NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Strainer Head Loss and Vortexing

March 2008

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EXECUTIVE SUMMARY

In response to Generic Letter (GL) 2004-02, US PWR licensees and their strainer vendors have conducted prototypical head loss testing to qualify designs of replacement strainers. The NRC staff has been following the industry's head loss testing through testing observation trips and plant audits. In order to establish appropriate evaluation criteria for staff to review the GL 2004-02 submittals from licensees in early 2008, the NRC staff has developed review guidance and documented the staff's positions in the areas of scaling, debris near field settlement simulation, surrogate debris similitude requirements, testing procedures, and post-test data processing and extrapolation. Since the procedures for integrated prototypical head loss testing including chemical effects are still being developed by the industry and lessons may be learned from the testing, this document may be revised to reflect new information. While the NRC staff plans to use this guideline in its review, licensees may or may not choose to use this guidance in preparation of their GL 2004-02 submittals. Licensees may use any approach to resolve sump performance issues as long as the approach is adequately justified and complies with the NRC's regulations.

This document has a primary section that includes basic guidance for NRC staff review of GL 2004-02 submittals in the areas of strainer head loss and vortexing. Appendix A provides more detailed information on the various issues associated with strainer head loss and vortexing, especially positions identified by the staff regarding prototypical head loss testing and scaling issues. Licensees are not expected to address the details of the topics in Appendix A in their GL submittals unless so noted in the primary review guidance section of this document. However, the information may prove useful for licensees to review before and during the preparation of their submittals.

ACRONYM LIST

ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
CFD	computational fluid dynamics
CSS	containment spray system
DBA	design basis accident
DDTS	Drywell Debris Transport Study
DP	differential pressure
ECCS	emergency core cooling system
EPRI	Electric Power Research Institute
HPSI	high pressure safety injection
GL	Generic Letter 2004-02
GR	NEI 04-07 Volume 1, PWR Sump Performance Evaluation Methodology (Guidance Report)
GSI	Generic Safety Issue
LANL	Los Alamos National Laboratory
LBLOCA	large break loss of coolant accident
LOCA	loss-of-coolant accident
LPI	low-pressure injection
LPSI	low-pressure safety injection
NEI	Nuclear Energy Institute
NPSH	net positive suction head
NRC	Nuclear Regulatory Commission
NRR	Office of Nuclear Reactor Regulation
PWR	pressurized water reactor
RCS	reactor coolant system
RG	Regulatory Guide
RHR	residual heat removal
RMI	reflective metallic insulation
RWST	refueling water storage tank
SBLOCA	small break loss of coolant accident
SE	safety evaluation
SRP	standard review plan
TKE	turbulence kinetic energy
ZOI	zone of influence

HEAD LOSS AND VORTEXING REVIEW GUIDANCE

The numbered items below are taken directly from the Content Guide for Generic Letter 2004-02 Supplemental Responses (ML073110278). Below each number is additional detail on the information expected to be provided for each section.

1) Provide a schematic diagram of the emergency core cooling system (ECCS) and containment spray systems (CSS).

Inclusion of this item enables the reviewer to gain a basic understanding of the operation of the system. The diagram should be detailed enough so that the reviewer can determine the flow paths for ECCS and CSS during injection and recirculation phases. This item should require little further explanation.

2) Provide the minimum submergence of the strainer under small-break loss of coolant accident (SBLOCA) and large-break loss of coolant accident (LBLOCA) conditions.

Inclusion of this item enables the reviewer to verify that the strainer is fully submerged prior to and during recirculation. Inadequate submergence can lead to flashing in the strainer or air ingestion into the ECCS and CSS pumps. The strainer submergence should be greater than the total strainer head loss. If submergence is not greater than head loss, an evaluation of the acceptability of this circumstance should be included. In addition, the submergence should be adequate to preclude vortexing. Information on head loss and vortexing is discussed in items below and in detail in the appendix to this document. It is expected that more detailed information on sump level will be included in the licensee GL 2004-02 submittal in the net positive suction head (NPSH) section.

Some plants assume different submergence levels for small and large break LOCAs. If this is the case, the acceptability for the lower level, usually associated with a small break LOCA, should be demonstrated in the head loss calculation for the small break case.

3) Provide a summary of the methodology, assumptions and results of the vortexing evaluation. Provide bases for key assumptions.

Inclusion of this item enables the reviewer to determine whether vortexing will not occur at the strainer. Vortexing can result in unacceptable quantities of air being ingested into the ECCS and CSS pumps, potentially resulting in unacceptable pump performance. The information provided should include the methods used to determine that vortexing will not occur during recirculation. In addition, any assumptions and their bases should be included. Key assumptions might include the minimum submergence, fluid temperature, and flow rate (velocity). Any particular design considerations for the reduction of vortexing should also be included in this section. Many strainer vendors performed testing to determine if vortexing would occur. If this was accomplished, a summary of the test observations should be included. If the strainer was tested at conditions worse than those expected in the plant (e.g., less submergence or higher flow velocity), and vortexing was observed, those observations should be summarized in this section along with a justification regarding whether such vortexing could occur in the plant. Testing may show some indication of pre-vortex formation. This should be evaluated in the submittal. However, any ingestion of air observed during testing at prototypical conditions would be unacceptable.

4) Provide a summary of the methodology, assumptions and results of prototypical head loss testing for the strainer, including chemical effects. Provide bases for key assumptions. (Ref. Appendix A, Sections 1, 2, 4, 5, and 7)

Inclusion of this item enables the reviewer to gain a good understanding of the conditions under which the head loss testing was conducted. This section should include information on the basis for scaling debris amounts and flow rates used during testing.

The discussion should also provide information on how the surrogate test debris was prepared and how the debris was prototypical or conservative with respect to the plant. Testing should be conducted with the most problematic mixture of debris that could occur at the plant. Specifically, the staff has noted issues with the preparation of fibrous debris. Frequently, fibrous debris has not been shredded finely enough to be prototypical of what would be expected in the post-LOCA pool. The use of excessively coarse fibrous debris in testing will likely result in non-conservative results. Other issues that the staff has noted with surrogate debris include use of particulate debris that is often larger than recommended by the NEI Guidance Report (GR) or use of debris that may not transport prototypically. This section should provide information on the surrogate debris, including a comparison with and justification for the use of the surrogate vs. the actual plant debris. If the surrogate is not the same density as the plant debris, this should be evaluated. If the density is different, the volume of the surrogate debris should be adjusted to ensure that it is similar to the scaled plant debris.

The choice of the use of paint chips or particulate paint debris should be discussed in this section. The evaluation should show that the form of paint debris chosen was conservative or prototypical with regard to head loss.

This section should discuss whether the testing required agitation or whether near field settlement was credited for the testing. If agitation was used, it should be stated to what degree it was successful (i.e., about what percentage of debris reached the strainer). If near field settlement was credited, the debris characteristics, preparation, and introduction become more critical. It should be verified that turbulence within the test facility does not affect debris bed formation non-prototypically.

The most critical area with which the staff has noted issues is the preparation and introduction of fibrous debris. For all tests, the fibrous debris should be shredded into a size distribution conservative or prototypical with regard to debris that would transport to the strainer in the plant. For testing crediting near field settlement it is especially important that the “fine” fibrous debris be individual or readily suspendable fibers. Fine fibrous debris includes all fibers destroyed as fines, all eroded fiber, and all latent fiber. In addition to the fiber preparation, the staff has noted issues with the agglomeration of debris during addition to the test flume. The fine fibrous debris should be introduced so that it tends not to tangle together or agglomerate with other debris. Justification should be provided for any deviation from this guidance.

Test termination criteria should be discussed in this section. The staff has noted that some testing is terminated before a maximum head loss value is attained. It has also been noted that bases for the anticipated maximum have not always been clearly stated. The basis for test termination should be provided. If a maximum value is not attained during testing, an evaluation should be provided that determines what the expected maximum head loss is and what the basis for this determination is.

Testing should be representative of conditions within the plant. For example, strainers installed in a sump pit should be tested in a similar configuration. The geometries of sump pit and similar situations should be modeled during testing or further evaluated.

This section should include information on how chemical effects were accounted for during testing. If the testing was conducted using specific industry guidance (e.g., WCAP-16530-NP) this should be noted. The method of application of the WCAP guidance should be described. Testing for thin bed and circumscribed beds should be discussed as appropriate. Sections in this document discuss each of these areas.

It is acceptable to include vendor test reports, calculations and specifications in the submittal.

5) Address the ability of the design to accommodate the maximum volume of debris that is predicted to arrive at the screen. (Ref. Appendix A Section 6.2.3 and 6.2.4)

Inclusion of this item enables the reviewer to determine whether the strainer can continue to perform its function loaded with the maximum debris accumulation expected to arrive at the strainer. This section should discuss the maximum debris load expected to arrive at the strainer and how the strainer design accommodates the debris. For testing, the maximum debris load should include (scaled) 100 percent of the debris from the break being tested. If significantly different debris mixtures can result from various breaks, each should be tested or evaluated. The staff has noted testing that resulted in the strainer becoming completely packed with particulate-laden fibrous debris resulting in an unacceptable head loss. The other potential issue during maximum load testing is the formation of a circumscribed bed. If a circumscribed bed is formed, the area through which the sump fluid flows is reduced. This reduction in area increases the velocity of the fluid and therefore increases the head loss across the debris. The increased head loss results in additional compaction of the bed and further head loss. The potential for a circumscribed bed creating unacceptable head loss is greater when the strainers are located in a pit due to the higher velocities generally associated with this arrangement. An evaluation of the ability of the strainer to not experience excessive head loss under maximum loading conditions should be provided. Homogeneous debris addition is acceptable for maximum load tests, provided that non-prototypical agglomeration of the test debris does not occur.

6) Address the ability of the screen to resist the formation of a “thin bed” or to accommodate partial thin bed formation. (Ref. Appendix A, Section 6.2.1, 6.2.2, and 6.2.4)

Inclusion of this item enables the reviewer to determine the ability of the strainer to accommodate the formation of a thin bed. During strainer testing, it has frequently been observed that thin debris beds can create a limiting condition for strainer designs. A thin bed can be more challenging than thicker beds because a relatively small amount of fibrous debris captures a relatively large amount of particulate debris. This type of bed can become very dense and non-porous. Higher fluid velocities across the bed tend to create more problematic thin beds. The information in this section should show that the testing for the strainer attempted to form a thin bed by incremental addition of fibrous debris in an attempt to conservatively determine the peak head loss. In some low-fiber plants this may not be necessary because the amount of fibrous debris predicted to reach the strainer is significantly less than the amount that could lead to a thin bed.

If this is the case, all fiber may be added at once. In all cases, the fiber should be adequately prepared (fines should be fibers that remain easily suspended) and introduced to ensure that agglomeration or hold up of the fibers is minimized.

Thin bed testing should be conducted with the most problematic debris combinations. The staff has observed thin bed testing that did not provide incremental addition of fiber, did not include debris from the break that resulted in the maximum particulate debris, and did not include the maximum amount of problematic debris such as microporous insulations (Cal-Sil, et al). The section on thin bed testing should provide a description of how the most problematic debris loads were included in the test.

Recent vendor test results have underscored that thin beds formed by fine fibrous debris can create significantly larger head losses than beds formed with larger fibrous debris pieces. Under realistic post-LOCA conditions, the staff considers it likely that fine fibrous debris may be the only fibrous debris capable of accumulating on all surfaces of many replacement strainer designs. Therefore, the staff expects that thin bed tests be conducted using the finest fibrous debris in the plant size distribution unless a different approach is justified based on plant-specific conditions.

Sequencing the debris for thin bed testing by adding 100 percent of the plant particulate load to the test flume and subsequently adding fibrous debris in incremental batches of an appropriate size is an acceptable method for performing thin bed testing. Depending on the scaling ratios for the test, this procedure may be overly conservative. As an alternative, a series of tests using homogeneous debris addition is also acceptable provided that a sufficient number of tests is performed to provide confidence that the limiting thin bed head loss has been achieved. Recent testing indicates that addition of fiber prior to addition of particulate may result in significantly lower head losses then the two approaches noted above. Therefore, the staff considers this addition sequence to be non-conservative, unless the licensee can show that it is prototypical of the expected plant accumulation sequence.

7) Provide the basis for the strainer design maximum head loss. (Ref. Appendix A, Sections 3, 7, and 8)

Inclusion of this item enables the reviewer to understand the basis for the design maximum head loss and how the maximum allowable head loss compares to the head loss determined via testing and clean strainer evaluation. Usually the design maximum head loss is the differential pressure across the strainer that results in zero NPSH margin for the limiting CSS or ECCS pump. Alternatively, the design maximum head loss can be limited by strainer submergence. In some cases, the design maximum may be a structural limit.

8) Describe significant margins and conservatisms used in the head loss and vortexing calculations. (Ref. Appendix A, Section 2.3)

This section is intended to allow the licensee to provide the reviewer any information related to head loss and vortexing that may not be included elsewhere in the submittal that would help justify that the strainer solution installed at the plant contains adequate margin. An example of an item within the scope of this section could be a measure that has been taken since head loss testing was completed that adds conservatism to the head loss test results. Any other conservatisms related to head loss and vortexing that are not described in other sections should be included here.

