July 21, 2010

Mr. Anthony R. Pietrangelo
Senior Vice President and Chief Nuclear Officer
Nuclear Energy Institute
1776 I Street NW, Suite 400
Washington, DC 20006

Dear Mr. Pietrangelo,

This is in response to the letter dated April 7, 2010, in which the Nuclear Energy Institute (NEI) expressed the view that the methods used for performing analyses and testing to demonstrate adequate performance of pressurized-water reactor (PWR) replacement sump strainers are very conservative and unrealistic. The NEI presented its perspective regarding conservatisms used in many PWR licensees' treatment of Generic Safety Issue 191 (GSI-191) phenomena and qualitatively contrasted those conservatisms with post-accident behavior NEI considers realistic. The NEI stated that the purpose of this discussion was to provide a basis for ongoing discussions with the U.S. Nuclear Regulatory Commission (NRC) management regarding GSI-191 and to assist efforts to reach a conclusion of "reasonable assurance" that sump performance concerns have been adequately addressed for the PWR fleet.

In the April 7, 2010, letter the NEI also requested that leak-before-break (LBB) analysis be considered an acceptable means to close out GSI-191. This aspect of the NEI letter is briefly addressed in a separate letter to you from Eric Leeds, Director, Office of Nuclear Reactor Regulation, and our complete analysis will be in our forthcoming commission paper on GSI-191, due in late August 2010.

The staff remains open to new information that can justify the application of more realistic methods that are consistent with the requirements of Title 10 of the *Code of Federal Regulations* (CFR) 50.46. This regulation requires that licensees demonstrate adequate core cooling through either a bounding analysis with a conservative evaluation model or a realistic analysis that estimates and explicitly accounts for uncertainties. In both cases, the rule requires a determination that there is a high probability that the acceptance criteria are not exceeded. The concept of design-basis accident analysis using prescribed models with known conservatisms that is embodied in 10 CFR 50.46 is intended to demonstrate the existence of acceptable safety margins, even in the face of substantial and largely unquantified uncertainties, such as those which presently exist regarding a number of key aspects of GSI-191. In our view your letter identified conservatisms but did not meet the standards required by the rule. That is, we believe the rule requires us to support our safety decisions with valid models, or appropriate testing, and robust analyses. Our detailed response to your paper is enclosed.

Since the guidance for strainer performance evaluations was issued in 2004, the staff has interacted extensively with licensees, vendors, and industry groups through our efforts to resolve GSI-191. When more realistic analytical methods have been adequately justified either by individual licensees or generically, such as industry efforts to demonstrate reduced insulation erosion and a reduced zone of influence for epoxy coatings, the staff has accepted these methods, and we remain willing to review future approaches in these and other areas. However, the responsibility for demonstrating adequate strainer performance, including adequately justifying the evaluation methods used in this demonstration, ultimately resides with each licensee.

As you are aware, the NRC has implemented a review and decision process that minimizes the potential for requiring an overly conservative demonstration of sump strainer performance. Specifically, the review charter directs the staff to determine whether, given the conservatisms, non-conservatisms, and uncertainties, there is reasonable overall assurance of adequate performance. This process has repeatedly demonstrated an ability to achieve issue closure when a licensee has reduced the number of non-conservatisms and uncertainties to a manageable level. For example, although one plant credited debris settling using a basis the staff does not accept, the staff concluded that numerous significant conservatisms in the plant strainer performance evaluation obviated the need to retest without crediting settlement. There are numerous other examples, and over half the PWR plants have resolved sump performance issues benefiting from this approach. Also, a number of conservatisms mentioned in the NEI letter, while valid, can be reduced through NRC-approved methods. Many plants have already reduced conservatisms using these methods, which are described as analysis refinements in industry and NRC guidance.

Through this approach, the NRC staff has concluded that a majority of PWRs have adequately demonstrated acceptable sump performance, though the related in-vessel effects issue remains unresolved. Many of the remaining plants that have not reached resolution have relatively large amounts of fibrous and particulate insulation in containment. Given the uncertainties and absence of reliable models for some aspects of debris behavior and strainer performance, the staff has not been able to conclude that plants whose evaluation and testing methods are the subject of numerous potentially significant NRC staff questions have shown adequate sump strainer performance. The decisionmaking process becomes highly challenging in cases where numerous questions remain because many of the conservatisms, uncertainties, and non-conservatisms cannot be reliably quantified using current state-of-the-art analyses.

