Appendix V

Confirmatory Head-Loss Analyses

V

Confirmatory research was performed to determine whether specific parameter assumptions made in the Nuclear Energy Institute (NEI) guidance report (GR) are conservative with respect to more realistic parameters. This research also provided additional insights into the estimation of head-loss parameters for the NUREG/CR-6224 head-loss correlation. Additional guidance is provided for determining appropriate parameters for a mix of multiple fiber and particulate components. This appendix also provides procedures for applying the NUREG/CR-6224 head loss correlation.

V.1 <u>Fibrous Debris Head-Loss Parameters</u>

A comparison of specific surface areas (*Sv*) deduced from head-loss test data and the simple geometric correlation of four divided by the characteristic fiber diameter (4/d) is presented for NUKON™ and Kaowool™ insulation debris. The Boiling Water Reactor Owners Group (BWROG) head-loss tests documented in Volume 1 of the BWROG Utility Resolution Guidance (URG) provide the test data used in both of these deductions.

V.1.1 NUKON™ Fibrous Debris

The URG has three head-loss tests that used only NUKON™ insulation debris and used a type of strainer that behaved similarly to that of a flat-plate screen (i.e., a truncated cone strainer). These tests were numbered 2, 4, and 5 and used 8, 8, and 16 lb of NUKON™, respectively, and no particulate. The flow velocities through the bed varied from approximately 0.15 to 0.75 ft/s, resulting in a total of 15 head-loss data points. A specific surface area was deduced for each data point using the NUREG/CR-6224 head-loss correlation and using an as-manufactured density of 2.4 lb/ft^3 and a fiberglass material density of 175 lb/ft^3 (NUREG/CR-6224 study recommendations). Figure V-1 compares the resultant *Sv* values.

The comparison was based on the debris bed compression as determined by the NUREG/CR-6224 correlation (the ratio of the compressed thickness divided by the uncompressed thickness), which is directly affected by the flow pressure (i.e., flow velocity). The average value for *Sv* was approximately 170,600 ft^{-1}. The nominal diameter for NUKON™ fibers has been specified as 7.1 μm, which translates into an *Sv* of 171,710 ft^{-1}. The NUREG/CR-6224 study recommended an *Sv* of 171,420 ft^{-1}. For NUKON™ insulation debris, the *Sv* determined using 4/d is in excellent agreement with the experimentally deduced value.

The NEI guidance has recommended using a material density of 159 lb/ft^3 rather the NUREG/CR-6224 study value of 175 lb/ft^3. Confirmatory analysis using the NUREG/CR-6224 correlation verified that it is conservative to use 159 lb/ft^3 rather than 175 lb/ft^3, provided that the remaining head-loss parameters of 2.4 lb/ft^3 for the as-manufactured density and 171,000 ft^{-1} for the specific surface area are maintained. The lower value for the material density estimates a slightly higher head loss than does the larger value.

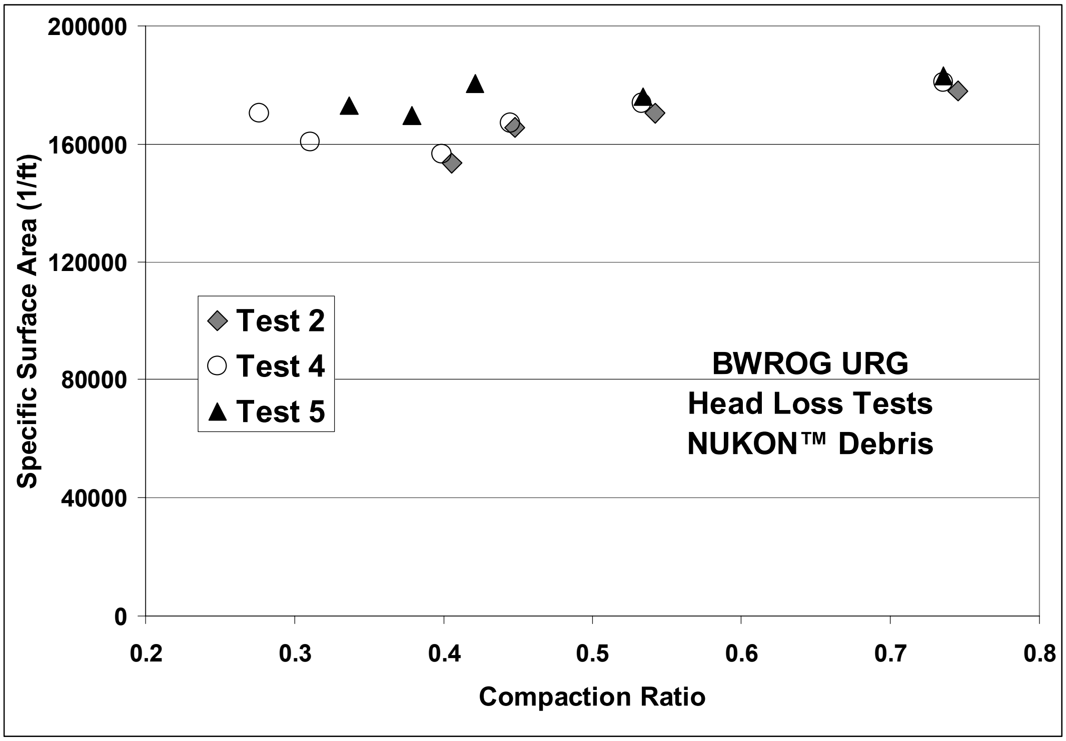

Figure V-1. NUKON™ Specific Surface Area

Similarly, the NEI guidance recommended using 1.0 g/cm^3 (62.4-lb/ft^3) for material density of latent fibers to enhance transport (neutral buoyancy). The latent debris characteristics test results (LA-UR-04-3970, 2004a) that analyzed latent debris collected in the containments of several volunteer plants show that the latent debris fibers had material densities ranging from 1.3 to 1.9 g/cm^3. Again, confirmatory analyses verified that it is conservative from a head-loss prediction perspective to assume that the latent fiber material density is 1.0 g/cm^3 rather than 1.3 to 1.9 g/cm^3, provided that the remaining head-loss parameters are appropriately specified.

V.1.2 Kaowool™ Fibrous Debris

The URG has one valid head-loss test that used Kaowool™ insulation debris and used a type of strainer that behaved similarly to that of a flat-plate screen (i.e., a truncated cone strainer). Test J13 initially had added 12 lb of Kaowool™, then later added 5 lb of iron oxide corrosion products (CPs), and subsequently added another 5 lb of CP. The flow velocities through the bed varied from approximately 0.31 to 0.62 ft/s, resulting in a total of nine head-loss data points (three data points without particulate). A specific surface area was deduced for each data point using the NUREG/CR-6224 head-loss correlation, with the NUREG/CR-6224 study-recommended parameters for the corrosion products used as input.* The recommended fiber material density for Kaowool™ is 160 lb/ft^3.

* The NUREG/CR-6224-recommended parameters are 183,000 ft^{-1} for the specific surface area, 324 lb/ft^3 for the particulate material density, and 65 lb/ft^3 for the granular packing-limit density.

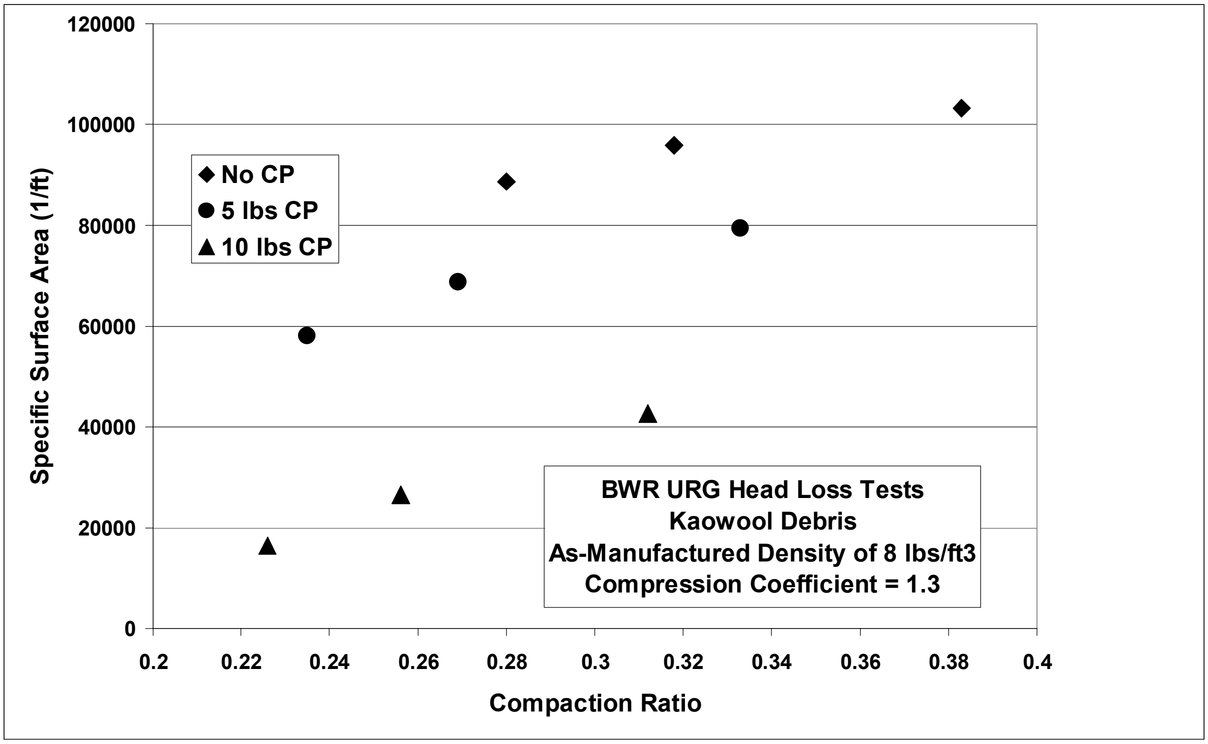

Figure V-2. Kaowool Specific Surface Area Assuming Base Parameters

The NEI guidance recommends an as-manufactured density of Kaowool™ ranging from 3 to 12 lb/ft^3, whereas the URG recommended a value of 8 lb/ft^3, apparently a mid-range value. First, the *Sv* values were deduced from Test J13 data by assuming an as-manufactured density of 8 lb/ft^3 and the same bed compression correlation that was so successful for NUKON™. Figure V-2 compares these resultant *Sv* values. The values of *Sv*, as shown, are very scattered, ranging from 16,000 to 103,000 ft^{-1}. All in all, the NUREG/CR-6224 correlation does not work well with these input parameters. Noting that the as-manufactured density cited in the GR ranged from 3 to 12 lb/ft^3, it was subsequently determined that a smaller value of the density would reduce the scatter in the resultant *Sv* values. Further, it was discovered that stiffening the compression function also reduced the scatter. Figure V-3 shows the results from a second comparison of the deduced *Sv* values that was developed assuming an as-manufactured density of 4 lb/ft^3 and a leading compression coefficient of 0.5 (rather than the standard 1.3). The comparison in Table V-3 has the deduced values in good agreement, with an average value of 165,500 ft^{-1}.