9) Provide a summary of the methodology, assumptions, bases for the assumptions, and results for the clean strainer head loss calculation. (Ref. Appendix A, Section 8.4)

Inclusion of this item enables the reviewer to understand the basis for the clean strainer head loss. An evaluation of the clean strainer head loss should be included in this section. The evaluation should include the internal strainer head loss, any manifold or plenum losses, and any exit losses associated with flow out of the strainer and into a manifold and from the manifold into the sump. In addition to the head losses, the evaluations should include any temperature scaling that was conducted during the clean strainer head loss evaluation. The basis for the temperature used and the method selected for the scaling should be discussed. If scaling other than temperature scaling was performed, the methods and bases for the additional scaling should be provided. The method used for the calculation of the clean strainer head loss and any other hydraulic losses associated with the strainer and attached conduits should also be included in this section.

It is acceptable to summarize or include vendor test reports, calculations and specifications in the submittal.

10) Provide a summary of the methodology, assumptions, bases for the assumptions, and results for the debris head loss analysis. (Reference Appendix A, Sections 5, 6, and 8)

Inclusion of this item enables the reviewer to understand the basis for the debris head loss analysis. An evaluation of the limiting debris head loss should be included in this section. The evaluation should include a discussion of how the limiting debris head loss was determined, what other potential debris head losses were considered and what their magnitude was, and which debris mix created the largest head loss. In addition to the head losses, the summary should include any temperature scaling that was conducted during the debris head loss evaluation. If scaling was conducted, the basis and the method selected for the scaling should be discussed. In general, scaling is limited to temperature effects. However, in some cases scaling for alternate approach velocities has been performed. Provided that boreholes and other debris bed disruptions are not present, scaling upward in temperature and downward in approach velocity incorporates a degree of conservatism, since the tested debris bed would experience greater compression than expected at the scaled condition, and vice versa. If applicable, the method used for the calculation of the debris head loss and any other hydraulic losses considered in the debris head loss section should also be included.

This section should include a summary of all losses associated with the strainer and debris. The losses should be summed to determine the maximum head loss caused by the debris, strainer, and any interconnecting piping. The design maximum will be compared with the total head loss calculated in this section. It is acceptable to summarize or include vendor test reports, calculations and specifications in the submittal.

11) State whether the sump is partially submerged or vented (i.e., lacks a complete water seal over its entire surface) for any accident scenarios and describe what failure criteria in addition to loss of net positive suction head (NPSH) margins were applied to address potential inability to pass the required flow through the strainer.

Inclusion of this item enables the reviewer to understand the physical hydraulic phenomenon that the strainer will be subject to during an accident and how this could affect the ability of the strainer to perform its function. In general, most strainers are designed to be completely enclosed and covered by the water in the post-LOCA pool prior to the beginning of recirculation.

If the strainer is not fully submerged, it undergoes different physical stresses as the head loss across the strainer increases. The licensee should state whether the strainer is fully enclosed or vented, and whether the strainer remains submerged during all phases of recirculation. Strainer submergence should be verified by comparing the height of the strainer with the post-LOCA pool level calculated by the licensee.

If the head loss across a strainer that is not fully submerged exceeds one-half the height of the pool, the strainer is considered to fail unless an evaluation can show that the strainer will continue to perform its function. If the strainer is vented to an area above the surface of the sump pool, even with a small opening, the potential for air ingestion into the strainer and ECCS/CSS pumps becomes more likely. A comparison of the static head available to push the fluid through the strainer from its upstream side should be compared to the strainer head loss to ensure starvation of the ECCS pumps does not occur. For strainers that are not fully submerged, or have vents above the minimum pool level, these issues should be addressed.

It is likely that most strainers will be designed to be fully submerged and to have no vents above the post-LOCA pool level. If a strainer does not meet these criteria, additional review in this area is warranted.

12) State whether near-field settling was credited for the head-loss testing and, if so, provide a description of the scaling analysis used to justify near-field credit. (Ref. Appendix A, Section 4)

Testing with credit for near field settlement was discussed under the testing section. This section requests information to enable the reviewer to verify whether the flow and turbulence in the area around the test strainer are prototypical of the flow and turbulence expected in the plant. This area is difficult to evaluate because strainers are frequently spread out, and flows vary greatly from one section of the strainer to another. A Computational Fluid Dynamics (CFD) analysis is usually required to understand the flow and turbulence around the strainer. In some cases, an evaluation of the CFD analysis may indicate that there is little variation between sections of the strainer. In this case, the test case would be a relatively straightforward application of similar flows and turbulence in the test case. In cases where there is a large variation in flows among different sections of the strainer in the plant, an evaluation should be done to ensure that testing is conducted in a conservative manner. The staff has considered this issue and has stated that a simple average flow is not adequate for a plant that has complex or widely variable flow parameters in the post-LOCA sump. The staff believes that the higher velocity areas will transport a greater amount of debris than would be expected by taking a linear average of the velocities approaching the strainer. Plants that have varying strainer approach velocities should consider how this will affect debris bed formation and debris transport, especially in the near field of the strainer. These considerations should be factored into the testing procedures and evaluation of test results. For tests that are agitated to ensure that most of the debris is transported to the strainer these issues are less important. Testing that credits near field settlement could test various flow velocities and evaluate the effects of the flow rates on transport. These results could be applied to the development of test protocols and evaluation of test results.

If near field settling was credited, a discussion of how prototypical (or conservative) flows and turbulence were maintained in the test flume should be included. The flow and turbulence in the test rig should be compared to these parameters in the plant and an evaluation of the similarity should be conducted. If the approach velocities to various strainer sections are not relatively similar, the test methodology and interpretation of results should discuss these issues.

13) State whether temperature/viscosity was used to scale the results of the head loss tests to actual plant conditions. If scaling was used, provide the basis for concluding that boreholes or other differential-pressure induced effects did not affect the morphology of the test debris bed.

Inclusion of this item allows the reviewer to determine whether temperature scaling, if performed, was conducted conservatively. If differential pressure related phenomena such as boreholes resulted in a lower differential pressure across the strainer, it is not appropriate to scale to a lower viscosity resulting from a higher temperature at accident conditions. Because temperature is usually lower at test conditions than would occur post-LOCA resulting in higher differential pressure, it is more likely for pressure-related bed degradation to occur in the test, resulting in reduced differential pressure. Temperature/viscosity scaling of head loss values that are already reduced by pressure-related bed morphology changes would be non-conservative. In addition, many calculations assume 100 percent laminar flow through the debris bed when performing temperature scaling. For most homogeneous debris beds this has been accepted. However, if areas of the bed are disturbed and have high flow velocities through them, the assumption of laminar flow is no longer valid and a straight viscosity-based temperature correction is non-conservative. It is recommended that testing protocols include measures to verify that neither bore holes nor channeling has occurred. Visual examination of the bed will often be inadequate for identification of bed degradation. Therefore, it is recommended that flow sweeps be performed during or at the end of the test to verify that head loss across the strainer changes as expected with flow. Flow variations should be performed gradually to avoid disturbing the debris bed. If channeling has occurred, the maximum head loss value determined during testing (at lower than accident temperatures) may be assumed to be the head loss value for the strainer. If indications of channeling were observed during testing, any correction for temperature should be justified from both the perspective of laminar and turbulent flow regimes, and from the perspective that the head loss could have been higher if debris bed morphology changes due to differential pressure had not occurred. (Ref. Appendix A, Section 8.1)

14) State whether containment accident pressure was credited in evaluating whether flashing would occur across the strainer surface, and if so, summarize the methodology used to determine the available containment pressure.

The inclusion of this item allows the reviewer to determine whether the strainer and related debris head loss will result in voiding and potential entrainment of vapor into the ECCS pumps. The item allows the reviewer to determine if any credited overpressure is available, and if so whether it is sufficient to prevent flashing. Inclusion of this item also provides the reviewer a clearer picture of operating margin for the system.

In many cases it has been determined that the head loss across the strainer is greater than the submergence of the strainer. Some plants also assume that the saturation pressure of the liquid is equal to the vapor pressure. Under these conditions, if the head of water over the strainer does not exceed the head loss expected across the debris bed, plus that associated with the clean strainer, flashing would be expected to occur. If the head loss exceeds the strainer submergence, an evaluation that shows that adequate pressure is available to prevent flashing within the debris bed or strainer should be performed. The evaluation should verify NPSH margin throughout the mission time of the strainer.

The following information should be provided:

1) strainer submergence and head loss for any time period that head loss is greater than submergence (may be presented in graphical format)
2) for these time periods, verification that adequate pressure exists within containment to provide margin to flashing based on accident analyses
3) the minimum margin to flashing during the event based on the strainer head loss and minimum available containment pressure
4) If the strainer head loss is considered to vary during the event, a graphical representation of head loss, submergence, and available containment pressure for the entire mission time of the strainer

APPENDIX A
STRAINER HEAD LOSS TESTING AND ITS APPLICATION TO PLANT HEAD LOSS

1.0 INTRODUCTION

In response to Generic Letter (GL) 2004-02, US PWR licensees and their strainer vendors have been conducting prototypical head loss testing to qualify the design of new replacement strainers. The NRC staff has been following the industry's head loss testing through testing observation trips and plant audits. In order to establish appropriate evaluation criteria for staff to review the GL 2004-02 submittals from licensees in early 2008, the NRC has documented the staff's positions in the areas of scaling, debris near field settlement simulation, surrogate debris similitude requirements, testing procedures and post-test data processing and extrapolation. This appendix is not intended to provide requirements to the industry, but is intended to provide information and insights into what the staff has observed in dealing with this issue. Section 1.1 describes the evolution of the strainer head loss evaluation methodology. It provides the background and history of the plant specific strainer head loss testing and the rationale for why the NUREG/CR-6224 correlation-based evaluation methodology was not used by most of the licensees. Section 1.2 discusses the prototypical head loss testing, and Section 1.3 lists several examples of issues identified by the staff regarding certain vendors' testing programs.

1.1 NUREG/CR-6224 Correlation and Plant-Specific Head Loss Testing

In May 2004, the Nuclear Energy Institute (NEI) submitted the report, "Pressurized Water Reactor Sump Performance Evaluation Methodology" (proposed document number NEI 04-07, (NEI, 2004a), referred to herein as the Guidance Report or GR), for review by the U.S. Nuclear Regulatory Commission (NRC or the staff). The NRC's approval of this guidance would allow licensees of pressurized water reactors (PWRs) to use the document to respond to NRC Generic Letter (GL) 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized-Water Reactors" (GL-04-02), issued on September 13, 2004. NRC approval would cite the document as the NRC-approved methodology for evaluating plant-specific sump performance. The GR, as approved in accordance with the staff's safety evaluation report, "Safety Evaluation by the Office of Nuclear Reactor Regulation Related to NRC Generic Letter 2004-02, Nuclear Energy Institute Guidance Report Pressurized Water Reactor Sump Performance Methodology" (SE), provides an acceptable overall guidance methodology for the plant-specific evaluation of the emergency core cooling system (ECCS) or containment spray system (CSS) sump performance following all postulated accidents for which ECCS or CSS recirculation is required. Specific attention is given to the potential for debris accumulation that could impede or prevent the ECCS or CSS from performing its intended safety functions.

The GR recommended a generic debris-laden screen head loss calculation methodology using a head loss correlation (NUREG/CR-6224). The computation of head loss in the GR involves input of design characteristics and thermal-hydraulic conditions into this correlation. During the review of the GR, the staff found that, although the correlation was the only analytical method available to the industry to predict the head loss at that time, the correlation was developed by an NRC-sponsored research program with the intent to provide a confirmatory analysis capability for the NRC staff. The research program was intended to gain understanding of hydraulic characteristics of debris on a flat screen rather than to develop a generic methodology applicable to different types of complex geometry strainers and various combination of debris. Because of limitations of the correlation, the staff stated in the SE that the licensees should ensure the validity of the NUREG/CR-6224 correlation for the application of specific types of insulation and the range of parameters based on plant-specific strainer configurations. Alternatively, licensees could perform plant-specific prototypical head loss testing for the debris amount, debris type and flow rate expected at each plant. As a result of the staff position regarding the applicability of the NUREG/CR-6224 correlation, most licensees have chosen to perform prototypical head loss testing to qualify the new strainer design.

1.2 Prototypical Head Loss Testing

The goal of the prototypical head loss testing is to determine the strainer potential peak head loss that could occur during the postulated plant loss of coolant accident (LOCA) scenario during the mission time of the recirculation sump. The mission time here is considered to be the time from accident initiation to when the flow was permanently and substantially reduced by licensee Emergency Operation Procedures (EOPs). In theory, the head loss testing should continue until the mission time is reached, but practical considerations may limit the period of testing. Because of the limited test time, the peak head loss may be estimated by extrapolating the test head loss results when those head loss results can be demonstrated to have approached the final head loss reasonably closely. In prototypical head loss testing, the accumulation of debris depends upon the gradual filtration of the suspended debris within the test tank by the fibrous bed. The filtration is dependent on the debris dependent strainer filtration efficiency. The establishment of a relatively steady-state head loss can sometimes occur slowly since the filtration process gradually clears the water of finer and finer particles until the remaining particulate is too fine to be filtered. Assurance is needed that the test termination criteria are suitable to determine the potential peak head losses. In addition, there are potential time-related phenomena that can affect debris bed head loss.

