Appendix VIII

Formation and Prediction of Thin-Bed Head Losses and Behavior of Compacted Calcium Silicate

VIII.1 Introduction

Relatively high head losses have occurred across relatively thin layers of debris consisting of fibrous and particulate debris, whereas substantially thicker debris beds have caused lesser head losses. This behavior has been referred to as the “thin-bed effect” where the head loss per unit thickness of debris is relatively high. Such debris beds have caused head losses high enough to threaten boiling-water reactor (BWR) emergency core cooling system (ECCS) sump recirculation pumps with modest quantities of debris on the strainers, and such debris beds can threaten pressurized-water reactor (PWR) sump recirculation sump screens as well. These types of debris beds have occurred operationally at nuclear power plants, have been created during head-loss testing, and have been analytically simulated with the NUREG/CR-6224 head-loss correlation.

VIII.2 Operational Incidents

Two operational strainer clogging events occurred at the Perry Nuclear Power Plant (PNPP) and one event occurred at the Limerick Generating Station, Unit 1, whereby in each event a high head loss occurred with a relatively thin layer of debris present on the strainers.

VIII.2.1 Perry Nuclear Power Plant

On May 22, 1992, during a refueling outage inspection at the PNPP, inspectors found debris on the suppression pool floor and on the residual heat removal (RHR) suction strainers. In addition, the buildup of debris on the strainers caused an excessive differential pressure across the strainers and resulted in deformation of the strainers. PNPP replaced the strainers and cleaned the suppression pool. Then in March 1993, several safety/relief valves (SRV) lifted, and the RHR was used to cool the suppression pool. The U.S. Nuclear Regulatory Commission (NRC) Information Notice (IN) 93-34, “Potential for Loss of Emergency Cooling Function Due to a Combination of Operational and Post-LOCA Debris in Containment,” dated April 26, 1993, discusses this issue. PNPP subsequently inspected and found the strainers covered with debris. A test of the strainers in the as-found condition was terminated when the pump suction pressure dropped to zero. The debris on the strainers consisted of glass fibers (from temporary drywell cooling filters inadvertently dropped into the suppression pool), corrosion products, and other materials filtered from the pool water by the glass fibers adhering to the strainer surfaces (IN-93-34, Supplement 1). The suppression pool debris also consisted of general maintenance types of materials and a coating of fine dirt that covered most of the surface of the strainers and the pool floor. Fibrous material acted as a filter for suspended particles, a phenomenon not previously recognized by the NRC or the industry. This event suggested that filtering of small particles, such as suppression pool corrosion products (sludge), by the fibrous debris would result in significantly increased pressure drop across the strainers.

VIII.2.2 Limerick Generating Station, Unit 1

Another event occurred at the Limerick Generating Station, Unit 1 on September 11, 1995. The NRC discusses this event in IN-95-47, “Unexpected Opening of a Safety/Relief Valve and Complications Involving Suppression Pool Cooling Strainer Blockage,” dated November 30, 1995. An SRV opened on Unit 1 while at 100-percent power. Before the SRV opened, Limerick was running Loop A of the RHR in suppression pool cooling mode. The operators initiated a manual scram in response to the SRV opening and a second loop (Loop B) of suppression pool cooling. Approximately 30 minutes later, operators observed fluctuating motor current and flow on Loop A. The cause was believed to be cavitation, and Loop A was secured. Following the event, a diver’s inspection revealed a thin mat of material covering the Loop A strainer. The mat consisted of fibrous material and sludge. The Loop B strainer had a similar covering but to a lesser extent. Limerick subsequently removed about 635 kg (1400 lb) of debris from the pool. Similar to the PNPP events, the mat of fibers on the strainer surface converted the strainer into a filter, collecting sludge and other material on the strainer surface.

These strainer-clogging events caused substantial loss of pump flow and fluctuating conditions, indicating cavitation, resulting from debris beds consisting primarily of fibers and corrosion products. The debris bed descriptions “coating of fine dirt” and “thin mat of material” describe thin beds of debris. The conclusion is that relatively thin layers of debris caused relatively high head losses. Following these events, the thin-bed effect behavior has been experimentally replicated and analytically simulated, which has resulted in an understanding of how such thin layers caused such high head losses. These types of debris accumulation came to be known as the “thin-bed effect.”

VIII.3 Phenomenological Description

The head loss across a bed of debris is directly related to the porosity of that debris bed (i.e., the lower the porosity, the higher the head loss). For fibers similar to low-density fiberglass insulation such as NUKON™, the porosity of a bed of these fibers typically ranges from 90 to 99 percent, depending upon the mechanical compression of the bed by the frictional drag caused by the flow. The porosity decreases with the compression of the debris. The porosity of a bed of particulate (without any fibers), however, is substantially less than the porosity of a fibrous debris bed. The iron oxide corrosion products sludge that is typically formed in BWR suppression pools has a porosity of about 80 percent. In sludge, the particulate cannot be compressed significantly because the particles are hardened, and the particles are already in contact with other particles. The porosity varies with types and size of the particulate. Common sand in soils has porosity in the neighborhood of 40 to 46 percent.

When fibrous and particulate debris are mixed, the porosity of the mixture depends upon the relative quantities of fiber and particulate and the mechanical compression of the fibers. When quantities of particulate are relatively small compared to the quantities of fibrous debris, the individual particles are trapped in the fibers such that the particles do not generally interact. Figure VIII-1 shows an example of a debris bed that has been referred to as a mixed debris bed. The particles contributed to the head loss, but the particles still resist flow individually.

As the quantity of particulate relative to the quantity of fibers increases (typically referred to as the particulate-to-fiber mass ratio), the contribution of particulate increases and head loss increases. As head loss increases, the fibrous bed further compacts thereby reducing the spacing between the fibers, which also increases the ability of the bed to filter finer particulate from the flow. Eventually, further increases in the particulate to fiber mass ratio results in increasing particle interaction. When this interaction reaches its maximum limit, based on the particulate bulk density or sludge density, further compaction becomes difficult. As this maximum limit is approached, the bed porosity approaches that of the particulate sludge, which is substantially less than the fibrous debris, and the head loss increases correspondingly. Once the porosity of the debris bed approaches the porosity of the particulate sludge, high head loss can occur in a thin layer of debris (i.e., the thin-bed effect). A definition of the thin-bed effect follows:

The thin-bed effect refers to the debris bed condition in a fibrous/particulate bed of debris whereby a relatively high head loss can occur because of a relatively thin layer of debris, by itself or embedded as a stratified layer within other debris, because the bed porosity is dominated by the particulate, and the bed porosity approaches that of the corresponding particulate sludge.

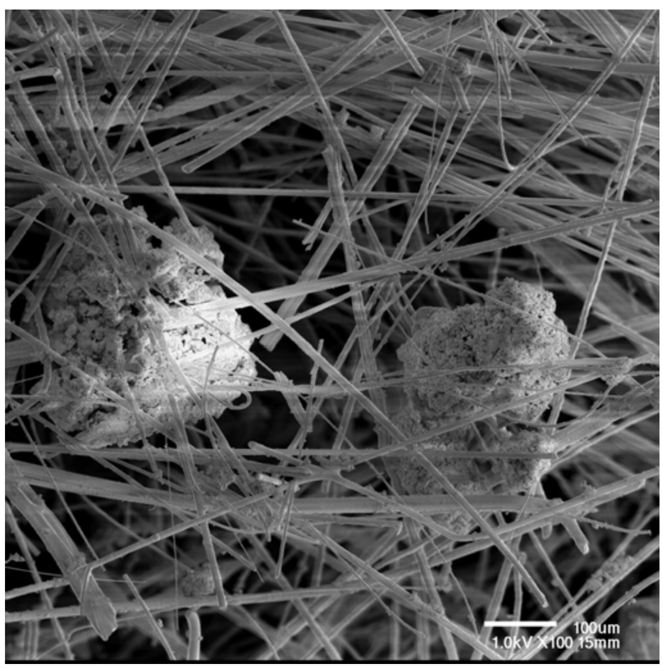

Figure VIII-1. Example of Particulate Embedded in Fibrous Debris[1]

During the PNPP and Limerick events, relatively small quantities of fibrous debris and relatively large quantities of corrosion product particulate debris were discovered in each suppression pool. When the recirculation pumps were operated, both the fiber and particulate would have been drawn to the strainers, but initially the particulate would pass through the strainers whereas the fibers preferentially filtered from the flow. Once

[1] Previously unpublished posttest scanning electron microscope (SEM) photo taken during the conduct of the NRC-sponsored calcium silicate head-loss tests (LA-UR-04-1227).

the screens accumulated sufficient fibers, the fibers filtered the particulate. The particulate would then have dominated subsequent accumulation such that the resultant accumulation would appear to be a layer of iron oxide sludge. As such, the pump had to draw water through this layer of sludge, which had a porosity near 80 percent. Fibers would have been interspersed throughout the bed but likely were concentrated nearer the screen surface, and associated pressures would have tightly compressed those fibers. The bed would have a high particulate-to-fiber mass ratio, which is characteristic of thin beds involving typical hardened particles.