The NEI guidance specified 2.7 to 3.0 µm as the nominal diameter for Kaowool™ fibers, which translates into an *Sv* of 406,400 to 451,500 ft^{-1} using the 4/d formula. Although using such high values for *Sv* is conservative, the simple formula is not even close to the experimentally deduced value of 165,500. The application of an *Sv* of 406,400 ft^{-1} would substantially overpredict the results of Test J13.

The coefficient of the NUREG/CR-6224 compression correlation is an important issue. The standard coefficient of 1.3 was developed and validated essentially using NUKON™; therefore, the validation of other fibrous insulation must assess the validity of

this value for the insulation under consideration. It is noted that the baseline guidance in the GR considers this point by including the constant K (Equation 3.7.2-4 in Section 3.7.2.3.1.1 of the baseline guidance with a default value of 1 for K). For Kaowool™, a K = 0.385 and a Sv of 165,500 ft^{-1} in the NUREG/CR-6224 correlation predict URG Test J13 results reasonably well.

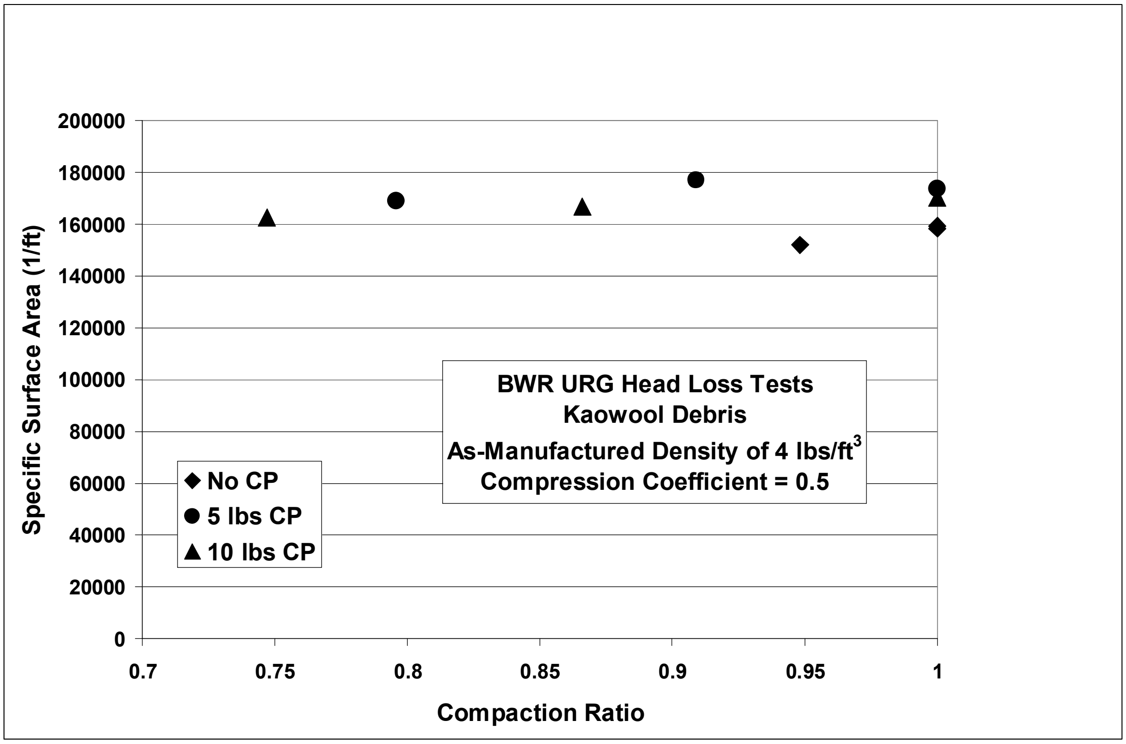

Figure V-3. Kaowool™ Specific Surface Area Using Modified Parameters

V.1.3 Comparison of Fibrous Debris

Figure V-4 compares the specific surface areas for areas determined using the 4/d formula and the two experimentally deduced values presented herein for NUKON™ and Kaowool™. The figure illustrates the following three points:

(1) The coefficient(s) for the compression correlation also have a role in the application of the NUREG/CR-6224 correlation to the various types of fibrous debris.

(2) The 4/d formula was formerly validated using NUKON™, but not necessarily for other types of fibrous insulations.

(3) The 4/d formula is not reliable and should not be applied indiscriminately. It should not be assumed that because this formula overpredicts Kaowool™ head-losses that it will be conservative for untested types of fibrous debris. The only reliable method of determining the specific surface area of a particular insulation material is deduction from applicable test data.

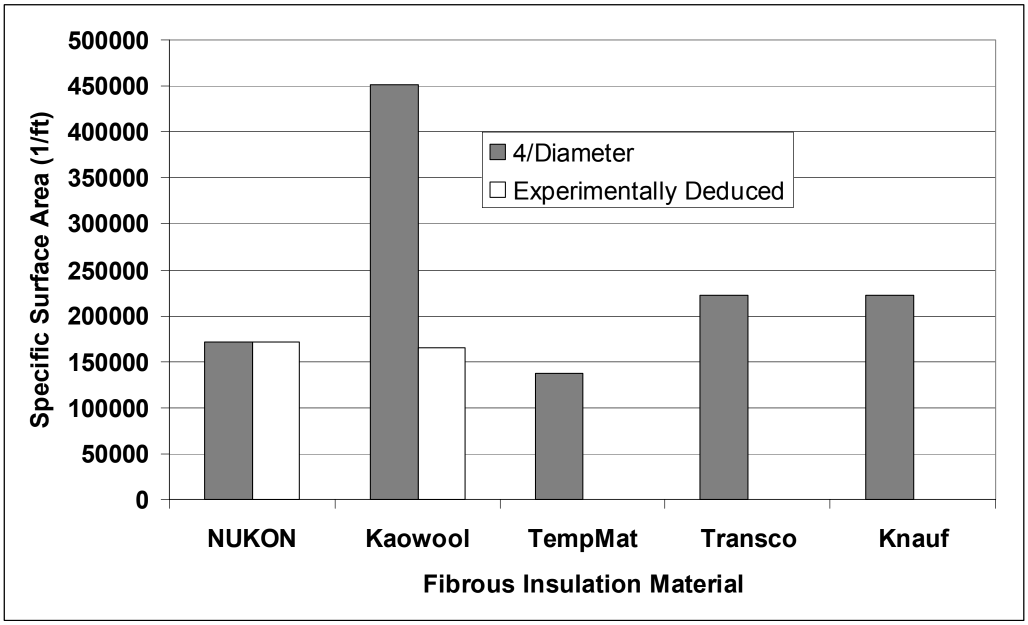

Figure V-4. Comparison of Fibrous Insulation Specific Surface Areas

V.2 Particulate Debris Head-Loss Parameters

In Section 3.7.2.3.1.1 of the GR, the NEI recommends using the simple formula of six divided by the characteristic particle diameter (6/d) to determine the specific surface areas for particulate debris. The following confirmatory analyses provide insights into this relationship and experimentally deduced values for particulate *Sv.*

V.2.1 Iron Oxide Corrosion Products

During the resolution of the boiling-water reactor (BWR) strainer blockage issue, the iron oxide CPs that accumulate in a BWR suppression pool were the primary particulate in the head-loss calculations. The size distribution shown in **Error! Reference source not found.** characterizes the BWR sludge CP.

The NUREG/CR-6224 correlation recommends a specific surface area of 183,000 ft^{-1} for head-loss estimates with CP, which has been validated by comparison with test data. Using the mid-range diameters from **Error! Reference source not found.** to estimate the *Sv* for the CP distribution using the 6/d formula, the *Sv* estimate becomes 48,400 ft^{-1} (almost a factor of four less than the NUREG/CR-6224 recommendation). Note that an error of a factor of 4 in the *Sv* can result in an error of a factor as large as 16 in the head loss at low-flow velocities.

If the minimum value of the range is used (assuming a minimum particle size of 2 μm for the 0- to 5-μm size group), then an *Sv* of approximately 290,000 ft^{-1} is calculated (approximately 58 percent higher than the recommended validated area). The smaller particles have more effect on the particulate *Sv* than do the larger particles, which is why the mid-range diameters are not a valid representation of the distribution. Using the smallest diameters of each group is conservative but can result in large estimates of *Sv*.

Further, these examples illustrate that it is difficult to determine where in a size range is an appropriate diameter for the *Sv* determination using 6/d.

Table V-1. Size Distribution of BWR Suppression Pool Iron Oxide Corrosion Products

Size Range (µm)	Percent by Number of Particles	Percent by Weight
0–5	81%	0.3%
5–10	14%	1.5%
10–75	5%	98.2%

Figure V-5 illustrates an example of how the 6/d formula works over a particle-size grouping, where 6/d is plotted for particle diameters ranging from 5 to 75 µm (typical distribution grouping). If it is assumed that particles are uniformly distributed (by weight) across this size range (which is not necessarily a valid assumption), then the average 6/d corresponds to a diameter of 25.8 µm, whereas the mid-range diameter is 40 µm. Because this simple arithmetic relationship arrives at differing conclusions, depending on the range specification, this method cannot be used reliably in a general sense, even if the uniform distribution assumption is valid.

In summary, the only reliable method of determining the *Sv* for a particulate, unless the particulate-size distribution is known in much greater detail than has been typically specified to date, is to deduce *Sv* from valid head-loss test data. It is conservative to use the lower diameter of each size group but this can lead to large estimates of the *Sv*. However, this method is valid when applicable head-loss data are lacking. Another difficulty is the determination of the smallest particles in the distribution. Although most particulates will have submicron particles in the distribution, fiber debris beds may not filter such small particles; certainly, the efficiency of filtration could be rather low and is difficult to determine.

