically accounted for in a bounding fashion during each phase of the process. The combined effect of these bounding calculations is a pessimistic prediction of ECCS recirculation performance that, while conservative, provides little insight into the realistically expected performance during a design basis event. An additional complicating factor is the realization that, unlike most design basis calculations, there is no unique set of conditions that can be repeatedly shown to represent the worst case for recirculation performance. This necessitates either a full scope set of calculations looking at an effectively boundless set of possible permutations and combinations of conditions, or a more limited set of calculations that combines conditions in a bounding, often unrepresentative, manner.

While it is not the intent of this paper to address the full set of calculations necessary to assess ECCS and CSS operation in the recirculation mode, it is informative to discuss current guidance and practices for the debris generation phase of the calculations.

Break Size and Location

Because the size and location of the break have a key influence on a number of key parameters that are specific to each plant's design and operation (e.g., debris generation quantities, debris transport capability, containment flood-up level and timing), it is not possible to predetermine the limiting break size or its location. The current practice is to analyze a full range of break sizes, ranging from the smallest break that has the potential to lead to ECCS recirculation operation to a full double-ended guillotine break of the largest reactor coolant system pipe. This full range of break sizes is postulated for a wide range of potential break locations to address factors such as variations in insulation materials on and around postulated break locations and proximity to the recirculation sump and its influence on debris transport.

Current guidance calls for debris generation to be calculated for a number of postulated LOCAs of different sizes, locations, and other properties sufficient to provide assurance that the most severe postulated LOCAs are calculated. Proposed revision 3 to Regulatory Guide 1.82 (Reference 1) calls for the following postulated break sizes and locations to be considered.

1. Breaks in the hot leg, cold leg, intermediate leg, and, depending on the plant licensing basis, main steam and main feedwater lines with the largest amount of potential debris within the postulated zone of influence,

2. Large breaks with two or more different types of debris, including the breaks with the most variety of debris, within the expected zone of influence,

3. Breaks in areas with the most direct path to the sump,

4. Medium and large breaks with the largest potential particulate debris to insulation ratio by weight, and

5. Breaks that generate an amount of fibrous debris that, after its transport to the sump screen, creates a minimum uniform thin bed (1/8-inch layer of fiber) to filter particulate debris[2].

This process is applied in a deterministic fashion without consideration of the probability of a limiting size break occurring at the limiting location on the RCS. This can lead to a condition where the limiting break is controlled by a unique combination of break size, location and transport assumptions. This factor, in conjunction with other, more traditional, design basis assumptions (e.g., limiting single failure, maximum uncertainties on setpoints, timings, and flowrates) can easily lead to one or more extremely low probability events dominating calculation results.

[2] Screen blockage experiments have determined that a 1/8 inch layer of fiber combined with particulate debris can result in significant headloss. Fiber layers thicker than 1/8 inch result in lower headloss, while layers less than 1/8 inch are unstable and tend toward self destruction as headloss increases. The uniqueness of the set of conditions that result in a stable "thin-bed" of fiber and particulate is not addressed in current guidance.

Debris Generation

Given a postulated break size and location, the next step is to calculate (or estimate) the quantity and size distribution of debris that could be generated as a direct consequence of the break. The debris generation capability of a break is dependent on a number of factors including break size, break opening characteristics and break orientation, as well as characteristics of materials and structures surrounding the break. While a number of tests have been performed to investigate the mechanics of debris generation, these tests are limited in scope and both the tests and the resultant interpretation of test data have incorporated simplifying/bounding assumptions to address variability in key parameters.

One important simplifying assumption used in both debris generation tests and subsequent modeling of the tests is that the break opening time is instantaneous[3]. This is a carry-over assumption from thermal hydraulic analyses of reactor coolant system response performed in accordance with Appendix K to 10 CFR Part 50[4]. A consequence of this assumption for debris generation is the generation of an acoustic shock wave. This pressure wave is believed to be a major contributor to debris generation surrounding the break. Component insulation is destroyed initially by the blast effects of a shock wave that expands away from the break. This destruction is continued by the two-phase jet of fluid emanating from the break. Experiments show that the shock wave may cause substantial damage to even the most heavily reinforced insulating constructions (e.g., steel-jacketed RMI or fiber) if they are located sufficiently close to the break.

In order for a shock wave to occur, the break opening time (BOT) must be on the same order as the acoustic propagation time across the piping. If the BOT is long relative to the acoustic propagation time then a shock wave will not occur and debris generation will be predominated by jet impact and displacement forces. As part of its evaluation of the potential for shock waves following a double-ended guillotine break General Electric (Reference 2) estimated that a shock wave will not be generated for large bore piping break opening times greater than approximately 10 milliseconds. Realistic estimates of break opening times for a full double-ended rupture derived from mechanical response analyses show that the quickest opening time for large bore PWR piping is on the order of 100 milliseconds. However, the presumption of an instantaneous break opening time and resultant shock wave remains in regulatory guidance applicable to debris generation. Regulatory guidance contained in Revision 3 (proposed) to RG 1.82 states:

[3] Instantaneous break opening is simulated in debris generation tests through the use of fast opening rupture disks designed to open in a time span of approximately one millisecond.

[4] Appendix K to 10 CFR Part 50 covers required and acceptable features of ECCS evaluation models designed to address core response and ECCS cooling performance following a design basis LOCA event. These analyses are performed to demonstrate compliance with 10CFR50.46 performance criteria addressing peak cladding temperature, maximum cladding oxidation and core coolability (flow channel blockage resulting from fuel rod ballooning). Separate analyses, using other “non Appendix K” models are used to demonstrate compliance with 10CFR50.46 criteria not addressed by Appendix K.

The shock wave generated during postulated pipe break and the subsequent jet should be the basis for estimating the amount of debris generated and the size or size distribution of the debris generated within the zone of influence.

The assumption of an instantaneous opening of the break is an unwarranted conservatism, and leads to a significant overestimation of the debris generation potential for a postulated break.

Determination of the amount of debris that is generated for a given break is also complicated by the complexity in modeling a three-dimensional jet of two-phase fluid expanding into a region composed of a multitude of materials in widely varying geometric configurations. A number of conservative simplifications of the problem have been proposed and used. One method for estimating the amount of debris generated by a postulated LOCA is to define a spherical zone of influence. The size of the zone of influence is dependent of the size of the break and on the materials considered within the zone. Once the zone of influence is defined, all materials within the zone are assumed to be damaged. The simplicity of these models inevitably results in an overestimation of the quantity of debris generated by a postulated break.

The quantity of debris that can be generated by a break based on assumptions and conservatisms cited above can be seen in results presented in NUREG/CR-6762 (Reference 3). The reported results of debris-generation simulations show debris volumes of 1700 ft^3 for a Large LOCA (> 6 in. diameter), compared to 40 ft^3 for a Medium LOCA (4 to 6 in. diameter) and 25 ft^3 for a Small LOCA (2 to 4 in. diameter).

In summary, current guidance calls for ECCS performance to be assessed in response to the most limiting set of conditions. One of the main controlling factors in calculations to assess ECCS recirculation performance is debris generation. The set of assumptions called for by current regulatory guidance result in ECCS performance being assessed in response to a spectrum of break sizes and locations. The probability of the limiting size break(s) occurring at specific locations is not accounted for in these calculations. The debris generation occurring at this limiting break size/location is then conservatively estimated based on models that are constructed from

1. unrealistic break characteristic assumptions (introducing phenomena that would not be expected to occur), and
2. a conservative expansion of limited test data, necessitated by the wide variety of materials and configurations involved and the large uncertainties associated with expansion of small scale experiments to PWR conditions.

The inevitable consequence of the current analysis methodology is an ECCS recirculation design that is based (focused) upon an extremely low probability event scenario.

In response to the large debris generation values resulting from the current approach, licensees may find it necessary to proactively reduce the debris generation potential in ways that may be detrimental to operation. Utilities may conclude that the only practical way to reduce the debris generation source term to a manageable size is to limit break size by installing (reinstalling) guard pipes, piping restraints, or other similar devices. The irony of such a change is that the justification for removal of such devices from plant designs origianlly was, in part, the low frequency of the same postulated breaks that would now be responsible for their return. The end result of such action is that the reactor coolant piping would be less accessible than was the case prior to these modifications. The modifications will result in less accessibility inside containment. This, in turn, will result in making the performance of some inspections no longer practical, cause other inspections to take longer, and cause plant personnel to receive increased doses for routine maintenance and inspection procedures.

Physical modification of the containment sump screen as a means to address GSI-191 concerns will likely be considered by many licensees. While an increase in sump screen area is an appropriate and perhaps necessary means to address GSI-191, large increases in sump screen area can have unintended consequences and every means should be taken to ensure that the size of the screen is appropriate for the issue. The large debris loadings resulting from non-mechanistic modeling of breaks could dominate the sizing requirements for containment sumps which, in turn, could lead to screen area requirements that lead to modifications that compromise other aspects of plant design and operation. Depending on the location of the containment sump, a large increase in screen area could result in an encroachment on reactor coolant piping. This may require additional plant modifications, such as the addition of piping restraints to preclude damage to the enlarged sump screen. Large increases in sump screen flow areas are also likely to greatly impede access inside containment. This would make maintenance and inspection activities more difficult, and potentially impractical.

3 Description of Proposed Model

As discussed in Section 2, current guidance calls for ECCS and CSS recirculation performance to be evaluated for a full range of break sizes across a full range of break locations. These calculations are performed to demonstrate that the ECCS can meet requirements for long-term cooling per 10 CFR 50.46(b)(5). In order to determine the quantity of debris that is generated as a direct consequence of the break it is necessary to specify the characteristics of the postulated break.

The following section summarizes the break characteristic models currently used to meet ECCS performance requirement specified in 10 CFR50.46. This is followed by a summary of the proposed approach for debris generation modeling.

3.1 Break Characteristic Models Currently Used to Meet 10 CFR 50.46

There are currently two general methods for assigning the break characteristics for use in meeting requirements of 10 CFR 50.46. These are:

1. Models for In-core Thermal Hydraulic Response and Mass/Energy Release (Appendix K Models)
2. Models for In-core Structural Response (LOCA Forces Models)

Appendix K to 10 CFR Part 50 covers required and acceptable features of ECCS evaluation models designed to address core response and ECCS cooling performance following a design basis LOCA event. These analyses are performed to demonstrate compliance with 10CFR50.46 performance criteria addressing peak cladding temperature (10CFR50.46(b)(1)), maximum cladding oxidation (10CFR50.46(b)(2) and core coolability[5] (10CFR50.46(b)(4)). Separate analyses are performed to demonstrate compliance with the core coolability criterion of 10CFR50.46 by calculating the impact of break forces on vessel internals (e.g., fuel assemblies).

3.1.1 Models for In-core Thermal Hydraulic Response and Mass/Energy Release

For the purpose of demonstrating compliance with 10 CFR50.46 (b)(1) and (b)(2) (peak cladding temperature and maximum cladding oxidation) and for determining mass and energy release for containment response calculations, the postulated break is assumed to be an instantaneous double-ended opening of a pipe up to and including the largest piping in the reactor coolant system. These calculations are deterministic in that they do not take into consideration the frequency of piping rupture of a given size. The calculations are also non-mechanistic since no

[5] Appendix K analyses address core coolability primarily from the impact of flow channel blockage resulting from clad ballooning.

known failure mechanism can lead to an instantaneous pipe rupture[6]. The assumption of an instantaneous break opening vs. a more defensible opening time (e.g., 100 milliseconds), has little impact on the associated in-core thermal hydraulic calculations.

The assumption of an instantaneous break opening time does have a significant impact on calculations performed for the purpose of meeting other 10 CFR50.46 requirements.

3.1.2 Models for In-core Structural Response

Calculations performed to demonstrate compliance with 10 CFR 50.46(b)(4) (coolable geometry) typically incorporate the likelihood of various break locations in accordance with the provisions of GDC-4, using “leak-before-break” analysis techniques. Such consideration allows the elimination from the design basis of the dynamic effects of pipe rupture in piping systems so qualified. For piping systems that have not been qualified for “LBB exclusion” the analyses determine the effective break area resulting from the postulated break and determine, based upon the break forces, existing structures and restraints, the piping displacement. The effective break area, taking into account limited displacement, results in an effective break area that is, in most cases, significantly less than the full pipe diameter. Further, in select applications, the calculations apply a realistic break opening time (BOT) based on the consideration of fracture mechanics and dynamic system structural analyses. Realistic BOT’s are typically calculated using finite element dynamic analysis methods based on the assumption that the crack is developed instantaneously. Although testing and analysis results indicate a finite crack propagation time, this is conservatively neglected in the BOT determination. While BOT has relatively little effect in the long term on the blowdown transient, a realistic time for the break to develop to its full break area can have a considerable effect in the initial stages of the blowdown.

3.2 Application of Current Models to Local Debris Generation

For the purposes of demonstrating compliance with 10CFR50.46(b)(5) (long-term cooling), either of the above two approaches for defining break characteristics could be considered, but each has noted limitations. The modeling characteristics used for in-core thermal hydraulic analyses (e.g., instantaneous break opening time) should not be considered appropriate for use in debris generation calculations because they are unrepresentative of break opening behavior and lead to an overly conservative estimation of debris quantities. The methods utilized for in-core structural analyses to demonstrate compliance with 10 CFR50.46(b)(4) are considered more appropriate for debris generation calculations, however, full application is constrained since experiments that have been conducted to determine debris generation have typically modeled instantaneous break openings using fast opening rupture disks. As such there is little

[6] For this discussion, instantaneous can be considered to be a break opening time less than ~10 milliseconds, i.e., the break opening interval necessary to generate a shock wave.

experimental data available to support the debris generation that would occur for realistic break opening times.

The exclusion from consideration of LBB qualified piping that is currently applied in structural analyses for 10CFR 50.46(b)(4) could be considered in debris generation calculations and was proposed by NEI in a letter to NRC dated October 4, 2002 [Reference 4]. The NRC has not provided a written response to the NEI request to utilize this approach; either accepting it as an appropriate method or by identifying the basis for its denial. Therefore, use of LBB piping exclusions remains a potential method for use in debris generation calculations.

The uncertainty associated with the schedule for NRC staff response on the proposed use of LBB exclusions led to the development of an alternative proposal that incorporates attributes of the two currently accepted pipe break characterization models.

3.3 Proposed Break Characteristic Model for Debris Generation

The proposed model utilizes fracture mechanics considerations to establish a maximum credible flaw size in qualified piping. The area associated with this flaw size is then increased by three orders of magnitude to determine the break size (area) to be used in debris generation calculations. The calculation of the debris quantities generated from these pipe break areas have as a basis a conservative estimate of the actual behavior of the piping material under normal and off-normal conditions.

The proposed model for determining the size of the pipe breach will utilize stable yet detectable leakage cracks already calculated for PWR primary coolant piping as a key input parameter. Compilations of stable leakage cracks that have been calculated for a number of PWR plants are presented in Table 3-1, along with the crack opening area for each crack. As seen in this table, the crack opening areas of the stable leakage cracks are quite small and would have little debris generating capability.

For the purposes of conservatively calculating debris generation for a postulated through-wall flaw, the breach area associated with the stable leakage crack is increased by a factor of 1000. Use of a pipe breach area that is three orders of magnitude larger than the calculated area of the associated stable leakage crack results in maximum pipe breach areas for use in evaluating debris generation as follows:

- For B&W / Framatome plants 83 in^2
- For Combustion Engineering plants 40 in^2
- For Westinghouse plants 40 in^2

Using a circular hole for the break geometry, the equivalent hole diameters for the break areas identified above are calculated as:

- For B&W / Framatome plants 10.28 inch diameter
- For Combustion Engineering plants 7.10 inch diameter
- For Westinghouse plants 7.10 inch diameter

The geometry of the circular hole is assumed to be in the pipe centered at the midpoint of the through-wall crack or flaw. The proposed model could be applied to piping segments for which fracture mechanics analysis results are available for determining stable leakage crack areas. Piping segments for which the calculation of stable leakage cracks do not exist will assume the full cross sectional area of the inside diameter of the pipe for the purposes of debris generation.

It is important to note that the proposed break model is used only for the determination of dynamic effects impacting local debris generation. All other phenomena affecting long-term cooling, such as break flow, global effects within containment, debris transport, and screen blockage, will utilize a full range of break sizes and locations (up to full double-ended guillotine rupture of largest pipe).

3.4 Comparison of Current and Proposed Break Characteristic Models

Table 3-2 provides a comparison of key attributes of current break modeling used to demonstrate compliance to 10 CFR 50.46 and break modeling proposed for use in calculating debris generation potential for postulated breaks.