The formation of a thin bed is somewhat variable. In laboratory testing, fibrous debris has been introduced before the particulate, in conjunction with the particulate, and after the particulate. During an actual event, the fibers and particulate debris would arrive in a mixed concentration that would likely vary with time, depending upon such factors as pool turbulence and relative densities. It is highly unlikely that the fiber could all arrive at the screen in advance of the particulate. If the particulate arrived at screen before significant fibers, then it would pass through the screen (i.e., the fibers are required to filter the particulate). Calcium silicate is a possible exception to this rule because this material has its own fiber component, and that fiber component must be on the screen to filter the fine particles. The efficiency of the particle filtration depends upon the thickness of the fibrous debris and on its porosity. Further, the porosity of the fibers depends upon how tightly it is compacted by the flow (e.g., a fibrous bed will filter more efficiently at a flow velocity of 1 ft/s than it will at 0.25 ft/s given the same thickness of fibers).

From a practical standpoint, a certain minimum thickness of fibers is needed to uniformly cover a strainer surface and to subsequently filter the particulate. For NUKON™ fibrous insulation debris, studied extensively during the BWR strainer-clogging resolution, NUREG/CR-6224 recommended an 1/8-in. fibrous debris bed thickness (based on the original bulk density generally referred to in head-loss analyses as the as-manufactured density). The NRC based the 1/8-in. recommendation on experimental observations, which show that typically at lesser thicknesses, the bed does not appear to have the required structure to bridge the strainer holes and filter the sludge particles. During an NRC-sponsored head-loss test program (NUREG/CR-6367), five tests were conducted with 1/8-in. fibrous debris beds (formed with shreds of NUKON™ debris) and iron oxide particulate with mass ratios ranging from 10 to 60. The head losses associated with these tests were minor because of the inability of the fibrous debris to filter sufficient particulate. In addition, Pennsylvania Power and Light Company (Brinkman) sponsored tests that demonstrated low head losses for thin fibrous debris beds (i.e., beds nearly as thin as 1/8 in.).

When the Boiling Water Reactor Owners Group (BWROG) conducted its head-loss tests (URG), in many of the tests it introduced the particulate into the test apparatus before introducing the fibrous debris, then allowed sufficient time for the particulate to become thoroughly dispersed. Once this was accomplished, the fibrous debris was introduced to allow a fibrous debris bed to slowly form, which subsequently filtered particulate from the flow once sufficient fibrous debris collected on the test screen. This type of bed formation created debris beds that were well intermixed, although it cannot be guaranteed that the bed was completely homogeneous. Like the PNPP and Limerick events, it is likely that some fibrous debris was concentrated at the screen to hold onto the particulate. Another aspect of particulate filtration is the particle size. Within any particulate distribution, some particles may be so fine that these particles pass through the fibrous debris bed whereas the larger particles are readily trapped. The in-between sizes could have varied behavior such that some of these particles may be alternately trapped and freed, thereby contributing to homogeneity. The fineness of the particles that become firmly trapped depends upon the tightness of the fiber matrix. When a thin bed is formed, the filtration process becomes more efficient, and more of the fine particulate is filtered from the flow because of its associated reduced porosity. It should be noted that on a per mass basis, the finer particles have a substantially greater impact on the head loss (i.e., the resistance to flow is correlated with surface area, and smaller particles have more surface area per unit volume than do larger particles [specific surface area]).

The method of introducing the particulate debris before the fibrous debris is likely more realistic with respect to actual plant conditions; however, many tests have been conducted where the fibrous debris was introduced before the particulate. When conducting thin-bed debris tests, it is advantageous to establish as uniform a fibrous debris bed as reasonably possible before significant head loss is achieved. This can be achieved more easily when the particulate is not involved with the fibrous bed formation. When the fibrous and particulate debris are introduced at the same time, the debris bed tends towards homogeneity for thicker debris but can lead to lesser head losses for thin-bed formations compared to establishing the fibrous debris bed first at flow velocities sufficient to compact the fiber before the arrival of the particulates.

Establishing a fibrous debris bed first and then introducing the particulate can create a more stratified debris bed (sometimes referred as a sandwich configuration), especially if a higher rate of flow compacts the bed before introducing the particulate. Such stratified beds have been achieved[2]. Such a configuration is analogous to a typical coffee filter, where the filter corresponds to the fibers and the particulate is the coffee grounds. Although a truly stratified bed is not the anticipated plant accident condition debris bed, it is useful for determining specific debris head-loss properties and generally leads to more severe head losses than the truly mixed debris beds.

This discussion has so far focused on particulate that can be characterized as hardened (i.e., the particles do not deform under the pressures encountered in a debris bed and are therefore considered solid). Head-loss testing using calcium silicate insulation debris as the particulate has encountered behavior that is apparently different from the behavior of hardened particulate.

The calcium silicate insulation tested was manufactured primarily from diatomaceous earth (DE) and lime (calcium carbonate) in roughly equal portions (approximately 90 percent of the total mixture). The remaining 10 percent consisted of small quantities of fiberglass fibers and a binder added for strength. The components were mixed, shaped, and baked, whereby the DE and lime reacted to form the calcium silicate in a porous crystal lattice structure that provides good insulation properties. The particulate debris created from the destruction of this insulation was examined under a scanning electron microscopy (SEM), which showed substantial very fine particulate and indicated voiding within the particles. Figure VIII-2 shows an example SEM photo, where a white bar scaled to 20 µm in the upper left corner indicates the magnification.

[2] As an example, during the conduct of the surrogate latent particulate head-loss tests documented in LA-UR-04-3970, the fibrous and particulate debris for an intended mixed debris bed test was inadvertently introduced separately instead of the being premixed as intended. Because the particulate was coarse sand (75 to 500 µm), the particulate essentially remained in place above the fibrous layer.

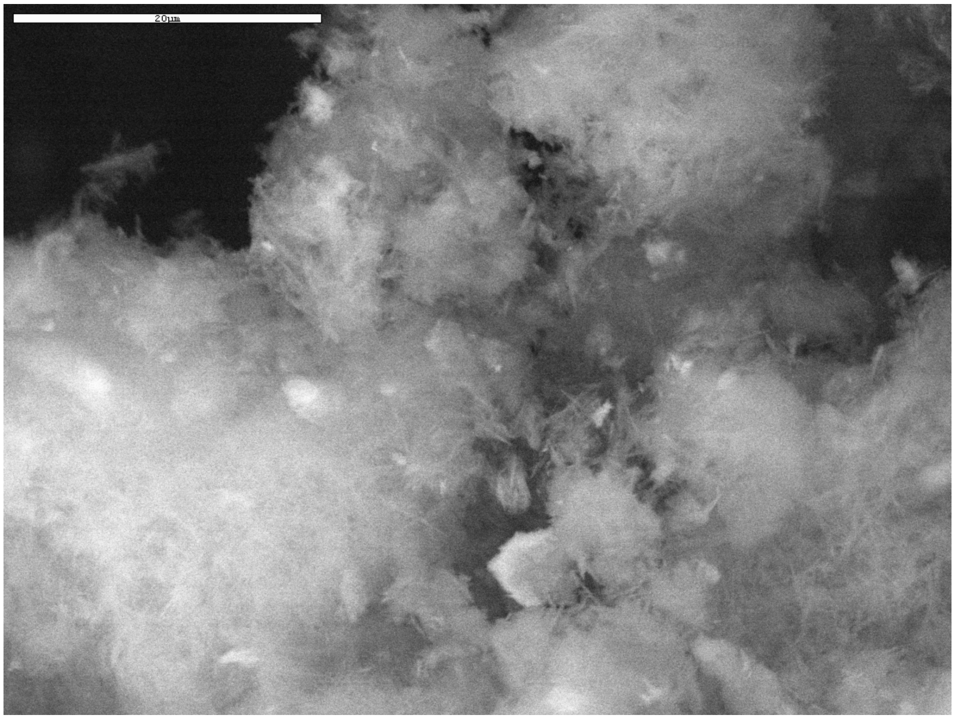

Figure VIII-2. Pretest SEM Photo of Calcium Silicate Particulate Debris

Because of the porous crystal lattice structure of the particulate, it is likely that these particles could deform under pressure. Figure VIII-3 shows a posttest photo that indicates that the calcium silicate particulate appears to have been pressed into a near continuous mat, which likely resulted in substantial reduction in porosity. If this particulate does deform under pressure, then the porosity through the continuous mat could decrease considerably. In addition, its specific surface area and density properties would not necessarily remain constant during this process. The debris bed in the test associated with Figure VIII-3 created a relatively high head loss across a thin layer of debris.