Prototypical head loss testing usually consists of a scaled strainer module tested in a representative fluid flow environment with the scaled plant-specific debris loading. The strainer test modules are usually scaled down versions of the plant replacement design. Specifically, the test module strainer surface areas are much smaller than the replacement strainers. Assurance is needed that the scaling between the test strainer module and the plant replacement strainer has been correctly evaluated. The primary scaling parameters include the screen area, the dimension of the strainer elements (e.g., disks), the submergence level, the number of strainer elements, the debris amounts, and the local fluid flow conditions, as applicable. These parameters affect the flow velocities approaching the test strainer and the velocities through accumulated debris. In addition, the debris surrogate material should be introduced into the test loop in a conservative or realistic way so that the debris accumulation on the testing module either represents the actual debris accumulation or bounds the realistic debris distribution.

1.3 Issues Identified With Ongoing Head Loss Testing

The NRC staff has observed vendor head loss testing of prototype strainer modules that were designed to be representative of the PWR replacement strainers. The staff has observed phenomena and testing practices that have generated potential issues regarding the assurance of the prototypicality or conservatism of the testing. Aspects of the head loss testing that have generated such issues include:

- the scaling of the test strainer module with respect to the plant replacement strainer design;
- whether or not the surrogate materials used to simulate postulated plant debris are prototypical of the plant materials,
- whether or not the debris transport within the test flume and the subsequent accumulation of debris on the test strainer module are prototypical of the plant;
- whether or not the duration of the testing was long enough to ensure the determination of peak potential head losses;
- the post-test scaling of the test data to alternate plant conditions, such as sump pool temperature;
- whether or not the fibrous debris used for thin bed testing was prepared sufficiently finely to be prototypical or conservative; and
- the sequencing of the debris added to the head loss test

Some specific examples are discussed below.

Example 1 - Surrogate Material Selection

For a number of reasons, licensees typically are not able to obtain or create test debris that exactly replicates the debris that would be formed in the plant following a LOCA. Some common reasons are that the material is no longer commercially available or the material is too environmentally hazardous to handle from a practical standpoint. Therefore, surrogate materials are being used to simulate the postulated plant debris. Justification should be provided to demonstrate the similitude of the surrogate material.

Example 2 - Near Field Debris Settlement

Whenever a vendor introduces the surrogate debris into the test tank at some distance from the strainer, a portion of that debris typically settles within the test tank rather than accumulating on the test strainer module. Some vendor testing of prototype strainer modules has effectively combined debris transport with debris accumulation and head loss in the same test. The staff identified that this near field settling may not be simulated realistically for some cases. For example, the settling could be due to non-prototypical flow conditions in the test tank, or other specific effects such as unrealistic debris agglomeration due to low velocities or debris introduction methods. In some cases, the turbulence level upstream of the strainer was not modeled correctly. The staff had identified concerns regarding the excessive settlement of debris upstream of the strainer. Licensees wishing to take credit for near-field settling should justify that test flow conditions are prototypical or conservative with respect to debris transport.

Example 3 - Testing Protocol - Debris Introduction Sequence

Debris settlement within the test tank may be prototypical or conservative with respect to the plant sump. However, this depends on the testing procedures regarding the location, timing, and method of debris introduction into the test tank. The strainer should be qualified for the full debris load predicted by the transport calculation, as well as lesser quantities (i.e., the amount that would lead to a thin bed), since all debris may not transport as predicted. In addition, based on recent testing, the staff has concluded that the debris introduction sequence has an effect on head loss. The introduction of fibrous debris without particulate debris is considered non-conservative. This issue is discussed further in other areas of this guidance. For some cases the NRC staff found that licensees introduced the debris into the test tank without proper justification regarding the prototypical or conservative debris arrival sequence.

Because of these issues regarding the licensees' head loss testing programs, this document discusses the NRC staff positions on various aspects of head loss testing. Section 2 discusses the role of head loss testing as part of the overall strainer design evaluation methodology and the staff's view regarding head loss testing uncertainty. Section 3 discusses the scaling of the plant replacement strainer design to the test strainer module. Section 4 discusses the similitude considerations for debris transport and debris accumulation on the strainer when a licensee proposes to take credit for near-field settlement. Section 5 discusses the similitude requirements for the surrogate debris. Section 6 discusses recommendations for developing conservative head loss testing procedures. Section 7 discusses the criteria for terminating a head loss test. Section 8 discusses potential scaling of post-test data to actual plant conditions.

2.0 ROLE OF PROTOTYPE HEAD LOSS TESTING IN GSI-191 RESOLUTION AND ITS UNCERTAINTIES

2.1 Current Trend of Replacement Strainer Design

The primary trend in replacement strainer design has been the installation of large passive strainers. The effects of the large strainers are: (1) to distribute the debris over a larger area resulting in thinner beds of debris accumulation, and (2) to reduce the effective water flow velocity through the debris accumulation. Both effects reduce the head losses through the debris. The vendor designs vary primarily on how the design incorporates large screen areas into a relative small volume that can be tailored to fit a specific licensee's containment sump. One distinguishing design feature is whether or not the internal strainer flow resistance is structured to encourage uniform flow across the strainer surface.

Given a specific replacement strainer design, the head loss depends primarily on the quantities, compositions and distribution of the accumulated debris on the strainer. Some types of debris are relatively non-problematic. For example, reflective metal insulation (RMI) debris tends to be very porous unless overlaying sheets of foils accumulate on strainers. This overlay is not realistic at the low approach velocities expected with the new strainers. Some other types of debris are problematic and have caused serious head losses even at low surface approach velocities. These types of debris include microporous insulation types and the chemical effects precipitates. Typical microporous insulation includes calcium silicate, Min-K, and Microtherm.

With the typical screen approach velocity less than 0.01 ft/s, the fiber debris bed accumulated on the screen can be porous. The primary threat to the typical large replacement strainer designs is a thin-bed formation that includes substantial quantities of particulate debris and/or chemical effects precipitates. In addition, a thick bed accumulation of fiber with relatively large quantities of particulate debris or chemical precipitates can also potentially cause a high head loss, especially if the strainer becomes engulfed with debris to such an extent that a circumscribed or transitioning debris bed is formed.

For RMI and/or paint chips to result in high head losses on a large strainer, the debris would have to be piled on top of and around the strainer in a circumscribed accumulation. For this type of accumulation, at typical low approach velocities, the strainer would likely have to be located inside a pit below the containment floor level such that the debris falls onto the strainer from above. It is unlikely that sufficient debris to engulf the strainer would fall directly into the pit. However, approach velocities toward pit installations are generally much higher than for strainers installed on the containment floor. The higher velocity makes transport of this type of debris more likely.

2.2 Inputs and Outputs of Prototypical Head Loss Testing

Head loss testing of strainer prototypes was not covered in either the NEI-sponsored resolution guidance (NEI 04-07), referred to as the guidance report (GR), or the subsequent NRC Safety Evaluation (SE) of the GR. Based on NRC staff observations of vendor head loss testing during audits of licensee GSI-191 resolutions, an understanding is emerging regarding the role that prototypical head loss testing is apparently taking in GSI-191 resolutions. Figure 2.1 illustrates schematically the steps in this overall resolution process. This scheme is discussed in this section to put the steps in perspective before focusing on prototype head loss testing.

Head loss testing consists of testing a reduced section of the licensee replacement strainer design in a tank of water. The test strainer module is connected to a recirculation loop that pumps water from the tank through the test strainer and returns the water back into the tank. A prototypical load of debris is introduced into the tank where it accumulates on the test strainer resulting in a measurable head loss. Other typical features include a method of introducing turbulence or stirring to reduce debris settling or resuspend debris once settled, and a method of taking water samples downstream of the test strainer for subsequent analysis of debris bypassing the strainer. Measurements include the differential pressure across the strainer, the flow rate, and the water temperature. The challenge in prototype head loss testing is ensuring that the conditions within the test tank are prototypical of the plant sump pool. These conditions include the postulated debris loading, the recirculation system hydraulics, and key aspects of the various accident scenarios. The testing matrix box shown in Figure 2.1 illustrates the input logic and information for the head loss test.

The GR/SE guidance provides a methodology for the determination of conservative bounds for the maximum quantities of different types of debris that could potentially reach the replacement strainers. A new strainer should be capable of handling all this debris and any reasonable combination of lesser quantities as well. The strainer should manage any realistic order the different types of debris could arrive at the strainers. The chaotic nature of debris generation and transport following a pipe break, variety of post-LOCA debris types, and the extensive variation of break types and locations make it difficult to determine debris quantities and arrival sequences with any accuracy. In general, licensees determine the maximum debris quantities that could be produced for various breaks. For strainer testing, these maximum quantities are scaled down to the test strainer module and either the actual plant material or a suitable surrogate is used to create prototypical debris for the head loss test (shown in Figure 2.1).

The licensee specifications, often determined from accident analyses, provide the operating conditions for the sump strainer, including pump flow rate, sump pool water temperatures and pool depths. As part of the GSI-191 evaluation the licensee is to perform an upstream analysis to ensure that a blockage of the flow of water into the sump cannot cause a reduction in the expected pool depth at the strainer following the LOCA. The licensee NPSH analysis determines how much debris-generated head loss across the replacement strainer can be tolerated. All of this information is used to determine prototypical hydraulic conditions for the conduct of the head loss testing.

The design of the test facility, in conjunction with the test strainer module, should be such that the hydraulic conditions within the test tank are prototypical of the sump pool and plant strainer.

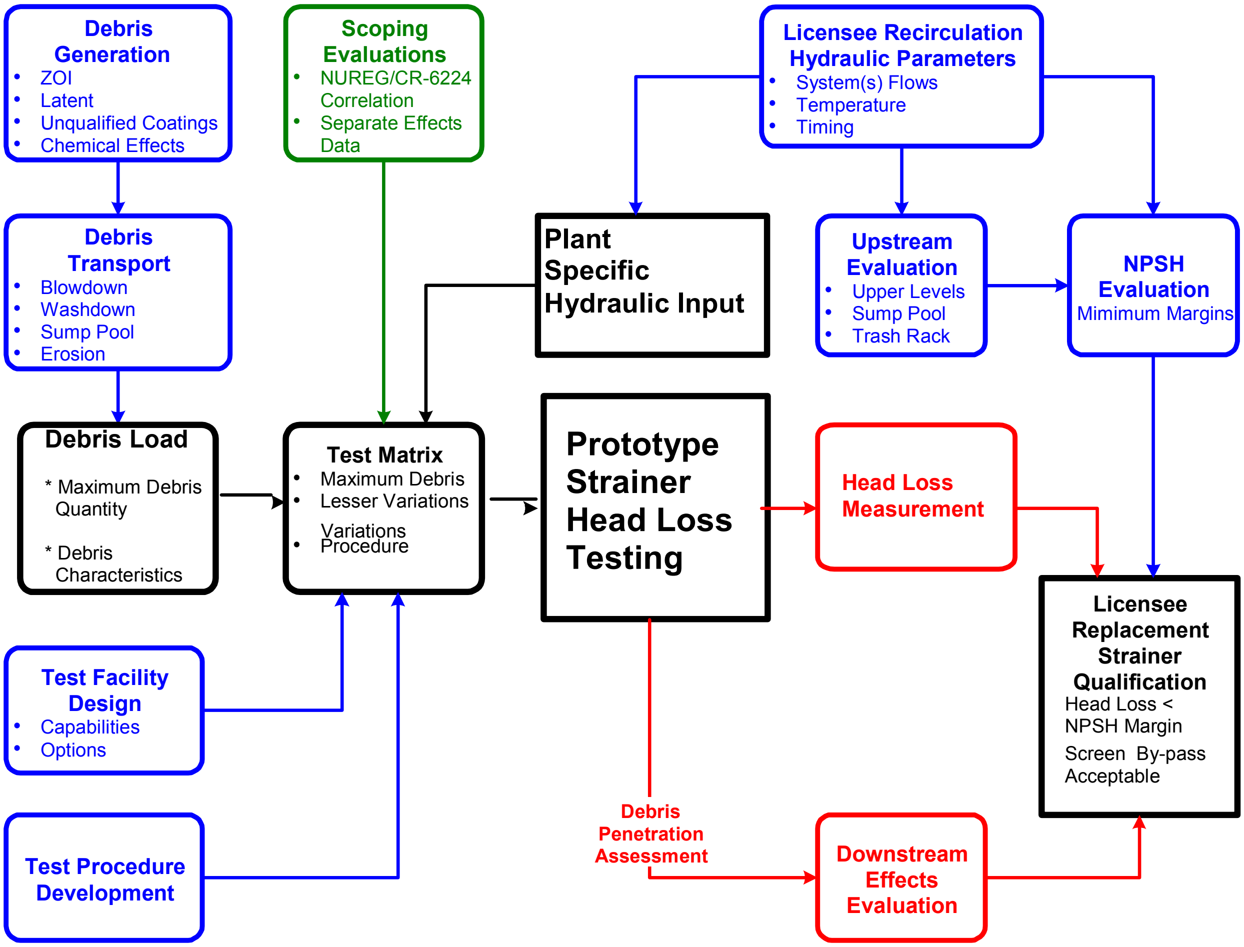

Figure 2.1 - Schematic of Processes Used to Qualify Replacement Strainers

These conditions include the flow velocities that transport debris and the turbulence levels that influence debris suspension and deposition on the strainer. The facility design should also accommodate variations necessary to simulate features of the accident scenario. The test specifications should be designed to determine the worst-case head loss from all the possible types of debris beds that could accumulate given the bounding quantities of debris (i.e., thin-bed versus maximum debris accumulations and potentially stratified beds). Scoping evaluations using the NUREG/CR-6224 correlation and alternate data have been used by strainer vendors or licensees to facilitate the design of the test matrix and the test facility.