Table 3-1: Stable Leakage Crack Sizes for PWR Primary Loop Piping

Westinghouse Designed Plants

Pipe OD (in)	Pipe Wall Thickness (in)	Stable Crack Length [Note 1] (in)	Crack Opening Area (in^2)
32.12 – 37.75	2.21 – 3.27	2.5 – 8.55	0.030 – 0.040

CE Designed Plants

Case	Pipe Wall Thickness (in)	Stable Crack Length [Note 1] (in)	Crack Opening Area (in^2)
Circumferential Crack in Pump Discharge	3.0	7.0	0.040
Circumferential Crack in Hot Leg	3.75	7.0	0.040
Axial Slot in Pump Suction Elbow	3.0	4.0	0.040
Circumferential Crack in Pump Suction Elbow	3.0	11.0	0.040
Circumferential Crack in Pump Discharge	2.5	7.0	0.040

B&W Designed Plants

Applicable Plants	Piping Segment	Stable Crack Length [Note 1] (in)	Crack Opening Area (in^2)
Plants A, B, C, D, E, and F	Cold Leg, Straight	9.2	0.075
	Cold Leg, Elbow	9.0	0.075
	Hot Leg, Straight	8.0	0.068
	Hot Leg, Elbow	10.8	0.083
Plant G	Cold Leg, Straight	9.39	0.065
	Cold Leg, Elbow	9.41	0.074
	Hot Leg, Straight	11.39	0.074
	Hot Leg, Elbow	12.63	0.083

Notes: 1) Stable crack length is based on a leak rate of 10 gpm.

Table 3-2
Comparison of Break Characteristic Models for Debris Generation

Break Characteristic Models	(A) In-core T/H, M&E Model	(B) In-core Structural Response Model	(C) LBB Application Proposed in 10/04/02 NEI Letter	(D) Fracture Mechanics Approach
Current Application	Used to support analyses that demonstrate compliance to 10 CFR 50.46(b)(1) and 10.46(b)(2)	Used to support analyses that demonstrate compliance to 10 CFR 50.46(b)(4)	Proposed for use in analyses that demonstrate compliance to 10 CFR 50.46(b)(5)	Proposed for use in analyses that demonstrate compliance to 10 CFR 50.46(b)(5)
Break Opening Time	Instantaneous	Varies by vendor. Ranges from instantaneous to value determined by fracture mechanics and structural analysis.	Instantaneous	Instantaneous
Break Locations	All high-energy RCS piping (no exclusions)	All non-LBB qualified piping (LBB piping excluded per GDC-4)	All non-LBB qualified piping (debris generation from LBB piping excluded per GDC-4)	All high-energy RCS piping (no exclusions)
Effective Break Size	Full double-ended guillotine	Effective break area determined based upon calculated piping displacement for non LBB piping	Full double-ended guillotine	Break size for debris generation determined using fracture mechanics principles
Similar Applications	In-core T/H analyses performed to demonstrate compliance with 10 CFR 50.46(b)(1) and (2)	Structural calculations performed to demonstrate compliance with 10 CFR 50.46(b)(4)	Similar to In-core Structural Response model but conservatively retains modeling of instantaneous DEG opening for non LBB piping.	Similar to In-core T/H analysis model with exception of fracture mechanics based break size modeling in lieu of double-ended break

4 Technical Bases for Proposed Break Characteristic Model for Debris Generation

Significant testing and analyses have been performed to characterize the behavior and response of flaws that may be present in reactor coolant piping. These efforts have provided a comprehensive and realistic basis for defining stable through-wall cracks in large PWR reactor coolant piping. The fracture mechanics analytical techniques, applied reactor coolant system loadings, actual material properties, and installed leak detection capabilities are discussed below. Combined in a comprehensive plant-specific analysis, these techniques demonstrate that a conservatively postulated through-wall crack would be large enough to be detected by plant leak detection systems, yet remain stable in the full power operating environment, including faulted loading conditions (References 5, 6, and 7).

The following discussion is applicable to and includes both stainless steel and carbon steel piping with stainless steel clad.

4.1 Piping System Loading Conditions

The loads resulting from both normal operating conditions and faulted plant conditions are applied in the evaluation of both the stability and leakage of through-wall cracks or flaws. These conditions conservatively bound other loading conditions on the piping systems of interest. The components for normal loads are pressure, dead weight and thermal expansion.

Normal condition loads are used in the leak rate calculations. For a given length crack or flaw, the application of normal operating condition loads determines the flow area and leakage rate.

For the faulted condition loading, loads associated with the safe shutdown earthquake (SSE) are considered in addition to the normal loads. This load combination is used in the demonstration of crack stability.

4.2 Material Characterization

Material properties for the fracture mechanics evaluations are taken from the certified material test reports (CMTRs). Properties are determined both at room temperature and/or at operating temperature. Forged and cast stainless steels both typically have high fracture toughness values. However, cast stainless steels are subject to thermal aging during service. This thermal aging causes an elevation in the yield strength of the material and a degradation of the fracture toughness. Detailed fracture toughness testing has been performed for cast stainless steel, the results of which are used to establish the end-of-service life (40 or 60 years, as determined by the plant) fracture toughness values for specific materials. Detailed fracture toughness testing has also been performed for the low alloy ferritic steel pipe materials and associated weldments.

4.3 PWR Primary Loop Piping Leak Rate Determination

The determination of leakage crack size is based on the leak detection capability of the plant leak detection systems.

LEAK DETECTION

Early detection of leakage in components of the reactor coolant pressure boundary (RCPB) system is necessary to identify deteriorating or failed components and minimize the release of fission products. Regulatory Guide (R.G.) 1.45 (Reference 8) describes acceptable methods to select leakage detection systems for the RCPB.

R.G. 1.45 specifies that at least three different detection methods should be employed. Plant sump level monitoring and airborne particulate radioactivity monitoring are specifically recommended. A third method can be either monitoring of condensate flow rate from air coolers or monitoring of airborne gaseous activity.

R.G. 1.45 also recommends that flow rates from identified and unidentified sources should be monitored separately, the former to an accuracy of 10 gpm and the latter to an accuracy of 1 gpm. (Note that plants with coolant activity levels sufficiently low as to suggest radiation monitoring will not detect leakage with an accuracy of 1 gpm have implemented alternate leakage monitoring methods.) Indicators and alarms for leak detection should be provided in the main control room. The sensitivity and response time for each leakage detection system used should be such that each is capable of detecting 1 gpm or less in one hour.

All US PWR's meet or exceed the leak detection guidance of the preceding paragraph. Specific leak detection capabilities of a plant are identified in its technical specifications.

LEAK RATE CALCULATIONS

The first step for calculating the leak rates is to determine the crack opening area when the pipe containing a postulated through-wall flaw is subjected to normal operating loads. Using the crack opening area, leak rate calculations are performed for the two-phase choked flow condition. From the actual pipe stress analysis, deadweight, normal 100% power thermal expansion and normal operating pressure loads are used in the calculation of the crack opening area and hence the leak rate. All loads are combined by the algebraic summation method.

It is noted that a through-wall circumferential flaw is postulated in the piping that would yield a leak rate of 10 gpm. A flaw that results in a 10 gpm flow rate is used to assure a factor of 10 in margin between the calculated leak rate compared to the leak detection capability of the plant.

4.4 Fracture Mechanics Evaluation

The stability of a calculated leakage crack or flaw is demonstrated based on material properties and faulted applied load conditions. Based on extensive analyses, significant margins on crack stability have been demonstrated for the calculated leakage cracks.

4.4.1 Local Failure Mechanism

The local mechanism of failure is primarily dominated by the crack tip behavior in terms of crack-tip blunting, initiation, extension and finally crack instability. Local stability will be assumed if the crack does not initiate at all. It has been accepted (Reference 9) that the initiation toughness measured in terms of J_{Ic} from a J-integral resistance curve is a key material parameter defining crack initiation. If, for a given load, the applied J-integral value is shown to be less than the J_{Ic} of the material, then the crack will not initiate (Reference 9).

If the initiation criterion is not met, then stability is said to exist when the applied tearing modulus value is less than the material tearing modulus value, and the applied J-integral value is less than the J_{max} value of the material.

4.4.2 Global Failure Mechanism

Determination of the conditions which lead to failure in stainless steel is done with plastic fracture methodology because of the large amount of deformation accompanying fracture. One accepted method for predicting the failure of ductile material is the plastic instability method, based on traditional plastic limit load concepts, but accounting for strain hardening and taking into account the presence of a flaw. The flawed pipe is predicted to fail when the remaining net section reaches a stress level at which a plastic hinge is formed. The stress level at which this occurs is termed as the flow stress. The flow stress is generally taken as the average of the yield and ultimate tensile strength of the material at the temperature of interest. This methodology has been shown to be applicable to ductile piping through a large number of experiments (Reference 9).

5 Compliance with Applicable Regulations

5.1 Regulatory Requirements

Title 10, Section 50.46 of the Code of Federal Regulations (10 CFR 50.46) requires that licensees design their ECCS systems to meet five criteria, one of which is to provide the capability for long-term cooling. Following successful system initiation, the ECCS shall be able to provide cooling for a sufficient duration that the core temperature is maintained at an acceptably low value. In addition, the ECCS shall be able to continue decay heat removal for the extended period of time required by the long-lived radioactivity remaining in the core. The requirements of 10 CFR 50.46 are in addition to the general ECCS cooling performance design requirements found elsewhere in 10 CFR Part 50, in particular the system safety function requirements in General Design Criterion (GDC) 35 of Appendix A to 10 CFR Part 50.

The Containment Spray System is required to meet, in part, GDC 38 and GDC 40 of Appendix A to 10 CFR Part 50. These criteria specify requirements regarding heat removal from the reactor containment following any loss-of-coolant accident and to control fission products that may be released into the reactor containment.

5.2 Current Regulatory Guidance

The regulations are not specific as to the manner in which ECCS “capability for long-term cooling” is to be demonstrated. The regulations are also not specific as to whether or how debris generation, as a direct result of a design basis LOCA, is to be determined. Methods that are acceptable to the NRC for determining whether designs maintain a “capability for long-term cooling” and that meet regulatory requirements are currently specified in regulatory guidance. The applicable regulatory guide for this purpose is Regulatory Guide 1.82, *Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident*, Revision 3 (proposed). This regulatory guide has undergone significant revision since its initial release in 1974, reflecting new insights and results of ongoing research. The revisions also reflect significant changes in the regulatory treatment of debris generation. As is discussed in the following section, the regulatory treatment has progressed from a fully non-mechanistic treatment (Rev. 0) which only accounts for the effect of debris generation on containment sump performance, to a mechanistic treatment that allows for consideration of the probability of pipe rupture (Rev. 1), to a mechanistic treatment with no allowance for consideration of the probability of pipe rupture (Rev. 2 & proposed Rev. 3).

The following paragraphs summarize the evolution of regulatory guidance addressing debris generation following a LOCA event.

Regulatory Guide 1.82, Revision 0

The containment recirculation portions of the ECCS and CSS for U.S. PWRs were originally designed and licensed in conformance with Regulatory Guide 1.82 Revision 0[7] or predecessor guidance. In accordance with guidance contained in Revision 0 to RG 1.82, the 'capability for long-term cooling" was demonstrated in a non-mechanistic fashion, by assuming 50% of the containment sump screen area was unavailable for flow due to blockage.

Debris Generation Guidance 1974-1985

- o Applicable guidance contained in Regulatory Guide 1.82, Revision 0
- o Non-mechanistic treatment
- o Assume accident debris results in 50% blockage of containment sump screen(s)

Regulatory Guide 1.82, Revision 1

Regulatory Guide 1.82 was revised in November 1985 as part of the resolution to Unresolved Safety Issue (USI) A-43, "Containment Emergency Sump Performance." The staff concluded at that time that no new requirements would be imposed on licensees; however, the staff did recommend that Revision 1 to RG 1.82 be used as guidance for the conduct of 10 CFR 50.59 reviews dealing with change out and/or modification of thermal insulation installed on primary coolant system piping and components. As part of this revision, guidance was added that called for "*evaluation or confirmation of …debris effects (e.g. debris transport, interceptor blockage, and head loss) …to ensure that long-term recirculation cooling can be accomplished*."

For the purpose of defining break or rupture locations, Revision 1 to RG 1.82 refers the user to Standard Review Plan (SRP) Section 3.6.2[8], which provides guidance for selecting the number, orientation, and location of postulated ruptures within a containment. SRP 3.6.2 provides instruction and guidance to NRC staff reviewers regarding break and crack location criteria and methods of analysis for evaluating the dynamic effects associated with postulated breaks and cracks in high- and moderate-energy fluid system piping. SRP 3.6.2 is the primary review guidance for ensuring that a design meets the requirements of General Design Criterion (GDC) 4. GDC 4 requires that structures, systems, and components important to safety shall be designed to accommodate the effects of postulated accidents, including appropriate protection against the dynamic and environmental effects of postulated pipe ruptures.

Compliance with GDC 4 requires that nuclear power plant structures, systems, and components important to safety be designed to accommodate the effects of, and be compatible with, environmental conditions associated with normal operation, maintenance, testing, and

[7] Regulatory Guide 1.82, *Sumps for Emergency Core Cooling and Containment Spray Systems*, Revision 0, June 1974
[8] Standard Review Plan, Section 3.6.2, "*Determination of Rupture Locations and Dynamic Effects Associated with the Postulated Rupture of Piping*"

postulated accidents, including loss-of-coolant accidents. These structures, systems, and components are to be protected against pipe-whip and discharging fluids. GDC-4 allows such dynamic effects to be excluded from the design basis if the probability of pipe rupture is shown to be extremely low.

For determination of debris generation from identified break locations, RG 1.82 Revision 1 identifies a multiple region insulation debris model developed in NUREG-0897 as an acceptable model.

Debris Generation Guidance 1985-1996

- o Applicable guidance contained in Regulatory Guide 1.82, Revision 1
- o Available for use, however, PWR licensees not required to adopt and revise design basis
- o Break locations determined per guidance contained in SRP 3.6.2 and Branch Technical Position EMEB 3-1
- o SRP 3.6.2 provides guidance for exclusion of dynamic effects of break locations (in accordance with GDC-4) based on low probability of piping rupture under design basis conditions
- o Debris generation from identified break locations determined using experimentally developed multi-region insulation destruction model

Regulatory Guide 1.82, Revision 2

Regulatory Guide 1.82 was revised a second time in May 1996 to alter the debris blockage evaluation guidance for boiling water reactors. While the Introduction section notes that only the section concerning BWRs were changed from Revision 1, a noted change to sections applicable to PWRs is the deletion of any reference to SRP section 3.6.2 for use in determining break locations.

Debris Generation Guidance 1996-2003

- o Applicable guidance contained in Regulatory Guide 1.82, Revision 2
- o Available for use, however, PWR licensees not required to adopt and revise design basis
- o Removed allowance for consideration of extremely low probability of rupture per SRP 3.6.2, BTP EMEB 3-1 and GDC-4.
- o No specific guidance on break locations or break sizes for PWRs. BWR guidance revised to include consideration of debris generation from a range of break sizes, locations and other properties to provide assurance that most severe postulated LOCAs are calculated.

Debris generation from identified break locations determined using experimentally developed insulation destruction models

Regulatory Guide 1.82, Revision 3 (Draft)

In a proposed revision 3 to RG 1.82, guidance for debris generation is revised primarily to provide more detailed guide for PWRs. Consistent with Revision 2, the guidance calls for determination of debris generation for a range of break sizes, break locations, and other properties to provide assurance that the most severe postulated LOCAs are calculated.

Debris Generation Guidance 2004(?)

- Proposed revision 3 to Regulatory Guide 1.82
- Consistent with Revision 2, no allowance for consideration of extremely low probability of rupture per SRP 3.6.2, BTP EMEB 3-1 and GDC-4.
- PWR guidance revised to include consideration of debris generation from a range of break sizes, locations and other properties to provide assurance that most severe postulated LOCAs are calculated.
- Debris generation from identified break locations determined using experimentally developed insulation destruction models

5.3 Precedence for Consideration of Fracture Mechanics in Meeting 10CFR50.46 Criteria

5.3.1 GDC-4 – Leak Before Break

In October 1987, General Design Criterion (GDC) 4 in Appendix A to 10 C.F.R. Part 50 was revised to allow the use of fracture mechanics to exclude dynamic effects from the design basis of qualified piping (i.e., piping for which the probability of rupture can be demonstrated to be extremely low). Specifically:

> *"**Criterion 4 - Environmental and dynamic effects design bases**. Structures, systems, and components important to safety shall be designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation, maintenance, testing, and postulated accidents, including loss-of-coolant accidents. These structures, systems and components shall be appropriately protected against dynamic effects, including the effects of missiles, pipe whipping, and discharging fluids, that may result from equipment failures and from events and conditions outside the nuclear power unit. <u>However, dynamic effects associated with postulated pipe ruptures in nuclear power units may be excluded from the design basis when analyses reviewed and approved by the Commission demonstrate that the probability of fluid system piping rupture is extremely low under conditions consistent with the design basis for the piping</u>."*
> [Emphasis added]

The broad-scope rule introduced an acknowledged inconsistency in the design basis by excluding the dynamic effects of postulated pipe ruptures while retaining non-mechanistic pipe rupture for containments, ECCS, and environmental qualification (EQ) of safety-related electrical and mechanical equipment.