Please do not hesitate to call me at (301) 415-3283 if you have additional questions.

Sincerely,

***/RA/***

William H. Ruland, Director
Division of Safety Systems
Office of Nuclear Reactor Regulation

Enclosure:
As stated

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**STAFF RESPONSE TO NEI PAPER CONCERNING DESIGN BASIS CONSERVATISM AND EXPECTED BEHAVIOR EMPLOYED IN GSI-191 ANALYSES**

In Enclosure 1 to its letter dated April 7, 2010 (ML1010503540), the Nuclear Energy Institute (NEI) presented a paper titled "ECCS [Emergency Core Cooling System] Recirculation Performance Following Postulated LOCA [Loss-of-Coolant Accident] Event, GSI-191 [Generic Safety Issue 191] Expected Behavior." NEI stated that the paper attempts to compare the modeled behavior of ECCS recirculation under design basis assumptions with the behavior that would typically be expected. Sections 2.1 through 2.8 of the paper contain NEI's discussion of the predominant conservatism along with the expected behavior. The summary of the staff's review below first quotes the design basis conservatisms and expected behavior stated by NEI and then provides the U.S. Nuclear Regulatory Commission (NRC) staff response.

It is important to put the NEI and NRC views in appropriate overall perspective. The NRC staff agrees that there are numerous conservatisms in the evaluation and testing of sump performance. Some of those conservatisms are cited in the NEI paper. The NRC encourages, and in many cases has approved, licensees' technically justifiable bases to reduce those conservatisms. However, the NRC staff does not find NEI's list of conservatisms, absent appropriate characterization of the uncertainties and nonconservatisms, a compelling argument that the overall evaluation and testing result is conservative or overly conservative. Balancing conservatisms against nonconservatisms and uncertainties is a very challenging activity. It is also plant-specific because of the wide variance in plant conditions, configurations, and approaches to issue resolution.

GSI-191 is a highly complex issue. There are several basic phenomena that govern strainer performance evaluations. Despite NRC and industry attempts to develop models for these phenomena, reliable models for some of the aspects of sump performance do not exist. Frequently during the course of GSI-191 reviews, what intuitively appears to be conservative was not borne out by testing. A majority of the conservatisms discussed in the NEI paper have been the subject of many past discussions and interactions between the staff, licensees, vendors, the Pressurized Water Reactor (PWR) Owners Group, and NEI. The NEI paper states that the combined impact of multiple bounding calculations is a pessimistic prediction of ECCS recirculation performance that while conservative, provides little insight into the realistically expected performance during a design basis accident. The staff does not agree with NEI's position given the uncertainties associated with the issue. Rather, the path to closure involves a licensee demonstration of an overall conservative evaluation and testing approach. The NRC staff does not require conservatism in each aspect of that approach, as long as the overall result is demonstrably conservative. The staff has implemented a review strategy that accomplishes this objective.

**<u>Section 2.1 - Break Size and Location</u>**

***NEI-Stated Key Design Basis Conservatism***: *For design basis ECCS performance calculations, the limiting break is controlled by a unique combination of break size and location that make it highly improbable*.

***NEI-Stated Expected Behavior**: The likelihood of a large rupture in PWR coolant piping is less than $1x10^{-5}$ per year. Estimates for the frequency of a double-ended rupture of the main coolant piping are on the order of $1x10^{-8}$ per year. Smaller piping ruptures, while still unlikely, provide a better measure of expected behavior.*

**NRC Staff Response**: NEI states that the break selection process is conservative because it searches for the limiting break. The NRC staff's reviews have shown that this may be true for a plant for which one break dominates the evaluation (e.g., due to insulation limited to one primary area of the plant), but the conservatism for a plant that has similar insulation installed throughout the plant would likely be much smaller. Therefore, the staff expects that the break selection process may be conservative for some plants but prototypical for others. The issue is plant-specific. Plants with substantial amounts of fibrous insulation, which tend to be most challenged in the resolution of GSI-191, generally have fibrous debris installed widely in containment, and therefore, would not likely be among the plants that are dominated by a single limiting break.