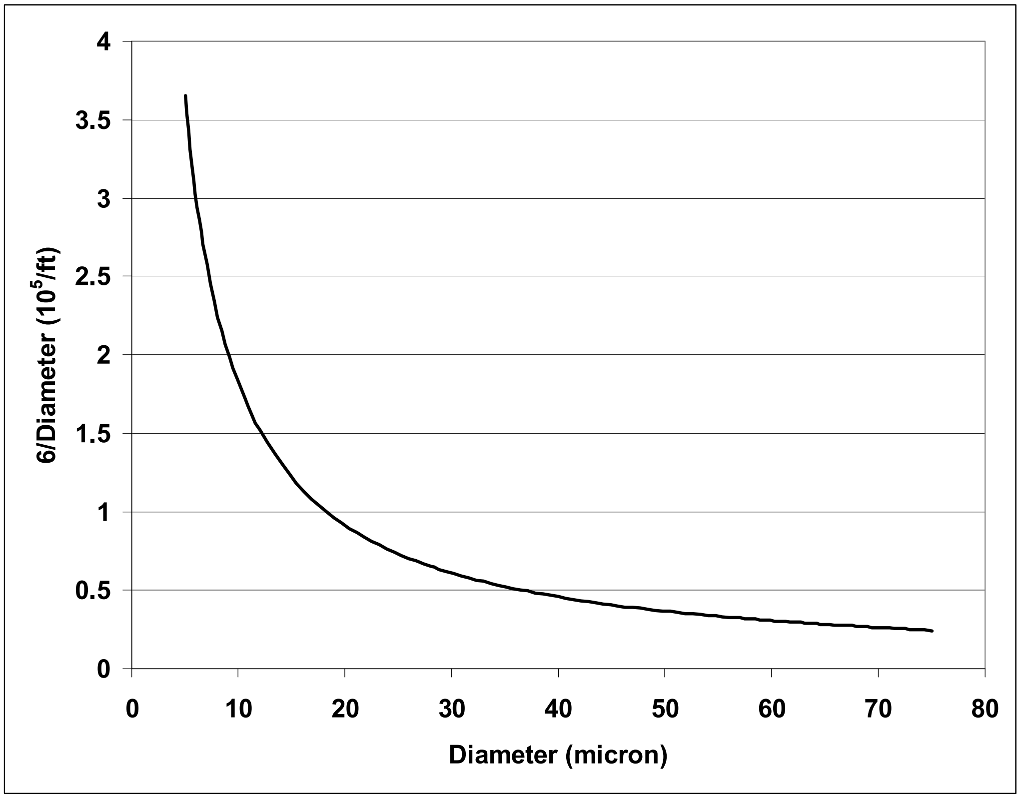

Figure V-5. Example of *Sv* Variation with Particle Diameter

V.2.2 Latent Debris

Los Alamos National Laboratory (LANL) (LA-UR-04-3970, 2004a) determined the characteristics of latent debris collected from inside containments of several nuclear plants. These characteristics included properties of material composition and hydraulic flow properties (e.g., specific gravities and characteristic dimensions). Based on these characteristic properties, surrogate latent particulate debris* was formulated for testing in the closed-circulation head-loss simulation loop operated by the Civil Engineering Department at the University of New Mexico (UNM).† Applying the NUREG/CR-6224 head-loss correlation to the test data for the surrogate latent debris resulted in parameter recommendations for the application of the correlation to plant latent debris. Summaries of those recommendations follow, together with insights gained from the surrogate latent debris data reduction. The calcium silicate debris test report (LA-UR-04-1227, 2004b) describes the test apparatus and base test procedures in detail.

The plant debris characteristics pertinent to the specification of a recipe to create a suitable latent particulate surrogate include the particulate specific gravity and the particulate-size distribution. Table V-2 shows the particulate-size distribution that was

* A surrogate was required to provide the quantities of debris needed for head-loss testing. The latent debris collected in containment required the special handling associated with radioactive materials.

† NUKON™ insulation debris was selected to form the fiber bed to filter the surrogate particulate from the flow because of its well-established head-loss properties.

used as a recipe for the particulate. The surrogate particulate debris tested at UNM was constructed from common sand and soil (referred to as dirt), with the sand used for the two larger size groups and the dirt for the less than 75-μm-size group. The specific gravity of the latent debris characterized at LANL varied but is well represented as a specific gravity of 2.7, and both the sand and dirt used to formulate the surrogate were found to have a specific gravity near 2.7. The dirt had a clay component that tended to disintegrate, in part, in water, thereby adding substantial particulate less than 10 μm to accommodate the LANL, finding that the filters collected substantial very fine debris. Both granular (thin-bed) and nongranular debris beds were tested.

Table V-2. Surrogate Particulate Size Distribution

Size Range (μm)	Fraction
500 to 2000	0.277
75 to 500	0.352
<75	0.371

Tests were conducted using the individual size groupings for the 75- to 500-μm sand and the less than 75-μm dirt (without the other groups present) to determine specifically the head-loss characteristics of these individual size groupings; then the latent debris recipe was tested with all three size groups represented according to the recipe. The largest size group (500 μm to 2 mm) was not individually tested because of its relatively minor impact on the recipe head loss; its small specific surface area was estimated using the 6/d equation. For the other two size groups, the specific surface area was deduced from the head-loss data. The bulk densities of the three components were estimated by measuring the bulk volume in a calibrated beaker for a weighted mass of particulate. Given the particle specific gravity and the bulk densities, the granular debris bed porosities were estimated. Table V-3 summarizes the test results for the surrogate latent particulate debris.

Table V-3. Summary of Test Results

Particulate (μm)	Bulk Density (lbm/ft^3)	Limiting Granular Porosity	Limiting Granular Solidity	Specific Surface Area (ft^{-1})
500 to 2000 (Sand)	104	0.38	0.62	2,000
75 to 500 (Sand)	99	0.41	0.59	10,800
<75 (Dirt)	39	0.77	0.23	285,000
Recipe	63 to 75	0.62 to 0.55	0.38 to 0.45	106,000

The table shows a range of numbers for the bulk density and limiting granular porosity and solidity because of the uncertainty associated with filtration of the very fine dirt from the water flow (i.e., how much of the dirt introduced into the test loop actually resided in the debris bed). Test-loop water turbidity measurements clearly showed that the fibrous

bed did not filter significant, sometimes substantial quantities of the fine dirt from the flow. If there is a minimum particle size for effective filtration, it is most certainly significantly less than 10 μm and likely less than a few microns. Table V-3 presents nominal estimates for the specific surface area for each component; however, there is significant uncertainty in determining these numbers. The primary uncertainty associated with the less than 75μm particulate was the filtration efficiency of the finer particles. Assessing the uncertainties in the turbidity resulted in the conclusion that between 30 and 45 percent of the particulate remained in solution, which corresponded to a range of about 250,000 ft^{-1} to 340,000 ft^{-1} in the specific surface area when the correlation was applied. For the two larger particulate size groups (75 to 500 μm and 500 to 2000 μm), the uncertainties were analytically estimated using the 6/d formula where the diameter was ranged from the smallest diameter particles up to 25 percent of the range. Figure V-6 compares these estimated uncertainties.

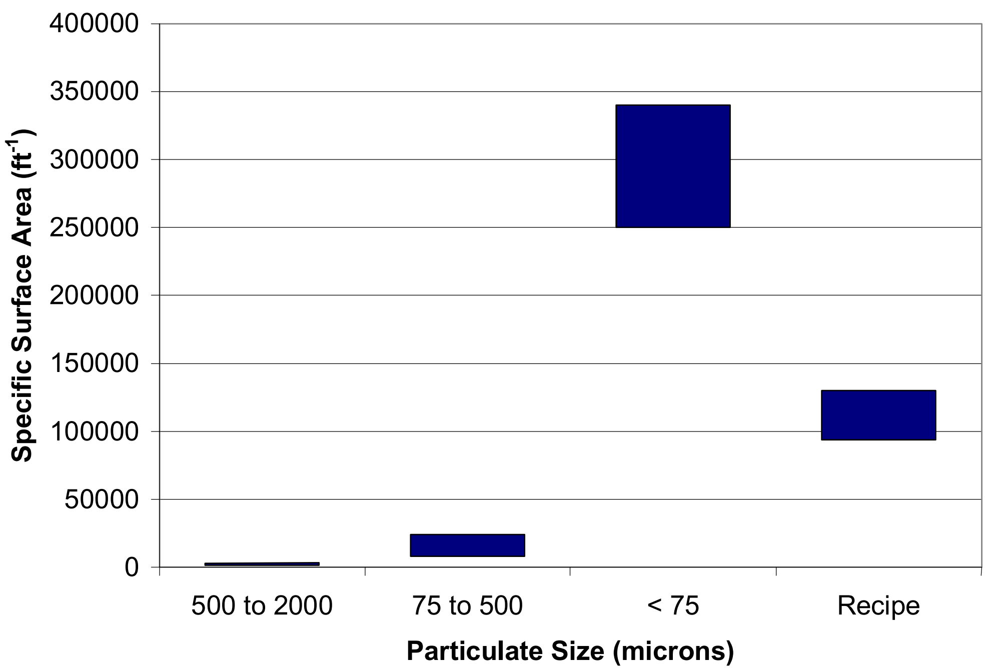

Figure V-6. Comparison of Component and Recipe Specific-Surface-Area Ranges

The following eight key points can be deduced from the foregoing discussions relative to latent debris:

(1) The limiting porosity (solidity), which depends on the composition of the debris, controls the head loss through granular (thin-bed) debris. Solidity certainly is not a fixed number, as is indicated in the presentation of the NEI guidance as a solidity of 0.2. Handbooks on soils show many materials with limiting porosity less than 0.8 (e.g., common sand is approximately 0.40 to 0.43 and was experimentally verified in the LANL tests).

(2) The major contributors to the head loss are the increasingly smaller particles (less than 75 μm), as illustrated by the 6/d formula, until the particles become

too small for filtration. However, it is difficult to determine some limiting particle diameter that will not filter.

(3) It is difficult to formulate specific recommendations for the appropriate parameters to use in the NUREG/CR-6224 correlation for pressurized-water reactor (PWR) containment latent particulate because the latent debris composition will vary from plant to plant and because the latent debris transported to the sump screen will also be plant-specific because of such differences as flow velocities. In addition, the uncertainties associated with whether the surrogate recipe suitably represents actual containment latent debris further compound the problem of developing recommended characteristics for latent debris. More important than specific recommendations are the methods for ascertaining appropriate head-loss parameters once the plant has assessed latent debris accumulation on the sump screen.

(4) The surrogate latent particulate debris head-loss tests effectively demonstrate the necessity of characterizing the latent particulate so that appropriate parameters can be estimated. For example, if deposition of the entire mass of the latent debris onto the sump screen is assumed, then a lower specific surface area, such as the recipe in these tests, can be applied. However, if transport analyses are used to limit the transport of latent particulate to only the fine particulate, then the appropriate specific surface area would be more like that of the fine dirt in these tests. The same consideration also applies to the limiting packing density.

(5) It is recommended that plant latent debris estimates be separated into as many particle size groupings as reasonably possible and then that subsequent transport analysis be applied to each group to determine the particulate makeup on the sump screen.

(6) Wherever possible, specific surface areas should be determined for each size group based on test data. When the areas must be estimated from the particle diameters, the appropriate diameter is clearly not the mean or average diameter of the size group but a diameter closer to the minimum diameter of the group. The minimum diameter should normally result in a conservative specific surface area.