The NRC staff subsequently clarified its intended treatment of the containment, ECCS, and EQ in the context of LBB applications in a request for public comment on this issue that was published on April 6, 1988 (53 FR 11311). In its clarification the staff stated that the effects resulting from postulated pipe breaks can be generally divided into local dynamic effects and global effects. Local dynamic effects of a pipe break are uniquely associated with that of a particular pipe break. These specific effects are not caused by any other source or even by a postulated pipe break at a different location. Examples of local dynamic effects are pipe whip, jet impingement, missiles, local pressurization, pipe break reaction forces, and decompression waves in the intact portions of that piping or communicating piping. Global effects of a pipe break need not be associated with a particular pipe break. Similar effects can be caused by failures from such sources as pump seals, leaking valve packings, flanged connections, bellows, manways, rupture disks, and ruptures of other piping. Examples of global effects are gross pressurizations, temperatures humidity, flooding, loss of fluid inventory, radiation, and chemical condition.

The application of LBB technology eliminates the local dynamic effects of postulated pipe breaks from the design basis. However, global effects may still be caused by something other than the postulated pipe break. Since the global effects from the postulated pipe break provide a reasonably conservative design envelope, the NRC staff continue to require the consideration of global effects for various aspects of the plant design , such as EQ, ECCS, and: the containment.

5.3.2 Industry Proposal to Apply GDC-4 Exclusion to Local Debris Generation

In a letter dated October 4, 2002 (Reference 4), NEI provided its view on the application of the LBB considerations of GDC-4 to local debris generation from a postulated break. NEI presented the position that debris generation, as a result of break jet expansion and impingement forces, is a dynamic effect uniquely associated with pipe rupture and, as such, is appropriately encompassed within the scope of the revised GDC-4.

In its letter, NEI made the following points:

- Debris generation within the zone of influence of a break is a local dynamic effect covered by GDC-4

  The dynamic effects addressed by GDC-4 are delineated in the Federal Register notice that modified GDC-4 (52 FR 41288): *"Dynamic effects of pipe rupture covered* *by this rule are missile generation, pipe whipping, pipe break reaction forces, jet impingement forces, decompression waves within the ruptures pipe and dynamic or nonstatic pressurization in cavities, subcompartments and compartments."* The initial blast wave exiting a DEGB and the ensuing break jet expansion and impingement forces are the dominant contributors to debris generation following a LOCA. Other contributors are pipe whip and pipe impact.

- Debris generation does not fall within the scope of functional and performance requirements for containment, ECCS and EQ that were retained in the GDC-4 revision

The rule change acknowledged inconsistencies in the design basis by excluding the dynamic effects of postulated pipe ruptures while retaining non-mechanistic pipe rupture for containments, ECCS, and environmental qualification (EQ) of safety-related electrical and mechanical equipment. As stated in 53 FR 11311, , "*…local dynamic effects uniquely associated with pipe rupture may be deleted from the design basis of containment systems, structures and boundaries, <u>from the design basis of ECCS hardware</u> (such as pumps, valves, accumulators, and instrumentation), and from the design bases of safety related electrical and mechanical equipment when leak-before-break is accepted.*" (Emphasis added)

- For PWR licensees, LBB considerations for debris generation would be applied as part of a revision to design bases that specifically incorporates mechanistic processes addressing debris generation, debris transport and debris blockage.

The ECCS recirculation designs for most PWR plants in the U.S. are based on guidance provided in Revision 0 of Regulatory Guide 1.82, *Sumps for Emergency Core Cooling and Containment Spray Systems*. This guidance accounts for screen blockage in a non-mechanistic fashion by assuming that one-half of the vertical screen area of the sump is unavailable for recirculation flow. Since the impact of LOCA-generated debris on sump blockage is not addressed directly through this approach, consideration of leak-before-break for LOCA-generated debris would have no affect on ECCS designs that utilize this guidance in their design bases. Subsequent revisions to Regulatory Guide 1.82 (Revision 1 – November 1985, Revision 2 – May 1996, Revision 3 – draft) have incorporated a more mechanistic process that provides a more phenomenologically accurate, but conservative, estimate of the debris blockage that PWR sumps could experience following a LOCA.

In a letter to NRC dated April 30, 2003 (Reference 10), NEI recommended that the proposed revision 3 to Regulatory Guide 1.82 incorporate language that acknowledges treatment of debris generation under the LBB provisions of GDC-4. Specifically, NEI recommended that the following paragraph be included in the proposed revision to Regulatory Guide 1.82:

"Consistent with the requirements of 10 CFR 50.46, debris generation should be calculated for a number of postulated LOCAs of different sizes, locations, and other properties sufficient to provide assurance that the most severe postulated LOCAs are addressed. In accordance with GDC-4, dynamic effects associated with postulated pipe ruptures (including local debris generation) may be excluded from the design basis when analyses reviewed and approved by the Commission demonstrate that the probability of fluid system piping rupture is extremely low under conditions consistent with the design basis for the piping."

5.3.3 Status of NRC Response to NEI Proposal

NRC has not issued a written response to the NEI positions on use of GDC-4 to exclude local debris generation as a local dynamic effect for qualified piping. NRC staff have stated during public meetings that they believe that the requested exclusion of local debris generation is not in accordance with the requirements of 10 CFR 50.46. Specifically, 10 CFR50.46(c)(1) which defines LOCAs as "*hypothetical accidents that would result from the loss of reactor coolant, at a rate in excess of the capability of the reactor coolant makeup system, from breaks in pipes in the reactor coolant pressure boundary* <u>*up to and including a break equivalent in size to the double-ended rupture of the largest pipe in the reactor coolant system*</u> [emphasis added]." The preliminary staff position appears to preclude the use of GDC-4 in analyses performed to meet the "long-term cooling" requirements of 10 CFR 50.46 criteria. Although, it is noted that NRC has reviewed and approved break-size exclusions allowed by GDC-4 in analyses performed to meet the "coolable geometry" criterion of 10 CFR 50.46.

5.3.4 Use of Fracture Mechanics to Meet 10CFR50.46 "Coolable Geometry" Criterion

Subsection (b) of 10 CFR50.46 specifies 5 criteria that must be met by the ECCS. They are:

1) Peak cladding temperature. The calculated maximum fuel element cladding temperature shall not exceed 2200º F.

2) Maximum cladding oxidation. The calculated total oxidation of the cladding shall nowhere exceed 0.17 times the total cladding thickness before oxidation.

3) Maximum hydrogen generation. The calculated total amount of hydrogen generated from the chemical reaction of the cladding with water or steam shall not exceed 0.01 times the hypothetical amount that would be generated if all of the metal in the cladding cylinders surrounding the fuel, excluding the cladding surrounding the plenum volume, were to react.

4) Coolable geometry. Calculated changes in core geometry shall be such that the core remains amenable to cooling.

5) Long-term cooling. 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.

The first three criteria (peak cladding temperature, maximum cladding oxidation and maximum hydrogen generation) are met through the use of approved ECCS models that meet requirements of 10CFR50.46(a). These models meet either the requirements of Appendix K to 10 CFR50.46 or make use of NRC approved best estimate models. These "core response" models model the full range of break sizes (up to and including full double-ended guillotine break of the largest pipe in the reactor coolant system) in accordance with 10CFR50.46(c)(1). The assumptions on break opening time range from "instantaneous" (a requirement for all Appendix K models) to 1 millisecond (for some NRC approved Best Estimate LOCA models). Fracture mechanics considerations are not taken into account in either the Appendix K models or Best-estimate models.

The fourth criterion (Coolable Geometry) is demonstrated through the performance of dynamic analyses of the assembled reactor vessel, internals, and fuel and is performed for a range of postulated LOCAs in accordance with applicable regulatory guidance. The results of these analyses provide assurance that the forces resulting from the postulated LOCAs will not result in fuel assembly deformation to an extent that would lead to a loss of "coolable geometry."

For most, if not all PWRs, the range of LOCAs that are considered is limited through application of Leak-Before-Break considerations, supported by fracture mechanics. Using NRC approved guidance, forces resulting from breaks in LBB qualified piping are not included in the set of analyses performed to demonstrate compliance to 10 CFR 50.46(b)(4).

The proposed use of fracture mechanics to demonstrate compliance with the fifth criterion (long-term cooling) is significantly more conservative than the NRC approved methods used to demonstrate "Coolable Geometry." In the modeling that will be used to demonstrate long-term cooling following a postulated LOCA, a full range of break sizes (up to full double-ended guillotine rupture of largest pipe) will continue to be addressed for all relevant phenomena with the exception of the dynamic effects which impact local debris generation. All other phenomena affecting long term cooling (e.g., break flow, global effects within containment, debris transport, screen blockage) will model a full range of break sizes and locations.

6 Retained Safety Margins

The determination of debris generation that results as a direct consequence of the local dynamic effects of a postulated pipe break is a single step in the larger effort necessary to assess the recirculation performance of the ECCS and CSS following a design basis LOCA.

In order to calculate plant response to a postulated pipe break event and the potential for significant blockage of the containment sump screens, it is necessary to take into account a wide range of phenomena and processes. Figure 6-1 illustrates some of the phenomena and processes that must be considered. These phenomena and processes are highly dependent upon plant design and operation as well as the specifics of the postulated LOCA event. The complexity and multivariate nature of the event progression, coupled with the absence of a comprehensive database addressing the full range of encountered phenomena inevitably leads to a calculation process that accounts for the resulting uncertainties in a conservative manner.

As noted before, typically the analyses investigating ECCS operation during the recirculation phase divide the process into three separate phases: (1) Debris Generation, (2) Debris Transport and (3) Debris Accumulation and Headloss. Each phase of the calculation process, while interdependent, involves its own set of phenomena and uncertainties. Known limitations in the knowledge base of these phenomena and associated calculation methods are typically accounted for in a bounding fashion during each phase of the process. Thus, it is important to note that the more realistic treatment of the debris generation phase using the break characteristics model described in this paper, neither eliminates nor alters the conservative treatment of other phenomena and processes. As such, the overall results from the analyses will retain a significant degree of conservatism.

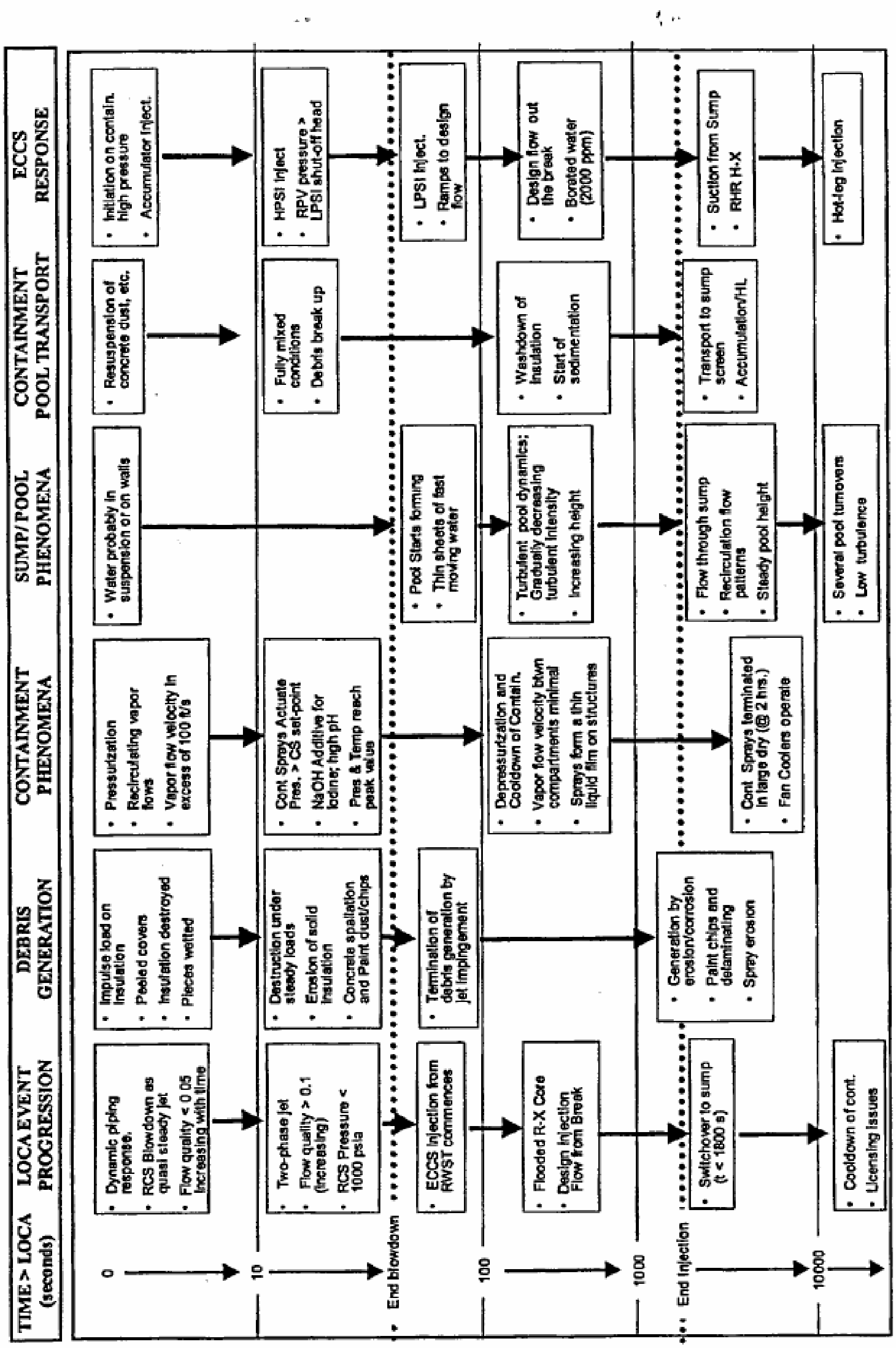


Figure 6-1
PWR LLOCA Accident Progression in a Large Dry Containment (Ref. 1)

7 Summary

This paper outlines a method of using fracture mechanics analysis techniques to define pipe break areas for the evaluation of consequential debris generation for post-accident containment sump performance evaluation. The proposed break characterization model is based on stable leakage crack sizes that generate detectable leaks and have already been calculated for PWR primary coolant piping and, in some cases, surge line piping. The debris generated from the proposed break characteristic model areas are meaningful with respect to sump performance and are based on the actual behavior of the piping material under normal and off-normal conditions.

For added margin, the proposed break characteristic model incorporates a factor of 1000 applied to the flow area of a stable through-wall flaw that produces a 10 gpm leakage rate. The geometry of the breach will be taken to be a circular hole in the pipe of interest.

Fracture mechanics analysis techniques have been used successfully, in conjunction with plant leak detection systems, to determine the size of stable cracks for PWR primary loop piping. The leakage flow of these stable cracks has been evaluated to be 10 gpm, or a factor of 10 above the leak detection capability of PWR plants.

It is therefore concluded that the proposed break characteristic model based on calculated stable leakage cracks using proven fracture mechanics techniques provides an acceptable, conservative, yet realistic approach for the evaluation of containment sump performance.

8 References

1) Regulatory Guide 1.82, Revision 3, *Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident*, February 2003 (proposed)

2) DRF A74-00003, *Evaluation of Existence of Blast Waves Following Licensing Basis Double-Ended Guillotine Pipe Breaks*, Moody, F.J., Green, T.A., August 1996 (Provided in Technical Support Documentation of NEDO-32686-A, Utility Resolution Guidance for ECCS Suction Strainer Blockage)

3) NUREG/CR-6762, Volume 1, *GSI-191 Technical Assessment: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance*, August 2002

4) Letter, Alex Marion, NEI to Gary Holahan, NRC, *Application of Leak-Before-Break Technology to Pipe Break Debris Generation and Request for Public Comment Opportunity*, October 4, 2002

5) WCAP-15131, Revision 1, *Technical Justification for Eliminating Large Primary Loop Pipe Rupture as the Structural Design Basis for the D. C. Cook Units 1 and 2 Nuclear Power Plants*, [Proprietary] (This topical report is representative of a large number of plant specific analyses performed for Westinghouse designed plants.)