Post-test evaluations are required to validate the head loss results, apply the results to the replacement strainer, and ensure that the fine debris penetrating the replacement strainer cannot cause adverse effects to downstream equipment. Results of head loss tests conducted using colder water are often scaled to the plant sump water temperatures. Sometimes scaling to an alternate approach velocity is performed. Scaling is discussed in Section 8.2 below.

Debris settlement within the test tank, referred to as the near-field effect or near-field settling, should be evaluated to ensure that similar or larger amounts of debris settling would actually occur in the plant sump pool. Some strainer vendors agitate the test pool in an attempt to keep all debris in suspension and therefore make it much more likely to get all debris to the strainer. It should be ensured that agitation does not prevent prototypical debris transport and that debris is not prevented from accumulating on the strainer as it would in the plant. Other vendors do not agitate the pool thereby allowing debris to settle. Because of the unknowns surrounding many of the variables in a post-LOCA pool, it is much more difficult to ensure conservative testing when near-field settling is allowed and credited.

Sampling of flows downstream of the test strainer is conducted to determine the amount of debris bypassing the strainer. This debris could potentially damage or clog components such as pumps, throttling valves or the reactor core. The downstream debris characteristics are used to determine the likelihood that downstream blockage could threaten long-term core cooling.

Some vendors use closed-loop testing to determine head loss characteristics for test debris. In a closed loop test, essentially all of the debris accumulates on the test screen so the closed loop head loss can be correlated with the debris quantities and characteristics. Based on debris-specific head loss tests, vendors can use a version of the NUREG/CR-6224 relationship to correlate the measured head losses with debris quantities by backing out effective head loss parameters, such as the particulate specific surface area, so that the plant-specific head loss correlation reproduces the head loss test results. Subsequent application of the revised plant-specific correlation to replacement strainer design is valid as long as the application conditions are close to the closed loop test conditions. Uncertainty occurs in the extrapolation to alternate conditions as variations from the closed loop condition occur. One approach to evaluation of replacement strainers could be to use the validated correlation with parameters deduced from applicable closed-loop head loss testing to design the replacement strainer. A prototype of that strainer would then be tested to ensure the prototype functions as intended.

2.3 Uncertainties and Conservatism Associated With Head Loss Testing

The inputs to prototypical head loss testing can be divided into two categories. The first is the plant hydraulic conditions, which use the maximum ECCS/CSS flow rate based on the worst-case single failure assumption, the minimum containment sump pool sub-cooling, and the minimum sump level. The second is the debris load on the strainer based on debris generation and transport analyses. The GR and SE conservatively assume that all the debris accumulated during the post-LOCA ECCS mission time for a given break location is present on the strainer surface at the beginning of the recirculation.

Significant conservatism has been built into the methodology to develop inputs to the head loss testing. In the area of plant hydraulic conditions at the beginning of recirculation, it has been assumed by many licensees that all ECCS pumps and CSS pumps are in operation for an extended period of time, up to the 30 day-mission time. For those plants whose design includes LPSI pumps shutting down during switchover from the RWST to the sump according to the LPSI control logic, licensees should consider one LPSI train failure to stop. This assumption leads to a very conservatively calculated maximum flow rate through the screen. In addition, the sump pool subcooling is assumed to be at a minimum at the beginning of the recirculation phase. This results in minimum NPSH margin. In reality, the NPSH margin increases significantly after the heat removal systems have removed significant heat from the reactor coolant system and the containment. NPSH margin usually increases from its minimum value prior to the beginning of recirculation.

In the area of debris load input to the head loss testing, both the GR and the SE call for conservative debris generation and debris transport analyses. The approved methodology conservatively assumes all the eroded fine fiber is present with other debris to cause head loss at the beginning of recirculation. In reality, the erosion is a relatively slow process. The eroded fiber may not cause a significant head loss concern because the NPSH margin may increase significantly before most of the eroded fiber reaches the screen. In addition to the conservatism associated with erosion, different kinds of debris may agglomerate on their path toward the strainer and cause debris settlement. Other debris may settle on its own without any agglomeration. As a conservative approach, agglomeration is not considered in the approved transport analysis.

The methodology to predict the key inputs to the head loss testing has been conservatively developed and documented in GR and SE. If the test facility is scaled properly and the testing procedures are conservative it is expected that the measured head loss is also conservative. In this case no analysis is needed to identify the uncertainty band of the measured head loss data. To ensure conservatism, licensees should design the test facility properly and conduct the test following conservative testing procedures. Sections 3 through 8 contain NRC staff positions on specific topics regarding the test facility design and testing procedures and treatment of test data following the test.

3.0 STRAINER TEST MODULE SCALING

3.1 Overall Considerations and Strainer Vendor Scaling Approaches

Ideally, a scaled down test facility would be designed whereby the debris transport and head loss processes that would occur in a plant following a postulated accident would also occur in a similar manner in the test facility. That is, the dimensions of the test facility would all be reduced by some common scaling parameter (i.e., 1/nth the size) or parameters from that of the plant sump pool and replacement strainer based on the dominant processes. If the essence of the dominant processes can be captured in one or more of the accepted dimensionless parameters, then the maintenance of the dimensionless parameters between the plant sump and the test facility becomes the basis of scaling down design.

For prototype head loss testing, a number of considerations tend to impact licensees' options associated with scaling. These include:

- Each strainer vendor will likely only construct one or a limited number of test facilities that can be modified to represent the various configurations.
- The plant replacement strainers are typically designed interactively with the head loss testing, where the head loss measurements provide data critical to sizing the strainer.
- The strainer designs are variable in geometric configuration and size.
- The plant sump pool geometries, pool depths, and flow conditions are different for different plants.
- The types and quantities of postulated LOCA-generated debris vary with the plants.
- The head loss tests are generally conducted using essentially room temperature water rather than water at plant sump pool temperatures.

Only one geometrical scaling approach has been adopted by the industry to date. That approach is area ratio-based scaling between the plant strainer and the test strainer. Based on this scaling principle, a full size strainer module or a portion of a strainer module is placed in a test loop where the total flow rate is determined by multiplying the total plant sump flow rate by the ratio of the test module surface area to the plant strainer array total surface area. In this way, the screen surface approach velocity is kept the same. The debris loading on the testing module is also scaled based on the strainer surface area ratio with the assumption that the debris accumulation is representative or bounding of the actual plant condition. In some cases the debris loading and approach velocities have been based on the ratio of the circumscribed areas between the plant and test strainers. In general, this is done if the plant strainer can become completely engulfed in debris and an additional thin bed test is run using the strainer surface areas for scaling.

The design of the flow channel upstream of the testing module varies among different strainer vendors. Some have decided not to scale the upstream flow path. Instead, testing procedures involve agitating the test pool so that most of the debris introduced into the test loop accumulates on the screen surface. Some vendors have decided to take credit for near field settlement and have developed specific approaches to design the upstream flow path of the test loop. In addition to the geometrical scaling effort, the strainer vendors have proposed different extrapolation schemes to address temperature scaling. This is discussed further in Section 8.0 of this document.

Based on the observed licensees' scaling approach, the NRC staff's evaluation of the theoretical basis of the scaling analysis is discussed in Section 3.2. The detailed scaling requirements regarding the testing module design and the scaling approach based on area ratio are discussed in Section 3.3. Evaluation of the debris accumulation pattern is discussed in Section 3.4. The scaling consideration and requirements regarding near-field simulation are discussed in Section 4.0.

3.2 Theoretical Considerations

When scaling a large fluid field to a smaller test loop, dimensionless numbers are normally derived from the governing equations or based on the experience and understanding of the dominant physical processes. A preliminary evaluation conducted by a contractor for the NRC indicates that a dimensionless analysis of fluid flow associated with head loss testing will include primarily the Froude and Reynolds dimensionless parameters.

Reynolds number: ratio of inertial forces to viscous forces
Froude number: ratio of inertial forces to gravity forces

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

- The settling rate of debris within a calm pool water near the strainer
- The level turbulence within a pool
- The pool floor boundary layer thickness
- The drag force on debris residing on the pool floor near the strainer
- The lift force on a piece of debris if the flow goes over a curb or debris lifts from the floor onto a screen surface

The analysis of particles settling in calm or still water is usually treated using a Stokes Law approach where the terminal settling velocity is inversely proportional to viscosity and directly proportional to the water density. Therefore, the relationship contains significant temperature dependence. Debris settling involves gravity; therefore, the Froude number is relevant. Since settling is also influenced by pool turbulence, which is typically correlated using the Reynolds number, the Reynolds number is also relevant. Once a piece of debris has settled on the pool floor, a balance of drag and weight forces determine whether or not that piece of debris will move along with the flow toward the strainer. The flow velocity around the debris piece is affected by the thickness of the boundary layer relative to the debris height. Boundary layer models typically use Reynolds number (e.g., to define the transitions between laminar and turbulent regimes layers). The force of drag on a piece of debris depends on the flow velocity, the debris dimensions, and a drag coefficient that is typically correlated using the Reynolds number. It is worth noting that the length parameter (L) resides in the numerator of the Reynolds number but it resides in the denominator of the Froude number, meaning that a decrease in L would decrease the Reynolds number but inversely increase the Froude number.

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

Debris will settle significantly faster in still hot water than still cold water, which tends to make near-field settling in room temperature head loss testing somewhat conservative. However, as temperatures increase, the viscosity will decrease, and hence the Reynolds number will increase, which indicates more turbulence in the hotter sump pool than in the head loss test tank. More turbulence tends to keep debris suspended. This effect may tend to make room-temperature head loss tests less conservative. The drag forces on floor debris will change somewhat due to an increase in Reynolds number as temperature increases. Colder water would enhance the drag and increase the chance of debris being transported to the strainer. In addition to, and affected by the temperature driven considerations, are the complexity of the sump pool geometry relative to the head loss test tank and the variations in water returning to the sump pool from the break overflow and the containment drains. Justifications regarding the extrapolation of the room-temperature near-field head loss testing should be provided by a licensee seeking credit for near-field settlement. CFD analyses of the sump pool and the test tank may be useful in the comparison of the test and predicted plant conditions.

3.3 Test Module Design - Area Ratio-based Scaling

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

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

For non-uniform velocity replacement strainers, two phenomena have been postulated that may not be adequately represented by testing according to the average approach velocity rather then the fastest strainer approach velocity. These phenomena are the potential for vortexing near the suction line and severe non-uniform sequential debris accumulation.

The potential for vortex formation would increase with the strainer approach velocity. Therefore, the strainer module in a string of modules that is closest to the pump suction intake would have the greater likelihood of forming a vortex if no uniform flow control device is used. Therefore, the determination of whether or not an adverse vortex could form should be based on the velocities associated with the module closest to the pump suction intake whether the determination is experimentally or analytically based.

It has been hypothesized that non-uniform debris accumulation near the pump suction intake can occur such that localized strainer blockage would result at that location and subsequently progress along the strainer until the entire strainer is blocked. The presence or absence of a concern regarding the non-uniform debris accumulation depends on whether a greater strainer head loss would occur under non-uniform flow conditions than under uniform flow conditions. In the event sufficient debris is present to block the entire strainer, the greater bed compression caused by higher than average approach velocities could lead to higher head loss in the non-uniform configuration than would be calculated using average flow velocities. No evidence has been presented to the staff that this effect is significant. Absent such evidence, licensee testing is not expected to address this possible non-uniform issue.

Summary

The following criteria are important for test designs that are based on screen area ratio scaling:

1. The fiber and particulate amount based on the area-ratio scaling is not sufficient to form a circumscribed debris bed.

2. The testing module screen surface approach velocity is equal to or higher than the average velocity. In cases where the strainer approach velocity varies significantly due to local flow patterns or due to variations in internal strainer head loss it may be necessary to test with a somewhat increased velocity to ensure conservatism.