A calcium silicate debris bed can form in the same manner as a hardened particulate debris bed; however, calcium silicate is less dependent upon having a source of fibrous debris to filter it from the flow because calcium silicate has its own fibers (roughly 10 percent by mass). If the screen has a small enough mesh, it is likely that a bed of calcium silicate could form without any other fibers added to the bed. At first, the calcium silicate particulate might pass through the screen while the fibers from the calcium silicate accumulate. Then, if the fiber accumulation is sufficient, the fiber would filter the calcium silicate particulate. Existing test data are not sufficient to define the size of the screen mesh needed to form a debris bed with only calcium silicate. In addition, the screen would filter larger pieces of calcium silicate debris. To ensure conservative predictions, it is prudent to assume that debris beds with only calcium silicate will form unless adequate data are obtained to conservatively demonstrate otherwise.

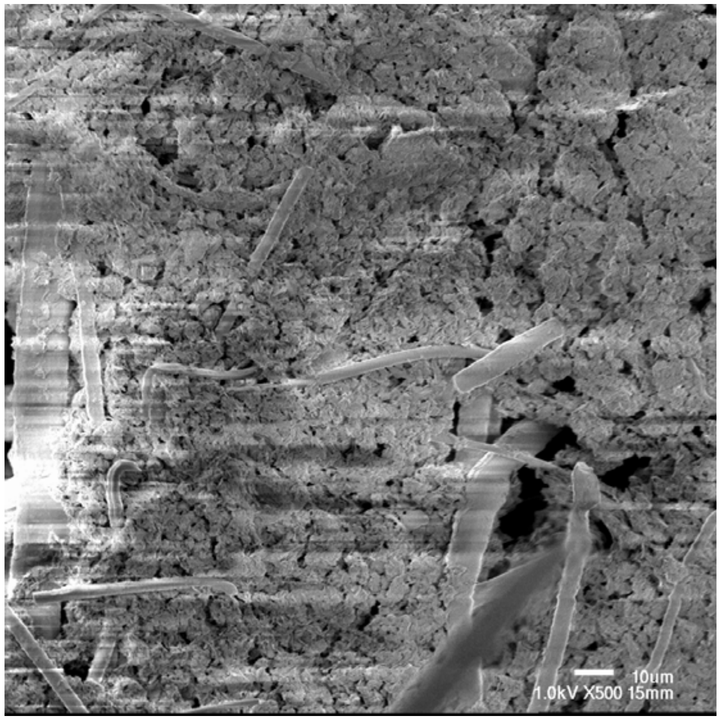

Figure VIII-3. Posttest SEM Photo of Calcium Silicate Debris from a Thin-Bed Test

Filtration efficiency is also an important aspect of head-loss behavior. As porosity decreases, finer particles may be filtered than before. When a thin bed exists, the filtration efficiency will increase so that the smaller particulate is filtered, which can further decrease porosity.

In summary, the parameters that affect the formation of a thin-bed debris bed and the resultant head loss include the following:

- existence of a sufficient quantity of fiber to filter the particulates
- porosity of the fibrous bed
- quantities of particulates
- size distribution and densities of the particulate that affect its porosity, specific surface area, and filtration efficiency
- whether the particulate is hardened or can deform under pressure
- sump screen mesh size
- flow approach velocity

VIII.4 Thin-Bed Head-Loss Testing

Various testing programs have demonstrated the thin-bed effect during head-loss testing. The following examples provide additional insights into thin-bed formations. The associated analyses were performed using the NUREG/CR-6224 head-loss correlation.

VIII.4.1 BWROG Test 7 (URG Technical Support Document, Vol. 1)

A truncated cone strainer with a screen area of 18 ft^2 was tested by first introducing 60 lbm of iron oxide corrosion products into the test tank, followed by 1 lbm of NUKON™ insulation debris about an hour later, at a pump flow of 5000 GPM and a water temperature of 63°F. The corresponding screen approach velocity was 0.62 ft/s. The particulate was allowed to circulate and become distributed before the fibers were added. Following the addition of the fibrous debris, the head loss increased rapidly to about 32 ft-water. The uncompressed thickness of the fibrous debris without the particulate would have been 0.28 in., but the debris bed formed with the particulate would have been about 0.63 in. thick if complete filtration were assumed. Based on the accepted sludge density of the corrosion products of 65 lbm/ft^3 and the material density of 324 lbm/ft^3, the porosity would have been about 80 percent. Analysis indicated the head loss should have been about 200 ft-water, which is much higher than the head loss actually measured. It is likely that holes developed in the debris because of the high pressure differentials that relieved the pressure across the bed. NUREG/CR-6224 notes that damage occurs to the fibrous bed whenever pressure drops exceed approximately 50 ft-water/in. (Note that 32-ft-water/0.63-in = 50.8 ft-water/in.) A layer of corrosion products held in place by the NUKON™ fibers formed the debris bed in this test. This debris bed consists primarily of a layer of particulate, its porosity would essentially be that of the sludge, and the resultant head loss is high; therefore, this bed is a thin-bed debris bed. The results of the test demonstrate the higher head losses that can be created by a thin bed even with the bed penetrations.

VIII.4.2 BWROG Test 8 (URG Technical Support Document, Vol. 1)

A truncated cone strainer with a screen area of 18 ft^2 was tested by first introducing 3 lbm of NUKON™ insulation debris, followed approximately an hour later by 16 lbm of iron oxide corrosion products, into the test tank at a pump flow of 5000 GPM and a water temperature of 61°F. The corresponding screen approach velocity was 0.62 ft/s. The particulate-to-fiber mass ratio was 5.3. The uncompressed thickness of the fibrous debris without the particulate would have been 0.83 in., and the debris bed formed with the particulate alone would have been about 0.16 in. thick if complete filtration were assumed. Based on the accepted sludge density of the corrosion products of 65 lbm/ft^3 and the material density of 324 lbm/ft^3, the porosity would have been about 80 percent. The measured head loss at 5000 GPM was quoted greater than 41.7 ft-water. It is likely that the debris bed lost integrity at these high head losses, which is indicated by the reported test measurement. In this test, the fibrous debris bed was formed at relatively high flow velocities before introducing the particulate; therefore, it is apparent that the fiber was well compacted before the arrival of the particulate and that the bed likely remained substantially stratified.

VIII.4.3 Latent Particulate (Surrogate) Test 17 (LA-UR-04-3970)

In this test, 15 gm of NUKON™ and 200 gm of particulate (less than 75 µm) were introduced into the test apparatus (fiber was introduced first, then the particulate). The particulate used included a clay component that appeared to break up in water into very fine particles. Posttest analyses of water clarity data indicated that approximately half of the particulate was not filtered from the flow, primarily because of the extreme fineness of the particulate; therefore, the subsequent analyses assumed that approximately 58 gm of particulate was in the debris bed, which resulted in a particulate to fiber mass ratio of 3.8 in the debris bed. A substantial uncertainty exists regarding the accuracy of the determination of the percentage of particulate not filtered from the flow. The 15-gm of NUKON™ formed a thin layer of fibrous debris 0.23 in. thick (at the as-manufactured density) but only about 0.07 in. thick at full test compression (analytical estimate). The particulate in the bed by itself would have formed a layer about 0.055 in. thick. At a flow approach velocity of 0.25 ft/s and a temperature of 94 °F, the measured head loss was 15.8 ft-water. Under these conditions, the analytically determined porosity was 77 percent, which is only slightly higher than the porosity of the particulate by itself (i.e., one minus the sludge density of 39-lbm/ft^3 divided by the particle material density of 166.6-lbm/ft^3 (1 – 39/166.6 = 0.766)). At faster approach velocities than the 0.25 ft/s that produced 15.9 ft-water head loss, the debris bed deteriorated, which was most likely because of the high pressure differential across the bed. Although substantial uncertainty is associated with the determination that approximately half of the particulate did not filter from the flow, a relatively thin layer of fibrous/particulate debris with bed porosity near that of the particulate alone caused a relatively high head loss.

VIII.4.4 Latent Particulate (Surrogate) Test 16 (LA-UR-04-3970)

In this test, 15 gm of NUKON™ bed and 600 gm of sand particulate ranging from 75 to 500 µm were introduced into the test apparatus (fiber was introduced first, then the particulate). Filtration of this relatively coarse sand was essentially complete. The particulate to fiber mass ratio for this test was 40. Figure VIII-4 shows the resultant bed of debris, approximately 0.23 in. thick, consisting mostly of the coarse sand with the fibers compressed underneath the sand (stratified). At a flow approach velocity of 0.46 ft/s and a temperature of 96.5°F, the measured head loss was 9.9 ft-water. Under these conditions, the analytically determined porosity was 41 percent, which is only slightly higher than the porosity of the particulate by itself (i.e., one minus the sludge density of 99-lbm/ft^3 divided by the particle material density of 166.6-lbm/ft^3 (1 – 99/166.6 = 0.406)). At a velocity of 0.25 ft/s, the head loss was 4.4 ft-water compared to 15.9 ft-water for latent particulate Test 17, even though the porosity of the coarse sand was much less than that of the fine particulate, because of the much smaller specific surface area of the coarse sand compared to the fine particulate. Although the porosity of the bed in Test 16 was much lower than the porosity in Test 17 (41 percent compared to 77 percent), the head loss for Test 16 was much lower than the head loss for Test 17. This outcome resulted from the much lower specific surface area of the coarse sand in Test 16 compared to the very fine particulate in Test 17.