(7) The use of the simple geometric relationship of 6/d to estimate the specific surface areas for particulate is not reliable because the appropriate diameter within the range is not known. Table V-4 illustrates this point, where values for *Sv* are estimated using both the mid-range and minimum diameters for each size group in the surrogate latent particulate recipe. These values are compared to the *Sv* deduced from the experimental head loss and the particle diameters that correspond to the experimental *Sv*. This minimum diameter in the size range estimates a conservative *Sv*; however, that number could be unacceptably large if the minimum size for the smallest particles is not well known. The use of mid-range diameters is unacceptable because this approach excessively underpredicts *Sv* values for plant-specific evaluations. If the specific surface areas corresponding to the minimum particle diameters in each size grouping range are unacceptable, then head-loss test data are required to determine a specific surface area for the particulate size distribution in question.

(8) The NEI guidance recommends the use of 100 lb/ft^3 for the material density of latent particulate, whereas LA-UR-04-3970 indicates a density of approximately 168 lb/ft^3 (specific gravity of approximately 2.7). The use of the lighter density of 100 lb/ft^3 is conservative relative to a heavier density of 168 lb/ft^3, for example, if the other head-loss parameters are appropriately specified.

Table V-4. Comparison of Specific Surface Area Estimation Methods

Particulate Size (µm)	Analysis			Experimental *Sv*	
	Mid-Range Diameter (µm)	*Sv* = 6/d Mid-Range *Sv* (ft^{-1})	*Sv* = 6/d Mid-Range *Sv* (ft^{-1})	*Sv* Deduced from Experimental Head-Loss Data (ft^{-1})	6/*Sv* Experiment (µm)
500 to 2000 (Sand)	1250	1,460	3,660	2,000	914
75 to 500 (Sand)	287.5	6,360	24,380	10,800	169
<75 (Dirt)	37.5	48,770	914,000*	285,000	6.4
Recipe	88.2	20,740	349,000	106,000	17.3

* Assuming a 2-µm minimum particle size.

V.3 Formulas for Mixing Multiple Fiber and Particulate Components

Most head-loss testing has been performed with a single type of fibrous debris (e.g., NUKON™) and particulates such as CPs. However, plant-specific analyses may well postulate debris beds containing more than one type of fiber and several types of particulate. The application of the NUREG/CR-6224 correlation requires the head-loss properties for the mixture to be estimated from the individual species properties.

V.3.1 Mixture of Specific Surface Areas

The equation for the mixture of the specific surface areas simply multiplies each area by the species volume and sums these products to calculate the total surface area, which is then divided by the total volume to obtain the mixture-average specific surface area. Such an equation was recommended in NUREG/CR-6371. Section 3.7.2.3.1.1 of the NEI guidance on the mixing equation recommends using the square of the specific surface area rather than the linear relationship. The following equation for the mixing is set up to accommodate the linear (n = 1), the square (n = 2), or any other exponent. Performing example-mixing evaluations demonstrated that using the square results in larger values for the mixture of specific surface areas than does using the linear relationship; therefore, it is conservative to use the square of the specific surface area in the mixing rather than the linear

$$Sv_{Mixture} = \left[\frac{\sum_i \frac{m_i}{\rho_i} Sv_i^n}{\sum_i \frac{m_i}{\rho_i}} \right]^{\frac{1}{n}} \quad ,$$

where

Sv = the specific surface area for component i or for the mixture,

m_i = the mass of component *I*,

ρ_i = the material (solid) density of the particles in component *I*, and

n = the weighting exponent.

For the surrogate latent particulate debris, mixing the three constituents to get the recipe test result seemed to work best using an n = 4/3 (assuming that approximately 40 percent of the fine dirt did not filter from the flow). Because of the substantial uncertainties associated with head-loss predictions, it is prudent to include a safety factor; therefore, the NEI recommendation of using the square of the specific surface area in the mixing equation is a good recommendation.

V.3.2 Mixture Densities

The equation for the mixture of densities (bulk, material, or granular) simply adds all of the species masses and then divides by the total of the species volumes as

$$\rho_{Mixture} = \frac{\sum_i m_i}{\sum_i \frac{m_i}{\rho_i}} \quad ,$$

where

ρ_i = the density of the particles in component *I* and

m_i = the mass of component i.

This density mixing equation can be reduced to the following, even simpler form:

$$\frac{1}{\rho_{Mixture}} = \sum_i \frac{f_i}{\rho_i} \quad ,$$

where

f_i = the mass fraction of component i.

V.4 Procedures for Applying the NUREG/CR6224 Correlation

The application of the NUREG/CR-6224 head-loss correlation requires several input parameters that must be conservatively specified to ensure bounding head-loss predictions. The most reliable method of determining these input parameters is the application of the correlation to appropriate head-loss test data. Analytical determinations are suitable under some conditions if sufficient conservatism is used throughout the determination. Although the correlation was developed for flat screen geometries, the correlation has been successfully applied to other strainer geometries, such as the stacked-disk strainers.

V.4.1 Experimental Determination of Correlation Parameters

The proper application of the NUREG/CR-6224 correlation to applicable head-loss test data leads to input parameters that ensure bounding head-loss prediction when the correlation is applied to postulated plant conditions that would form debris beds similar to those in the tests. The closer the test data is to the postulated debris beds the more certain the determination of the input parameters. Appropriate conservatism is required whenever the test data are dissimilar to the postulated conditions.

V.4.1.1 Success Criteria for Applicable Test Data

The assumptions associated with the development of the NUREG/CR-6224 correlation included the following:

- The debris bed consists of fibrous debris with or without particulate debris.
- The debris bed has a uniform thickness.
- The debris bed is homogeneous.
- The flow approach velocity is perpendicular to the debris bed.
- The flow and debris accumulation on the screen are relatively quasi-steady-state.

Therefore, the success criteria for applicable test data to determine applicable correlation input parameters include the following:

- The test debris bed consists of some mixture of fibrous debris with or without particulate debris.
- The debris bed must be relatively uniform.
- The debris bed must be relatively homogenous.
- The approach velocity must be perpendicular to the flow.
- The debris accumulation, flow rate through the debris bed, the temperature, and the measured pressure differential across the bed must be relatively steady.
- The quantities of debris in the bed must be known.

When tests are conducted, care must be taken to minimize edge effects where a portion of the flow can leak through an edge gap between the debris bed and the test chamber.

Flow that bypasses the debris bed, such as edge leakage, or holes penetrating the debris bed reduce the debris bed flow velocity below that deduced from the flow instrumentation. A nonuniform bed can have shallow locations where water preferentially flows through the bed, thereby reducing the measured head loss.

Typically, in head-loss testing, debris is introduced into a closed loop test apparatus and then allowed to settle onto the test screen. Some debris, especially the particulate, can penetrate the screen and subsequently return to the screen after transiting the flow loop. The gradual filtration process of the finer particulate causes the pressure differential measurements to be initially transient. Therefore, sufficient time must be allowed to let the filtration become relatively steady-state before recording the test data point. The filtration process is such that the finest of the particulate is the most difficult to filter completely out of the flow, but the finer particulate has a greater impact on head loss on per mass basic than does the coarser particulate. The finest of the particulate might not be filterable under some conditions. All these considerations are taken into account when assessing the quality of the head-loss test data for application to determining correlation input parameters.

V.4.1.2 Parameter Deduction

The input parameters required by the NUREG/CR-6224 correlation include the following:

- debris quantities
  - quantity of fibrous debris expressed as the thickness of the debris on the screen assuming its nominal density before destruction (referred to as as-manufactured density)—equivalent to specifying its mass.
  - mass of particulate debris
- flow approach velocity
- temperature-dependent water properties
  - viscosity
  - density
- material specific surface areas
  - — fibrous debris
  - — particulate debris
- densities
  - material density of fibers in the fibrous debris
  - material density of the particulate
  - as-manufactured density of the fibrous insulation

– sludge density of the particulate (also referred to as the granular density or packing limit density)

- compression function coefficients (e.g., 1.3 and 0.38 for NUKON)

The experimental determination of a set of parameters for a specific debris bed would be performed along the following five steps:

(1) Select the appropriate head-loss test for each particulate parameter determination. When applying the correlation to the data from a particular test, the test parameters specify the approach velocity, the quantities of debris, and the temperature.

(2) Determine a set of densities for the debris bed test data. Manufacturer's data can often supply the densities, but if those data are not readily available, volume displacements for measured masses of debris can determine densities for typical debris. Bulk densities are determined from bulk displacements and material densities from water displacement.

(3) If possible, experimentally evaluate the compression function coefficients from test data where the particular fibrous debris is the only debris in the bed and the bed is thick enough to allow reasonable thickness measurements as a variety of velocities and bed thicknesses. Statistical analysis of the thickness data can determine the coefficients. If applicable thickness test data are not available, initially assume the coefficients validated for NUKON™ (i.e., $\alpha = 1.3$ and $\gamma = 0.38$).

(4) With these other parameters determined, as discussed, the remaining parameters are the specific surface areas for the fibrous and particulate debris. Starting with a fibrous debris bed without any particulate, adjust the specific surface area until the correlation reasonably bounds the data. The resultant specific surface area then applies to that particular fibrous debris. Note that other uncertainties are subsumed into the specific surface area.

(5) With the specific surface area for the fibrous debris determined, another test(s) is selected that uses that fibrous debris but also has the particulate under study. The specific surface area of particulate is adjusted until the correlation reasonably bounds the data. This specific surface then represents the specific surface area for the particulate.

The above procedure has developed a set of parameters from a set of tests. The quality of the recommended parameters is greatly improved by simulating as many tests as reasonably possible because the resultant parameters will vary somewhat from test to test. If the NUKON™ compression coefficients were initially assumed and do not reasonably apply to the fibrous debris in question, then the data analysis may need to vary these parameters. An example is the lead alpha coefficient (as proposed in GR Section 3.7.2.3.1.1) in steps 3, 4, and 5 in an attempt to align the parameter deductions from the specific tests into coherent set of parameters.

The evaluation should include thin-bed head-loss tests as well as mixed bed tests (i.e., the granular packing limit compression was not reached). The filtration efficiency can

increase substantially when the flow must pass through a granular bed as opposed to a fibrous bed because of the reduced porosity. The determination of the particulate specific surface area should consider the worst-case particulate filtration.

V.4.1.3 Parameter Recommendations (Bounding)

The recommended correlation input parameters should ensure that the most severe head losses associated with a particulate type of debris bed are conservative enough to provide a bound prediction of the head loss associated with a particular postulated bed of debris. The recommendation should consider the uncertainties associated with head-loss testing (e.g., nonuniformities in the test debris bed could have reduced the measured head loss below that which would have been measured if the bed had been truly uniform). Other considerations include the potential variability in manufacturing processes of the debris. If, for example, parameters are recommended for calcium silicate debris, then it can be expected that those parameters will likely be universally used for any calcium silicate debris calculation. However, the recommendations should include a built-in safety factor because the manufacturing of calcium silicate varies with manufacturer, and even by a single manufacturer from one batch to another.