3.4 Test Module Design - Debris Accumulation Pattern

The pressure drop caused by a debris bed depends directly on the velocity of flow passing through the debris, and that velocity depends on the strainer surface debris accumulation pattern for a given pump flow rate and strainer design. For replacement strainers of relatively complex geometry, such as a stacked disk strainer, debris can accumulate differently for very fine debris than for coarse debris. Further, the accumulation pattern depends upon the total volume of debris that has accumulated and the types of debris present. For very fine debris, such as individual fibers or small particles, accumulation is quite likely relatively uniform initially because this type of debris is typically suspended in a more or less uniform concentration that follows the flow. If this fine suspended debris (typically fibers and/or particles) were to build up somewhat non-uniformly, the flows would be redistributed to follow the path of least resistance, thereby rerouting additional debris to locations of thinner accumulation. In this manner, a uniform thin layer of fiber debris can accumulate over the entire screen area, and this layer of fiber can filter particulate. This type of debris accumulation can lead to the so-called thin-bed effect where a modest layer of fibers forms an effective particulate filter. The subsequent particulate buildup within the fiber bed results in a debris bed with a porosity similar to that of a bulk accumulation of that particulate. For a thin uniform debris accumulation over the entire screen area, the test strainer approach velocity that is appropriate for similitude to plant conditions is determined by dividing the volumetric flow by the total screen area. Vendor prototype testing observed by the NRC staff has focused on this total screen area approach velocity, which is correct for thin-bed accumulations.

Some types of debris, specifically coarser debris, can bridge the entrances into the interior gaps of the strainer and thereby accumulate on the outer perimeter of the strainer. This type of accumulation is referred to as circumferential accumulation. This type of debris could also include RMI debris, paint chips, or larger pieces of fibrous debris. Consider the case where a mixture of RMI, coating, and miscellaneous debris were to pile up around a strainer to such a degree that the strainer was essentially fully engulfed. Here, the correct flow area would be the circumscribed or perimeter area of the strainer. The correct velocity to use in estimating the head loss would be the circumscribed velocity determined by dividing the volumetric flow by the circumscribed strainer area. The licensees' testing module design could preserve the circumscribed velocity either by using a full-scale module or by increasing the testing module flow rate to achieve the average circumscribed flow.

Even fine suspended debris can accumulate in a non-uniform manner depending on the strainer design and sump layout configuration. Given a stacked disk strainer design, if the flow entering the gaps between the disks is fast enough, it may push surface accumulations deeper into the gaps, essentially filling the gaps from inside to the outside. Because the pushing of debris deeper into the gaps functions to clear some areas, the cleared areas keep the head loss from building up. In addition, the non-uniformities can work toward preventing the formation of a thin-bed accumulation. The effective approach velocity for this type of non-uniform accumulation can vary from the total screen area velocity to the circumscribed velocity, similitude is more complex and testing may have to focus on the two extremes.

For some proposed plant strainer designs, it may be possible to have testing similitude for both screen and circumscribed approach velocities simultaneously. Figure 3.1 schematically shows several modules connected end-to-end where the ratio of the screen to circumscribed areas for a single module could be reasonably close to the same ratio for the entire assembly. Therefore, during prototype testing of a single module, it is conceivable that the similitude for both the total screen and the circumscribed velocities can be simulated simultaneously. But for other strainer designs, it may not be possible to achieve similitude for both velocities simultaneously. Figure 3.2 schematically shows modules connected into a common plenum with the modules arranged in an array. In this type of arrangement, the center modules may only have one outer surface contributing to the circumscribed area. During prototype testing of a single module, it is unlikely that the similitude for both the screen and the circumscribed velocities can be simulated simultaneously. For these strainers, the test matrix may have to include tests where the respective similitude is achieved piecemeal. A simple area-ratio scaled head loss test may not be conservative.

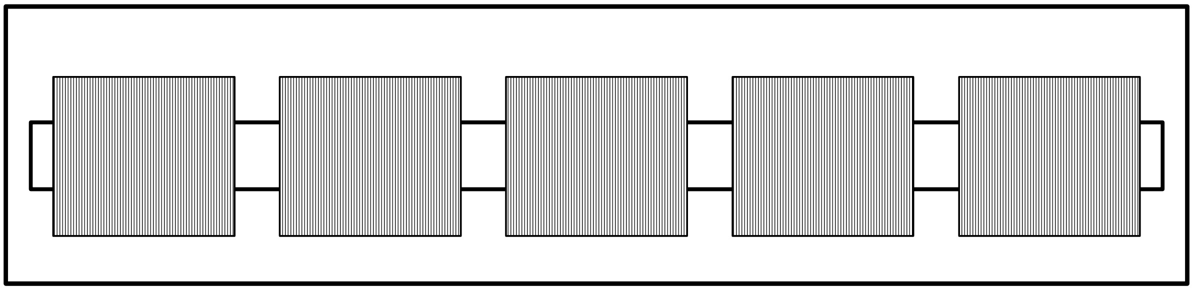

Figure 3.1 - Schematic of Modules Connected End-to-End With Common Central Flow Plenum

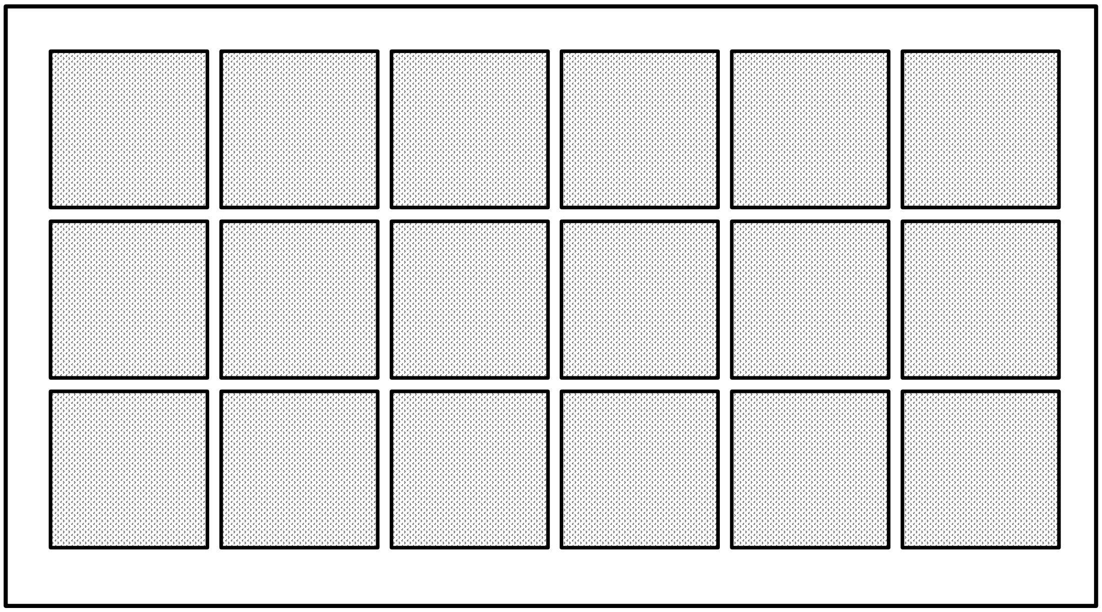

Figure 3.2 - Schematic of Array of Modules Connected to Common in-Floor Plenum

For high-fiber and high-particulate plants, the sump configuration plays a significant role in the debris accumulation pattern. The licensee could choose to design a cluster of strainer modules installed inside a sump pit with the interstitial volume higher than the estimated total debris volume. This type of design may experience a non-uniform high debris accumulation at the top of the strainer array or at the entrance of the sump pit. Bridging may occur, and a debris bed may form over the top of the strainer at the entrance to the sump pit. In this case, high flow velocity could be expected through the debris bed and the effective circumscribed area could be equivalent to the cross-sectional area of the sump pit opening. The head loss in this situation would be expected to be significantly higher than that measured by a testing module loaded with a scaled average debris load based on area ratio scaling. For this type of configuration, the strainer surface area-ratio based scaling practice is likely non-conservative. Licensees with this configuration should test at the circumscribed velocity or provide justification to demonstrate that the measured head loss using the area-ratio scaling (or other approach) is conservative.

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

Summary

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

4.0 NEAR-FIELD DEBRIS TRANSPORT AND ACCUMULATION SIMILITUDE CONSIDERATIONS

When the surrogate debris is introduced into a test tank at some distance away from the strainer, a substantial portion of that debris will typically settle within the test tank rather than accumulate on the test strainer module. In effect, if settling is allowed (agitation is not provided to the test tank), strainer module testing effectively combines debris transport with debris accumulation and head loss all in the same test. Some strainer vendors and licensees are considering taking credit for debris settling during testing and consider this phenomenon realistic. The settling phenomenon is referred to as near-field settling or the near-field effect. Licensees taking credit for near-field settling should show that this settling is realistic for the plant replacement strainer and ensure that non-prototypical conditions in the test do not result in unrealistic transport to the strainer. Assurance is needed that the near-field debris settling within the test tank is similar to or less than the settling that would actually occur within the plant following a postulated LOCA. Due to the complexities involved with predicting and creating realistic debris transport within a test facility, some conservatism should be applied to any test that credits near-field settling. An issue related to near field settling is the prototypicality of the accumulation of debris on the strainer. For example, excessive turbulence in the test tank can drive debris onto the strainer non-prototypically or wash debris from the strainer. Some debris, particularly larger pieces of fibrous debris, may have the effect of creating lower head loss. Debris types that are not predicted to reach the strainer should not be forced onto the strainer by non-prototypical flow patterns or turbulence. This is also related to the preparation and introduction of surrogate debris for the test. The design of a test that balances the prevention of near field settling with prevention of non-prototypical transport is not trivial. To some extent non-prototypical transport can be controlled by proper debris preparation and introduction.

The quantity of debris introduced into the test tank is usually scaled down from the bounding quantities determined from replacement strainer debris generation and transport analyses based on the area-ratio scaling approach. The GR resolution guidance [1] calls for testing to assume that all of the transportable debris could accumulate on the replacement strainer. Neither the GR nor the subsequent SE recognized the existence of near-field settlement. Acceptance of near-field debris settling could result in strainers being sized smaller than a strainer sized to meet the approved methodology. Therefore, the near-field effect represents a refinement to the existing resolution guidance and a potential reduction in conservatism.

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

4.1 Simulating Strainer Upstream Hydraulic Conditions

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

Licensees have used various methods to establish the hydraulic conditions within the tank including flow channeling, water level control, flow rate adjustments of the recirculation pump, water injection to cause pool turbulence, and baffles. Some vendors have controlled flow velocities through the test tank by installing paneling to create specifically shaped flow channels that could, for example, cause the water to speed up as it approaches the test strainer if that condition was predicted to occur in the plant sump. Paneling has been used to simulate plant features in the immediate vicinity of the replacement strainer, such as a nearby wall or sump installation. The overall flow velocity is controlled by the flow rate of the recirculation pump, and this flow rate is usually established so that the strainer screen approach velocity matches that of the replacement strainer design for a specific accident scenario. The tank water level is typically controlled to establish a prototypical water level above the test strainer, and in some cases a vendor may implement a time-dependent water level corresponding to water build up in the plant sump. Water-injecting downcomers have been used to introduce turbulence into the tank water pool in an attempt to represent the predicted sump pool turbulence or to artificially suspend debris within the pool. The pump, which takes suction downstream of the test strainer, discharges back to the test tank. The returning water can result in non-prototypical turbulence around the test strainer. Some test setups use baffles between the pump discharge and test strainer module to prevent this turbulence from disturbing the debris bed non-prototypically.

4.2 Analytical Verification of Prototypical Hydraulic Conditions

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

The available analytical tools used by licensees and vendors include: (1) the application of a CFD code to perform comparative analysis between the plant sump pool and the prototype test, and (2) the application of simple models such as a method referred to as the nodal network method. The key flow parameters that most need to be prototypically represented in the tests are the flow velocities and the pool turbulence. The flow drag on the debris that could move settled debris across the test tank floor is a direct function of the flow velocity. Pool turbulence affects the settling of debris within a pool.

CFD codes provide a numerical modeling method of comparing both flow velocities and pool turbulence between the plant sump pool and the test tank. Although uncertainty exists in all such analytical evaluations, the CFD tools have proven to simulate key features of hydraulic flow reasonably well. Using the same CFD code and modeling options to simulate both the plant sump with the replacement strainer and the test tank with the prototype strainer should provide reasonable comparisons of both three-dimensional flow velocities and pool turbulence. The CFD simulations can account for flow channeling in the sump pool due to nearby structures. The CFD analyses should account for containment spray drainage flows into the plant sump pool and the LOCA break overflow into the pool, both of which could cause turbulence within the sump pool that can in turn suspend debris that could otherwise settle in a calm pool. The CFD analyses could also consider the effects of debris accumulation near or on the replacement strainer that could significantly alter subsequent flow patterns. Effective average flow velocities near the replacement strainer or at key sump pool locations can be determined from the CFD results.

On the other hand, the simplified methods, such as the nodal network method, are limited in capabilities, and the results may have a relatively large uncertainty. These methods are limited in general to one-dimensional predictions of average flow velocity. Therefore, the best uses for these methods are to apply them to flow channels that are reasonably well defined. These methods cannot predict pool turbulence. The use of non-CFD methods will usually require a significant conservatism to account for the aspects of the flow stream that are not predicted by the model.