VIII.4.5 Calcium Silicate Test 6H (LA-UR-04-1227)

In this test, 15 gm of NUKON™ debris and 7.5 gm of calcium silicate insulation particulate was introduced into the test apparatus (fiber was introduced first, then the particulate). The particulate to fiber mass ratio was 0.5. Posttest analyses of water clarity data indicate that all but the very finest particulate had filtered from the flow. The 15-gm of NUKON™ formed a thin layer of fibrous debris 0.23 in. thick (at the as-manufactured density), but the test bed under full compression was substantially thinner. Figure VIII-5 shows a photo of this debris bed. At a flow approach velocity of 0.4 ft/s and a temperature of 110°F, the measured head loss was 12.7 ft-water. An analysis deduced both the specific surface area and the sludge density for the calcium silicate. In the analysis, the sludge density was adjusted in the simulation until the particulate packing limit coincided with the rapid rise in head loss observed in the test data, which occurred when the approach velocity was increased beyond 0.35 ft/s. The working theory for the analysis of the calcium silicate thin-bed tests was that the formation of a relatively continuous layer of matted calcium silicate caused the rapid increases in the head losses as velocities increased. Figure VIII-3 shows the posttest SEM photo, which illustrates an apparent matted layer of calcium silicate. Under these conditions, the bed porosity apparently rapidly decreased with a corresponding increase in the bed's ability to filter finer particulate, which was demonstrated by the water clarity data. Under these conditions, the analytically determined porosity was 88 percent, which is significantly higher than the porosity of the particulate by itself (i.e., one minus the sludge density of 22-lbm/ft^3 divided by the particle material density of 115-lbm/ft^3 (1 – 22/115 = 0.808)). The most astounding feature of this thin-bed test was that such high head losses were achieved with a particulate to fiber mass ratio of only 0.5, even though the porosity apparently did not drop below approximately 0.8. To achieve such high head losses, the specific surface area had to be much higher than those determined for the hardened particulate. The analytically deduced specific surface area was 800,000-ft^2/ft^3. The higher specific surface areas were attributed to both the relative fineness of the particulate and internal voiding of the particles, whereby some flow potentially moved through these voids at higher pressure differentials.

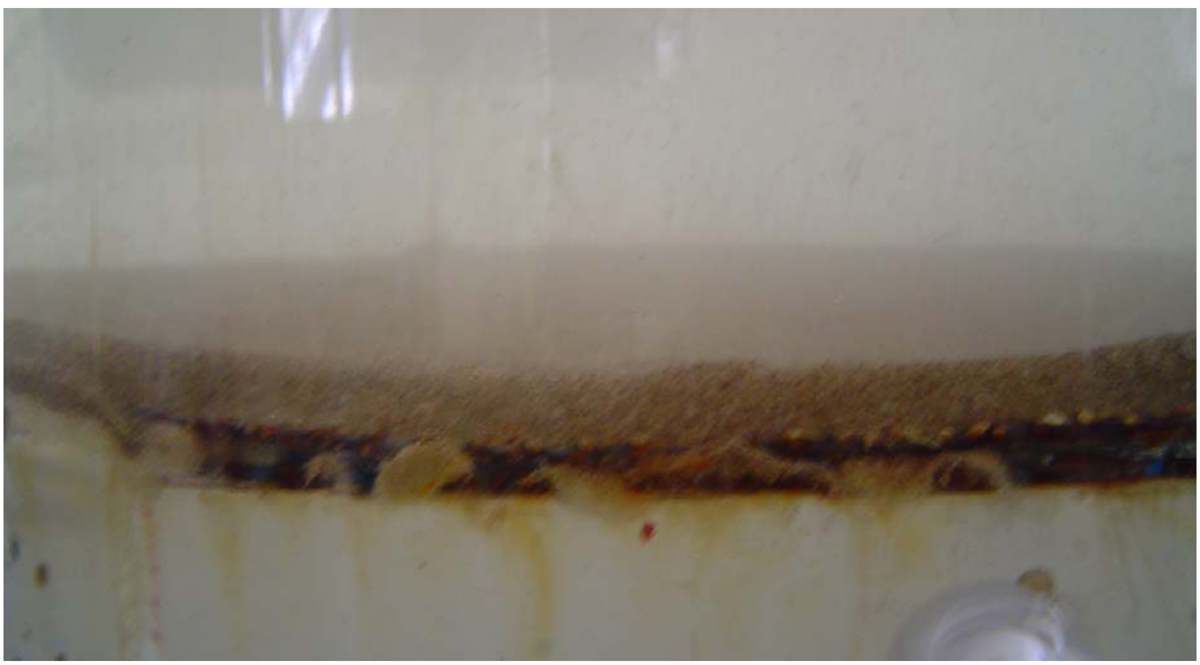

Figure VIII-4. Debris Bed for the Surrogate Latent Particulate Head-Loss Test 16

This set of relatively thin and relatively high head-loss tests illustrate the formation of debris beds whereby primarily the porosity of the particulate compacted into a sludge drives the head loss for four distinctly different particulate materials and a variety of particulate-to-fiber mass ratios. The two corrosion product tests involved head losses that became so high the debris bed probably developed penetrations that relieved the head loss; however, these thin-bed tests serve to illustrate how easily extreme head loss can occur. The latent thin-bed tests illustrate the differences between two distinctly different particulate size distributions. The calcium silicate test illustrated the potential effect of particulate deformation. Tests of this nature have been used to achieve an understanding of the thin-bed effect.

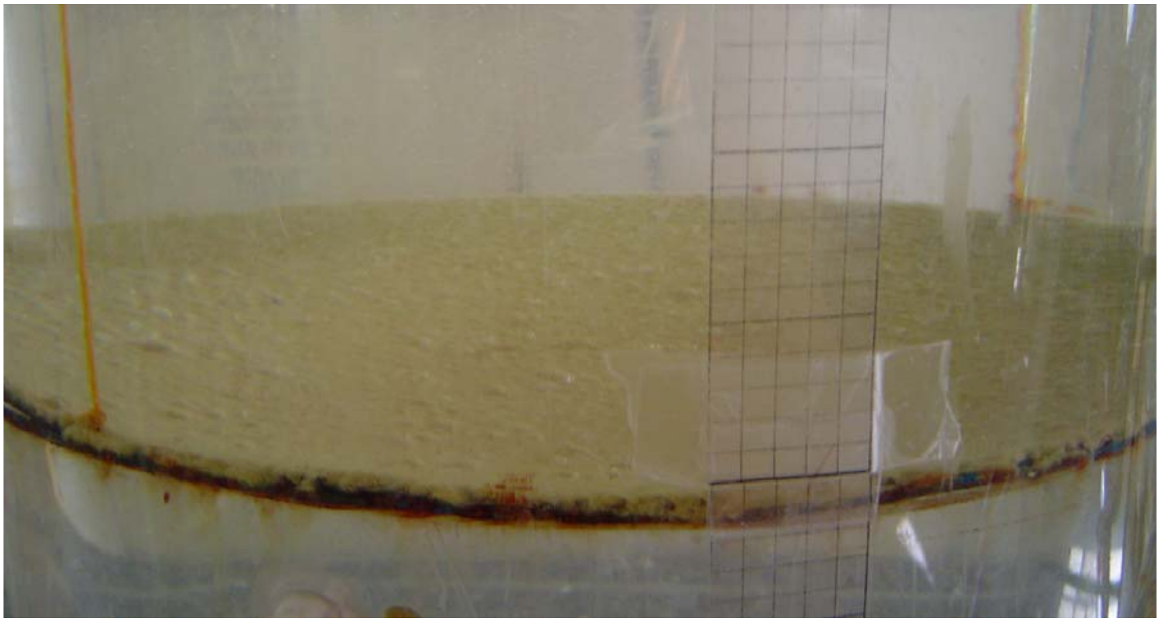

Figure VIII-5. Debris Bed for the Calcium Silicate Head-Loss Test 6H

VIII.5 Analytical Approach to Predicting Thin Beds

For a head-loss correlation to successfully predict the thin-bed behavior, as well as the porosity of a mixed debris bed, the correlation must have a debris bed porosity model that simulates not only mixed debris beds but also the porosity of the particulate by itself when enough of the particulate is in the debris bed to form a particulate layer. The NUREG/CR-6224 head-loss correlation porosity model contains a debris-packing limiting equation to limit bed compaction whenever the head loss and/or high quantities of particulate cause the bed compaction to reach the limit. The correlation porosity model includes a bed compaction term. When the particulate-to-fiber mass ratios become significantly large, the bed porosity from the porosity model approaches the porosity of the respective sludge.

The NUREG/CR-6224 correlation and its associated constitutive equations (porosity, compression function, and compression limiting) were developed assuming a uniform and a homogenous debris bed. Under thin-bed conditions, the fibrous debris could well be nonuniform because fiber would accumulate first before the particulate would filter from the flow; therefore, a layer of fiber next to the screen is likely. However, in a thin bed, the bed generally contains so much particulate that the fiber contribution to the head loss is small, thereby making the nonuniformity of the fibrous debris far less important.