V.4.1.4 Ranges of Validated Parameters

The NUREG/CR-6224 correlation was developed and initially validated to support the resolution of the BWR strainer blockage issue. This development focused on validation of NUKON™ fibrous debris and iron oxide corrosion products. The insulation in the volunteer plant was NUKON™, hence the validation focused on NUKON™. For all BWRs, the dominant form of particulate was the corrosion products that formed and collected in the suppression pools. Therefore, the baseline validation compared the correlation results to head-loss tests using these two types of debris. In addition to the baseline, other validations were performed using other types of materials. A lesser amount of corrosion products is expected in a PWR containment than in a BWR containment. Therefore, the more likely particulates in a PWR containment will be latent particulate, coatings debris, and particulate insulation debris (e.g., calcium silicate).

Over the years, many analyses have applied the correlation to head-loss test data over various ranges of test data. These test programs typically explored the head loss until a judgment was made that the test encompassed the parameter space needed for a particular application. The maximum head loss tested was typically not larger than approximately 25 ft of water, primarily resulting from the limits of the test apparatus, which is generally sufficient for most applications.

Because most test apparatus were constructed of materials that were not able to reliably withstand the higher temperatures expected in a post-loss-of-coolant accident (LOCA) sump pool, the available test data does not extend the range of postulated sump temperatures. However, because the data on the effect of temperature-dependent water viscosity and density are available, it has been deemed acceptable to test at lower temperatures and then analytically extend calculations into the higher temperatures. However, this recommendation does not necessarily include the potential for debris decomposition at higher temperatures, which in some tests was factored into the tests by pre-aging the debris using techniques such as boiling the debris for a period to break down the binder. For other parameters, the correlation is not validated beyond the ranges of the test parameters tested. Care must be taken, in reviewing the data, to

ensure that a significant gap in data does not exist within the validation range at a parameter that significantly affects the current application.

Table V-5 and Table V-6 list the specific validations for screens that function effectively as flat plates for fibrous and particulate debris, respectively. Section V.4.2 discusses validations that involved special geometries.

Table V-5. Validation Ranges for Fibrous Insulation Debris

Debris Type	Velocity (fps)	Temperature (°F)	Debris Bed Thickness (in.)	Comments	References
NUKON™	0.15 to 1.5	60 to 125	1/8 to 4		NUREG/CR-6224 NUREG/CR-6367 NEA/CSNI/R (95)11 LA-UR-04-1227 SER Appendix V
Kaowool	0.3 to 0.62	~85	2		SER Appendix V
Transco Thermal-Wrap	0 to 0.5	129			NEA/CSNI/R (95)11
Mineral Wool	0 to 0.23	55 to 131	1.6 to 4		NEA/CSNI/R (95)11

Table V-6. Validation Ranges for Particulate Insulation Debris

Debris Type	Velocity (fps)	Temperature (°F)	Particulate to Fiber Mass Ratio	Comments	References
Iron Oxide Corrosion Products	0.15 to 1.5	60 to 125	0 to 30	With 0 to 2-in. bed of NUKON™ or Kaowool	NUREG/CR-6224 NUREG/CR-6367 NEA/CSNI/R (95)11 SER Appendix V
Calcium Silicate	0.1 to 0.8	70 to 140	0.5	With NUKON™ 0.1 to 1.6 in. Few test to mass ratio up to 2	LA-UR-04-1227
Latent Particulate (surrogate)	0.1 to 0.5	70 to 140	1 to 40	With NUKON™ 0.2 to 2.3 in.	LA-UR-04-3970 SER Appendix V

The staff extended the applicable temperature range of the NUREG/CR-6224 head loss correlation as summarized below and described in detail in Attachment V-1. The acceptable operating conditions for flow through a sump screen are bounded by the operating containment pressure, the sump water temperature, and the pressure drop through the sump screen. The acceptable operating conditions require that no significant two-phase flow conditions exist in the region downstream of the sump screen. Consequently, the pressure downstream of the sump screen cannot fall below the

saturation pressure at the sump water temperature, and no significant amount of noncondensible gas dissolved in the sump water can come out of solution. It is generally accepted that a pump will experience cavitation problems when its inlet void fraction exceeds about 0.03 (3%). Using 3% void fraction as the upper limit for acceptable conditions downstream of the sump screen, Figure 1 can be used to determine the maximum acceptable temperature for flow through a sump screen. This figure is used in the following fashion.

1. Identify the actual sump water temperature.
2. Identify the containment pressure.
3. Calculate the pressure drop through the sump screen.
4. Using the containment pressure and calculated sump screen pressure drop, read the maximum allowable sump water temperature off Figure 1.

5a If the actual sump water temperature is lower than the maximum allowable temperature, acceptable pump inlet conditions exist and the sump screen pressure drop calculation is acceptable.

5b If the actual sump water temperature is higher than the maximum allowable temperature, the void fraction at the sump screen exit exceeds 3% which indicates that pump cavitation is possible. This condition indicates that the sump screen pressure drop calculation in inapplicable.

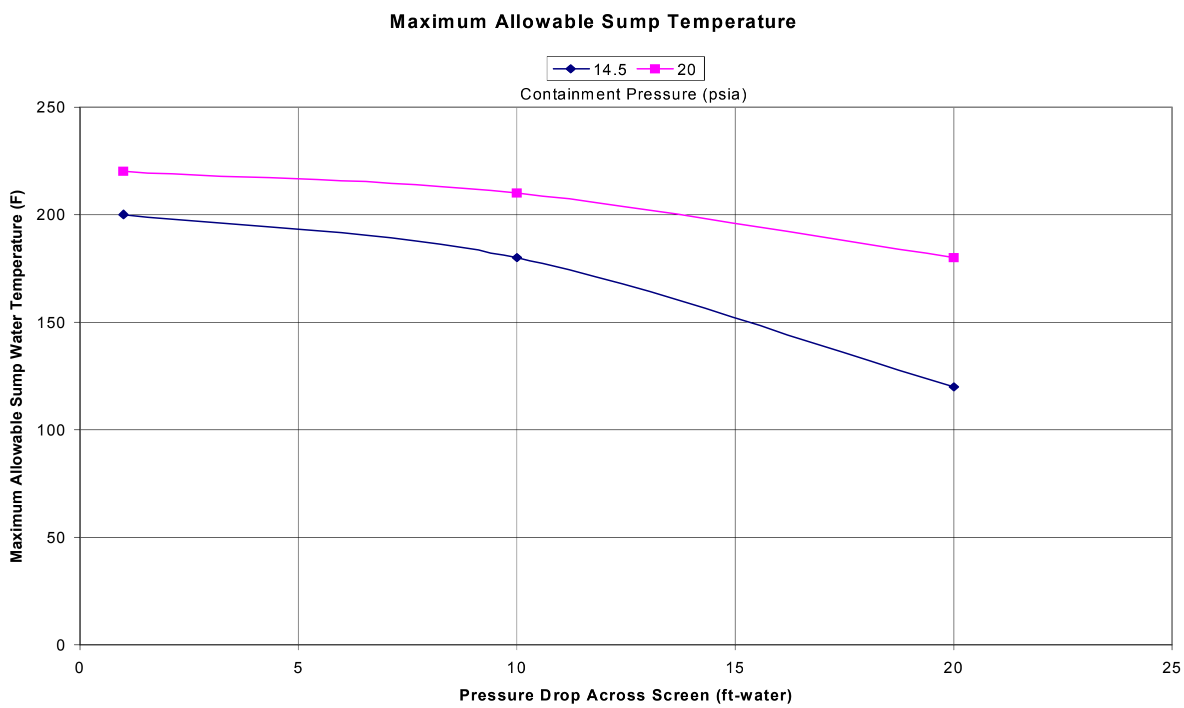

Figure V-7. Sump screen pressure drop versus maximum allowable sump water temperature for downstream void fraction < 3%.

V.4.2 Analytical Determination of Correlation Parameters

When test data are not available, the specific surface area may be calculated for some materials. For fibrous debris of low-density fiberglass in which the fibers have relatively uniform cross sections (e.g., NUKON™), the specific surface area can be reasonably estimated using the 4/d calculation. The extension of this relationship to fibrous insulations with fine fibers such as mineral wool has not been documented. Some evaluation is needed to generally accept the specific surface area of fiber as equivalent to 4/d. Until such a demonstration is documented, a significant safety factor should be factored into the specific surface area estimate to compensate the uncertainties.

The specific surface area particulate can be calculated using 6/d. For the NEI guidance assumption that coatings debris forms 10μm particulate, the use of 6/d is appropriate because the particles all have the same diameter. However, for a realistic particulate, the particle sizes vary over a wide range, typically from sub-micron to a few millimeters. If the size distribution is known in fine detail, a reasonable specific surface area can be estimated, but typically, the size distribution is specified by mass fractions associated with only three or foursize groups. The latent debris discussed in Section V.2.2 of this report is an example of coarse size distributions. Because the smaller particles contribute substantially more to the specific surface area than the coarser particles, using the mid-range size of each grouping results in estimates of specific area which is significantly smaller than the actual. Using the smaller diameter of each size group to calculate the specific surface area would result in a conservative estimate. However, the smallest diameter of the smallest size group, which corresponds to the finest particulate that can be filtered by the debris bed, depends upon several other factors. If too small a minimum particle size is estimated, the resultant specific surface area can become significantly larger than actual, leading to overly conservative head-loss estimates.

When applying the specific surface areas for the latent debris specific surface areas given in Section V.2.2, the value of 106,000 ft^{-1} applies to the entire recipe. If analytical refinement in a plant-specific analysis seeks to reduce the transport such that the larger particulate is assumed not to transport to the sump screens, thereby reducing the particulate mass in the debris bed, the 106,000 ft^{-1} specific area no longer applies. If, for example, only the particulate of diameter less than 75 μm is assumed to reach the screens, the appropriate specific surface area would be 285,000 ft^{-1}.

The above discussion on using 6/d to calculate the specific surface area of particulate applies to hardened particulate that does not change shape under debris bed pressures. For particulate consisting of materials that can deform (e.g., calcium silicate), special care must be taken because the 6/d specific area may not adequately represent the particulate behavior that has been demonstrated that causes the high head loss associated with calcium silicate.

V.4.3 Application to Special Strainer Geometries

Section 7.3.2.2 of NUREG/CR-6808 provides the application of the NUREG/CR-6224 correlation to a special strainer geometry of the stacked disk strainer. Several full scale or prototype scale test programs have been performed where the application has been validated.

V.4.3.1 Beginning and Ending Strainer Conditions

The correlation can be applied to the initial debris loading on these strainer designs by using the total screen area and the appropriate input parameter determined from flat screen head-loss testing or other means as discussed above. Then the correlation can be applied to the fully engulfed debris loading by assuming what has been referred to as the circumscribed screen area, which neglects the screen area within the gaps that has been completely filled with debris. In between, many analyses have assumed a linear extrapolation between the end conditions. Section V.4.3.2 discusses another alternative.