Simple flow calculations, such as estimating the average strainer approach velocity at the perimeter of the strainer, provide a rough characteristic velocity that can be compared to separate effects data for debris transport. This information may be used to demonstrate the likelihood that settled debris reaching the base of the strainer could subsequently lift off the floor and accumulate over the entire surface of a strainer that is positioned well above the sump floor. Further, average screen approach velocities can be compared to separate effects data that measured the minimum screen velocity required to hold a piece of debris to a vertical screen surface. Such considerations could potentially show that heavier debris, such as RMI, could not effectively accumulate over the entire surface of a strainer.

Summary

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

4.3 Debris Introduction with Respect to Hydraulic Conditions

The method of debris introduction into the test loop upstream of the strainer testing module can significantly alter the head loss measurement and the debris settlement. In most cases, licensees or strainer vendors cannot identify a particular realistic debris arrival sequence. Various introduction methods have been developed. These methods define the location, rate and timing of debris introduction, and the sequence of the introduction of different types of debris. Some vendors typically introduce the debris well away from the test strainer and then take credit for near-field debris settling, while other vendors introduce debris very near to the strainer to limit the near-field settling. The advantage of introducing the debris immediately upstream of the strainer is that the licensee may be able to avoid analyses to demonstrate the prototypicality of near-field debris settling. However, a significant disadvantage of this approach is that the debris accumulation can easily become skewed resulting in a non-prototypical accumulation compared to expected plant conditions. For some cases, the staff is concerned that a non-prototypical, artificially skewed debris accumulation could affect the potential for thin-bed formation. Conversely, the introduction of debris well away from the strainer allows the finer suspended debris to become relatively uniformly distributed within the tank pool so that it follows the flow as the fluid seeks the paths of least resistance through the strainer debris bed.

Another important aspect of debris introduction is whether to introduce the debris before or after starting the recirculation pump. Following a LOCA, some debris would be deposited directly at the containment pool level, and some other debris that was initially deposited at the upper level would be washed down to the containment pool level by the containment sprays prior to the switchover to the recirculation mode. After the start of recirculation debris would continue to wash down into the pool. Analytical capabilities are not sufficiently developed to make reasonable estimates regarding what the debris distribution would be in the containment pool prior to the operation of the recirculation pumps or how much debris would be located near the containment sump. In addition, pool turbulence due to the break effluents and containment spray drainage would be substantial. A decision on whether debris is introduced before or after starting the test pump should be based on ensuring a conservative, if not realistic, test based on the discussions in the following paragraphs.

If the debris is introduced into the test tank prior to starting the pump, then the turbulence associated with the LOCA break effluence and containment spray drainage should be present in the tank so that the debris does not settle in still water as opposed to prototypically turbulent water. It would be non-conservative to introduce the debris into still water prior to the start of the test pump. Further, introducing the debris prior to starting the pumps can agglomerate the debris non-prototypically. The agglomeration concern is of particular importance for the fine normally suspended debris such as fibers that erode from settled fibrous insulation over a relatively long period of time. In addition, current strainer vendor test flumes have not been designed in a manner that readily allows scaling of phenomena associated with transport modes other than recirculation. For example, based on typical test scaling ratios, the debris loading (scaled based on the ratio of the test strainer area to the plant strainer area) added to a test flume prior to the start of the test pump will result in an average debris layer thickness in a test flume that is significantly greater than that of the layer expected in the plant containment. The likely result of this situation is that the test debris will experience greater agglomeration, and less transport will occur when the test pump is started. Similarly, the increased concentrations of suspended debris in the water may also tend to result in increased debris agglomeration. For these reasons, debris introduction prior to pump start has not been considered an acceptable approach for head loss testing, absent justification to the contrary.

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

Summary

Proper debris introduction procedures should take into account the fact that variations in the sequence and rate of debris introduction can potentially affect the head loss measurement. The introduction approach that is considered most conservative is to introduce the debris slowly into the test tank with the pump running and prototypical hydraulic conditions established. The most transportable debris should be added first and the least transportable last. Other approaches may also be used if justified.

5.0 SURROGATE DEBRIS SIMILITUDE

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

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

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

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

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

Licensees likely will need to introduce chemical precipitates into their head loss debris mix. The Integrated Chemical Effects Test (ICET) reports and the latest WCAP-16530 report [8] form the basis for the types of chemicals and quantities added to the head loss tests. The methods of introducing chemicals into the test are discussed in the staff's review guidance for chemical effects. For example, the chemicals can be introduced already formed or be precipitated out in the head loss apparatus. Additionally, the manner of controlling the water pH and temperature should be considered. Prototype testing should address these considerations.

The debris preparation process should first render the surrogate material into debris that reasonably represents the size distribution determined by the debris generation and transport analyses. Once the debris has been generated, debris preparation typically pre-wets the debris to remove trapped air and to reduce subsequent agglomeration prior to introducing the debris into the test tank. For some head loss testing, prepared fibrous debris has been preheated to effectively age new insulation material so that it resembles insulation that has been installed at a plant for an extended period of time. However, this would only be necessary if the aging process significantly alters the materials' head loss characteristics. Boiling or mixing the prepared fibrous debris in hot water can shorten the time required for entrained air to escape.

Of particular concern is the preparation of the very fine fibrous debris that would remain effectively suspended and would therefore be likely to accumulate on the strainers. Such very fine fibers consist of a portion of the LOCA-generated fibrous insulation debris, eroded fibers from settled fibrous debris, and the latent fibers. Typically, vendors have used some form of shredded insulation debris to represent these very fine fibers. This approach has led to concern that the debris may not be prototypically fine. A representative portion of the fibrous debris should be rendered into very fine pieces for maximum debris load testing. For thin bed testing, the finest fibrous debris present in the plant-specific debris size distribution should be used unless another approach is justified on a plant-specific basis.

The specification of surrogate fibrous debris should consider the filtration characteristics such as bed porosity and compressibility. The debris should be prototypical in the transport characteristics such as floor tumbling velocities and settling velocities. The specification of surrogate particulate and fibrous debris should consider the head loss characteristics such as the specific surface areas, porosity, compressibility, and fiber diameter. The debris surrogate should also consider the settling characteristics of the various sizes of debris. The specific surface area has typically been related to the particle size distribution, but this has not always been the case. Settlement behavior of potential chemical surrogate materials should be considered during the material selection and preparation process.

Summary

Surrogate debris materials used in head loss testing should be either the actual plant materials or suitable substitutions. Substitutions should be justified by comparing the important characteristics of the plant debris sources and the surrogate to ensure that the debris preparation creates prototypical or conservative debris characteristics.

6.0 TESTING MATRIX

Once prototypical hydraulic conditions are established and the surrogate debris material is properly selected and prepared, the testing matrix becomes the important factor in controlling different testing input conditions and testing parameter variations. In principle, all test variables for a particular test case should be considered so that the effects of potential variations are understood. The variables should be controlled such that either a prototypical or conservative approach can be adequately specified. If a variable cannot be shown to be controlled prototypically, it should be shown to be conservative. For example, if a test procedure for a given plant cannot be shown to be completely prototypical of the plant accident scenario, and two different but potentially valid tests are run to bound the scenario, the test resulting in the highest head loss would be the more conservative result for strainer qualification. Either result could be used if shown to be conservative.

6.1 Consideration of Head Loss Testing Input Parameters

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

6.1.1 Break Selection for Testing

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

Summary

The testing matrix should be developed to test a spectrum of break locations if unable to show that a single break location can bound rest of the break locations with regard to debris generation and transport. The test matrix may include bounding amounts of debris from several breaks in order to reduce the required number of tests performed. This practice is acceptable as long as it can be demonstrated that combinations of debris that result in limiting head loss results are included in the test matrix.

6.1.2 Debris Configuration for Testing

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

Fully Loaded Case

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

Thin Bed Case

The test matrix should consider situations whereby smaller debris quantities than the upper bounding quantities can cause a higher head loss than would the bounding quantities. Such a situation is the thin-bed debris bed configuration where a limited quantity of fine fiber filters and traps a layer of particulate on the strainer screens. With this configuration, the bed porosity effectively corresponds to that of packed particulate which is substantially less porous than a typical layer of fibrous debris. The thin-bed term originated because observations have been made in which a relatively thin layer of debris resulted in a large head loss.

For plants with minimal fibrous debris, a test with the upper bound fiber quantities may also serve to determine whether or not a thin-bed configuration can occur, and at the same time determine the head loss associated with the upper bounding debris quantities. In this situation, the test matrix may consist of a single test per break scenario selected for testing. The one consideration for plants that cannot generate a fibrous thin bed is that it may be more conservative to add coating debris as chips rather than particulate. For low-fiber plants, in the absence of a plant-specific evaluation on the characteristics of coating debris it may be necessary to test with paint chips. It may also be possible for plants to show that paint chips will not transport to their strainers, in which case it would be conservative to test with coatings as particulate. In general, the staff believes that testing with coatings as particulate will yield conservative head loss results. Unless there is significant bare screen, the staff will accept the treatment of coatings as particulate as conservative.

Historically the thin bed has been viewed as about a 1/8-inch bed of fiber. However, in the presence of particulate insulations, such as Cal-Sil, much thinner fibrous beds have resulted in high head loss. In addition to the issues noted with particulate insulations, chemical debris has also been shown to result in a large head loss when accumulating on fibrous debris beds significantly less than 1/8 inch in thickness. The historical 1/8-inch bed thickness criterion was also based on other historical testing practices, such as the use of shreds (small pieces) of fiber rather than fines and the use of a small, horizontal flat plate strainer with a 1/8-inch mesh spacing. The use of fibrous fines (as opposed to shreds) for thin bed testing will tend to decrease the bed thickness necessary to generate a thin bed. A screen with smaller openings than 1/8-inch may also reduce the fibrous debris thickness needed for thin bed formation. On the other hand, some non-uniform approach velocity strainer modules may require average bed thicknesses somewhat greater than those observed on flat plates prior to experiencing a thin bed.

For plants with the potential to generate relatively large quantities of fibrous debris, the test matrix should provide confidence that the peak head loss has been conservatively or prototypically determined. The preferred approach is to cover the thin-bed and fully loaded debris bed case either in a single test or multiple tests. Even if the plant has enough fiber to form a thick fibrous bed, the accumulation process should pass from zero accumulation to bed thicknesses greater than the typical thin-bed thickness incrementally to ensure that the peak head loss is determined. Once enough fiber has been added to ensure that the thin bed thickness has been exceeded, the remaining fiber may be added relatively quickly. However, it should be added at a rate to ensure prototypical fiber deposition on the bed is maintained. For high-fiber plants, the testing should ascertain the peak potential head losses associated with the thickness of fiber supporting the thin bed since it has been demonstrated that the thin-bed head loss can depend on the quantity of supporting fiber, which is known to affect the filtration efficiency for the particulate. For high-fiber plants, the thin bed test can be performed during an early part of a thicker bed test or it can be performed individually. A complication to performing only a single test arises when chemical debris is added to the test loop. Because there are many potential interactions between the chemical and non-chemical debris, it may be necessary to perform a series of tests to ensure that a conservative bounding head loss is achieved.

Summary

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

6.2 Tailoring Test Matrix to Test Objectives

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

- Determining whether or not sufficient fibrous material can accumulate on the plant replacement strainer to effectively filter particulate.
- Determining the worst-case head loss for a thin-bed accumulation.
- Determining the worst-case head loss for the maximum debris quantities as determined by the licensee's conservative debris generation and transport analyses.

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

6.2.1 Validating Insufficient Fiber to Filter Particulate

The primary source of fibrous debris in containment is fibrous insulation, fire barrier materials and latent fiber. Some plants, where the containment insulation is exclusively RMI or nearly so, may not have sufficient fibrous debris sources to accumulate a fibrous layer sufficient to effectively filter particulates. In this case, the resultant head loss from fibrous and particulate debris could be well below the level of concern. However, even if a plant's insulation were exclusively RMI, latent fibers will exist in containment in some quantity. Other sources of fibers could include the fiber component in particulate insulations such as calcium silicate. If, for example, a plant had 100 lbm of latent debris and 15 lbm of that were fibrous, this would be sufficient fiber to cover roughly 600 ft^2 of strainer surface with a one-eighth-inch layer of fiber. Fibrous debris loads with a theoretical thickness much less than one-eighth-inch have resulted in significant head loss during testing.