The NEI paper states that breaks of PWR recirculation cooling system (RCS) piping are low-probability events. The frequencies cited by NEI represent initiating event frequencies and do not address conservatism of the evaluation of the consequences of the event. The staff agrees that design-basis LOCA events are of low probability. However, NRC regulations require that the plants be protected against them. Further, based on observations of the potential impacts of thin debris beds on strainers, the staff believes that the sump performance issue is not confined to the limiting large breaks. An even smaller, and more likely, break could also lead to unacceptable sump clogging. The NEI paper states that the amount of debris generated can vary from 1700 cubic feet ($ft^3$) for a large break to 25 $ft^3$ for a small break. Strainer testing has shown that debris amounts smaller than 25 $ft^3$ can adversely affect the performance of sump strainers at some plants.

**<u>Section 2.2 - Break Characteristics</u>**

***NEI-Stated Key Design Basis Conservatism**: Break opening time is instantaneous.*

***NEI-Stated Expected Behavior**: The assumption of an instantaneous opening of a full double-ended rupture is physically impossible and leads to a significant overestimation of the debris generation potential for a postulated break. Even conservative estimates of a minimum break opening time for large bore piping remain long enough to preclude formation of damaging pressure waves. The wide recognition that a large RCS pipe is more likely to leak and be detected by the plant's leakage monitoring systems long before cracks grow to unstable sizes is referred to as leak-before-break (LBB) and is an accepted part of regulatory compliance with GDC 4 for most, if not all, PWRs.*

**NRC Staff Response**: The NEI paper states that the assumption that a break opens instantaneously brings into consideration the potential formation of a damaging pressure wave. It implies that air-jet testing, which provides the basis for much of the industry and NRC staff debris generation guidance, may have damaged insulation systems (due to shock waves) that would not have otherwise been damaged and that two-phase breaks would not result in similar damage because shock waves are not predicted to occur. The NRC staff agrees that the potential for a pressure wave is greater for single-phase testing (like air-jet testing) than two-phase breaks. However, the staff has not determined that the air-jet testing resulted in significantly more damage than similar tests using two-phase jets. The staff also notes that even air-jet tests were not conducted with instantaneous opening times.

The NRC staff agrees that air-jet testing could result in pressure waves that would not be present in RCS breaks involving subcooled water. However, a potentially damaging pressure wave would still be present for subcooled breaks, and the staff has not found any basis to conclude that testing conducted using air jets, resulted in significantly more damage than similar testing that used two-phase water for the jet.

The NEI paper also discussed the application of LBB to GSI-191 under this item. As stated in our letter from Eric Leeds (ML101900363) in response to NEI's letter dated April 7, 2010, the NRC staff is reevaluating the application of LBB to GSI-191. The staff will provide the results of its review to the Commission for consideration.

**Section 2.3 - Zone of Influence**

***NEI-Stated Key Design Basis Conservatism**: A non-prototypic spherical zone of influence is used to maximize the affected volume surrounding the postulated break. It is stated that this approach maximizes the quantity of material that is calculated to be destroyed by the postulated break because the zone of destruction will generally be focused in a single direction.*

***NEI-Stated Expected Behavior**: While dependent on postulated break characteristics, the zone of destruction around a break will generally be focused in a single direction, significantly limiting the "zone" of materials subjected to break forces.*