6) CEN-367-A, Revision 000, *Leak-Before-Break Evaluation of Primary Coolant Loop Piping in Combustion Engineering Designed Nuclear Steam Supply Systems*

7) BAW-1847, Revision 1, *The B&W Owners Group Leak-Before-Break Evaluation of Margins Against Full Break for RCS Primary Piping of B&W Designed NSS*, September 1985 [Proprietary] (This topical report is representative of the evaluations performed for the B&W designed plants.)

8) USNRC Regulatory Guide 1.45, *Reactor Coolant Pressure Boundary Leakage Detection Systems*, May 1973

9) NUREG-1061, Volume 3, Report of the U.S. Nuclear Regulatory Commission Piping Review Committee, *Evaluation of Potential for Pipe Breaks*, November 1984

10) Letter, Anthony Pietrangelo, NEI to NRC Rules and Directives Branch, *Comments on Draft Regulatory Guide DG-1107, Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident, (68 Fed. Reg. 13338)*, April 30, 2003

Attachment C
Comparison of Transport Factors Obtained from Nodal and CFD Approaches

1 Background

In the event of a loss of coolant accident (LOCA) within containment of a PWR there is the potential for the generation of debris with the attendant concern of containment sump screen blockage. The debris, consisting piping or equipment insulation, paint, concrete dust or general containment housekeeping materials may be transported to the containment sump during the recirculation phase of ECCS and containment spray operations. The transport and subsequent deposition of debris on the containment recirculation sump screens has been identified by the NRC as Generic Safety Issue (GSI) -191: "Assessment of Debris Accumulation on PWR Sump Performance". The NRC concluded from the results of research on BWR ECCS suction strainer blockage that new phenomena and failure modes were not considered in the resolution of Issue A-43. Unresolved Safety Issue A-43, "Containment Emergency Sump Performance" had been previously been previously evaluated and declared as resolved by the NRC in 1985. In addition, operating experience identified new contributors to debris and possible blockage of PWR sumps, such as degraded or failed containment paint coatings. Thus, this issue was identified by NRR to address an expanded research effort to address these new safety concerns.

The NRC subsequently issued Bulletin 2003-01, "Potential Impact of Debris Blockage on Emergency Sump Recirculation at Pressurized-Water Reactors," to address near-term interim measures. The purpose of the bulletin was to request information from the PWR licensees describing:

1. compliance with existing requirements or
2. The implementation of interim compensatory measures.

The NRC has issued a Temporary Instruction with the primary purposes to:

1. Ensure that licensee actions are consistent with bulletin responses and the bulletin's intent and
2. Verify PWR licensees are performing containment condition assessments to ensure that they are prepared to perform sump evaluations soon after guidance is issued.

Further the NRC intends to issue a Generic Letter which will likely request the following information from licensees:

1. The guidance/methodology used to perform the sump evaluation
2. An implementation schedule for any modifications the evaluation demonstrates to be necessary
3. A description of interim compensatory measures to be taken until necessary modifications can be performed
4. A basis for concluding that the debris blockage concerns associated with GSI-191 do not adversely impact sump performance once any necessary modifications are complete
5. A description of any controls in place to ensure material brought into containment would not degrade sump performance.

The regulatory focus on this issue will ultimately require licensees to analyze containment sump performance with a focus on the generation and transport of debris to the sump screens. The intent of this analysis and report is to provide operators the means to analyze post accident fluid velocities on the containment floor without the complexity and manpower investment required to perform a computational fluid dynamics analysis.

2 Introduction

2.1 Los Alamos National Laboratory CFD Analysis

Los Alamos National Lab (LANL) Nuclear Design and Risk Analysis Group developed a computational fluid dynamics (CFD) model of the Comanche Peak Steam Electric Station. The simulation model was formulated to evaluate fluid movement within the Comanche Peak flooded containment floor region following a loss of coolant accident. The objective of the program was to determine the expected water velocities in the containment pool following a theoretical LOCA scenario and determine debris transport probability. The model developed and cases investigated utilizing a commercial CFD code included among other scenarios a Large break LOCA with maximum pool depths and safeguards flow rates. The modeling was a three dimensional steady state simulation and included nearly 500,000 cells. The boundary conditions were provide by Texas Utility Services (TUS) personnel and included flow input points and magnitudes to the containment pool, safeguard pumped flow rates, the containment flood levels and the containment structural configuration. The data had been previously developed by TUS to support other analyses related to Comanche Peak sump debris issues.

2.2 Westinghouse Owners Group Analysis

As an option to doing a CDF analysis, an effort was conducted to replicate the results of the LANL CFD analysis results utilizing a conservative but less complex approach in an attempt to support utilities evaluations expected to be required. The results of the LANL simulations provided benchmark against which the results of the analysis were judged. A channel flow network model was developed and evaluated with network analysis software tool and then the results were compared to the LANL results. The results compared favorably with the LANL benchmark and are discussed in detail in section 4.

3 Open Channel Flow Network Development

3.1 Purpose

It is fully expected that the plant operators will be required to provide an analytical evaluation of the containment sump performance in light of the GSI 191 and the anticipated NRC Generic Letter. See the discussion of regulatory actions discussed in Section 1.0. An integral part of that evaluation by necessity will be the transport of event generated and other debris to the containment sump to ascertain the potential for ECCS sump blockage. Deposition on the containment sump screen then becomes a concern for increased differential pressure across the screen during ECCS and containment spray accident recover operations.

Integral to debris transport is the fluid velocity from the cooling water sources following the accident scenario to the containment sump. One method of evaluating fluid transport velocities is to develop a CFD model and simulate break and spray flows to determine local velocities. Although the CFD analysis provides an accurate prediction of flow velocities the manpower requirements in generating the model presents economic basis for pursuing other approaches. An alternative method was evaluated for other potential means of predicting flow velocities within containment flooded regions. Westinghouse focussed on a channel flow network analysis of the Comanche Peak containment floor. The results of the CFD analysis assisted in developing an appreciation of containment channel flow and also served as a benchmark against which the analysis results could be compared.

3.2 Model Inputs

The pre-requisites for successful open channel flow network modeling of the post accident ECCS sump include the following. For the Westinghouse efforts the inputs were provided by the identified sources.

3.2.1 Containment Configuration

Floor Plan and Elevation Configuration: It is essential that an accurate configuration of containment flooded region be well defined including any obstacles to flow. For the Comanche Peak work TUS personnel provided structural and architectural drawings of Unit 1 providing the necessary depiction of the containment sump and flooded plane. Both plan and elevation views are required.

3.2.2 Containment Water Definition

Water Sources: TUS had defined for the LANL CFD analysis the sources of post accident water into the flood plane to be used as the boundary conditions for the modeling. TUS had precisely defined 24 water sources to the containment floor based on previous containment debris analysis work. Although the precise definition of sources is advantageous for the accurate definition and modeling of channel flows, a similar exhaustive definition for an open channel flow evaluation consisting of approximately 8 to 15 open channels is likely not required. The water sources (magnitudes and physical locations) used in the LANL CFD model was also used within the Westinghouse analysis to assure any comparison to the CFD results was valid.

Flood Plane: It is necessary to define the flooding elevation on the containment floor. The flooding level used within the Westinghouse analysis was based on the value used by LANL supplied by TUS to assure any comparison to the CFD results were valid.

Post Accident Flow Rates: The post accident containment sump flow rates including (ECCS and containment spray flows) are necessary in the determination of velocities. The Westinghouse analysis used the same value used in the LANL to assure any comparison to the CFD results was valid. TUS had provided the flow rate data to LANL.

3.3 Model Development

3.3.1 Channel Definition

The open channel specification was based on identifying major flow areas from the various sources to the final destination, i.e., the sump. In the case of the Comanche Peak containment the basic channel model definition is a ring of channels around the containment floor with sources defined along the ring header and a destination of the containment sumps. Although most containments are expected to be a similar contiguous ring from sources to destinations it is not essential to the modeling.

The boundaries of the individual channels are defined based on either major structural or flow changes. Essentially, at any point there is a significant change in flow area (increase or decrease) the channel should be terminated and new one defined until the next structural or flow change. The same approach is taken at points of significant flow input to the network. If less than major changes in flow are introduced along the defined channel it conservatively assumed to occur at the beginning of the channel.

Depiction of the Comanche Peak channel network definition is illustrated in Figure 1.

Finally, the results of the LANL were used to enhance the understanding of fluid motion on the flooded containment floor and influence the definition of channel boundaries. The visual representation of the CFD results proved valuable in the understanding of flow movement. Figure 2 provides the channel definition superimposed over the velocity vector field.

3.3.2 Flow Resistance Calculations

Form and channel frictional losses were included in channel resistance to flow. Form losses were primarily based on the reduction or increases in flow areas and were calculated based on hydraulic diameters. K factors were taken from Crane Technical Paper 410 (Reference 1).

Frictional losses were calculated based on Altsul's Formula as presented in Reference 2 and then verified with the Colebrook-White formula (Reference 2).

Altsul's Formula

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

Colebrook-White Formula

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

Where f is the Darcy friction factor coefficient
R_e is the Reynolds number
D_h is the hydraulic diameter
k_s is the roughness height

Figure 1 provides the results network channel definition and includes the calculated friction and form resistances, Flow area and hydraulic diameter for each channel. Figure 2, then superimposes the channel network defined on the above basis onto an yx plot of the LANL CFD model results. The figure is a composite of the results presented at the NRC public meeting of March 5, 2003 in Albuquerque, NM.

4 Results

4.1 Network Code versus CFD Code Results

LANL provided electronic files of the results of their CFD code simulation at specific containment elevations. The data was reduced and used to calculate the channel flow velocities within the defined Westinghouse network analysis. These values were then compared to the results of network code analysis to ascertain the success in replicating the flow results. Table 1 provides a tabulation of the network analysis flow velocities versus the CFD results. This comparison is for a Large Break LOCA in the lower left loop compartment with maximum ECCS and containment spray flow rates and a maximum flooding level.

Table 1

From Node	To Node	Network Analysis Results – Velocity	CFD Analysis Results - Velocity
		(ft/sec)	(ft/sec)
2	3	0.042	0.057
3	4	0.135	0.120
4	5	0.381	0.296
5	6	0.449	0.400

6	7	0.594	0.457
8	9	0.053	0.034
9	10	0.158	0.084
10	7	0.315	0.660

The results compare very favorably with the network analysis providing slightly higher flow velocities. This result should be expected since typically the width of the channel is not the full width of the flow area but represents the major flow area. The exception to the comparable comparison occurs in node 10 to 7. At this node the calculated flow rate from the CFD data reduction appears to be inconsistent with the specified boundary condition of 1021 gpm flow out of the lower left compartment containing the RCS break. With a revised flow rate consistent with the calculated velocities from the loop compartment is utilized then the velocity comparison is more acceptable for all channels. See Table 2.

Table 2

From	**To**	**Network Analysis Results – Velocity**	**CFD Analysis Results - Velocity**
Node	**Node**	**(ft/sec)**	**(ft/sec)**
2	3	0.084	0.057
3	4	0.165	0.120
4	5	0.438	0.296
5	6	0.490	0.400
6	7	0.642	0.457
8	9	0.015	0.034
9	10	0.080	0.084
10	7	0.682	0.660

5 Future Application

Based on the results of the channel flow network results and in particular when compared to the CFD results, it is apparent the technique may be applied to the determination of post accident fluid velocities in the flooded containment regions. Given accurate input and boundary conditions the network analysis approach can be used to provide conservative velocities.

The following pre-analysis information and guidance is necessary for successful application.

Pre-Analysis Data (Section 3.2 provides additional clarification):

- Accurate physical configuration of containment flooded region
- Sources of post accident water into the flood plane
- Definition of the flooding elevation
- ECCS and containment sump flow rates

Channel Definition Guidance

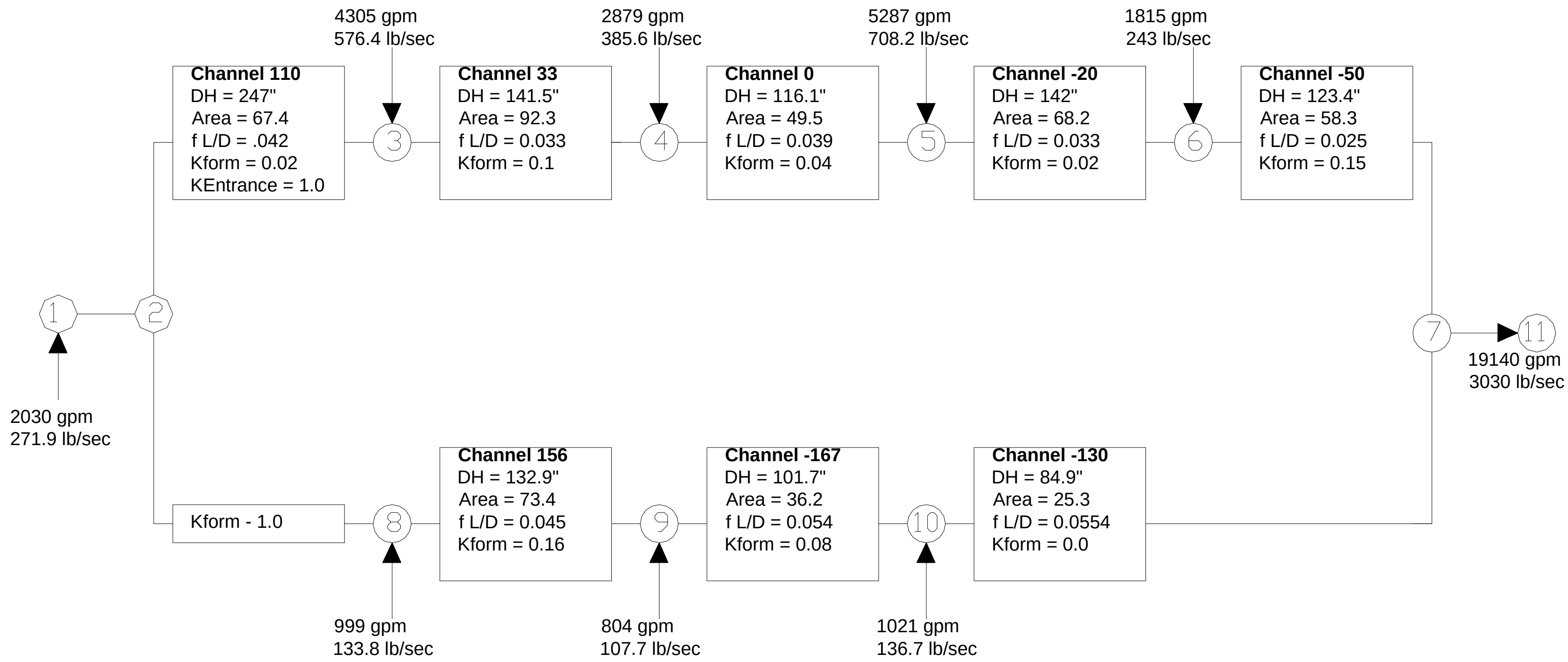
- Channels should be defined at every major restriction and expansion of flow area.
- Significant portions of the containment floor are not active in the transport of debris (the construction of smooth velocity vectors assist in the definition major active flow paths and therefor channel definition)
- The velocity vector profiles provided by the LANL illustrate the active flow areas versus pooling regions

6 Acknowledgments

Los Alamos National Lab personnel are acknowledged for their exhaustive work in generating the CFD analysis of the Comanche Peak containment pool flow and their support to in providing data and guidance in the reduction of the CFD data.