The GR, as accepted by the staff SE, recommends assuming a minimum of one-eighth-inch of fiber as the criterion for potential thin bed formation. The source of this criterion was an observation made in NUREG/CR-6224 that included statements to the effect: "to form a uniform debris bed, a thickness larger than 0.125 inches was needed. For a lesser thickness, the bed does not have the required structure to bridge the strainer holes and filter the sludge particles." This observation was made from tests that used shredded Nukon™ fibrous debris with approach velocities typically ranging 0.2 to 1 ft/s, and screens typically either manufactured using one-eighth-inch wire mesh screen or perforated plates with one-eighth-inch holes. However, the SE noted that this one-eighth-inch guideline may not apply for all types of fiber debris. During the NRC-sponsored calcium silicate tests [5], a head loss of 14 ft was achieved at 1.4 ft/s flow with a layer of Nukon™ and calcium silicate that was 0.11 inches thick (i.e., slightly less than one-eighth-inch). The NRC staff has also observed high head losses during vendor testing of prototype strainers with calculated fiber bed thicknesses of much less than one-eighth inch. These tests were conducted at prototypical plant approach velocities and using prototypical plant strainer modules, unlike the NUREG/CR-6874 testing described above. Fibrous debris accumulating from suspended individual fibers forms more uniformly than does shredded (larger) fibrous debris, for which the minimum thickness observation was made. High-density fiberglass insulations, such as Temp Mat, are substantially less porous than Nukon™; therefore it could take a lesser thickness of Temp Mat to cause effective filtration than for Nukon™. It seems to take some compression of Nukon™ to effectively filter calcium silicate, where less compression may be needed for Temp Mat. The particulate filtration efficiency for a layer of fibrous debris depends on the thickness of the fibrous layer, the porosity of the fibrous material, bed compression, approach velocity, particle size distribution, and likely the diameter of the screen holes or wire mesh size. Therefore, it is difficult to analytically evaluate whether there is insufficient fiber to form an effective thin-bed with chemical precipitates and particulate debris. An indicator of the improbability of forming a thin bed would be that a significant portion of the strainer area remained completely free of fiber after all fibrous debris is added to the test flume and allowed to accumulate on the strainer.

A prototype strainer test designed to experimentally determine whether or not an effective fibrous layer could form should ensure that a conservative quantity of fibrous debris actually accumulates on the strainer. Given the very low screen approach velocities of the replacement strainers, it is likely that the accumulation of fibrous debris over the entire strainer surface area would come almost entirely from suspended fibers or very fine shreds. The primary sources of suspended fibers include: (1) latent fibers, (2) the fraction of the LOCA-generated fibrous debris that is destroyed into individual fibers or very fine shreds, and (3) fibers that erode away from larger fibrous debris in the sump pool. From a conservative viewpoint, the latent fibers should be considered to transport completely as suspended fibers. When a fibrous insulation blanket is destroyed, a significant fraction of the debris is too fine to collect by hand [3], and this component should be considered to transport as suspended debris. When fibers erode from small and large fibrous debris in the sump pool, these fibers transport as suspended debris (SE Appendix III.3.3.3 of [2]). This erosion occurs over hours, if not days, and is enhanced by pool turbulence.

Testing has been observed by the staff for which latent fibers were simulated in the test using shredded Nukon™ and for which the majority of the Nukon™ shreds settled to the tank floor where they remained. In these cases, only a portion of the Nukon was accumulated on the strainer surface, and the accumulation of latent debris on the test strainer was considered neither realistic nor conservative by the staff. The staff reached this conclusion because the fibrous debris used in the testing was not prepared to match the size of the debris predicted to reach the strainer by the transport calculation. In some cases the flow was not prototypical or conservative with respect to the flow patterns expected in the plant. The test procedure should have been designed to ensure proper latent fiber debris preparation and a prototypical or conservative accumulation on the strainer before concluding that there was not sufficient fibrous debris to form a fibrous layer on the plant replacement strainer.

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

6.2.2 Determining Peak Thin-Bed Debris Head Loss

Once a licensee has determined that there would be sufficient fibrous debris to form a fibrous layer that could efficiently filter particulate, then the worst case thin-bed head loss will generally have to be experimentally determined. Even if the bounding maximum possible quantity of fiber debris would far exceed that needed to form a thin bed, the accumulation process in the testing should attempt to develop a thin bed to reflect the possibility of a smaller LOCA that would generate a smaller amount of debris or the possibility that a thin bed would develop as an intermediate condition in a full-load case. The head loss in such a scenario can be significant. The thin bed case in the plant could result from any amount of fibrous debris generation and transport, from a small amount up to the maximum postulated amount. Therefore, the thin bed testing should cover this range of potential debris generation in increments small enough to determine the limiting head loss for the plant-specific debris.

The following is guidance on testing to determine whether a thin bed will form. Variations from this guidance are acceptable as long as the objective of prototypical or bounding peak head loss is met.

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

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

3. Prepare the surrogate fibrous materials as very fine debris that will tend to remain suspended with relatively little pool turbulence. It has been demonstrated that a food processor can effectively break up shredded debris. Ensure that the concentration of the prepared debris slurry is adequate to prevent non-prototypical agglomeration of the fine debris prior to its addition to the test flume.

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

5. Debris addition should occur slowly to ensure representative accumulation on the strainers. Following are two possible approaches to sequence addition of the debris for thin bed testing (other approaches may be used if justified as conservative or prototypical):

   a. The total amount of particulate debris may be added first followed by small, incremental fiber additions until assurance exists that the limiting thin bed test head loss for the plant-specific debris loading has been achieved. This procedure may incorporate a significant degree of conservatism for some plants; however, it permits experimentation with various ratios of fibrous and particulate debris in a single test.

   b. Alternately, separate thin bed tests with the total particulate load and varying amounts of fiber can be performed with fibrous and particulate debris being added to the test flume simultaneously to create a homogenous mixture in the test flume. If this approach to debris sequencing is chosen by a licensee, an adequate number of independent tests should be performed to ensure that the limiting thin bed head loss has been achieved. It is anticipated that this method may result in a less conservative head loss during testing, and therefore may be a more desirable method of testing. In this case, incremental batching of fiber is not appropriate unless it can be shown that the first fibrous addition (with the total particulate load) would result in less than a thin bed. In this case, a hybrid of cases 5.a and 5.b could be performed with small incremental batches of fiber added after the first addition that included the total particulate load and a small amount of fiber. For all cases it should be noted that thin beds have been formed with much less than a one-eighth-inch theoretical fiber bed.

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

Regarding the homogeneous debris addition sequence in Step 5.b above, the staff considers this approach acceptable in concept, but notes that excessive debris agglomeration has been identified as a concern with the implementation of this approach in a number of previous tests that relied upon this practice. This agglomeration has typically occurred as a result of mixing high concentrations of particulate and/or fibrous debris together in buckets prior to addition to the test flume. This issue can be addressed by ensuring that the concentration of the prepared debris remains low enough to ensure prototypical behavior when added to the test flume. Mixing the particulate and fibrous debris separately and adding scaled batches of the debris to the test flume simultaneously to the test flume to create a homogeneous mixture in the flume is an additional practice that provides increased confidence that non-prototypical agglomeration does not occur. However, even when added separately, adequate dilution to prevent agglomeration should be ensured.

Summary

Although the GR indicates that a one-eighth-inch fiber bed is the criterion to determine whether a thin bed would form, testing should be performed to support the determination of whether or not a thin bed can occur on a given strainer. With the addition of chemical precipitates and particulate type insulations such as Cal-Sil, testing has demonstrated that a fiber bed significantly thinner than one-eighth-inch may result in a filtering bed and associated high head loss. Some strainers, due to their geometry, may require more than one-eighth-inch theoretical bed thickness to achieve a filtering bed. Based on the observation of recent tests conducted with similar debris loads added in different sequences, the staff has concluded that the debris introduction sequence has a large impact on thin bed head loss. During the bed formation process, the prompt accumulation of particulate in the interstitial areas of the fiber bed appears to create a thinner and more homogeneous bed. On the other hand, if the fibrous debris is added prior to the particulate, the fiber will tend to pile up more thickly, since, in the absence of particulate, larger quantities of fiber are necessary to create sufficient local head loss to redistribute debris-laden flow to clean areas of the strainer surface. As a result, adding fibrous debris prior to particulate tends to result in the formation of a more porous layer of debris on the strainer surface and requires more fibrous debris for complete strainer coverage.

Since the accumulation of fibrous debris in the absence of particulate debris is not expected to be prototypical of plant conditions, the staff expects that licensees choose one of two approaches unless another approach is justified: (1) add the full particulate load that could be transported to the strainer should prior to the addition of fiber, or (2) use a homogeneous addition sequence with the full particulate load and separate tests that vary the amount of fiber added to the test. The staff has also observed that the preparation of fibrous debris for testing can have a significant affect on its accumulation and resulting head loss. Because the thin bed test was proposed based on the premise that all postulated fibrous debris may not arrive at the strainer (particularly the less-transportable large pieces), the finest debris in the plant-specific size distribution should be added to any thin bed test first. Debris predicted to be fine should be easily suspendable. Debris should be added so that it is not agglomerated. This may require dilution of the debris by relatively large amounts of water. The staff has also observed testing in which turbulence, added to keep debris in suspension, affected the formation of the debris bed by disturbing the bed or forcing non-prototypically large debris onto the strainer. Turbulence should not affect debris bed formation non-prototypically. The presence of chemical debris or particulate insulation debris can result in a thin bed with less fiber than had previously been considered possible for thin bed formation.

6.2.3 Determining Maximum Debris Loading Head Loss

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

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

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

1. Determine the maximum quantities of debris of various types and select suitable surrogate materials with prototypical characteristics when the actual debris sources cannot be used in the head loss testing.

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

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

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

5. Establish the recirculation pump flow for prototypical flow conditions. If a circumscribed accumulation is expected, then scale the pump flow to achieve the replacement strainer circumscribed flow velocity. If the maximum fiber accumulation is not expected to approach a circumscribed accumulation, then scale the pump flow to the replacement

strainer full-screen area approach velocity. Ideally, test strainer modules would be designed to achieve prototypical circumscribed and total screen area approach velocities in the same test.

6. Introduce the debris slowly with most transportable being added first until all debris that the plant-specific analysis shows would transport to the strainer is added.

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

Summary

Maximum-load head loss tests should ensure that the testing properly models the circumferential debris accumulation with a correct circumferential approach velocity, if applicable. In addition, the debris should be introduced slowly at the beginning of the test to capture the possible non-chemical thin-bed formation unless a separate thin-bed case is also run.

6.2.4 RMI and Coatings Paint Chip Debris Head Loss

Heavier debris such as stainless steel RMI and most paint chips may transport along the floor of the sump pool, depending on the velocity and turbulence in the sump pool. There would likely be no significant quantities of suspended debris of this type, with the possible exception of very light-weight paint chips with densities near that of water. Before this heavier debris can cause blockage problems for a large replacement strainer, the debris must first transport along the sump pool floor to the strainer and then accumulate on the strainer. For strainer designs positioned well off the floor, the flow velocities must be relatively high to lift the debris from the floor onto the strainer. For stainless steel RMI, the flow velocity must be at least one ft/s to lift a relatively small piece over a six-inch high curb. For many of the replacement strainer installations, flow sufficient to lift such debris off of the floor and onto the strainer is unlikely. For this type of debris, near-field debris settling that approaches complete settling appears realistic. Exceptions to this situation could include strainers recessed below the sump floor where floor-transported debris simply falls onto the strainer from above, or strainers located directly below sources of debris.

If the debris transport analyses or testing clearly demonstrates that such debris in strainer prototype head loss testing is not going to accumulate on the strainer, it may be appropriate to simply leave it out of the head loss tests so the test can focus on fiber and particulate. On the other hand, if the strainer is recessed below the floor (in a pit), head loss testing should consider this debris because the large debris can cover the strainer and provide a surface for fibrous debris to deposit on. This fibrous debris can then form a filtering bed with a surface area much smaller than the strainer surface area. The smaller area would result in a high velocity through the bed and potentially high head losses. The large debris should be included in tests for pit installations unless the floor transport analyses can clearly demonstrate that such debris cannot reach the strainer in sufficient quantity to cause a blockage problem. If the analyses indicate this heavier debris could actually accumulate around the strainer test module, then the head loss test should be prototypical enough to result in similar debris accumulation. Given this situation, the prototypical strainer approach velocity is most likely the circumscribed velocity. However, the velocity in the test facility may have to be based on the flow velocity through the area of the pit opening in the containment floor if it is possible for the pit opening to be bridged with debris. If coating chips are light enough to transport as either suspended debris or can be easily moved across the floor and subsequently lifted onto the screen, then these chips should be tested with the strainer prototype module under prototypical flow velocity and flow turbulence conditions.

Summary

Both RMI and coating chips can be excluded from the head loss test if they are determined to not be transportable to the strainer surface based on proper transport tests or analyses. However, the coating debris may need to be added into the test tank in a particulate form to conservatively account for unknown coating debris size distribution. For pit strainer installations, strong justification should be supplied if the larger debris is excluded from the test. Testing for pit installations should ensure prototypical velocities approaching the strainer, prototypical paths for transport of larger debris, and prototypical test geometries that will allow simulation of plant debris accumulation. If this is not practical, the large debris may have to be placed in the test facility on the strainer prior to introducing the remainder of the debris. Test velocities should be scaled to be prototypical of the plant approach velocities.