V.4.3.2 Experimentally Determined Effective Strainer Areas

The NUREG/CR-6224 correlation is applied to the head-loss test data using appropriate input parameters determined from flat screen head-loss testing or other means as discussed above. Developing the correlation to fit the data, which have a range of debris loading (from a clean screen to a fully engulfed screen), involves plotting the effective screen area versus debris loading. This plot can then be used to determine head losses for the design as a function of debris loading.

V.4.3.3 Special Strainer Geometries Testing and Validation

The NUREG/CR-6224 correlation was applied to Performance Contracting Inc. (PCI) stacked disk strainers and General Electric (GE) stacked disk strainers.

V.4.3.3.1 PCI Stacked Disk Strainer

Performance Contracting Inc. (PCI) designed, developed, and supplied advanced passive stacked-disk strainers to the nuclear industry that accommodated large volumes of insulation debris without substantial increases in the head loss. The PCI strainer concept, referred to commercially under the trademark Sure-Flow strainer, consists of a stack of coaxial, perforated metal plate disks that are welded to a common perforated internal core tube. The design maximizes the surface area of the perforated plate while keeping the size of the strainer to a minimum. The Sure-Flow strainer is not a standardized strainer i.e., one size fits all. Instead, the concept promoted by PCI is to use similarly designed strainer modules of various sizes and quantities as necessary for each plant.

PCI fabricated and tested prototypes to evaluate the head loss performance of the Sure-Flow strainers. The hydraulic performance testing was conducted at the EPRI NDE Center. One prototype, referred to as Stacked-Disk #1 in the URG, was a 40%-scale prototype with six disks, five troughs, between the disks, a 13-inch core tube, a 30-inch outside diameter, and was a 2.5-ft long. A larger prototype, referred to as Stacked-Disk #2, was a 4-ft long strainer with a core tube diameter of 26-inches and a stack outer diameter of 40-inches. For generic calculations of head loss performance, PCI team member, the Innovative Technology Solutions (ITS) Corporation, programmed the NUREG/CR-6224 resulting in a proprietary computer code named HLOSS whereby the correlation was extended to the stacked-disk strainer geometry.

The PCI head loss data is documented in the PCI report "Summary Report on Performance of Performance Contracting, Inc.'s Sure-Flow™ Suction Strainer with

Various Mixes of Simulate Post-LOCA Debris," dated September 1997. At the request of the NRC, LANL reviewed the PCI test data and evaluated the adequacy of the head loss models. The results of that review are summarized in LANL TER LA-UR-00-5159, entitled "Technical Review of Selected Reports on Performance Contracting, Inc. Sure-Flow Strainer™ Test Data,' dated April 27, 2000. The head loss testing used NUKON™ fibrous debris, with and without sludge, and RMI debris.

LANL applied the NUREG/CR-6224 correlation to the PCI strainer design and its head loss test data. The application involved varying the strainer screen area (as input to the correlation) until the correlation predicted the test head loss, thereby determining an effective screen area for the strainer at varying debris loadings (volumes of fiber). The resultant effective area varied between the total perforated plate area and the strainer projected area (referred to as the circumscribed area). At the beginning of debris accumulation, the entire strainer screen area would be used. When debris accumulation covers the entire strainer such that the spaces between the strainer disks are filled, the circumscribed area would be appropriate. The effective strainer screen area varies between these two limiting areas depending upon debris volumes accumulated. The effective screen area is essentially an equivalent flat plate area that results in the same head loss at a particular volume of debris accumulation when applying the NUREG/CR-6224 correlation to that particular strainer.

V.4.3.3.2 GE Stacked Disk Strainer

General Electric (GE) designed, developed, and supplied advanced passive stacked-disk strainers (proprietary) to the nuclear industry that accommodated large volumes of insulation debris without substantial increases in the head loss and where each GE strainer could be designed specifically to suit a particular plant application. The GE provided it application methodology in the Licensing Topical Report (LTP) [NEDC-32721P], "Application Methodology for GE Stacked-Disk ECCS Suction Strainer," dated December 23, 1998 (Proprietary). The NRC staff reviewed this methodology as documented in LANL Technical Evaluation Report LA-CP-99-7, "Technical Review of GE LTR NEDC-32721P: Application Methodology for GE Stacked-Disk ECCS Suction Strainer," dated December 23, 1998 (Proprietary). The GE application methodology included: 1) hydraulic performance design methodology and 2) procedures for calculating hydrodynamic loads for new strainer installations that can be used in the structural analysis of the torus penetration, the strainer supports, and the strainer itself. GE fabricated a prototype strainer and tested its hydraulic performance at the EPRI NDE Center using both NUKON™ fibrous debris and RMI debris. GE developed an empirical correlation for NUKON™ fiber and corrosion products mixtures applicable within a limited range of tested parameters. The NRC staff examined the application of the NUREG/CR-6224 correlation to the GE strainer design whereby the strainer area was varied with debris loading.

V.4.4 Procedures for Determining Correlation Parameters for Mixtures

Plant-specific debris beds will likely contain a mixture of debris types including multiple types of fibers and multiple types of particulate (e.g., NUKON™ and latent fibers and calcium silicate insulation debris and latent particulates) whereas most head loss testing has involved one type of fibrous debris combined with one type of particulate. Formulas were presented in Section V.3 for estimating effective parameters for mixtures. The

effective parameters that need to be estimated for mixtures include the specific surface area, the bulk and material densities, and the coefficients for the compression function.

V.4.4.1 Mixture Specific Surface Areas

An equation was provided in Section V.3.1 to calculate the effective specific surface area for a mixture of debris. This equation can be applied to a mixture of fibrous debris, to a mixture of particulate debris, or to a mixture of fibrous and particulate debris combined. This equation simply performs a solid-volume averaging of the specific surface areas of each component of the mixture. Such an equation was recommended in NUREG/CR-6371. NEI GR Section 3.7.2.3.1.1 provides guidance for estimating specific surface area for mixtures that is based on volume averaging the square of the specific surface areas[*].

An exponent (n) was incorporated into the equation to accommodate both the NUREG/CR-6371 and the GR recommendations (i.e., n=1 for NUREG/CR-6371 and n=2 for the GR). Performing example-mixing evaluations demonstrated that using the square results in larger values for the mixture of specific surface areas than does using the linear relationship; therefore, it is conservative to use the square of the specific surface area in the mixing rather than the linear.

The staff recommends following the GR guidance of using the square (n=2) unless experimental data has established a value less than two but in no circumstances will the exponent be less than one. Note that the analysis of the surrogate latent debris testing (Section V.2.2) demonstrated that an exponent of 4/3 correlated (Section V.3.1) the data taken for the mixture with the data taken for the components.

V.4.4.2 Mixture Densities

Four densities are required in the application of the NUREG/CR-6224 correlation to a fiber/particulate debris bed. These include the bulk (as-manufactured) and material densities for fibrous debris and the bulk (sludge) and material densities for the particulate debris. Effective mixture densities must be determined for each of these four densities for debris containing more than type of fiber and/or more than one type of particulate. An equation is provided in Section V.3.2 that applies to each of these four densities. The NUREG/CR-6224 does not apply to coating debris in the form of significantly-sized paint chips. Inclusion of relatively minor quantities of paint chips can be performed by assuming the chips are decomposed into fine particulate (as recommended in the GR baseline methodology).

V.4.4.3 Compression Function Coefficients

The coefficients in the compression function that determines debris-specific compressibility of the debris bed may differ from one type of fiber to another. The coefficients documented in NUREG/CR-6224 were determined for NUKON™ and may or may not be valid for another type of fibrous debris. If the debris bed contains a

[*] The GR rationale for using the square was not provided. The GR reference points to NUREG/CR-6371 but this report does not recommend using the square of the specific surface area.

mixture of fibrous debris types (e.g., NUKON™ and mineral wool) then the compressibility may be based on a mix of two sets of coefficients. However, the correlation as now established does not accommodate multiple sets of coefficients and no guidance has been developed to facilitate such a determination.

The staff recommendation is to apply each set of coefficients to the head loss calculation individually and then used the worst case head loss as conservative. If however, the fibrous debris bed is clearly dominated by one type of fibrous debris (e.g., 99% NUKON™ and 1% latent) then it is acceptable to use the NUKON™ coefficients rather than the coefficients for the other 1% latent.

V.5 APPLICATION LIMITS OF NUREG/CR 6224 CORRELATION

The following three tier approach has been used to define the application limits of the NUREG/CR-6224 correlation.

1. Application limits inherent in the correlation due to assumptions and/or approximations implemented in the development of the correlation.
2. Application limits established by validating the correlation against head loss data applicable to specific test conditions (e.g., debris type, approach velocity, temperature, and bed thickness).
3. Application limits established by engineering judgment extensions of specific validations to more general parameter ranges.

The development of the correlation and supporting constitutive equations was based on previous correlation development work and basic assumptions. Therefore, the correlation does not apply for conditions beyond the conditions established during correlation development unless notable exceptions can be properly justified and validated. The developmental application limits are discussed in Section V.5.1. The most reliable method of establishing correlation applicability is to apply the correlation to head loss test data that was conducted with test parameter ranges that match the application parameter ranges. Validation for specific application-matching test conditions provides the reliability needed to support the relaxation of safety-related conservatisms required to ensure long-term recirculation. Existing validation studies are discussed in Section V.5.1.4.

The framework of NUREG/CR-6224 correlation was developed for a much wider application range than what the correlation is currently been validated. Therefore, additional validations can legitimately expand the current validation parameter ranges as needed, which is the responsibility of the licensees to perform. Validations for the complete range of each correlation input parameter would require extensive head loss testing due to the wide range of possible debris materials and quantities and mixture compositions for those types of debris, the variations in flow approach velocities, and water temperatures. The water temperature is a an example of a engineering judgment extension of existing validations. Difficulties associated with testing at the higher temperatures associated with postulated LOCA scenarios have kept the performance of head loss testing in temperature range of about 60 to 140 ^{o}F, whereas postulated temperatures in some scenarios approach the boiling point of water. Because the water temperature affects the head loss primarily due to the changing viscosity and density of the water, it has been considered through the years of testing that testing at practical

temperatures could be applied to postulated scenario temperatures. Such engineering judgment extensions to specific validations are the subject of Section V.5.2.

V.5.1 Application Limitations Inherent in the NUREG/CR-6224 Correlation

The semi-theoretical/semi-empirical NUREG/CR-6224 head loss correlation combines hydraulic concepts with experimental data for flow through fibrous media. In addition to the primary equation of the correlation, constitutive equations for porosity, fiber bed compression, and compaction limiting are required to close the solution [NUREG/CR-6224 and NUREG/CR-6371]. The application of the correlation is limited to conditions that satisfy the assumptions inherent in the development of the correlation. Therefore, these assumptions place limitations on the application of the correlation. Special case exceptions to these limitations must be properly supported and validated.