Table VIII-1 (last page of this Appendix) compares head-loss prediction using the NUREG/CR-6224 correlation with the thin-bed tests presented herein. For the two corrosion products thin-bed tests, the tests were apparently conducted with so much particulate that penetrations developed in the beds such that head loss was substantially less than if a uniform debris bed had been maintained. As such, the NUREG/CR-6224 correlation overpredicted the head-loss results by a substantial margin. For the two latent (surrogate) particulate debris tests (i.e., less than 75 µm and 75 to 500 µm particulate), the NUREG/CR-6224 correlation was used to estimate specific surface area that agreed well with other tests, including mixed bed tests, in that test series. The latent sludge density and porosities determined experimentally agreed well with the correlation predictions. For the calcium silicate head-loss tests, input parameters were recommended for the NUREG/CR-6224 correlation that would cause the correlation to bound the head losses, even though the packing processes whereby the calcium silicate comes together to form a sort of matting layer are not well enough understood to formulate a model for those processes.

The NUREG/CR-6224 correlation was developed assuming the particulate properties would not be altered under head-loss pressures (i.e., constant densities and specific surface areas). With a particulate capable of deforming under pressure, the densities and surface areas are not necessarily constant. The correlation should not necessarily be expected to predict accurately the behavior of calcium silicate when compacted together in a thin-bed configuration. Therefore, the analytical approach is to estimate a bounding head loss. The bounding recommendation for calcium silicate was primarily based on the results of Test 6H, which produced the most severe head-loss conditions (i.e., the bounding specific surface area). Although a limited number of valid calcium silicate head-loss tests were conducted to determine the most severe head-loss conditions, the set of applicable tests supports the use of Test 6H in making bounding head-loss recommendations. Supporting tests accomplished the following:

- One test essentially reproduced the results with Test 6H.
- Two tests bracketed the thickness of the Test 6H fibrous debris bed (i.e., one test was slightly thinner and another slightly thicker). The associated head-loss parameters were more severe for Test 6H. In the thinner bed test, the filtration efficiency dropped off substantially relative to the efficiency of Test 6H. In the thicker bed test, the fibrous debris bed was thick enough that the amount of compaction needed to form a thin-bed matting of calcium silicate apparently did not occur within the flow capacity of the test apparatus.
- One test used the same quantity of fibrous debris as Test 6H but significantly more calcium silicate. In this test, the data indicate that a lower specific surface area than the 800,000/ft deduced from Test 6H is needed to simulate the test results even though the head losses were higher for this test.

Based on these results, it was judged that the 800,000/ft specific surface area bounded the test results and that Test 6H represents the more limited debris bed configuration. The recommended 880,000/ft specific surface area (in conjunction with a sludge density of 22 lbm/ft^3) included a 10-percent enhancement as a safety factor because of experimental uncertainties and variances in calcium silicate manufacturing.
In summary, the thin-bed effect, originally recognized with respect to the response of ECCS long-term cooling systems at nuclear power plants after three BWR operational events where strainer clogging occurred, has been experimentally reproduced for a variety of particulate debris. The experimental data were subsequently used to study the

physical processes whereby recommendations can be made for the application of the NUREG/CR-6224 correlation to this type of debris bed accumulation.

VIII.6 Addressing the Potential of Forming Stratified Debris Beds in Plant-Specific Evaluations

Plant accident scenarios do not anticipate the establishment of highly stratified debris beds because the debris is expected to arrive at the screens as a mixture of varied concentrations. However, it is possible for the debris bed makeup to have concentrations of particulate debris (i.e., the concentration of the particulate with respect to the fiber varies with the depth in the bed). Concentrations of the finer particles, which have a greater impact on head loss, would be more difficult to form than coarser particles because the finer particles have a greater potential to pass among the fibers.

The head loss across the concentrated layer would be higher than that predicted for the homogeneous debris bed, but then the lower head loss associated with the remaining correspondingly reduced concentration layer would compensate in part. The impact of these concentrations has not been thoroughly studied because of the large number of possible variations. In plant analyses, the conservatism associated with the estimates for the quantities of debris postulated to accumulate on the sump screen also compensates for the uncertainty associated with potential concentrations.

However, if a plant-specific analysis identifies conditions where the potential is indicated for a stratified debris bed to have a substantial impact on head-loss analyses, then that plant should assess the impact of that stratified bed. The determination of whether a stratified bed should be considered would involve the evaluation of the types of debris accumulation on the screens and the likelihood of one type of debris arriving in a preferential timeframe, such as the BWR example discussed below. The evaluation approach of a stratified debris bed would likely be specific to a particular bed structure. In a uniformly stratified debris bed, the head total head loss across the bed is the sum of the head losses across each of the stratified layers, but one of those layers could dominate the total head loss, especially if that layer was a layer of particulate. As an example, consider a debris bed consisting of an inner layer of fibrous debris, then a layer of particulate, followed by a layer of mixed debris. The head loss across the innermost layer of fibrous debris would assume a thickness of highly compressed fibrous debris because this layer would support the forces associated with the outer layers (a bounding compression can be estimated). The head loss across the particulate layer would adapt the porosity of the particulate sludge and the particulate layer thickness determined using the particulate mass and sludge density (assuming a layer of the particulate without fibers). For the head loss across the outer layer, the evaluation would use an approach applicable to that debris accumulation, which might be able to treat this layer as a normal fiber/particulate head-loss calculation. Then the three head losses would be summed, but the particulate layer would likely dominate the total head loss. This example illustrates how a plant-specific stratified head-loss analysis could adapt an approach that makes sense to the plant-specific postulated debris bed. Because head losses associated with stratified debris beds have not been thoroughly examined and procedures have not been developed for predicting head losses across these beds, plant specific head loss evaluations involving stratified debris beds must be conservatively validated based on experimental data.

For perspective, during the BWR strainer resolution, it was recognized that the particulate-to-fiber mass ratio would likely decrease as debris accumulation progressed because of the preferential settling of the particulate in the suppression pool relative to the settling of fibers (caused by the heavier densities of the corrosion products). However, most plant analyses generally assumed that debris would not settle in the suppression pool, thereby overpredicting debris accumulation and subsequently the head-loss calculations. Similar arguments could potentially apply to a PWR sump pool on a plant- and scenario-specific basis. For example, quantities of higher density failed coatings particulate washed into a relatively slow-moving sump pool could potentially settle and then remain in place such that the concentration of particulate arriving at the screen early in the scenario is higher than later in the scenario. However, these kinds of arguments are plant and scenario specific.

VIII.7 <u>Estimating Conservative Thin-Bed Head Losses</u>

VIII.7.1 Parametric Examples of Thin-Bed Head Loss Estimates

Plant-specific analyses are required to consider the potential for a thin-bed formation unless (1) that plant can substantiate the presence of insufficient fiber to form the initial bed of fibrous debris required to filter the particulate or (2) that plant implements a sump screen design that has experimentally demonstrated that a thin-bed debris bed is very unlikely to form because of its special geometry. The determination of the potential to form a thin bed must first assess the quantities of fibrous debris that could potentially accumulate on the screens from all sources, including insulation and fire barrier debris and latent fibers. If enough fibrous debris can accumulate to form a 1/8-in.-thick layer across the screen, then the potential to form a thin bed subsequently depends upon the availability of particulate debris from all sources, including latent particulate, particulate insulation debris, and failed coatings. If a plant determines that there is not sufficient fibrous debris to form a 1/8-in. layer across the screen, then that evaluation should have sufficient conservatism to compensate for uncertainties associated with the 1/8-in. specification. When integrated particulate/fiber insulation (e.g. calcium-silicate) debris can accumulate on the sump screen, it is conservatively assumed that this can form a debris bed without any supporting fiber beyond that fiber that is inherent in the manufacture of the integrated particulate/fiber insulation. The determination of sufficient particulate typically involves a parametric evaluation of the head loss versus mass and type of particulate in the bed to ascertain the conservatively minimum quantity of particulate needed to overcome the available net positive suction head. If the available quantities of particulate exceed the minimum quantity, then the potential for a thin-bed debris bed compromising the ECCS pumps exists.

The NUREG/CR-6224 head loss correlation has the capability of predicting the thin-bed head loss phenomena as illustrated in the following parametric examples. First, Figure VIII-6 and Figure VIII-1 show the head loss and corresponding bed porosity, respectively, predicted by the correlation for the input parameters of (1) a minimal thickness of LDFG (1/8-in.), and (2) particulate to fiber mass ratio of 5 and 130°F water. As the approach velocity was increased in the parametric, the debris bed was increasingly compressed until the particulate limited further compression. At this point, at velocity of about 0.16 ft/s, the debris bed became a thin-bed where the bed porosity approached that of the particulate without fiber (approximately 59%), as indicated by the rapid rise in head loss and corresponding drop in porosity. Note that head loss tests are typically conducted by forming the debris bed at a low velocity then incrementally increasing the velocity and measuring the corresponding head loss.