7.0 TEST TERMINATION

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

During testing, the head loss may approach a steady state relatively soon after additional debris accumulation effectively ceases (i.e., the test debris either resides on the strainer debris bed or has settled to the test tank floor). Generally, once all debris has settled out or deposited on the debris bed, the water will appear clear. In other situations, the filtration efficiency may be poor enough that the water always remains cloudy. A final steady state can sometimes require many pool turnovers as the filtration process gradually clears the water of finer and finer particles until the remaining particulate is too fine to be filtered. In addition, there are potential time-based phenomena that may result in longer term head loss increases. Test termination and data extrapolation methods should consider this possibility as well. When a licensee throttles back pump flows, as would be typical of plant operating procedures, the reduced flow rate will also reduce the head loss associated with the debris accumulated at that time. If the debris continues to accumulate or head loss increases from other phenomena after the pumps are throttled back, a potential second head loss peak may need to be considered. The approach in head loss testing of prototype strainers has been to test at the full pump flow rate and early accumulation of all the debris. Test durations have been much shorter than the typical times for throttling back the pumps.

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

The processes that could cause the increase in head loss to continue for hours, if not days, include the continued filtration of the very fine particulate, continuing erosion of the fibrous debris effectively stalled on the test tank floor, a potential slow compression of the fiber, and potential chemical changes. It is known that shredded Nukon™, for example, will continuously give up fibers in a turbulent pool for several hours, if not days (Appendix III.3.3.3 of [2]). A longer-term vendor test conducted in 1992, in which the test was run for 24 hours, demonstrated that the head loss continued to increase at a somewhat constant rate until the test was terminated (Figure 7-23 of [6]). The staff has reviewed vendor test data that indicated that substantial overnight increases in head loss were likely attributable to achieving nearly complete filtration due to the extended testing period. Other vendor data has shown a rate of head loss increase that was approximately constant for a period of about twelve days.

Even if it is not practical to conduct all head loss tests for a long term, the head loss results would be more reliable if selected key design basis tests were run for extended periods of time. Test termination criteria should be based on experimental observations rather than simple engineering judgment. To illustrate this point, NRC-sponsored closed loop head loss testing was reviewed to ascertain the trend in how many times suspended debris circulated through the test screen before the head loss became effectively steady state. The NRC-sponsored tests that were reviewed included the calcium silicate head loss tests [5] and the surrogate latent particulate head loss tests [7]. The results of this review are shown in Table 7-1, which shows the number of flow circulations in the closed loop apparatus, which are akin to pool turnovers in the vendor tests. This table shows that the number of circulations needed to reach steady state typically exceeded 10 circulations, whereas some vendor test criteria specify a minimum of five pool turnovers.

Table 7-1 - Number of Tank Turnovers to Reach Steady State

Sub-Test ID	**CalSil Test 6B Series # of turnovers**	**CalSil Test 6H Series # of turnovers**	**Latent Test 11 Series # of turnovers**	**Latent Test 19 Series # of turnovers**
1	9.4	4.3	8.0	11.8
2	14.8	7.7	7.8	11.1
3	18.3	8.7	10.0	4.4
4	13.6	11.9	8.6	-
5	-	13.6	-	-
6	-	18.0	-	-
7	-	15.0	-	-
8	-	15.9	-	-
Total Tank Turn Overs	**56**	**230**	**34**	**27**

The minimum number of pool turnovers can also be examined analytically. For the purpose of illustration, simplifying assumptions are made (which may or may not be applicable to particular vendor testing) that the strainer filtration efficiency is constant, the debris within the test tank is uniformly distributed within the pool, and that no debris settles within either the tank or the recirculation piping. For this case the debris concentration within the pool could be represented by the following equation, if no debris bed morphology changes occur after the peak head loss is observed.

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

Where: $c(t)$ = the time-dependent debris concentration
c_o = the initial debris concentration
ε = the strainer filtration efficiency
N = the number of pool turnovers

Based on this equation, the analytical decrease in tank debris concentrations versus the number of pool turnovers is illustrated in Figure 7-1 at several filtration efficiencies. The figure shows that five turnovers are adequate to ensure filtration when the bed filtration efficiency is near one, but many more turnovers are needed for the slower filtration of the fine particulate. It should also be noted that the filtration of the particulate is dependent on the build up of the fiber layer which takes time. The results of Table 7-1 and Figure 7-1 are in general agreement that depending on filtration efficiency more than 10 turnovers may be needed before declaring a relative steady state in the head loss data whenever the tests include substantial quantities of fine particulate.

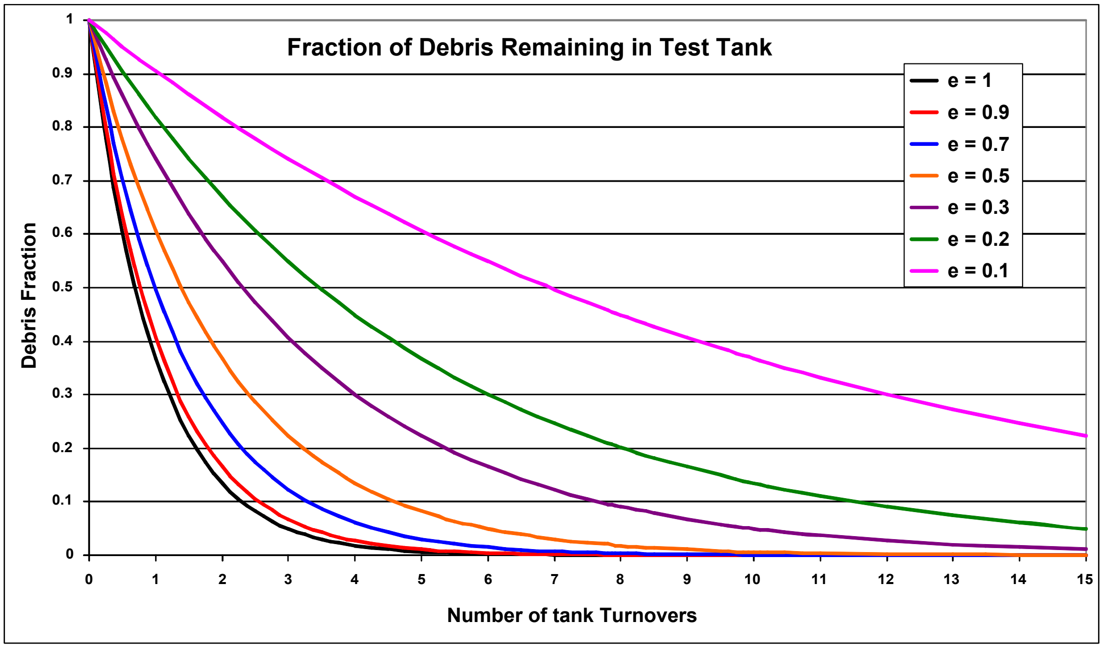

Figure 7-1 - Analytical Debris Concentration as a Function of Pool Turnovers

The chart and figure above represent a simplified presentation of filtration as a function of tank turnovers. In test setups other factors may influence the rate of filtration. Therefore, testing should use factors in addition to the number of tank turnovers for determination of test termination.

If a head loss test was terminated based on the rate of head loss increase dropping below a minimum criterion, but that rate is not continuing to decrease, then the head loss would be continuing to increase when the test is terminated. The head loss test represented in Figure 7-23 of [6] is one such test for which the head loss increased somewhat linearly throughout a 24-hour test period. The rate of head loss increase should be shown to be significantly decreasing at termination, or steady at a value below the test termination criteria, and the final head loss should be extrapolated appropriately. An extrapolation method could be as simple as applying a curve fit to test data plot, or a more sophisticated numerical analysis could be applied to the test data. It is important that the test flow rate be tightly controlled when determining that the head loss rate increase has decreased below a termination criterion minimum since a slight reduction in flow rate would also result in a slower rate of head loss increase.

It is also important to select a representative data range for performing extrapolation. Extrapolation may have to consider data much earlier in the test than that within the test termination criteria window because some tests have had relatively short periods of steady head loss or even decrease while increasing over the long term. The staff has observed many longer term tests that seemed to have no increase in head loss for significant periods, but actually had slowly increasing head loss. Variations in the range of data used for extrapolation could have resulted in significant differences in the extrapolated final head loss.

It may be helpful for a licensee to perform the extrapolation in real time on a lab test computer. The calculation of the second derivative of the head loss would illustrate whether or not the increase in head loss was actually slowing. Running a head loss test to the mission time would provide a more meaningful indication of test completion than simply looking at the rate of increase. One test, run to the mission time, could be compared to shorter tests (under similar test conditions) to determine an appropriate extrapolation method. The level of concern for this issue depends upon the margins between the test design head losses and the licensee's NPSH margin.

Summary

Licensees should provide sufficient information for the staff to have reasonable assurance that their head loss tests have realistically or conservatively determined maximum strainer head loss over the 30-day mission time. Test termination criteria should contribute to that high confidence. Criteria based on stability and predictability in test conditions are generally acceptable (e.g., specified number of turnovers plus limits on changes in head loss in a given period). To deal with continued increases in head loss at the time termination is proposed, the staff would find a linear curve fit and extrapolation of the head loss trend to the mission time of the sump (e.g., 30 days) acceptable. Licensees may also use and justify other criteria that provide confidence as discussed above, including perhaps running the test for a specified period (a day or two) after the stability criteria are met. The staff’s acceptance of linear extrapolation is based on the relatively little data available for longer term tests. The behavior of debris beds over the long term is not well known. However, the staff believes that the combined conservatisms associated with the approved processes that go into determining head loss provide margin to allow the linear extrapolation.

8.0 POST-TEST DATA SCALING AND ANALYSIS

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

8.1 Temperature Scaling

Vendor head loss testing is typically performed with water that is at relatively low temperatures when compared to the plant sump temperatures following a postulated LOCA. The methods for temperature scaling have ranged from simply applying the ratio of the water viscosities to applying a head loss correlation such as the NUREG/CR-6224 correlation. However, if the test debris bed incurred pressure-gradient driven mechanical disruptions, such as bore holes, then the scaling of these head losses cannot be based on either viscosity or the standard head loss correlations that are based on debris bed uniformity. Because bore holes and channeling may not be easily observed or detected, it is recommended that flow sweeps be conducted at the end of the test to verify that the head loss varies relatively linearly with flow. Increasing flow is more likely to create disruptions to the bed by increasing head loss, so decreasing flow at the end of the test would likely be the preferred method to verify bed uniformity (flow and head loss change linearly). The primary temperature-affected parameter is the water viscosity, which increases at colder temperatures. Therefore, the test head losses are typically substantially reduced when applied to the plant condition at higher temperature.

Summary

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

8.2 Deviations between Test Module and Actual Replacement Strainer

If the strainer test module does not accurately represent the plant replacement strainer, then scaling may be necessary to account for deviations. For example, if the design of the test strainer module was specified before the design of the replacement strainer was finalized, but the replacement strainer module total area was increased or decreased during finalization, then the test head loss may need to be scaled based on screen area. In another example, the licensee may remove problematic insulations from containment that had been included in the test specifications. In this case, licensees may desire to scale the test head losses for the alternate debris load. The scaling methods to account for these types of changes can be much more complex than simple temperature viscosity scaling. Scaling for a reduction in approach velocity should be relatively easy to justify. However, increasing approach velocity may be more difficult to evaluate. Scaling for significant differences in debris types and quantities is also challenging. Due to the complexities involved in some scaling it is recommended for situations that are not well understood, or cannot be conservatively estimated by the scaling analysis, that retesting with appropriate parameters be completed.

Summary

Scaling methods should conservatively correct the head loss data taking into account the actual strainer debris loading and approach velocity. For most of the cases, if the plant debris loading is increased or the strainer hydraulic conditions worsen (e.g., increase in approach velocity), retesting would be a conservative method of ensuring prototypical results. Alternately, if head loss is reduced due to removal of debris, decreased approach velocity, or increased strainer size, conservative calculations or retesting could be performed.

8.3 Post-Test Debris Characterization

It may be useful to a licensee to perform post-test analysis on their head loss data with the objective of better characterizing surrogate test debris, especially if the head loss behavior of a particular type of debris is not well understood. Such characterization would support the licensee's position that the surrogate is representative (or conservative) of the plant material it represents. Also, the post-test debris bed examination could provide certain information regarding the debris bed morphology. If it is shown that significant debris bed degradation occurs during the testing, the viscosity-based temperature scaling methodology should not be used.

8.4 Clean Strainer Head Loss

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

9.0 REFERENCES

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[3] NUREG/CR-6369, Volume 1, “Drywell Debris Transport Study,” September 30, 1999.

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[5] NUREG/CR-6874, “GSI-191: Experimental Studies of Loss-of-Coolant-Accident-Generated Debris Accumulation and Head Loss with Emphasis on the Effects of Calcium Silicate Insulation,” April, 2004.

[6] NUREG/CR-6808, “Knowledge Base for the Effect of Debris on Pressurized Water Reactor Emergency Core Cooling Sump Performance,” February, 2003.

[7] NUREG/CR-6877, “Characterization and Head-Loss Testing of Latent Debris from Pressurized Water Reactor Containment Building,” July 31, 2005.

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