First of all, the primary correlation and the constitutive compression equation were specifically developed for flow through a fibrous media and the constitutive equations for porosity and the compaction limiting provides the capability of simulating particulate embedded within the fiber matrix. Therefore, the correlation is not applicable to debris types that effectively behave like sheet material that partially block a portion of the screen, such as metallic foils, tags, tape, or large paint chips. The correlation is generally applicable to any type of fibrous debris typically in use in PWR and BWR containment provided the correlation input parameters for that type of fiber material have been determined and properly validated. These parameters include the bulk and material densities, the specific surface area, and the coefficients for the fiber compression function that determines fibrous bed compaction due to flow-driven pressure gradient on the bed. The compression coefficients documented in NUREG/CR-6224 were validated for debris formed from the destruction of a low-density fiberglass insulation known as NUKON™ debris with beds thicknesses less than 4-inches thick. (For NUKON fiber material?)

The porosity and compaction limiting equations that integrate the effects of the particulate with the effects of the fibrous debris are based on hardened particles that do not deform under pressure. As such the particulate bulk and material densities and specific surface area are constants. The same constancy is also assumed for the fibers. Particulate, such as pieces of soft rubber debris, could deform under pressure and therefore not behave as was assumed in the development of these constitutive equations and therefore are not generally suitable for the application of this correlation. Further, the development of the constitutive equations assumed the particles to be small enough to fit between the fibers without significantly impacting the behavior of the fiber matrix and the particles have generally been assumed to be somewhat spherical in nature. Coatings debris in the form of fine particles is acceptable to the correlation but significant quantities of larger paint chips are outside the limitations of the correlation unless applicable testing is performed that demonstrates otherwise. The use of the GR recommended postulated 10-micron coating particles are within the correlation limitations. Applicable test data is required to determine the boundaries on paint chip dimensions that fit within the applicability of the correlation.

Because the correlation was developed for a one-dimensional flow through the debris bed, the correlation applies to debris beds of uniform thickness with the flow entering perpendicular to the surface of the bed. However, from the standpoint of predicting conservative head losses across the debris bed, applying the correlation to a non-

uniform bed will overpredict the head loss for the non-uniform bed. Hence, for safety evaluations, it is acceptable to apply the correlation to a non-uniform debris bed. As an example, at high pressure differentials, channeling has been observed where ‘bore holes’ have formed in the bed such that substantial flow effectively bypasses the debris. In such cases, the measured head losses are substantially less than those predicted assuming a uniform bed, i.e., the predictions are conservative but may not be realistic.

The NUREG/CR-6224 correlation was developed for a homogenous debris bed, i.e., the mixture concentrations are constant throughout the depth in the debris bed. Therefore, the correlation cannot typically be directly applied to a stratified debris bed. In a thin-bed debris bed (discussed in detail in Appendix VIII), the mass of the particulate for most particulates (e.g., latent particulate typically consisting of sand and dirt) is much larger than the fiber mass. Therefore, a thin-bed can be a stratification that occurs with a modest quantity of fibrous material supporting a layer of particulate and it has been successfully simulated with the correlation. Analytically, in such a bed, the effects of the fiber are minor relative to the effects of the particulate; therefore the particulate layer dominates in the correlation. The debris bed in a thin-bed starts to approach the behavior of a layer of particulate. The correlation in that mode predicts a porosity that approaches that of the particulate in its bulk or sludge form; predicts a bed thickness that approaches that of the sludge without fiber, and the specific surface area approaches that of the particulate. Noting that the primary correlation was based on fibrous media but now being applied to a particulate media, it is even more important that the correlation be properly validated for the thin-bed based on each specific particulate, which has been done for a few particulates (e.g., surrogate latent particulate, see Sections V.2.2 and VIII.4).

For debris stratification within a mixed debris bed (with substantial quantities of fibers), the application of the correlation requires special handling. Assuming the stratification can be treated as stacked uniform layers, the head loss across each layer can be evaluated separately and then the head loss contributions summed to get the total head loss. For the upper layer, the correlation can be directly applied assuming this layer is compatible with the other noted limitations. For a layer of particulate, the application can be applied in the same manner as the thin-bed where the layer in based on the particulate sludge density (i.e., compression is not an issue for this layer). However, the correlation cannot be applied to a fibrous layer that has been compressed by the forces from an upper layer. The constitutive compression equation does not have a term to represent the externally applied force; hence the compression for this layer and the associated head loss would be underpredicted. The evaluation of a stratified debris bed in a plant-specific evaluation will require either the analytical application of a demonstrated-conservative compression ratio for this layer or appropriate experimental data.

The NUREG/CR-6224 correlation does not simulate the filtration of particulate from the flow. It is assumed that the particulate mass specified as an input parameter is embedded in the debris bed in a homogeneous manner. Filtration is a complicated process that depends upon the particle sizes, interfiber spacing, and number of passes that the particles may take through the bed in a recirculating system and has not been successfully modeled analytically. It is conservative to assume complete filtration even though some of the finest particulate may continue to pass through the bed.

The NUREG/CR-6224 correlation was developed for single phase incompressible flow; either laminar or turbulent flow. Although the form of the primary correlation may well be appropriate for compressible flow, as well, the sump screen blockage issue does not involve compressible flow, therefore no attempt has been made to make the correlation applicable to compressible flow. The correlation is only applicable to single phase flow (water being the only application for the sump screen blockage issue) due to the basic hydraulics and single phase experimental data used to develop the correlation.

At higher sump blockage application temperatures, it may possible that voiding could occur in the debris bed as the pressure drops across the bed. Based on analyses presented in Attachment V-1 “NUREG/CR-6224 Head Loss Calculation Temperature Assessment,” it was reasoned that an exit void fraction of 3% or less is acceptable for the application of the correlation. If a head loss evaluation determines a debris bed pressure drop high enough that the flow exiting the debris bed has a void fraction that exceeds 3%, then the correlation is not applicable to that evaluation.

The NUREG/CR-6224 correlation was developed for steady state flow conditions, i.e., transient behavior is not simulated. If a flow rate or sudden change in debris bed composition occurs, the correlation is not valid again until a relatively quasi-steady-state in again achieved. For example, the compression behavior following a substantial addition to the debris bed would lag behind the transient accumulation. The use of ‘quasi’ reflects on the fact that a debris bed may be slowly changing or there may be small pulsations in the flow that change slowly enough that effectively there is no significant transient behavior. A transient estimate of head loss would occur on a time scale such that the head loss at any given time would correspond to quasi-steady-state.

Most head loss testing has been performed using one type of fiber and one type of particulate in a given test. In reality, a sump screen debris bed is likely to contain multiple types of debris. For example, NUKON™ insulation debris combined with latent fibers and latent particulate combined with calcium silicate particulate. Simple supporting equations are used to volume or mass average correlation input parameters (as appropriate) to obtain parameters applicable to the mixture (see Section V.3). Note application limitations apply to mixtures, as well as, individual constituents.

The SER recommendations for applying the NUREG/CR-6224 correlation to thin-bed debris beds with calcium silicate contain exceptions to the application limits to the correlation that are based on experimental test data. First, there is microscopic experimental evidence that calcium silicate particles are not hardened (due to voiding internal to the particles) in that under pressure the particulate may deform somewhat such that the constituent porosity equation is not entirely accurate for this material. For mixed debris beds, it is apparent that the particulate would not deform but in thin beds where the particles interact under pressure, deformation may occur. The approach used in the SER thin-bed guidance for calcium silicate was established as a bounding approach rather than a realistic simulation of the calcium silicate behavior. This application limitation exception was based on applicable test data.

In the second calcium silicate exception, there is a possibility that calcium silicate could accumulate on a sump screen without any supporting fibrous debris, other than the fibers inherent to calcium silicate. That is, the fibers in the calcium silicate could be sufficient to support its particulate. Note that it has been the practice to assume that all of the calcium silicate was particulate rather than attempt to separate the components.

In an unlikely scenario where a plant can justify that no significant quantities of fiber are in containment (either latent or insulation) but the plant has significant calcium silicate, then a calculation of calcium silicate only on the sump screen may be needed (see Appendix VIII.7 for more detail). In this case, the NUREG/CR-6224 primary correlation is applied without fiber by specifying calcium silicate parameters for specific surface area and porosity and a non-compactable debris bed of calcium silicate with a thickness based on the bulk density of the calcium silicate. The success of this second exception is again based on experimentally determined recommendations designed for bounding calculations and that included a safety factor.

The application of the correlation to special geometry strainers (e.g., the stacked disk strainers) has been accommodated by deducing an effective screen area by applying the correlation to appropriate test data. As such, the debris-specific effective area varied from the total screen area down to a circumscribed area depending upon the loading of debris on the strainer. Once this area curve is determined, it can subsequently be applied to that particular strainer design to estimate plant-specific head losses as a function of the evaluated debris loading, as well as, the other parameters (discussed in Section V.54.3). In this manner, the effects of non-uniform debris accumulation are subsumed into an effective curve that represents a specific strainer design for a specific type of debris based on strainer-specific testing.

Perhaps,The greatest challenge with regards to the application of the NUREG/CR-6224 correlation to the resolution of the PWR sump screen blockage issue is the variety of debris materials available in the fleet of PWR containments. Existing head loss testing has focused on a relatively few of these materials and there is little if any head loss data for several materials. Filling in the gaps will requiresd additional applicable head loss testing to determine the appropriate parameters for these materials where data does not exist. An example is MinK, which is a particulate insulation material similar to calcium silicate, perhaps with even more severe head loss behavior. Head loss data does not currently exist to evaluate thin-bed behavior for Min-K debris.

In summary, the NUREG/CR-6224 correlation applies to one-dimensional single-phase incompressible quasi-steady-state flow through debris beds consisting of fibrous material with or without embedded particulate (no sheet type materials) that has accumulated uniformly and homogenously. An applicable particulate consists of hardened materials (non-deformable particles) that fit embedded among the fibers without significantly impacting the behavior of the fiber matrix. Complete filtration of the particulate from the flow is assumed. Certain applications beyond these conditions are known to predict conservative head losses, which may be satisfactory for safety analyses but may not be realistic (e.g., applying the correlation to a non-uniform debris bed). In certain plant-specific conditions, the correlation may be applied layer-by-layer to a stratified bed using special handling with the primary difficulty being the application to a compressible inner fiber layer where an external force is applied to that layer. Based on supporting analyses, it has been reasoned that voiding in the flow exiting the debris bed is acceptable provided that voiding does not exceed 3%. Other exceptions to the inherent limitations of the correlation must be properly validated to demonstrate that the head loss predictions are suitably conservative (or bounding) to that application, e.g., the application to thin-bed debris beds containing calcium silicate where there is microscopic experimental evidence that calcium silicate particles are not hardened (due to voiding internal to the particles).