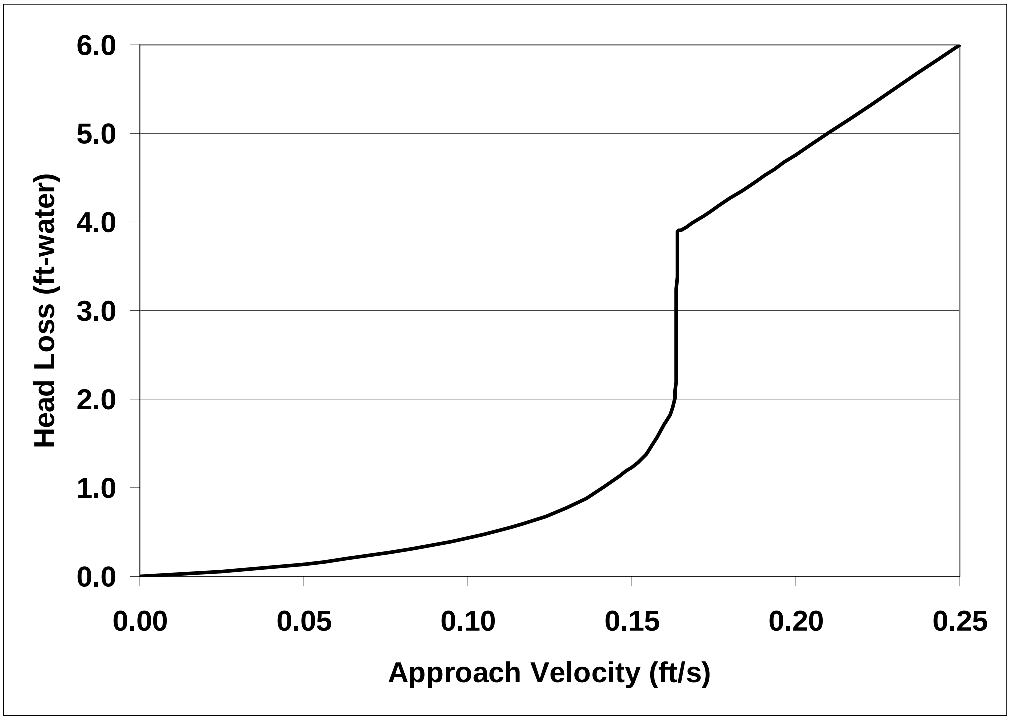

Figure VIII-6 Head Loss Example of Thin-Bed Formation Due to Bed Compression

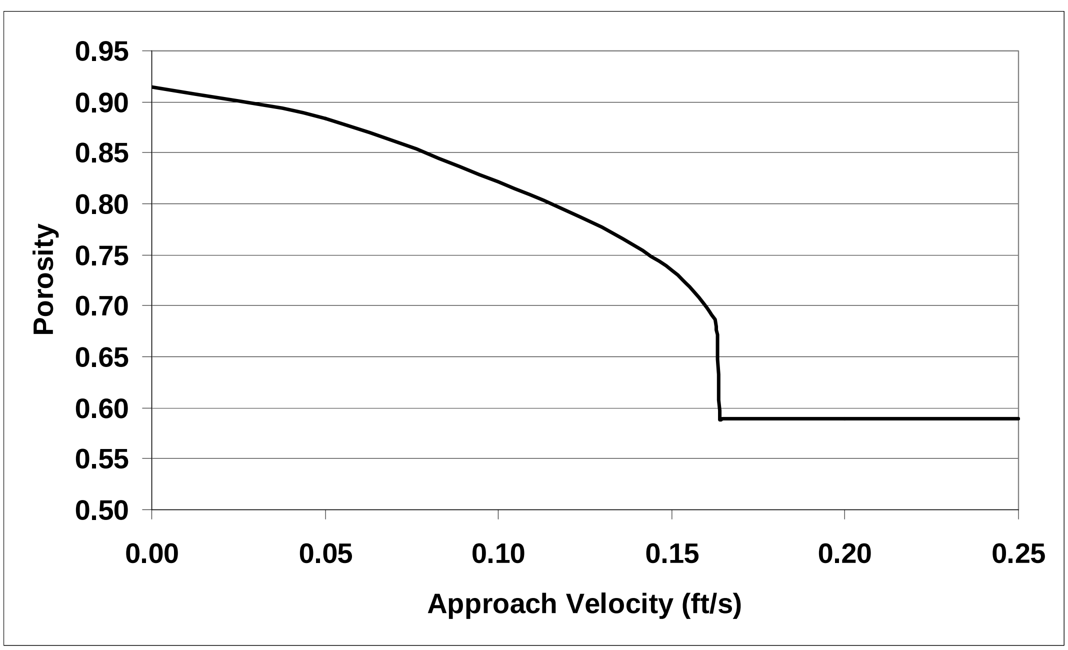

Figure VIII-7 Porosity Example of Thin Bed Formation Due to Bed Compression

In a second example, Figure VIII-8 shows a parametric example of the quantities of debris required in a thin-bed formation and the associated head losses (calculated using the NUREG/CR-6224 head-loss correlation). This example assumed the formation of a minimal thickness initial layer of fibrous debris (1/8 in. of NUKON™) and a variable quantity of latent particulate, as indicated by the particulate/fiber mass ratio. The figure shows the results for three approach velocities (i.e., 0.1, 0.3, and 1.5 ft/s). The debris bed was initially a mixed bed with relatively low head losses because the bed was primarily fibrous debris. As the particulate mass increased, the debris bed transitioned into a thin bed where the particulate dominated the porosity. This occurred at particulate-to-fiber mass ratios of 5.9, 4.0, and 2.0 for velocities of 0.1, 0.3, and 1.5 ft/s, respectively. If the screen area was 100 ft^2, the quantity of fibrous debris required to form a 1/8-in. bed would be 1.04 ft^3 (2.5 lb) and the mass of particulate needed to form a thin-bed debris bed would be 14.8, 10.0, and 5.0 lb, for velocities of 0.1, 0.3, and 1.5, respectively.

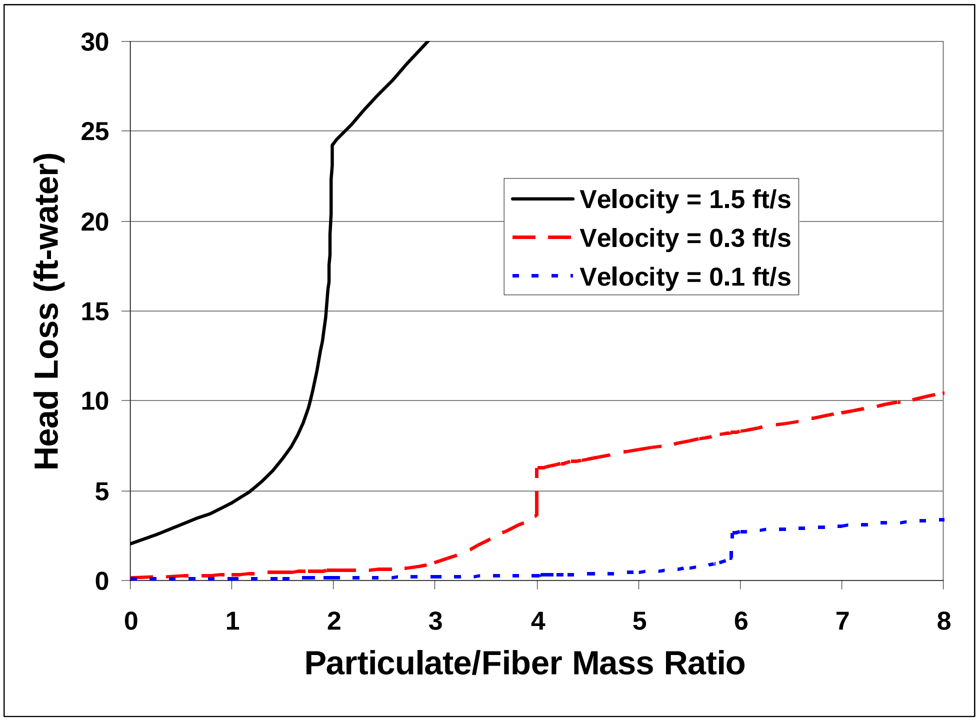

Figure VIII-8. Parametric Example of Thin-Bed Formation

Once it is determined that a thin-bed fiber/particulate debris bed can form, the maximum head loss based on the available particulate mass is determined by performing a parametric evaluation as demonstrated in Figure VIII-9. For an example approach velocity of 0.3 ft/s and three masses of available particulate, the figure shows the head loss as a function of the fiber bed thickness. If the postulated debris bed is less than 1/8 in., it was assumed that the fiber debris bed was too thin to filter the particulate from the flow. The head losses are shown to increase as additional fiber is added to the debris bed until enough fiber is in the bed to prevent the thin-bed effect from establishing. Figure VIII-9 illustrates the peak head loss for 10 and 20 lbs of latent particulate, which is the maximum head loss unless the volume of fibrous debris becomes so large that the fiber volumes dominate the head loss (Figure 7-2 of NUREG/CR-6808 provides an example). The peak head depends on the specific surface areas as well on the quantities. In this example, the specific surface area of the latent particulate is 106,000 ft^2/ft^3 compared to the NUKON™ specific surface area of 171,000 ft^2/ft^3. Therefore, increasing the quantity of fibrous debris increased the effective mixture specific area as well as the debris bed thickness. When the particulate surface area is greater than the fiber surface area, the maximum head loss would be closer to the head loss calculated for a 1/8-in.-thick bed than occurred in this example.