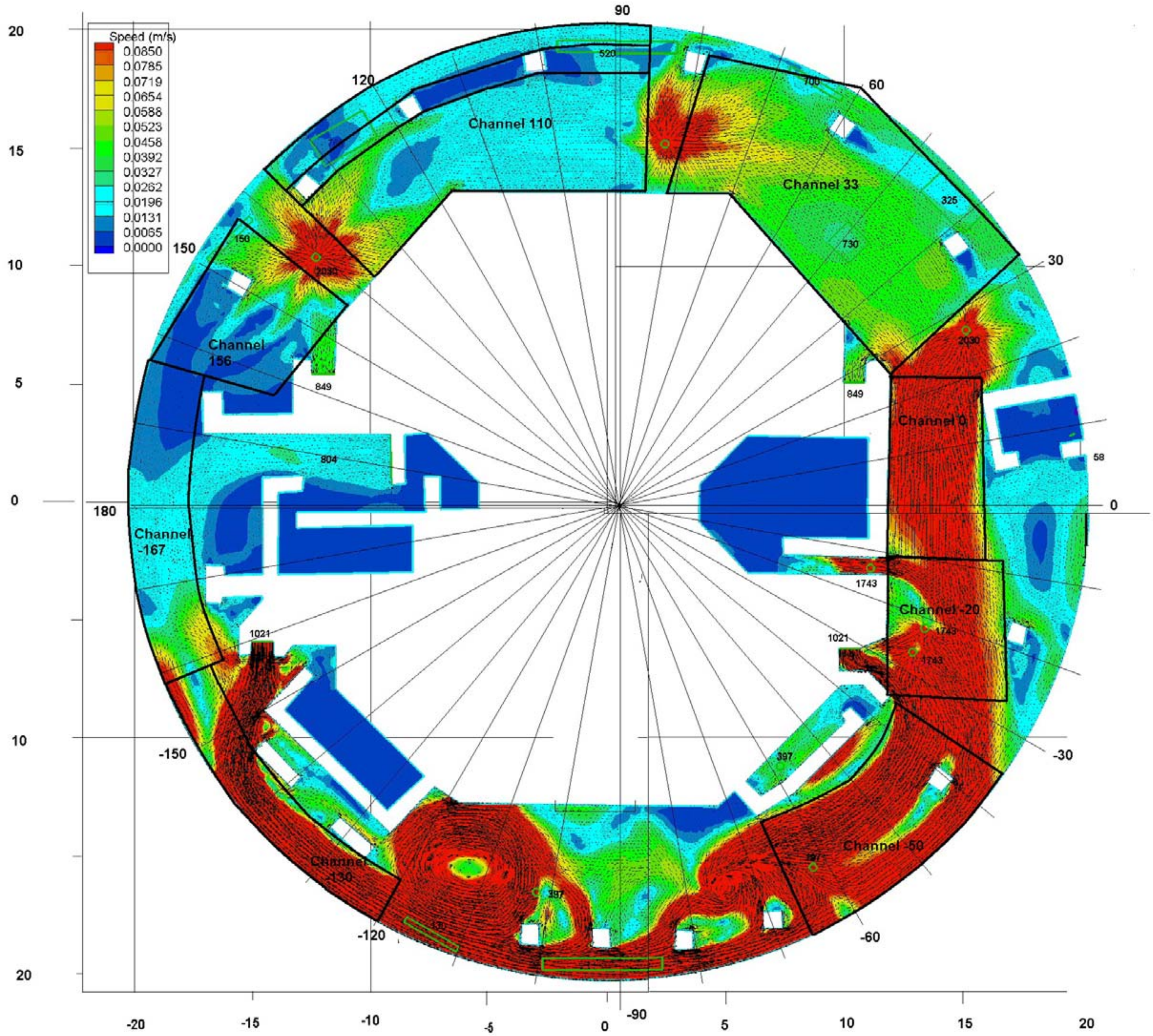
TUS personnel are acknowledged for their support of this effort in providing the necessary containment architectural and structural drawings and assistance in understanding containment configuration as well as boundary condition data.

Figure 1



4305 gpm
576.4 lb/sec
2879 gpm
385.6 lb/sec
5287 gpm
708.2 lb/sec
1815 gpm
243 lb/sec
Channel 110
DH = 247"
Area = 67.4
f L/D = .042
Kform = 0.02
KEntrance = 1.0
Channel 33
DH = 141.5"
Area = 92.3
f L/D = 0.033
Kform = 0.1
Channel 0
DH = 116.1"
Area = 49.5
f L/D = 0.039
Kform = 0.04
Channel -20
DH = 142"
Area = 68.2
f L/D = 0.033
Kform = 0.02
Channel -50
DH = 123.4"
Area = 58.3
f L/D = 0.025
Kform = 0.15
1
2
3
4
5
6
7
11
19140 gpm
3030 lb/sec
2030 gpm
271.9 lb/sec
Kform - 1.0
8
9
10
Channel 156
DH = 132.9"
Area = 73.4
f L/D = 0.045
Kform = 0.16
Channel -167
DH = 101.7"
Area = 36.2
f L/D = 0.054
Kform = 0.08
Channel -130
DH = 84.9"
Area = 25.3
f L/D = 0.0554
Kform = 0.0
999 gpm
133.8 lb/sec
804 gpm
107.7 lb/sec
1021 gpm
136.7 lb/sec

Figure 2



 10/31/03

Attachment D

A Review of Head Loss Correlations

A Review of Head Loss Correlations[1]

1. Background:

The head loss across a screen is highly dependent on the size and shape of the insulation debris reaching the screen. These debris characteristics depend on a variety of factors, including the type and manufacturer of the material (e.g., NUKON™ VS. mineral wool vs. Thermal-Wrap®); plant-aging effects such as the duration of exposure to high temperatures; the mode of transport (blowdown or washdown) to the recirculation pool; and the recirculation pool agitation at the time of the materials' transport (e.g., chugging or falling water). For example, fiber debris may vary in size from individual fibers, typically a few millimeters in length, to shreds or small pieces that retain some of the original structure of the insulation blankets.

Nearly all of the suspended fibrous and metallic insulation debris approaching the strainer will be trapped by the strainer, except for a small quantity of finely destroyed debris (e.g., small individual fibers) that may pass through the strainer during the early stages of bed formation. During these early stages, the debris beds would be very thin and have a nonuniform thickness. In extreme cases, the debris bed may result in a partially covered strainer with open voids until more debris materials are transported. Initially, such beds may not possess the required structure or strength to filter the particulate debris, especially particulates that are a few microns in size. As a result, the majority of the particulate debris approaching the strainer during these early stages will most likely penetrate the strainer and circulate through the reactor core region. The concerns arising from this consideration are know as "downstream effects" and are addressed elsewhere.

The nonuniformity of the bed during its initial formation may result in a redistribution of incoming flow, with more flow through the open areas where the flow resistance is lower. As a result of this redistribution, the newly arriving debris will be carried to the open areas of the strainer where they would be deposited. With time, continuous addition of debris in this manner will ultimately lead to formation of a thin, uniform debris bed on the strainer surface.

The PWR's with quiescent (i.e. low turbulence pools) and low approach velocities that the some or all of the material may not be transported to the screens. The material (particularly paint and RMI) which is transported near the floor may tend to accumulate near the front of the vertical or inclined

[1] This attachment was extracted from a draft section 5 entitled "Head Loss Analysis" prepared by John Gliscon for the OECD/NEA International Working Group on PWR ECCS Reliability. The extracted material underwent an editorial review to reflect recent developments and conformance to the NEI guideline format.

screens. These factors should be considered in the development of the actual debris loads that the screen will be subjected.

As the debris bed thickness increases, it acquires the required structure to commence filtering particulate debris passing through it. Filtration efficiencies close to 100% may be possible for larger particulates such as paint chips and concrete dust, but efficiencies on the order of 25 to 50 percent have been reported for filtration of particles ranging in size from 1-10 µm. As such, the quantity of particulate debris filtered by the fiber bed and, consequently, the head loss across the strainer (which is an increasing function of both the amount of debris trapped on the strainer and its geometry) are strong functions of the size distribution of the particulate debris reaching the strainer. This also brings into focus the important role played by filtration efficiency in estimating the head loss.

The head loss incurred during the debris bed buildup and the time at which such head loss may exceed the available NPSH margin are important factors in design considerations and in planning for mitigative actions. The rate of head loss increase and the magnitude thereof will be influenced by the following factors:

- the amount of various types of debris reaching the strainer and their rate of transport at any given time;
- size distribution and type of the debris reaching the strainer;
- the filtration efficiency of the fibrous bed to trap particulate matter;
- ECCS flow rate and approach velocity,
- The recirculation pool temperature;
- Plant-specific considerations such as screen/strainer area, hole or mesh size, design and arrangement

The detail to which such phenomena are modeled can significantly affect the calculated head loss at any given time. Experience has shown the need to adopt a plant specific transient analysis model that incorporates all these considerations for performance evaluations. Moreover, mixtures of fibrous materials and microporous insulation or calcium silicate may exhibit significantly high head loss for relatively low amounts of fibrous material. Consequently, it is not appropriate to extrapolate head loss obtained for one mixture of debris to another without taking into account the debris characteristics. Any predictive calculations should be based on test data that provides accurate debris characteristics of the constituents of the debris beds. Extrapolation of correlations that do not factor the debris characteristics explicitly should not be practiced.

2. Brief Summary of Significant Head Loss Tests

Table D-1 at the end of this attachment provides a compilation of the testing and data, results, and pressure drop relationships developed by several organizations that have issued publicly available head loss test information. In addition, Table D-1 provides a summary of experiments and tests. The insulating materials used or simulated in these experiments consisted of:

- mineral wool (rockwool)
- low-density fiberglass (NUKON™, Transco Thermal-Wrap®)
- high-density fiberglass
- Caposil (Unibestos) (calcium silicate containing asbestos2 fibers)
- calcium silicate (diatomaceous earth, “Newtherm”, “Calosil”)
- insulation particulates (e.g., calcium silicate and alumina)
- reflective metallic insulation with stainless steel foils
- reflective metallic insulation with aluminum foils
- Microporous insulation, including Min-K and Microtherm

Other debris materials included in some tests were:

- paint chips
- rust (iron oxide corrosion products)
- metallic particulates

a. Early Tests

Various techniques were used to generate insulation debris of representative classes of size. For fibrous insulation, these included manual (hand) shredding, mechanical shredding (meat mincer, leaf shredder) and jet fragmentation (steamjets, waterjets, and airjets). The actual size class of the fibrous debris varied from as- fabricated blankets (without covers or scrims) to finely destroyed debris consisting of a significant quantity of individual fibers. Production techniques such as manual shearing and jet fragmentation were used for generation of nonfibrous insulation fragments used in the experiments (e.g., metallic insulation).

U.S. boiling-water reactor (BWR) corrosion products were initially simulated using iron oxide particles that are larger than 75mm in size owing to the lack of information related to size characteristics of the rust particles usually found in the BWR suppression pools. The U.S. BWROG later provided the following information that was used to size the corrosion products:

Table 5.1: Size Distribution of Suppression Pool Sludge

SIZE, MM	% by weight
0-5	81
5-10	14
10-75	5

The paint chips varied from 0. 125 in. to 0.25 in. in size; and from 0.02 g to 0. 16 g in weight. The size of the paint chips used in the experiments was based on engineering analyses provided by the BWROG for BWR containment coatings.

The head loss experiments listed in Table D-1 can be broadly categorized as (1) separate effects experiments and (2) small-scale strainer qualification tests. The focus of the separate effects tests was to develop relationships that correlate strainer head loss to flow velocity and the amount of debris on the strainer. The intent of the investigators is to use these relationships, together with engineering judgment and assumptions regarding the debris generation and transport, to provide the basis for design and sizing of the strainers. Typically, these tests employed a flat plate strainer and a closed test loop to conduct experiments. Note that the results from a once-through column and closed-loop and open-loop recirculating experiments can produce significantly different results if these experiments are not preplanned to separate such effects.

Typical data reported by the closed-loop experiments included head loss as a function of strainer-approach velocity and the quantity and type of debris added to the test loop. Some of the European experimental data were reported in the form of coverage (kg/m^2) of insulation material required to produce a head loss of 2 m of water across the strainer as a function of velocity. The material in Table D-1 includes the parameters and range studied in each experiment. The head loss data were reported for theoretical bed thicknesses in the range of 3 mm to about 25 cm; approach velocities in the range of 1 cm/s to 0.5 m/s; at temperatures of 20 - 25^{O} C and 50 - 55^{O} C; and for nominal sludge-to-fiber mass ratios' in the range of 0 to 60. Considerable scatter exists in head loss data from different sources. Careful examination of the experimental data suggests that scattering can be attributed to the following:

- Variation in size classes of debris used in the experiments to simulate LOCA-generated debris (Typically, debris produced by manual methods is larger in size, that is, NUREG/CR-6224 classes 6 and 7, and resulted in lower pressure drops. On the other hand, debris produced by mechanical methods and jet fragmentation was much smaller in size and resulted in higher pressure drops. Further

discussions related to the effect of size class on the head loss across the strainer are presented in previous sections.)
- Variation in the age of the fibrous insulation debris
- Differences in experimental test loops
- Differences in the range of experimental parameters (For example, European experiments were conducted at very low velocities, 1-10 cm/s, while the U.S. experiments were conducted at much higher velocities, 5-50 cm/s.)
- The chosen method of correlating the data (In most cases, purely empirical relationships were sought to correlate the head loss data that were obtained for a limited range of experimental parameters. This seriously limited extendibility of these individual correlations beyond their original range of study.)

b. Testing Performed After ~1995

More recent tests and experiments were performed by different organizations either to provide a basis for design of ECCS recirculation strainers/screens or a basis for regulation. The organizations recognized the major shortcomings and limitations in the early testing programs and devised the more recent ones so as to provide sufficiently detailed and proven information for the intended purposes. Documents such as NUREG-6224 and the BWROG URG are based on and/or refer these recent investigations. Following are some of the functional areas investigated:

- Head loss characteristics of various types of fibrous insulation by itself and in combination with particulate matter (sludge)
- Head loss characteristics of other less common materials, such as containment coatings, microporous insulation debris (Min-K, and calcium silicate), in combination with fibrous insulation debris
- Head loss characteristics of reflective metallic insulation debris, by itself or in combination with other debris such as fibrous and particulate matter
- Head loss characteristics of insulation debris deposited on specific strainer or sump designs.

Some of the previous difficulty in obtaining repeatable and comparable results did lie in the testing methodology. Having results which can be directly correlated with the realistic plant configurations and arrangements or which can be properly scaled to these is important.

c. Head Loss Correlations

Several different approaches and methodologies have been employed for predicting head loss across debris beds. These approaches include theoretical or semi-theoretical relationships and empirical relationships. As discussed, below, some of the early empirical relationships, while adequate for their intended purpose of predicting pressure drop across a single media debris bed, are inadequate for predicting pressure drop across mixed debris beds. This inadequacy may have contributed to some of the events challenging ECCS recirculation capability. It is important to anticipate what debris may be transported to an ECCS screen, and to employ head loss correlations valid for the combination of materials, anticipated debris characteristics, and conditions expected. Different forms and approaches for head loss correlations are described in the following sections.

i. Empirical Correlation for Fiber-Only Beds

Early strainer or screen design methods typically assumed that the screen/strainer pressure drop was primarily due to an accumulation of fibrous debris. For pure fiber beds, most studies developed empirical relationships to relate velocity and bed theoretical thickness or fibrous debris accumulation to strainer pressure drop. The relationships were usually of the following form:

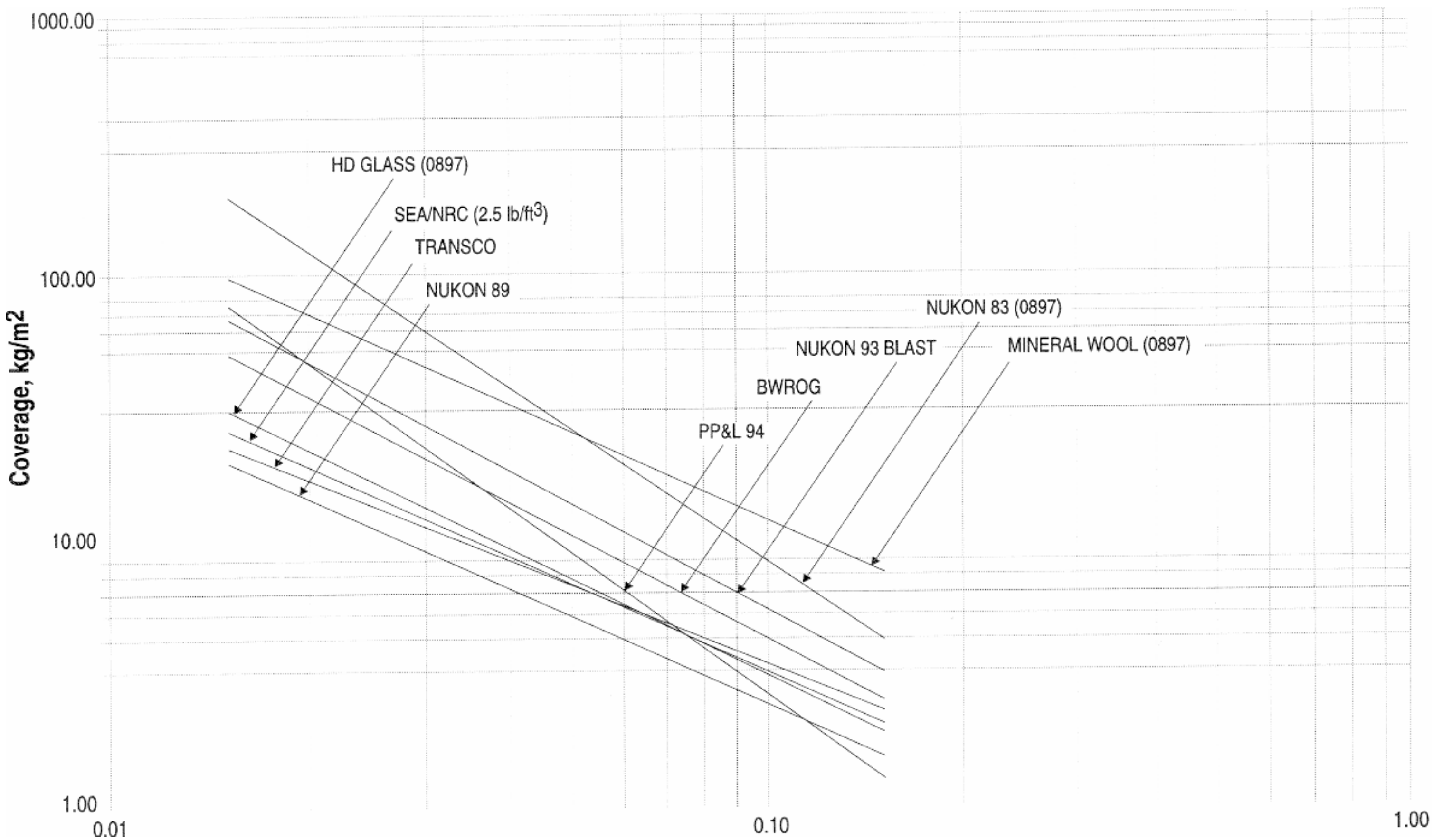
$$\Delta H = aV^b e^c \qquad \textbf{(1)}$$

where,

ΔH	is strainer head loss (ft)
V	is strainer approach velocity, (ft/s)
e	is debris bed theoretical thickness[4] (ft)
a, b, and c	are empirical constants determined in experiments