V.5.2 NUREG/CR-6224 Correlation Application Limitations Based on Validation

This section describes the establishment of application limits by engineering judgment extensions of specific validations to more general parameter ranges. Section V.5.1 describes the application limitations inherent in the NUREG/CR-6224 correlation due to the constitutive correlations and assumptions used in the development of the NUREG/CR-6224 correlation. Within these inherent limitations, the application of the correlation is necessarily limited to the validation of the correlation against applicable test data to ensure conservative head loss predictions. Parameters ranges associated with current validations are discussed in Section 5.1.4. The NUREG/CR-6224 correlation was developed for a much wider application range than has currently been validated. Therefore, additional validations can legitimately expand the current validation parameter ranges as needed. It is the responsibility of the licensee to provide necessary validation when applying the correlation using parameters beyond the parameter ranges of the current validations.

The parameters that are required to apply the correlation to a particular debris bed scenario include:

1. The water temperature that determines the viscosity and water density,
2. The approach velocity,
3. The area of the sump screen or strainer,
4. The quantities of fiber and particulate debris by debris type,
5. The bulk density for each type of fiber (as-manufactured) and each type of particulate (sludge) debris,
6. The material density for each type of fiber and each type particulate debris,
7. The specific surface area for each type of fiber and each type of particulate debris, and
8. The coefficients for the fiber bed compression function for fibrous debris that controls the bed compression.

The sump screen or strainer area is not an independent variable, i.e., it is used to calculate the flow velocity when the flow rate is specified and to calculate the debris bed thickness from the specified debris quantities. Therefore no application limits are applied to the screen area other than it cannot be zero. Rather, the application limits are applied to the flow velocity and the debris bed thickness. Several of these parameters (i.e., bulk and material densities, specific surface areas, and compression function coefficients) are associated with the particular type of debris. Therefore, the application limits are discussed in relation to debris types and no specific limits are applied to these specific parameters.

<u>Application Limits on Types of debris</u> The most severe limitation to the application of the NUREG/CR-6224 is the limited head loss test data for many of the debris types associated with PWR containment. Some engineering judgment extensions of existing validation are reasonably based on similarities with debris types where substantial testing and validation are available. For example, Transco fibrous insulation is very much like NUKON™, which has been tested and validated extensively with noted parameter application limits. Therefore, it is reasonable to extend the validation for NUKON™ fibrous insulation debris to Transco fibrous insulation debris. These two insulations are so similar that their associated densities and specific surface areas have been treated identically. This same engineering judgment extension cannot be applied

to dissimilar debris such as mineral wool, which is very different than NUKON™. However, a lesser engineering judgment extension may be reasonably applied where the bed thickness for a dissimilar material is extended to 4-inches provided existing head loss data has been validated for this dissimilar material over a reasonable portion of this thickness range. It is specifically noted that the compression function coefficients for the correlation (i.e., α = 1.3 and γ = 0.38) were established for NUKON™ and may therefore not be applicable for another type of fibrous debris. For example, confirmatory research in Section V.1.2 indicated that α of 0.5 is more appropriate for Kaowool than a value of 1.3. The application of the correlation compression function requires the validation of the compression function to types of fibrous debris grouped by similar characteristics over the applicable range of bed thicknesses. This validation optimally would apply the compression function directly to bed thickness data taken at various bed compressions or less optimally, the application of the entire correlation including its constitutive equations to applicable head loss data.

CalSil debris has its own unique behavior during the compression process due to its compressible particulate content. The confirmatory tests performed so far only provides reasonable assurance that the NUREG/CR-6224 can be used as a scoping tool to calculate the pressure drop across a CalSil debris bed. Therefore, the correlation and the applicable application procedures can not be used to design a sump involving CalSil debris. Licensees will have to use other verifiable methods to calculate the pressure drop across a CalSil debris bed.

<u>Application Limits on Water Temperature</u> Head loss testing has been performed in the range of about 60 to 140 ^{o}F but sump pool temperatures in postulated LOCA scenarios may approach the boiling point of water at atmospheric pressure or possibly higher if over-pressure credits are granted. Testing at higher temperatures would require more costly high-temperature equipment than has been typically used in head loss testing and pump cavitation would occur at relatively low head losses. Because the water temperature affects the head loss primarily due to the changing viscosity and density of the water, it has been consider through the years of testing that testing at practical temperatures could be applied to postulated scenario temperatures. It is a engineering judgment extension that the correlation is applicable to a temperature range that allows the water to remain liquid provided one of the following two qualifiers is not encountered. The correlation was specifically developed for single-phase liquid water flow; therefore the correlation cannot be applied if significant vaporization occurs. It was reasoned (Attachment V-1) that an exit void fraction of 3% or less is acceptable for the application of the correlation. The correlation is also not applicable if the higher temperatures cause the debris bed to destruct or deform due to heating of the debris, as opposed to simple pressure-driven compression. Because insulations typical of PWR containment are subjected to operational temperatures for long periods that exceed the sump pool water temperatures, it is reasonable to assume fibrous debris from such insulations can be subjected to sump pool water temperatures without undergoing significant temperature-driven deformation. With the structural properties of the fibrous debris being the primary concern with this qualifier, it is unlikely that the fibers would be significantly deformed due to the water temperature (note that temperature enhancement of potential chemical deformation of the fiber is not addressed here). However, before the high temperature application limit is used, the licensee should access the potential temperature effect for each plant-specific debris type.

Application Limits on Approach Velocity Head loss testing has been typically performed in the 0.1 to 1.5 ft/sec range. Many PWR plants currently have approach velocities less than 0.1 ft/sec and sump screen blockage resolutions will most likely result in many more plant justifying an approach velocity less then 0.1 ft/sec. At these low velocities, the first term in the correlation that is strictly a function of the velocity is expected to be as valid at 0.01 ft/sec as it is at 0.1 ft/sec. Therefore, the NUREG/CR-6224 correlation is expected to be valid at velocities approaching zero if it has been validated at a velocity of 0.1 ft/sec. At the other end of the range, if the correlation is validated at 1.5 ft/sec, it is expected that it is still valid at 2 ft/sec, which is as high as the maximum current plant approach velocities [computed using plant-specific data documented in NUREG/CR-6762]. In conclusion, if the correlation has been validated over a reasonable portion of the velocity range for each particular debris type, then it is considered valid for velocities ranging from 0 to 2 ft/s.

Application Limits on Debris Bed Thickness The thickness of a bed of debris depends upon the quantities of fibrous debris and the area of the sump screen. For thin-bed formations with large quantities of particulate, the bed thickness may be determined by the mass of the particulate, its bulk (sludge) density, and the screen area in combination with the fibrous debris. The thickness of debris beds that have been validated range from approximately 1/8 to 4 inches and these validations focused on NUKON™ insulation debris. For other types of fibrous debris, the testing and validation range has been in some cases substantially less than that of NUKON™. A engineering judgment extension is that if particular fibrous debris has been validated over a reasonable portion of the 1/8 to 4-inch range, then the correlation can be applied to this entire range. The validation of the bed thickness is interrelated to the validation of the compression function coefficients discussed above. The application limit of 4-inches may well increase should subsequent head loss testing with thicker debris beds justify the increase. An exception to the 1/8-inch minimum bed thickness is debris beds containing significant particulate insulation debris (e.g. calcium silicate) where the correlation is applied to debris beds less than 1/8-inch (refer to Section VIII.7).

Application Limits on Head Loss The NUREG/CR-6224 correlation does not have any inherent head loss limits on its application, therefore it head loss application limits depends upon validation against specific head loss data. Typical valid head loss data does not exceed approximately 20 ft-water because debris beds tend to disrupt whenever the head loss become excessive, e.g., bore-holes may form in the bed to relieve pressure. Establishing an upper application limit on the head loss of 20 ft-water is somewhat arbitrary but it does provide a boundary for validations to avoid unnecessary validation efforts since realistic NPSH availabilities at PWR will not allow debris bed head losses exceeding this value. Related to the maximum head loss is whether or not a maximum application limit on the particulate to fiber mass ratio should be established. Valid head loss testing has been performed at ratios up to about 40 and other testing has been performed at even higher ratios where bed disruption occurred due to excessive head losses. The difficulty with establishing some sort of ratio limitation is that the limit is so dependent upon the type of particulate (the ratio would be much lower for calcium silicate than it would be for latent particulates) and would be based on when head losses caused bed disruption. Hence, an application limit on head loss also effectively limits the mass ratio.

The application limits discussed in this section are summarized in Table V-7.

Table V-7. Application Parameter Limits and Ranges

Parameter		Current Correlation Validation Limits	Validation Limits Extensions Based On Engineering Judgment	Extension Qualifiers
Types of Debris	Fiber	NUKON TRANSCO	Similar to Types of Debris with Substantial Validation	Must be either very similar or a significant validation subset is available.
	Particulate	Iron Oxide Corrosion Products		
		Latent Particulate	NUREG/CR-6224 is only good for scoping analysis. Licensees will have to use other verifiable methods to calculate the pressure drop across a CalSil /Latent debris bed.	
		CalSil		
Water Temperature		60 to 140 ^{o}F	32 to 212 ^{o}F	Exit voiding less than 3%. No significant structural deformation to debris bed.
Approach Velocity		0.1 to 1.5 ft/sec	0 to 2 ft/sec	Correlation must be validated over a reasonable portion of this velocity range for each particular debris type.
Fibrous Debris Bed Thickness		1/8 to 4 inches for limited fibrous debris types	1/8 to 4 inches for all type of fibrous debris	Correlation must be validated over a reasonable portion of this bed thickness range for each particular debris type.
Head Loss		0 to ~20 ft-water	No Extensions	

Table V-7 covers the applicable parameter ranges of the correlation. Any extensions beyond its defined ranges require further validations and justifications. If a licensee decides to perform more validation tests, 10CFR50 Appendix B requirements need to be followed.

V.6 References for Appendix V

(LA-UR-04-1227, 2004b) Shaffer, C. J., et al., "GSI-191: Experimental Studies of Loss-of-Coolant-Accident-Generated Debris Accumulation and Head Loss with Emphasis on the Effects of Calcium Silicate Insulation," Los Alamos National Laboratory, LA-UR-04-1227, April 2004.

(LA-UR-04-3970, 2004a) Ding, M., et al., "Characterization of Latent Debris from Pressurized-Water-Reactor Containment Buildings," Los Alamos National Laboratory, LA-UR-04-3970, June 2004.

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

(NUREG/CR-6371, 1996) Shaffer, C., W. Bernahl, J. Brideau, and D. V. Rao, *BLOCKAGE 2.5 Reference Manual*, NUREG/CR-6371, U.S. Nuclear Regulatory Commission, December 1996.