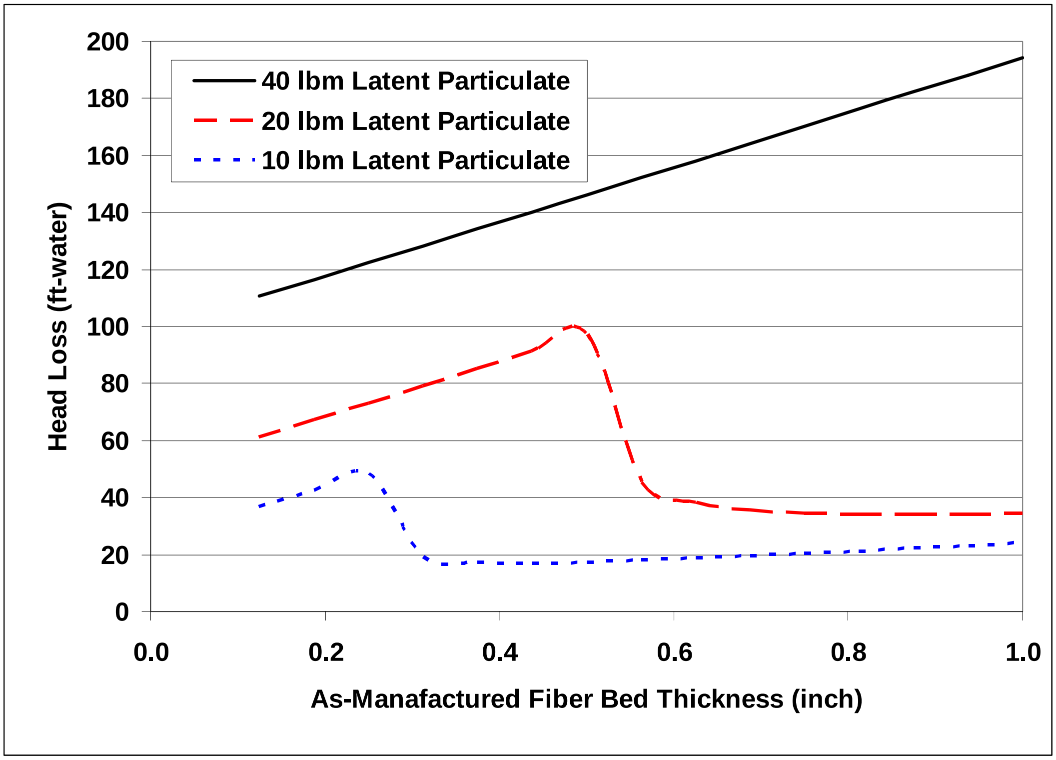

Figure VIII-9. Parametric Example of Peak Head-Loss for Given Mass of Particulate

The estimation of the peak thin-bed head loss is further demonstrated in a more specific example shown in Figure VIII-10. In this example, a maximum of 1000 ft^3 of LDFG and 300 lbs of latent particulate could accumulate in a 500 ft^2 sump screen. The approach velocity to the screen is 0.1 ft/s, the water temperature is 150 ^oF, and the containment does not contain any calcium silicate or other type of particulate insulation. If all the LDFG did accumulate on the screen, the resultant bed thickness would be 2-ft thick (uncompressed) resulting in a predicted head loss of 6.3 ft-water. In the figure, the debris bed thickness was varied, starting with a 1/8-in thickness, until a peak head loss of 8.8 ft-water was predicted at a thickness of approximately a 1/2-inch. This peak head loss is a thin-bed head loss with a porosity of approximately 59% (particulate sludge porosity). It would take a bed thickness nearly 3-ft thick to cause the same head loss as the peak thin-bed head loss.

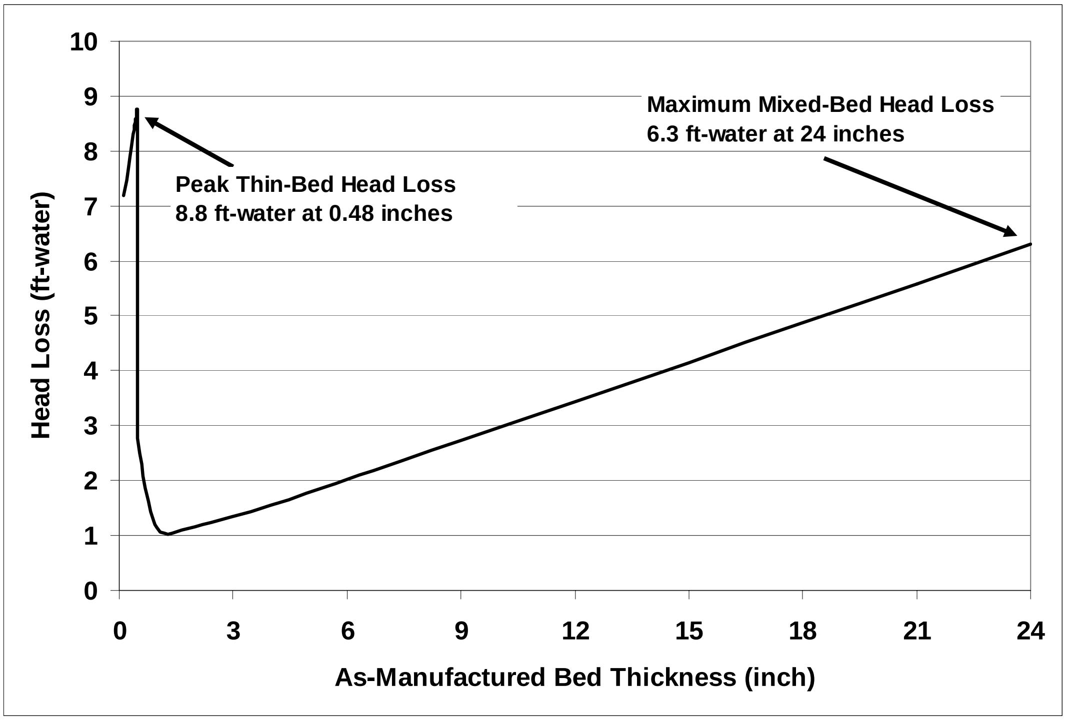

Figure VIII-10 Specific Example of Estimating Conservative Thin-Bed Head Losses

If a thin-bed debris bed cannot effectively form, then a continuous stratified bed should not be able to form. If the evaluation determines that there is not sufficient fiber to form a 1/8-in. layer of fibrous debris (without integrated particulate/fiber insulation debris present in the bed) required to establish a thin bed, then there is not sufficient fiber to establish a particulate layer in a stratified bed. If a thin bed cannot be established in a special geometry strainer because of nonuniform debris accumulation, then it is reasonable to assume that the same nonuniform accumulation in bed stratification would not lead to the continuous layer of stratification required to achieve the high head losses. If the plant sump screens have sufficient capability that a thin bed once formed does not compromise ECCS, then those screens should have enough capacity for a stratified particulate layer (same particulate mass) within a thicker debris bed. The establishment of a thin bed on a minimal fiber layer containing all available particulate should bound the head losses associated with a stratified layer of particulate within a mixed bed. The highest head loss is associated with the most concentrated and thickest layer of particulate, which corresponds to the establishment of the thin bed containing all available particulate. For all of these debris beds, the effects of other types of debris must be factored into a total head loss (e.g., reflective metallic installation and miscellaneous debris).

The term realistic in the above argument is used to acknowledge that total stratification is not realistic because fiber and particulate would arrive at the screen concurrently and the fine (most influential) particles have some ability to migrate within the fiber bed. However, one mechanism that could lead to stratification of some degree is late term erosion of larger debris in the sump pool (discussed in Appendix III.3.3.3). In such a scenario, the LOCA generated fiber and particulate would accumulate relatively early, then fibers from the erosion process could accumulate without significant embedded particulate. To demonstrate using the example above (Figure VIII-10): if after the peak thin-bed head loss was created, 1000 ft^2 of fiber were added to the top of the thin-bed (increasing the bed thickness to approximately 21 inches), an additional 5.6 ft-water head loss would be added to the peak thin bed head loss of 8.8 ft-water for a total head loss of about 14 ft-water. This shows that the head loss for worst-case bed stratifications can be estimated, however unlikely those debris beds are to form.

VIII.7.2 Procedure for Estimating Conservative Thin-Bed Head Losses

A procedure for estimating a conservative thin-bed head loss is illustrated in Figure VIII-11 and discussed in the following steps.