These relationships, together with engineering judgment and assumptions regarding the debris generation, debris characteristics, and transport, provided the basis for design and sizing of the strainers. Some attempts were also made to employ similar relationships to correlate experimental data obtained for mixed beds The various correlations developed for debris beds formed of pure mineral wool beds, pure low-density fiberglass beds, and mixed beds formed of fiber and sludge mixtures are contained in the summary material of Table D-1. The predictions of the correlations for low-density fiberglass are illustrated in Figure D-1 and clearly illustrates the variabilities and uncertainties associated with early correlations that apply only to the low-density fiberglass tested. Other insulation materials may exhibit different head loss characteristics.

Figure D-1: Comparison of Available Head Loss Correlation for Low-Density Fiberglass Material Plotted as Strainer Coverage Required To Develop Two Meters Water AP for Various Fibrous Materials



ii. USNRC NUREG/CR-6224 Head Loss Model

To minimize some of the shortcomings previously listed, the U. S. NRC sought a semi-theoretical approach for correlating the experimental data. Equation 2 is of a form containing two terms which account for head loss in the laminar and turbulent flow regimes, derived from the Kozeny-Carman and Ergun Equations as explained in Table D-1.

$$\frac{\Delta P}{t} = 3.55\, S_v^2 (1-\varepsilon)^{1.5}[1+57(1-\varepsilon)^3]\mu V + \frac{0.66 S_v (1-\varepsilon)}{\varepsilon}\rho V^2 \qquad (2)$$

Where,

ΔP	is the pressure drop that is due to flow across the bed (dynes/cm^2)
t	is the height or thickness of the fibrous bed (cm)
μ	is the fluid dynamic viscosity (poise)
ρ	is the fluid density (g/cc)
V	is the fluid velocity (cm/sec)
ε	is the bed porosity
S_v	is the specific surface area (cm^2/cm^3)

This correlation possesses the following salient features:

- Head loss dependence on the type of fibrous insulation material (e.g., mineral wool vs. low density fiberglass) can be directly handled by varying material properties (fiber-specific surface area, fiber strand density, and material packing density) in the equation. This eliminates the need for developing a separate equation for each debris type.
- Head loss dependence on particulate can be directly handled by varying the bed porosity.
- The same equation is valid for laminar, transitional, and turbulent flow regimes, which maximizes its usage in the plant analysis.
- Head loss dependence on water temperature can be explicitly handled through the use of flow viscosity in the equation.
- Compressibility effects can be handled by analysis.

A series of experiments was conducted by the U.S. NRC to obtain head loss data that can be used to validate the correlation previously listed. The experimental data obtained from these tests formed the most comprehensive head loss database for debris beds formed of NUKON™ and corrosion products, encompassing an experimental parameter range of 3 mm to 10.2 cm for thickness; 5 to 50 cm/s for approach velocity; 0 to 60 for sludge-to-fiber mass ratios; and at temperatures of 24 °C and 52 °C. Detailed comparison of the correlation predictions with these experimental data is presented in NUREG/CR-6224. This correlation was used for the plant evaluation reported in NUREG/CR-6224 and has also been incorporated into the BLOCKAGE computer code developed by the U.S. NRC.

The following limitations of this correlation are identified for the potential user:

- The correlation may not be applicable for nonuniform debris beds since the correlation is developed based on the assumption that the debris forms a uniform bed. This may limit equation applicability to very thin beds or thin beds formed on specialized strainers.
- The correlation may not be applicable to thin fiber beds coupled with high sludge-to-fiber mass ratios since nonuniform debris bed thicknesses, including open spaces, were observed in the ARL experiments.
- Although this correlation is expected to provide an upper-bound estimate for the head loss, these limitations and other factors presented in NUREG/CR-6224 should be reviewed before using this correlation.
- As explained below in Section 5.1.6.3, debris bed loadings of microporous insulation debris exceeding microporous to fiber mass ratio of 0.2 may result in somewhat nonconservative results from the above NUREG-6224 correlation.

iii. Impact of Microporous Insulation Debris

A postulated LOCA due to a high energy pipe break could generate a mixture of fibrous and microporous insulation debris that may be potentially transported to the ECCS pump intake screens. Experiments were conducted to address the head loss behavior due to mixtures of fibrous and microporous debris. In particular, these experiments considered several combinations of microporous insulation debris (i.e., Min-K®, Microtherm®, Cal-Sil) mixed with fibrous insulation debris and particulate debris.

The microporous tests showed that the contributions to head loss of microporous insulation could be neglected when conditions yielded a microporous mass to strainer surface area ratio of 0.02 lb/ft2. Scaling of the experimental results to the prototypical conditions can be accomplished by scaling to the actual installed strainers apportioning the microporous loads in the ratio of the flows when more than one strainer is operational.

The microporous tests also showed that it is possible to use the NUREG/CR-6224 head loss correlation to bound the observed test results for mixtures of fibrous and microporous insulation debris when the microporous-to-fiber mass ratio is less than 0.2. For quantities of debris for which the microporous-to-fibrous mass ratio exceeds the microporous-to-fiber mass ratio of 0.2, the head loss behavior appears to be dominated by the microporous component, and the NUREG/CR-6224 head loss approximation is no longer applicable.

Use of the NUREG/CR-6224 head loss correlation to approximate the observed head loss behavior due to fibrous and microporous insulation debris requires the specification of a characteristic size and density of the microporous particles. Reasonable agreement with the observed head loss results is obtained when the microporous particulate matter debris are assumed to be spherical particles, with a characteristic size of 5 µm and a density of 140 lb/ft3. With these parameters to characterize microporous particles, the NUREG/CR-6224 head loss correlation adequately bounds the observed test data when the microporous-to-fiber mass ratio is less than approximately 0.2. This comparison is shown in the next figure, which presents the NUREG/CR-6224 head loss correlation and the measured head loss results for 6 lb of fibers at a flow rate of 200 gpm (equivalent to an approach velocity of 0.09 ft/s) and a water temperature of 60°F.

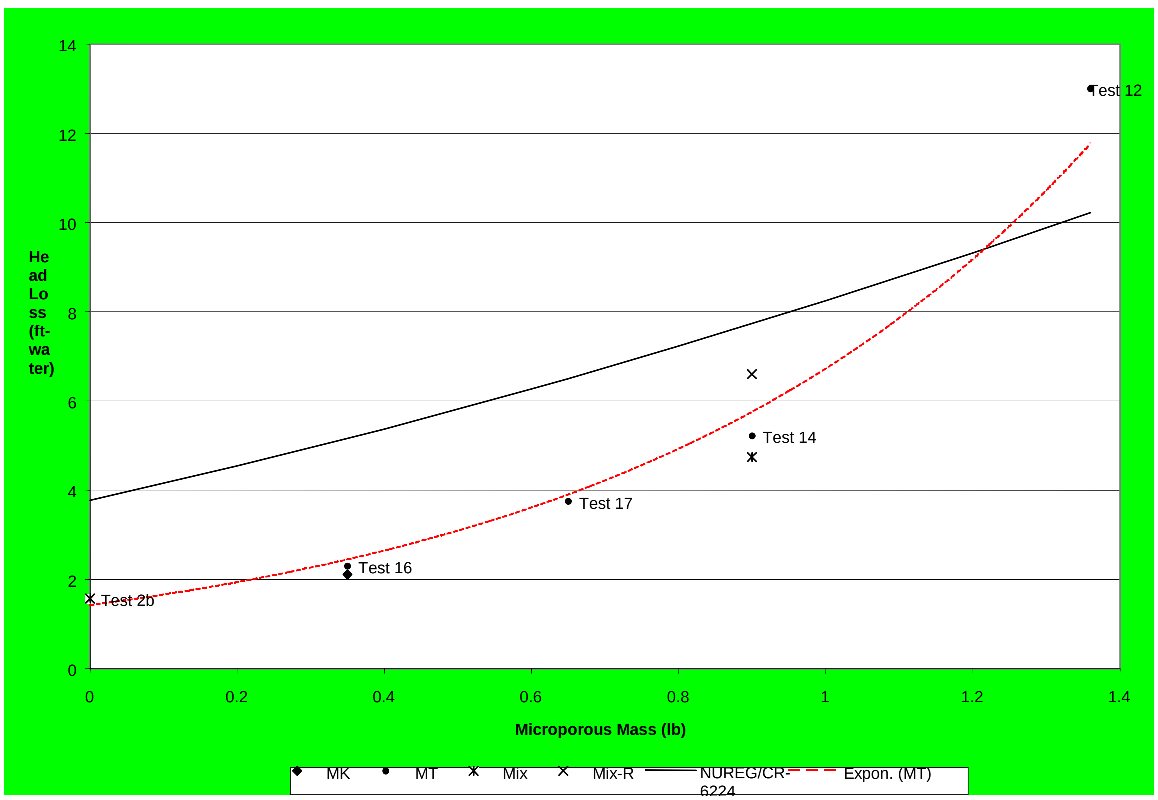


Figure D-2: Comparison between the NUREG/CR-6224 head loss correlation and the test data for 6.0 lb of fibrous insulation debris in the test tank.

As indicated in the above Figure, the NUREG/CR-6224 head loss correlation adequately bounds the test data when the microporous-to-fiber mass ratio is less than 0.2 and when the aforementioned parameters are used to characterize the microporous debris (i.e. size and density).

A comparison of the NUREG/CR-6224 head loss correlation with the test data for a microporous-to-fiber mass ratio less than 0.2, including a medium fiber load as well as the applicable test with simulated sludge, is presented in following Figure.

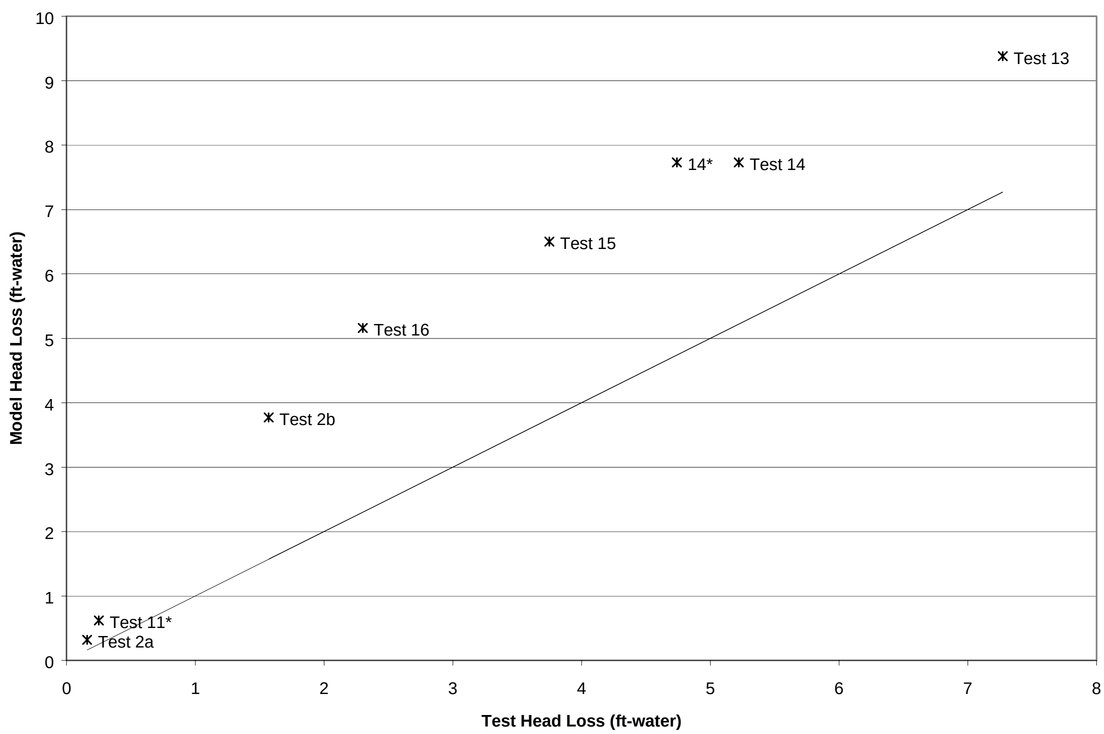


Figure D-3: Comparison between the NUREG/CR-6224 head loss correlation and the test data when the microporous-to-fiber mass ratio in the test tank is less than 0.2. (The straight line corresponds to an ideal agreement with the test results.)

As indicated in the above Figure, the proposed model of considering that microporous insulation debris may be treated as particulate matter debris, with the NUREG/CR-6224 head loss correlation, bounds the test data when the microporous-to-fiber mass ratio in the tank is less than 0.2..Consequently, estimation of head losses due to mixtures of debris with microporous insulation debris can treat the microporous insulation as a particulate matter debris in the NUREG/CR-6224 head loss correlation for fibrous debris, provided that the microporous-to-fiber mass ratio in the debris bed does not exceed 0.2.

iv. U. S. BWROG Characterization of Combined Debris Head Loss

The U.S. BWROG, while conducting combined debris testing to establish the bases for resolution of the ECCS suction strainer plugging issues, has observed phenomena that may have significant implications for potential resolutions of the ECCS suction strainer issue. In general, the BWROG observations indicate increasing head losses when both fiber loading and corrosion product loading on the strainer are increased together, which is what would be anticipated. A second and more significant observation was not initially expected. If the amount of fibrous debris in the bed is decreased while the amount of particulate material is held constant, the head loss could increase (depending on the ratio of the mass of corrosion products to the mass of fiber) rather than decrease as might be initially thought. This behavior had been previously suggested by Vattenfall.

While this phenomenon seems counterintuitive, this finding is consistent with other European experiments. As demonstrated during the Perry events and confirmed by subsequent testing, only a thin bed of fiber is required on the surface of a flat plate strainer to effectively filter out fine particulate materials that would have otherwise passed through the strainer. The BWROG testing program demonstrated that the highest head losses occur with thin layers of fiber and high ratios of corrosion product mass to fibrous debris on flat plate strainers.

Physically, a given amount of particulate material results in debris beds which can become increasingly compact and decreasingly porous as the amount of fiber present in the bed decreases. The end result is that a fiber bed of thickness just sufficient to bridge all of the strainer holes combined with an inventory of fine particulate materials can result in a very large head loss. Based on the testing performed and current understanding of the likely physical causes, these phenomena would not be expected to proceed beyond the point where the layer of fibrous material is insufficient to fully bridge all of the strainer holes. These observations were made during extensive testing both on fiber only and on debris beds comprised of fiber and corrosion products. The iron oxide corrosion products used for these tests had a larger average particle size than that typically present in U.S. BWR suppression pools. Use of the larger size particulate material was shown to result in a conservative estimate of the combined debris head losses, as larger particles are more likely to be captured in the fibrous bed. The following head loss correlation was documented in the BWROG URG (Ref. 5.2) (Note: Other correlations were developed by replacement strainer vendors.):

$$\Delta h = K_h \mu U t / (\rho g d^2) \qquad \textbf{(3)}$$

where,

Δh is strainer head loss, ft of water

μ is viscosity, lb-sec/ft^2

U is strainer approach velocity, ft/sec

t is fiber bed thickness, ft

ρ is water density slug/ft^2

g is gravitational constant, 32.2 ft/sec^2

d is inter-fiber spacing, ft

This equation has been simplified to:

$$\Delta h = a + bU \qquad \textbf{(4)}$$

where a and b are coefficients dependent on the ratios (Ms/Mf) of different masses of solids (e. g., corrosion products, paint chips, rust flakes, sand, cement dust, calcium silicate, etc.) and fibrous materials assumed to collect on the debris bed.