**NRC Staff Response:** The NEI statement does not accurately represent the spherical ZOI concept. To determine a spherical ZOI, the volume of a jet, focused in a single direction, is calculated using an approved jet model. The volume is then doubled to represent both sides of a pipe break. The total volume is then set equal to the formula of a sphere, the radius of the sphere is calculated, and this radius is expressed in number of pipe diameters surrounding a pipe break. This method will always result in a spherical ZOI with a radius much smaller than the axial distance of a destruction zone for a jet focused in a single direction. To illustrate, using the currently accepted jet model, a typical PWR jet pressure isobar of 40 pounds per square inch gauge (psig) will extend axially to about 8 pipe diameters (8D) from the break. However, when the jet volume associated with the 40 psig isobar is calculated, doubled, and converted to a spherical equivalent ZOI, the radius of the ZOI is only 4 pipe diameters (4D). This method has been criticized as nonconservative because the actual jet shape, in all possible directions, is not used to get the worst-case zone of destruction. The staff's response to this concern is that the jet is likely to reflect off of and be redirected by targets and obstructions surrounding the break location such that a spherical equivalent is a reasonable simplification that also results in an easier destruction zone analysis for licensees. While the spherical ZOI concept could represent a nonconservatism, the staff concluded that treatment of the ZOI area remains conservative overall, because it is balanced by other ZOI analysis conservatisms, such as not accounting for jet deflection losses and the fact that the accepted jet model very likely overpredicts jet volumes for low jet pressures. However, based on the current state of knowledge regarding LOCA jet behavior, the staff does not consider the currently accepted spherical ZOIs to be excessively conservative.

***NEI-Stated Design Basis Conservatism**: Full destruction of materials within a conservatively determined spherical ZOI based upon a conservative extrapolation of limited test data performed under non-prototypic conditions, with limiting configurations.*

***NEI-Stated Expected Behavior**: The sparse data base on insulation destruction testing has forced the use of bounding results. For example: results based on Aluminum encapsulated insulation is applied to SS encapsulated insulation; all insulation is presumed to have a limited seam orientation relative to the break. The ZOI for insulation materials is expected to be significantly smaller than that predicted by the NRC guidance due to real factors such as the absence of a damaging pressure wave, greater structural integrity than tested materials, non-limiting seam orientations, etc.*

**NRC Staff Response:** The staff disagrees that full destruction of materials is assumed within a ZOI. (See the staff response below under debris characteristics.) In addition, based on the current state of knowledge, the staff does not consider the spherical ZOI concept as excessively conservative as discussed above. The staff agrees that extrapolation was based on limited test data. However, this does not necessarily mean the extrapolation was conservative. The staff also agrees that limiting configurations were used with respect to worst-case jacketing seam orientation for two-phase tests. Two-phase Ontario Power Generation (OPG) tests with the limiting configuration were conservative as compared to boiling water reactor (BWR) air-jet tests that did not have the limiting configuration. The limiting configurations were used to bound the possibility of any plant or plants for which actual orientation of jacketing seams is close to a worst-case seam orientation. The staff is not aware of any information which indicates plant materials are of greater structural integrity than tested materials.

The staff also notes the conservatism in the assumption that the entire jet volume freely expands for ZOI volume calculations, while, in reality, redirections of the jet will result in pressure losses. Any interaction that results in debris generation lessens the jet forces available to create further debris. However, it is not feasible at present to quantify an appropriate reduction factor to account for this effect based on significant state of knowledge limitations regarding jet deflection behavior, as well as the wide variation of impingement angles and geometric obstacles uniquely associated with each potential break location at each plant.

The accepted model for calculating ZOIs contains conservatism when used to calculate jet volumes at very low pressures, because the model becomes unbounded as it approaches ambient pressure. However, the same model also includes non-conservative aspects, because it relies upon a simplified spherical shape and a steady-state model that neglects the true oscillatory nature of supersonic jets. These issues were noted by the Advisory Committee on Reactor Safeguards in 2004 during the review of the SE on NEI 04-07. The NRC staff considered these non-conservative aspects to be bounded by other conservatisms in the ZOI model, such as the potential for energy losses during deflection and the tendency to overpredict the volume enclosed by low-pressure isobars. The NRC staff is currently considering research to develop an improved ZOI approach that more realistically models jet behavior.

**<u>Section 2.4 - Debris Characteristics</u>**

**NEI-Stated Key Design Basis Conservatism:** *The test that generated the highest percentage of fines was used as the basis for the fiber small fines fraction. This size distribution applies* *over the entire ZOI neglecting the reduction in small fines fraction with increasing distance from the break.*

**NEI-Stated Expected Behavior:** *The debris size distribution of insulation debris caused by high energy pipe rupture will consist mostly of large pieces, with a small fraction of small fines due to jet impingement close to the break location. Most large pieces will not transport to the screen, hence the debris loads on the strainer will be significantly smaller than current analyses predict.*