1. An assessment of the debris that could potentially transport and accumulate on the sump screen involves the generation of debris, an assessment of latent debris, and subsequent transport of that debris, as outlined in the appropriate sections of the GR and SER. This assessment would provide quantities for each type of debris and the appropriate characteristics of that debris.

2. The design of certain alternate geometry sump screens could preclude the formation of the thin-bed debris bed. If sufficient data exists to determining that the particular screen design undergoing evaluation cannot form a thin-bed, then there is no need to proceed with this thin-bed evaluation. If this data does not exist, then proceed to the next step.

3. The minimum thickness of fiber needed to filter particulate from the flow stream and then support the formation of the debris bed must be specified.
    a. For debris types other than integrated particulate/fiber insulation debris, a thickness of 1/8-in (based on the as-manufactured density) has been specified as the minimum thickness required to form a uniform layer across the screen and effectively filter the particulate from the flow.
    b. For integrated particulate/fiber insulation debris (e.g., calcium silicate), the minimum thickness for supporting fibers (other than the fiber inherent to the manufacture of the integrated particulate/fiber insulation) has not been sufficiently determined to specify a minimum thickness because the fiber inherent to the integrated particulate/fiber insulation may be sufficient to form the bed. Therefore, the minimum thickness of fiber to form a debris layer when significant integrated particulate/fiber insulation debris is present is conservatively zero unless adequate data becomes available to specify otherwise.

4. Combining the fibrous debris available per the assessment with the minimum thickness required to form the debris bed, determine whether or not there would be sufficient fibrous debris to form a debris bed. If sufficient fibrous debris is available to form a debris bed then proceed to the next step.

5. The peak head loss associated with a debris bed is determined using a parametric evaluation where the fibrous debris is varied from the minimum from Step 3 to a value large enough that the bed transitions from a thin-bed into a mixed debris as illustrated in Figure VIII-10. All of the particulate is assumed to be in the debris bed. To ensure that the peak head loss is captured in the

parametric evaluation, the increments in fibrous debris must be small around the peak head loss. In a scenario involving calcium silicate or other integrated particulate/fiber insulation debris, all of the calcium silicate including its inherent fibers should be considered to be particulate because the recommended parameters for the NUREG/CR-6224 head loss correlation were based on this assumption. If fibrous debris, other than the fibers inherent in the calcium silicate, is present then the thickness of the bed formed is varied from zero to the maximum thickness possible using all the available fibers. In the unlikely case that there are no other fibers available, the debris bed would be formed as a layer of calcium silicate and any other particulate, which would automatically be a thin-bed. Therefore, the maximum bed thickness will be used to calculate the peak head loss assuming that the bed has been compressed to the particulate sludge limit. In this case, the NUREG/CR-6224 correlation compression equation would not apply.

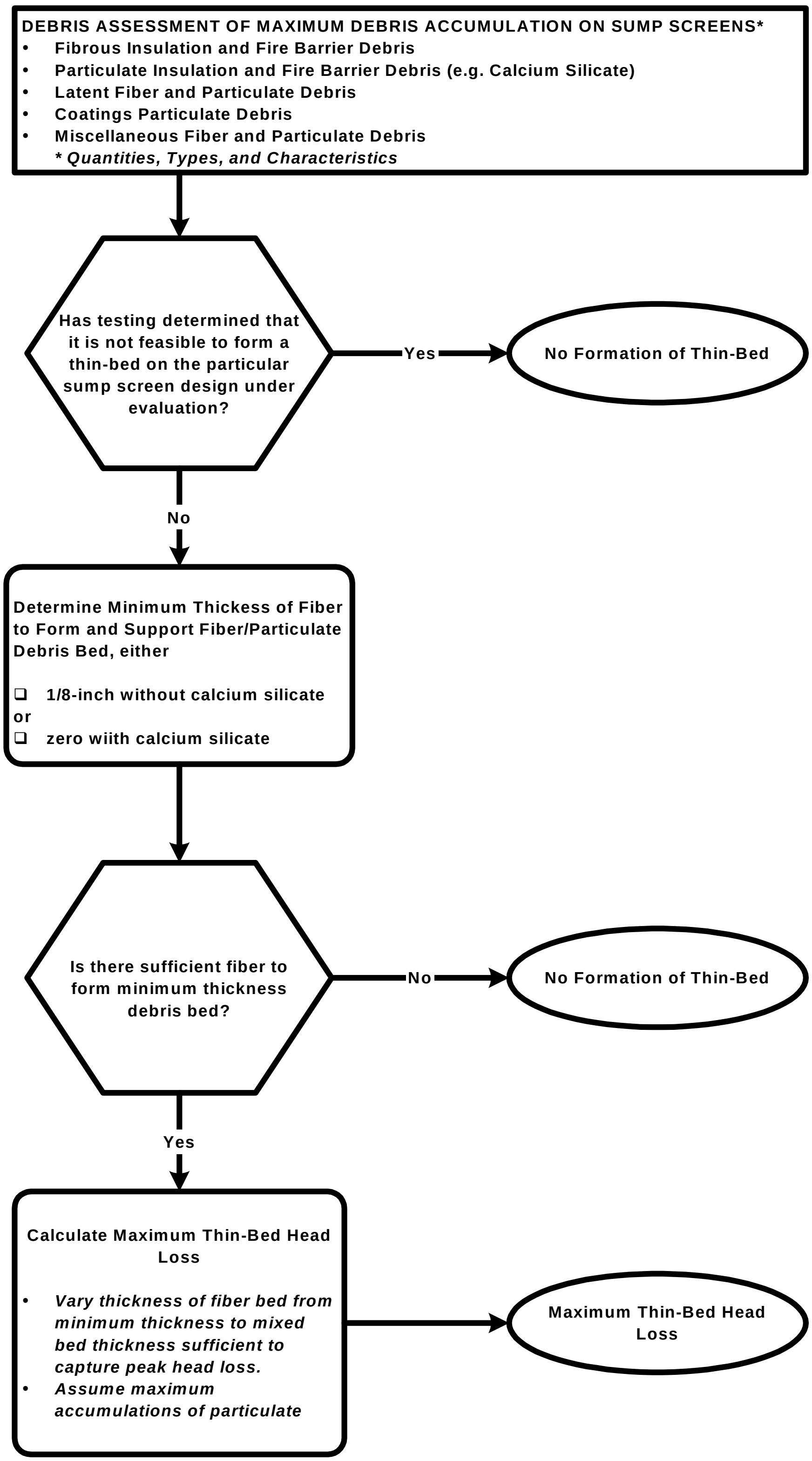

Figure VIII-11 Procedure for Estimating Conservative Thin-Bed Head Losses

VIII.8 References

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

NRC Information Notice 93-34, "Potential for Loss of Emergency Cooling Function Due to a Combination of Operational and Post-LOCA Debris in Containment," April 26, 1993.

NRC Information Notice 93-34, Supplement 1, "Potential for Loss of Emergency Cooling Function Due to a Combination of Operational and Post-LOCA Debris in Containment," May 6, 1993.

NRC Information Notice 95-47, Revision 1, "Unexpected Opening of a Safety/Relief Valve and Complications Involving Suppression Pool Cooling Strainer Blockage," November 30, 1995.

Table VIII-1. Comparison of Thin-Bed Test Data with NUREG/CR-6224 Simulations

Test No. and Particulate	Experimental Parameters					NUREG/CR-6224 Head-Loss Simulation Results				Comments
	Fiber[3] & Particulate[4] Bed Thicknesses (in.)	P/F Mass Ratio	Approach Velocity (ft/s)	Sludge Porosity and Density (lbm/ft_3)	Experimental Head Loss (ft-water)	NUREG/CR-6224 Head-Loss Prediction (ft-water)	Compacted Fiber/Part. Bed Thickness (in.)	Bed Porosity	Particulate Specific Surface Area (ft^2/ft^3)	
BWROG Test 7 Corrosion Products	0.28 (Fiber) 0.62 (Part.)	60	0.62	0.8 65	32	203	0.63	0.8	183,000	Debris Bed Damage Probable
BWROG Test 8 Corrosion Products	0.83 (Fiber) 0.16 (Part.)	5.3	0.62	0.8 65	> 41.7	83.3	0.19	0.8	183,000	Debris Bed Damage Probable
Latent Particulate Test 17 (< 75 µm)	0.23 (Fiber) 0.06 (Part.)	3.8	0.25	0.77 39	15.8	15.9	0.07	0.77	277,000	Uncertain in Debris Filtration Fraction
Latent Particulate Test 16 (75-500 µm)	0.23 (Fiber) 0.23 (Part.)	40	0.46	0.41 99	9.9	10.9	0.23	0.41	10,800	Stratified Debris Bed
Calcium Silicate Test 6H	0.23 (Fiber) 0.01 (Part.)	0.5	0.40	0.81 22	12.7	12.7	0.04	0.86	800,000	Bound Upper Head

[3] Experimental fiber beds thickness are based on the as-manufactured density without any bed compression.
[4] Experimental particulate bed thickness estimate assumed an equivalent thickness of particulate without the fiber present.

										Losses