A significant aspect of this section is that a large head loss can occur with relatively small fibrous loading in combination with a particulate inventory, and that the resolution options must be capable of dealing with or preventing unacceptable strainer head losses. Equations (3 and 4) and the BWROG URG methodology were developed by the U.S. BWROG for specific conditions and should, therefore, be used with caution and reviewed for applicability by the user.

Moreover, the NRC Safety Evaluation Report for the URG methodology noted in section ES.7, "... the staff finds that the head loss correlations in the URG are unreliable and incomplete for plant analysis and, therefore, is unacceptable. The staff strongly recommends that utilities use vendor-provided data to qualify strainer designs, rather that relying on the correlations and calculation procedures specified in the URG."

v. Characterization of Head Loss Due to Reflective Metallic Insulation

Many plants have some reflective metallic insulation (RMI) installed, and there has been significant interest in the behavior of this material. Experiments have been performed to determine how it and other materials react to blast and jet forces, and its transport characteristics. Head loss testing of debris beds comprised of RMI, or of mixed beds containing RMI have been conducted by several different organizations, as described in detail in Table D-1. The topic of RMI debris bed head loss has initiated some disagreement, and it would appear that much of the lack of agreement stems from RMI debris shape, bed morphology and transport characteristics fundamental to the head loss experiments. For one to evaluate the effect of RMI, the shape and form of RMI reaching the bed, and the predicted morphology of the bed under accident conditions should be carefully evaluated to assure that the testing and derived relationships properly represent the real situation.

The following observations provide the basis for the method of accounting for RMI contribution to debris bed head loss in the U. S.:

- The transport characteristics for RMI may be different than other debris, and must be accounted for in predicting the debris bed formation. Depending on the pool turbulence and approach velocities, RMI deposition may not be uniform.
- If RMI is does transport and is deposited on screens/strainers, it will produce head loss. The head loss developed is highly dependent on the type of RMI debris. For example, if a large, intact sheet of metallic foil is deposited over the screen or strainer, it will reduce the flow area significantly and increase the velocity and head loss in the remaining flow area. Based on various results from debris generation testing, RMI debris is expected to be small and crumpled in form, as opposed to large, intact sheets. The head loss characteristics of this type of RMI debris range from benign to small in comparison with that expected from combined fiber/particulate beds.

The BWROG has recommended, in its URG use of the following equation for determining RMI bed head loss (the equation is valid for head losses under ~ 10 ft H2O):

$$\Delta h = K_p U^2 t_p \qquad \textbf{(5)}$$

where,

Δh	is head loss, ft of water
K_p	is a constant depending on the type of RMI and strainer
U	is the approach velocity, ft/sec
t_p	is the projected RMI debris bed thickness

A similar relationship has been suggested by the NRC:

$$\Delta P \alpha \frac{S_v(1-\varepsilon)}{\varepsilon^2} U^2 N \alpha \frac{L_1 * L_2}{K_t^2} U^2 (A_{foil} / A_{str}) \qquad \textbf{(6)}$$

where,

ΔP	is head loss
L,S	are foil dimensions
K	is inter-foil channel size
U	is approach velocity
N	is number of foil layers

Where there is combined debris consisting of fibrous material, particulate matter or sludge, and RMI, the head loss due to the fibrous and particulate material are expected to dominate. Testing of BWR prototypic strainers has indicated that RMI does not cause significantly different head losses than that caused by fibrous debris and sludge only. The NRC and BWROG research does not indicate the presence of an autocatalytic or synergistic effect between RMI and other debris beds similar to combined fibrous and particulate beds. For mixed RMI and fiber beds, the NRC approach to consideration of RMI head loss is that it should be added (summed) to the head losses expected from other (fibrous and particulate) debris unless it can be demonstrated that this conservative approach is not appropriate. This recognizes and accounts for the NRC staff conclusion that the head loss of a fiber plus corrosion product bed does not bound the head loss of a fiber, corrosion product, and RMI debris bed in all situations.

Other investigators have reported results and conclusions which would differ from the above due to considerations associated with the structure of metallic debris beds. The bed structure, as alluded to before, will have a significant impact on the head loss. For example, consider a bed of metallic foils where most of the foils are arranged parallel to the flow direction. One might expect that relative head loss resulting from this configuration with or without other material would be less than other configurations. Consider a bed where most of the foils are deposited perpendicular to the flow. This type of bed configuration will be subject to compression effects, and combined debris would also tend to increase the head loss and bed compression. The realistic situation would probably exist between these two extremes. As previously stated, the bed structure depends on many factors including its shape as generated during the LOCA event, how it is transported (tumbling on floor vs. mid-stream suspension), and its formation sequence (mixed deposition of insulation and other debris, tumbling up from bottom or curb, etc.). Again, it is important to carefully consider the plant-specific situation to develop realistic models.

Another form of RMI head loss correlations takes into consideration the pressure drop in RMI debris beds with gap or bypass:

$$\frac{\Delta p}{\frac{\rho w_o^2}{2}} = f_{(R)} \frac{nW}{D} \qquad \textbf{(7)}$$

where,

Δp	is the pressure drop
ρ	is the fluid density
w_o	is velocity
$f_{®}$	is friction factor
nW	is path length of fluid traveled in the bed; *n* is the number of foil layers and *W* the foil lateral length
D	is the width of the flow channel; depth of foil crumpledness

This relationship assumes that pressure drop in a metallic bed behaves analogously to pipe flow. The friction factor, *f* depends on bed morphology (structure), and may also contain dependency on debris surface characteristics such as relative roughness, in addition to the Reynolds number, and must be determined experimentally. The correlation is presently limited by the following assumptions:

- The debris has uniform dimensions
- The debris bed area is independent of thickness

While investigating the RMI debris head losses, it was observed that the ratio of maximum to minimum head loss for different configurations (flatter RMI debris perpendicular to flow vs. parallel to flow) can vary by two or three orders of magnitude.

It should be noted that the variability of different vendor products (e.g., dimpled foils, waffle patterns, or smooth patterns) suggests caution and review of product lines before extrapolating results. In addition, some experimental results indicate that mixtures of foil pieces and fibrous debris can result in significantly higher head losses than would be derived from summing the individual contributions.

vi. Related Methodologies

Several companion methodologies have been developed utilizing the research results and methods discussed above. These methods have been primarily developed for use in calculating the pressure drop across replacement suction strainers, and are discussed in Table D-1. Typical of these methodologies is one developed that utilizes dimensional analysis for determination of head loss and has been further enhanced to account for bed compression and different strainer geometrical configurations such as would be present in a stacked disc or star strainer. The basic equation is of the following form:

$$\Delta H\ A_S^2\ \rho / QM\ (\nu / d_{if}^2)\ [1 + k\ Re] = f(\eta) \qquad \textbf{(8)}$$

where,

ΔH	is the head loss
A_s	is the surface area
ρ	is the bed density
Q	is volume flow
M	is mass of fiber M_f and mass of sludge M_s
ν	is kinematic viscosity
d_{if}	is inter-fiber spacing
k	is a constant
Re	is the Reynolds number, $Re=(Q/As)d_{if}/v$
η	is M_s/M_f

Table D-1: Overview of Head Loss Experiments and Correlations

<table>
<tr><th>Sponsor</th><th colspan="2">Test Facility</th><th>Date</th><th>Report Reference</th></tr>
<tr><td>BWROG, GE Nuclear Energy</td><td colspan="2">Continuum Dynamics, Inc at EPRI NDE Center, Charlotte</td><td>November, 1996</td><td>D.1</td></tr>
<tr><th>Variables Studied</th><th>Ranges</th><th>Results/Relationships</th><th colspan="2">Comments</th></tr>
<tr><td>Purpose of Tests: Full-scale tests to obtain pressure loss and performance data on different strainer types as a function of debris type, quantity, flow rate, and time</td><td></td><td rowspan="9">Qualitatively, this testing showed that passive strainers had been identified which show improved performance over the original strainers. 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.</td><td colspan="2" rowspan="9">An extensive matrix of tests were performed to obtain strainer performance information which does not lend itself to summary. Consultation of the reference is suggested to obtain specific information.</td></tr>
<tr><td>Materials tested: NUKON, Kaowool, Tempmat, Calcium Silicate, BWR Corrosion Product Sludge, RMI-Various</td><td></td></tr>
<tr><td>Insulation Preparation: See Reference, Per NUREG-6224 recommendations</td><td></td></tr>
<tr><td>Material introduction method: See Reference</td><td></td></tr>
<tr><td>Coverage: Various, see reference</td><td></td></tr>
<tr><td>Approach Velocity: Various, see reference</td><td></td></tr>
<tr><td>Maximum Head Loss 500 ins H2O</td><td></td></tr>
<tr><td>Temperature 60-86 F</td><td></td></tr>
<tr><td>pH 8-10</td><td></td></tr>
</table>

Table D-1: Overview of Head Loss Experiments and Correlations

Sponsor	Test Facility		Date	Report Reference
Commonwealth Edison Company	Continuum Dynamics, Inc., Princeton, N. J.		July 1997	D.2
Variables Studied	**Ranges**	**Results/Relationships**	**Comments**	
Purpose of Tests: Evaluation of the effects of paint chips on sump strainer head loss. Determination of head loss across the sump screen resulting from the buildup of paint chips.		The effect of paint chips by themselves on head loss was minimal.	Most paint chips remained on tank floor and did not reach strainer. When flow was stopped, chips on screen fell off.	
Materials tested: Epoxy paint chips, Ameron/Amercoat 90HS by itself on screens, no other materials.				
Material Preparation Dry paint peeled from plastic sheet, then broken up by hand or in a household blender				
Material introduction method: Chips were presoaked to avoid floating, and added to test tank near diffuser				
Coverage	1000 to 4700 ft^2 paint chips on 28 ft^2 screen, scaled			
Approach Velocity Prototypical, ~0.72ft/sec				
Maximum Head Loss	0.2 inches water			
Temperature	Ambient			
pH	Ambient			

Table D-1: Overview of Head Loss Experiments and Correlations

<table>
<tr><th>Sponsor</th><th colspan="2">Test Facility</th><th>Date</th><th>Report Reference</th></tr>
<tr><td>Northeast Nuclear Energy Company, Millstone Nuclear Power Station Unit 1</td><td colspan="2">Continuum Dynamics, Inc.</td><td>February 1999</td><td>D.3</td></tr>
<tr><th>Variables Studied</th><th>Ranges</th><th>Results/Relationships</th><th colspan="2">Comments</th></tr>
<tr><td>Purpose of Tests: To evaluate the amount of coating, fibrous, and RMI debris that can be transported to a PWR sump screen during post LOCA recirculation, and to measure the resultant head loss across the debris bed. The effect of boric acid on zinc chips was also evaluated.</td><td></td><td rowspan="9">Paint chips with boric acid: with pH at 6.0 and 1”to2” bed of paint chips at V=0.25ft/sec, no movement of chips or increase in head loss.

Similar results for paint chips by themselves, no boric acid.

0.115 ft^3 NUKON fiber placed ~20 ft from sump screen. Flow started at 0.2 ft/sec, approached to 1.5 ft from screen and stopped. No change in head loss. Ten times amount of fiber placed in tank, 20 ft from screen with velocities up to .25 ft/sec with none on screen, no increase in head loss. Even with fiber moved directly in front of sump, no motion along floor or increase in head loss. Further addition of RMI did not result in debris movement or accumulation on screen.
Paint chips added during flow resulted in some transport to screen, but resulted in a head loss of <1.32 inches water.</td><td colspan="2" rowspan="6">Paint chips, fiber and RMI on the sump floor at the initiation of flow are unlikely to transport to the sump and generate any measurable head loss. Addition of boric acid does not increase the likelihood of paint chip transport.</td></tr>
<tr><td>Materials tested: Phenolene 305 epoxy and carbozinc 11 inorganic zinc primer, NUKON® fibrous debris, 2 mil stainless RMI, boric acid</td><td>Size of paint: <1/8”-13%
1/8-1/4”-40%
¼”-1/2”-39%
½”-3/4”-7%</td></tr>
<tr><td>Material Preparation</td><td>Paint applied to plastic, sheets, cured and peeled off, shredded into chips. NUKON shredded into small pieces <1/2”, classified as NUREG 6224 type 3,4, and 5. RMI cut into 6”, 3”, 1”, and 3/8” squares and then crumpled</td></tr>
<tr><td>Material introduction method</td><td>Wetted debris added to tank (full scale segment of screen) and allowed to settle, pumps then started.</td></tr>
<tr><td>Coverage</td><td>500 ft^2 equiv. Paint, 0.115 ft^3 fiber, 2.5 ft^2 RMI in test matrix</td></tr>
<tr><td>Approach Velocity</td><td>0-0.25 ft/sec</td></tr>
<tr><td>Maximum Head Loss</td><td>1.3 ins H2O</td><td colspan="2" rowspan="3"></td></tr>
<tr><td>Temperature</td><td>ambient</td></tr>
<tr><td>pH</td><td>> 6.0 with boric acid</td></tr>
</table>

Table D-1: Overview of Head Loss Experiments and Correlations

<table>
<tr><th>Sponsor</th><th colspan="2">Test Facility</th><th>Date</th><th>Report Reference</th></tr>
<tr><td>Detroit Edison/Duke Engineering and Services</td><td colspan="2">ITS Corporation at EPRI NDE Center</td><td>October 14, 1997
Preliminary</td><td>D 4</td></tr>
<tr><th>Variables Studied</th><th>Ranges</th><th>Results/Relationships</th><th colspan="2">Comments</th></tr>
<tr><td>Purpose of Tests: To characterize the impact of Min-K insulation on prototype ECCS suction strainers</td><td></td><td rowspan="9">Min-K bed is different than fiberglass. Debris bed was <1/4” thick, uniform. Debris penetrated and plugged suction strainer holes. The debris bed did not resemble long fiber over the holes.

Addition of sludge did not produce significantly higher head loss than with Min-K by itself.

Head loss seems to continue to increase with time, even after “steady state” was achieved.</td><td colspan="2" rowspan="9"></td></tr>
<tr><td>Materials tested: Min-K core material, silica an titanium dioxide, and sludge</td><td></td></tr>
<tr><td>Material Preparation</td><td>Min-K core material supplied in loose powder form, and sludge stimulant developed by NRC</td></tr>
<tr><td>Material introduction method</td><td>Flow established, Min-K slurry introduced into tank. If sludge was used it was first introduced, followed by Min-K.</td></tr>
<tr><td>Coverage</td><td>0-96 lb Min-K, 0-17 lb sludge</td></tr>
<tr><td>Approach Velocity</td><td>6350 GPM flow rate</td></tr>
<tr><td>Maximum Head Loss</td><td>158 inches water</td></tr>
<tr><td>Temperature</td><td>Ambient, 78F</td></tr>
<tr><td>pH</td><td>Neutral, tap water</td></tr>
</table>

Table D-1: Overview of Head Loss Experiments and Correlations

<table>
<tr><th>Sponsor</th><th colspan="2">Test Facilty</th><th>Date</th><th>Report Reference</th></tr>
<tr><td>New York Power Authority, James A. Fitzpatrick (JAF) Nuclear Power Plant</td><td colspan="2">ITS at Alden Research Laboratory; 1:2.4 scale model of BWR Mk 1 Suppression Pool</td><td>Spring, 1999</td><td>D 5</td></tr>
<tr><th>Variables Studied</th><th>Ranges</th><th>Results/Relationships</th><th colspan="2">Comments</th></tr>
<tr><td>Purpose of Tests: Evaluate replacement strainers for JAF; head loss data for micorporous insulation was sparse and suggested higher head losses than for fiber beds</td><td></td><td rowspan="9">NUREG/CR-6224 conservatively modeled fibrous material.

Min-K head loss is greater than that for equivalent amount of microtherm.

NUREG/CR-6224 conservatively models head losses for microporous debris microporous to fiber mass ratios <0.2

Cal-Sil head loss characteristics similar to Min-K and Microtherm</td><td colspan="2" rowspan="9">Microporous applies to either Min-K or Microtherm</td></tr>
<tr><td>Materials tested: Fibrous: NUKON, Temp-Mat and Knauf; Min-K; Microtherm</td><td></td></tr>
<tr><td>Material Preparation</td><td></td></tr>
<tr><td>Material introduction method</td><td>Debris mixed with water to form slurry, added to test tank; additional debris added in steady state plateaus: Fibrous only, microporous only, microporous and fiber</td></tr>
<tr><td>Coverage</td><td>0-6 lb fiber, 0-1 lb Min-K, 0-1 lb microtherm</td></tr>
<tr><td>Approach Velocity</td><td>~0.096 ft/sec</td></tr>
<tr><td>Maximum Head Loss</td><td>~13 ft H2O</td></tr>
<tr><td>Temperature</td><td>Ambient</td></tr>
<tr><td>pH</td><td>Ambient</td></tr>
</table>

Table D-1: Overview of Head Loss Experiments and Correlations

<table>
<tr><th>Sponsor</th><th colspan="2">Test Facilty</th><th>Date</th><th>Report Reference</th></tr>
<tr><td>USNRC</td><td colspan="2">Alden Research Laboratory</td><td>December 1995</td><td>D 6</td></tr>
<tr><th>Variables Studied</th><th>Ranges</th><th>Results/Relationships</th><th colspan="2">Comments</th></tr>
<tr><td>Purpose of Tests: Determine the pressure loss characteristics of Thermal Wrap® insulation debris with and without iron oxide particles to simulate BWR suppression pool sludge</td><td></td><td rowspan="9">No significant differences were found for fibrous insulation head losses between : Thermal Wrap®(Knauf-Transco) and NUKON™(Owens Corning-PCI)

Head loss increased with bed thickness from 3 ft H2O for 0.25” to 34 ft for 4” without sludge. Head loss also increased for increasing sludge to insulation mass ratios; for 1” bed by a factor of 70 from 0 sludge to 7.5 ratio.

Variation in sludge particle size or the addition of paint chips had no measurable effect on head loss.</td><td colspan="2" rowspan="9">Higher water temperature reduces head loss because of viscosity effects.

This testing was similar to that conducted on NUKON™ insulation debris by Alden Laboratory and reported in June 1995.</td></tr>
<tr><td>Materials tested: Thermal Wrap® insulation debris, simulated iron oxide sludge, and paint chips</td><td></td></tr>
<tr><td>Material Preparation</td><td>Insulating blankets were heat treated and shredded in a leaf shredder</td></tr>
<tr><td>Material introduction method</td><td>Sludge added to test loop, well mixed, then insulation added at once</td></tr>
<tr><td>Coverage</td><td>Fibrous insulation thickness 0.25-4 inches, size class 3 &4; and 0-30 sludge to fiber mass ratios</td></tr>
<tr><td>Approach Velocity</td><td>0.15 ft/sec during bed formation; 0.15-1.5 ft/sec test</td></tr>
<tr><td>Maximum Head Loss</td><td>~55ft</td></tr>
<tr><td>Temperature</td><td>125F</td></tr>
<tr><td>pH</td><td>Not investigated</td></tr>
</table>

Table D-1: Overview of Head Loss Experiments and Correlations

Sponsor	Test Facilty		Date	Report Reference
Fortum Engineering, Ltd			May 20, 1999	D 7
Variables Studied	**Ranges**	**Results/Relationships**	**Comments**	
Purpose of Tests: To study the strainer differential pressure caused by different insulation types when subjected to the same debris generation, testing, and sump configuration.		Corrected differential pressure for this demonstration 67.5, 10, and 33 kPa for the three insulation types listed under materials. Transportable fractions of debris were 62, 34, and 100%, respectively		
Materials tested: Fine fiber (Al-Si) insulation, coarse glass fiber insulation, and Si-Ca mineral insulation	8 kg 27 kg 5 kg			
Material Preparation	Insulation was heat treated at 300C for 48 hours, and subjected to steam/water jet impingement; resulting debris was collected, examined			
Material introduction method	After examination, the material was introduced into the sump test facility			
Coverage				
Approach Velocity	18-25 mm/sec			
Maximum Head Loss				
Temperature	50C			
pH	H_3BO_3 conc. 12g/kg H_2O			

Table D-1: Overview of Head Loss Experiments and Correlations

Sponsor	Test Facilty		Date	Report Reference
U. S. Nuclear Regulatory Commission	Alden Research Laboratory		May 1996	D 8
Variables Studied	**Ranges**	**Results/Relationships**	**Comments**	
Purpose of Tests: To provide basic insights into the behavior of RMI debris under LOCA conditions, by itself and in combination with other debris.		Introduction of prototypical RMI debris in the presence of fiber and sludge does not cause significantly different head losses than the head losses observed with only fiber and sludge loadings. During testing, RMI debris, when intermixed with fibrous debris and sludge appeared to decrease head losses compared to similar conditions without RMI debris. Head losses for RMI without any other debris were relatively small, but increased with increasing mass of RMI. RMI debris size had no practical effect on head losses for a given mass/unit area of strainer.		
Materials tested: Diamond Power MIRROR® insulation, NUKON™ insulation.				
Material Preparation:	Prototypical RMI for sedementation and head loss testing was generated by Siemens AG/KWU in Karlstein am Main, Germany			
Material introduction method	Sludge added first, then fibrous insulation and RMI, alternatively.			
Coverage	Variable			
Approach Velocity	0.15-1.5 ft/sec			
Maximum Head Loss	~37 ft H2O			
Temperature	125			
pH	Not Investigated			

Table D-1: Overview of Head Loss Experiments and Correlations

<table>
<tr><th>Sponsor</th><th colspan="2">Test Facilty</th><th>Date</th><th>Report Reference</th></tr>
<tr><td>Commonwealth Edison, LaSalle Station</td><td colspan="2">Duke Engineering and Services at EPRI, Charlotte, N. C.</td><td>June 1998</td><td>D 9</td></tr>
<tr><th>Variables Studied</th><th>Ranges</th><th>Results/Relationships</th><th colspan="2">Comments</th></tr>
<tr><td>Purpose of Tests: To obtain fiber and Aluminum RMI data with an actual replacement strainer under prototypic conditions</td><td></td><td rowspan="9">Measured head loss confirmed an approach velocity squared relationship.

A synergistic effect of RMI and fibrous debris was observed resulting in head losses greater than adding each constituent’s head loss.</td><td colspan="2" rowspan="9">Measured head loss for RMI debris was found to be a strong function of the process of debris deposition or accumulation on the strainer. “Shepherding” debris into the strainer suction flow field resulted in higher head losses than more normal processes.</td></tr>
<tr><td>Materials tested: NUKON™ fibrous debris simulant, 1.5 mil aluminum debris simulant</td><td></td></tr>
<tr><td>Material Preparation</td><td>NUKON™ shredded using methodology from NUREG-6224. Al RMI prototypical debris was generated at CEESI. The test debris was developed based on the generation experiments, limited in size (for transport), and crumpled.</td></tr>
<tr><td>Material introduction method</td><td>Incremental RMI addition to operating system, and addition to tank followed by initiating system operation. RMI and fiber added together in tank followed by initiation of system operation.</td></tr>
<tr><td>Coverage</td><td>Limited by test d/p</td></tr>
<tr><td>Approach Velocity</td><td></td></tr>
<tr><td>Maximum Head Loss</td><td>8.17 ft H_2O</td></tr>
<tr><td>Temperature</td><td>Nominal ambient</td></tr>
<tr><td>pH</td><td>Not investigated</td></tr>
</table>

Table D-1: Overview of Head Loss Experiments and Correlations

<table>
<tr><th>Sponsor</th><th colspan="2">Test Facilty</th><th>Date</th><th>Report Reference</th></tr>
<tr><td>Finnish Centre for Radiation and Nuclear Safety (STUK)</td><td colspan="2">STUK</td><td>May 1999</td><td>D 10, 11</td></tr>
<tr><th>Variables Studied</th><th>Ranges</th><th>Results/Relationships</th><th colspan="2">Comments</th></tr>
<tr><td>Purpose of Tests: To shed light on the physical mechanisms that induce flow resistance in purely metallic insulation debris beds, to quantify the influence of bed structure on flow resistance, and develop an approach to identify and quantify facility related distortions.</td><td></td><td rowspan="9">Pressure drop caused by pure metallic insulation debris bed is strongly dependent on bed structure. It appears that this factor is more important than the characteristics of the debris. Minimal resistance is found when the debris is aligned with the streamlines, and maximum resistance is found with all debris perpendicular to the streamlines.</td><td colspan="2" rowspan="9">The raw data show that:
Orderly debris bed behaviour is qualitatively similar on a strainer in a pool and in a test tube section. With debris perpendicular to flow, flow is purely turbulent (as expected); with debris parallel to streamlines, laminar conditions can be achieved.
The ratio of maximum to minimum head loss for different configurations (debris bed morphologies) of the same debris can be as high as 160 (not correcting for edge effects).</td></tr>
<tr><td>Materials tested: DARMET panel insulation</td><td></td></tr>
<tr><td>Material Preparation</td><td>Simulated debris, cut DARMET inner foil, 16x2.5cm strips.</td></tr>
<tr><td>Material introduction method</td><td>Strips laid on net into the test section in geometry desired.</td></tr>
<tr><td>Coverage</td><td>12 layers parallel, 5 layers perpendicular, 10 layers perpendicular</td></tr>
<tr><td>Approach Velocity</td><td>Variable</td></tr>
<tr><td>Maximum Head Loss</td><td>Consult reference</td></tr>
<tr><td>Temperature</td><td>50C, 30C, 30C, not controlled</td></tr>
<tr><td>pH</td><td>Not investigated</td></tr>
</table>

Table D-1: Overview of Head Loss Experiments and Correlations

Sponsor	Test Facilty		Date	Report Reference
Swedish Nuclear Power Inspectorate	Studsvik Material Corporation		January 1995	D 12
Variables Studied	**Ranges**	**Results/Relationships**	**Comments**	
Purpose of Tests: The objective of the project is to ascertain if there is a risk of coagulation of debris particles or fibers which could result in subsequent strainer clogging		pH at the 'isoelectric points', where the particle surface is uncharged is at low value (pH<4) for most materials and some materials (iron oxide, fiberglass, minileit) show a tendency toward coagulation at this pH. SEM investigation of filtered material does not indicate a clear tendency toward coagulation at the isoelectric points. Mineral wool can possibly be a bigger problem for filtration than fiberglass. Small suspended particles are more problematic than large ones. Corrosion products of iron and biological slime can cause rapid pressure drop. Boronic acid can have an effecto by changing the external chemical conditions for filtration of small particles.		
Materials tested: Magnetite, iron oxide hydroxide, fiberglass, mineral wool, caposil, minileit, concrete, primary coloring, and biological slime				
Investigation: Tests and experiments were conducted to determine electrophoretic mobility, coagulation tendency, calculation of ζ-potential, and appearance/size of particles and fibers				

Table D-1: Overview of Head Loss Experiments and Correlations

Sponsor	Test Facilty		Date	Report Reference
CANDU Owners Group/ Ontario Power Generation	Ontario Power Generation		October 1999	TD 13
Variables Studied	**Ranges**	**Results/Relationships**	**Comments**	
Purpose of Tests: Available head loss correlation did not cover parameters of interest; material types, 90-day mission time, pH transient, and velocities		NUREG-6224 underestimates head losses for measured short term pressure drop. Iron oxide and calcium silicate short term results similar on volumetric basis. Calcium silicate beds show a tendency to increase head loss for an extended period of time		
Materials tested: Fiberglass, calcium silicate, paint, dirt, concrete, rust				
Material Preparation				
Material introduction method				
Coverage	1-14 inch thick beds of fiberglass and fiberglass/particulate mixtures			
Approach Velocity	0.025-0.41ft/sec fibrous material; 0.025-0.06ft/sec mixtures			
Maximum Head Loss				
Temperature	40C, 60C			
pH	7 (most), 10,10.7			

Table D-1: Overview of Head Loss Experiments and Correlations

<table>
<tr><th>Sponsor</th><th colspan="2">Test Facilty</th><th>Date</th><th>Report Reference</th></tr>
<tr><td>KAEFER Isoliertechnik,
Bremen, Germany</td><td colspan="2">Bremen Polytechnic Department of Naval Architecture and Ocean Engineering – Circulation Water Channel</td><td>July 1995</td><td>*,**</td></tr>
<tr><th>Variables Studied</th><th>Ranges</th><th>Results/Relationships</th><th colspan="2">Comments</th></tr>
<tr><td>Purpose of Tests: Generic tests to quantify head loss of different insulation materials as a function of debris thickness, flow velocity and water conditions (temperature and chemistry)</td><td></td><td rowspan="9">The experiments with the relevant material types (fibre shreds, mattress debris, foil bulks) showed a pronounced increase of head loss with the loading thickness of the screen and the flow velocity. For a flow velocity of 0.06 m/s and a loading thickness of 300 mm head loss for fibre-type material is typically in the order of 100 kPa. For these materials the head loss tends to increase for higher pH-values. However the opposite was found for glass fibre material. In general the higher temperatures reduced the head loss considerably, i.e. roughly by half.
In contrast the metal foil fragments showed very small head loss values.</td><td colspan="2" rowspan="9">The results define a general and unique data base for head loss of a variety of insulation materials.</td></tr>
<tr><td>Materials Tested:
Mattress-type insulation material (NGI type 2, mineral wool), cassette-type insulation material (fibre glass, mineral wool, reflective foils)</td><td>Bed thickness up to 300 mm in 8 inch circulation pipe with screen</td></tr>
<tr><td>Material Preparation: See reference</td><td></td></tr>
<tr><td>Material introduction method</td><td>Direct loading of a screen (0.25 inch mash size, 1 mm wire thickness)</td></tr>
<tr><td>Coverage</td><td></td></tr>
<tr><td>Approach Velocity</td><td>2-7 cm/s</td></tr>
<tr><td>Maximum Head Loss</td><td>See detailed reports</td></tr>
<tr><td>Temperature</td><td>18 and 49 ^{o}C
(64 and 120 deg F)</td></tr>
<tr><td>pH</td><td>Two different water qualities:
ph 7.0, boric acid 1800 ppm, sodium 84 ppm
ph 9.2, boric acid 1800 ppm, sodium 2400 ppm</td></tr>
</table>

References for Table D-1:

1 GE Nuclear Energy, "Utility Resolution Guide for ECCS Suction Strainer Blockage", Prepared by BWR Owners' Group, NEDO-32686-A, October 1998

2 Continuum Dynamics, Inc., "Evaluation of Paint Chip head Loss on Vertically Oriented Zion Station Screen: July 1997 Test Phase", July 1997

3 Continuum Dynamics, Inc., "Debris Transport and Head Loss Test report For the Millstone Unit II Sump", February 1999

4 Duke Engineering & Services, "ECCS Strainer Performance Analysis for Min-K", TR-VT5900.01, October 1997

5 New York Power Authority and ITS Corporation, "Characterization of Head Losses Due to Mixed Fibrous and Micorporous Insulation Debris", October 1999

6 Alden Research Laboratory, Inc., "Head Loss of Fibrous Thermal WrapÒ Insulation Debris and Sludge for BWR Suction Strainers, 265-95/M787F, December 1995

7 Fortum Engineering Ltd., "Comparison of Resulting Differential Pressure Over Sump Screen Using Different Types of Fibrous Debris Generated With High Pressure Water/Steam Impingement, May 1999

8 Science and Engineering Associates, Inc. "Experimental Investigation of Head Loss and Sedimentation Characteristics of Reflective Metallic Insulation Debris", SEA No. 95-970-01-A:2, May 1996

9 Duke Engineering & Services, "Test Evaluation Report for Test TPP-VL0400-005: LaSalle Strainer Fiber and RMI Debris Tests", TPP-VL04000-006, June 1998

10 Finnish Centre for Radiation and Nuclear Safety (STUK), "On the Mechanics of Metallic Insulation Pressure Drop Generation", Juhani Hyv@rinen and Nina Lahtinen, May 1999

11 Finnish Centre for Radiation and Nuclear Safety (STUK), "Metallic Insulation Behaviour in a LOCA", Dr. Juhani Hyv@rinen, October 1999

12 Swedish Nuclear Power Inspectorate, “The Effect of Chemicals on Strainer Filtration, Final Report: Laboratory Tests at Various pH Levels”, SKI Report 95:4, January 1995

13 Ontario Power Generation, “Status on Issue of LOCA-Generated Debris”, C. Slongo, October 1999