**NRC Staff Response**: The NEI paper states that the guidance in NEI 04-07, "Pressurized Water Reactor Sump Performance: Evaluation Methodology," dated May 28, 2004, regarding the generation of 60% fines is conservative. The staff notes that NEI proposed the baseline debris size distribution fraction of 60% fines and 40% small pieces for Nukon and some other types of fibrous insulation for use in the simplified baseline methodology. The NRC staff found this conservative approach acceptable but, in addition, defined a more realistic method for debris characterization in Appendix II to the safety evaluation (SE) on NEI 04-07, from which the NEI paper reproduces a figure showing debris fragmentation as a function of destruction pressure. Therefore, the approved SE already provides guidance on how licensees can remove this conservatism, and a significant number of plants have already successfully implemented this guidance.

Section 2.2 above contains the staff's response associated with break opening times, but this section will address an additional statement made by NEI concerning break opening time and its effects on debris characteristics. In particular, the NEI document suggests that an overpressure wave that is not representative of realistic break opening times would be a significant contributor to the fragmentation of generated debris. The staff is unaware of an acceptable basis to conclude that hundreds of milliseconds is a realistic break opening time, and it is also not possible to determine, from previous destruction testing, what degree of debris fragmentation was the result of an overpressure wave as opposed to jet impingement.

**Section 2.5 - Debris Transport**

**NEI-Stated Key Design Basis Conservatism:** *All fine debris is assumed to wash down to the sump pool elevation with no holdup on structures.*

**NEI-Stated Expected Behavior:** *Although fine debris would be easily carried by draining spray flow, significant quantity of fines would likely be retained on walls and structures above the containment pool due to incomplete spray coverage and hold up on structures. Even in areas that are directly impacted by sprays, some amount of fines would agglomerate together and likely be left behind.*

**NEI-Stated Key Design Basis Conservatism:** *All fine debris is assumed to transport to the surface of the strainer. Flows that are sufficient to cause any movement of individual pieces of small and large debris are assumed to transport the debris to the strainer.*

**NEI-Stated Expected Behavior:** *Debris present or generated at the beginning of the event will generally be pushed by break and spray flows into quiescent regions and will reside as debris piles. At the start of recirculation, it would take substantially higher flow rate to cause movement* *of these piles of debris. Even if these piles of debris were to move, there are numerous obstacles (supports, equipment, curbs, etc.) that would prevent debris from reaching the strainers.*

**NRC Staff Response:** The transport of fine debris is treated conservatively because fines readily wash down to the containment pool and remain suspended with minimal turbulence. Therefore, very high transport fractions are expected. The staff recognizes that some settling of fine debris would likely occur under plant conditions; however, there is no test or analysis available to permit a more realistic treatment. For small and large pieces, it is conservative to use the incipient tumbling velocity as a transport metric. This conservatism helps to account for uncertainties associated with the modeling of flow and debris transport in the containment pool. The staff also recognizes that some post-LOCA debris would likely agglomerate and would therefore be significantly less likely to transport to the strainers. However, there is no basis to define an expected level of interaction between debris pieces, nor is there a basis for the NEI expectation that debris will generally form agglomerated piles during pool fill or be unable to flow around obstacles.

**NEI-Stated Key Design Basis Conservatism:** *Credit for inactive pools in containment is limited to 15%.*

***NEI-Stated Expected Behavior:*** *In a prototypical plant, most of the debris generated would wash down quickly. Substantially more than 15% of the fine debris would transport to the inactive sump regions where it could not affect sump performance.*

**NRC Staff Response**: Guidance from the 2004 NRC SE includes this stipulation restricting credit for compartments lower than the pool, based on realistic concerns that inactive volumes are typically at the lowest levels of containment and would likely fill prior to significant quantities of debris washing down to the containment pool. The basis for the 15% limit for holdup in inactive containment pools was a detailed calculation performed by the NRC staff for a volunteer plant that was included in Appendix IV to the 2004 NRC SE. The staff's calculation found that the quantity of fine fiber that would be trapped in inactive pools was significantly smaller than the simplified volume-ratio method in the NEI 04-07 baseline guidance would have predicted. Although the staff would consider plant-specific justifications for exceeding the 15% limit, due in part to large uncertainties associated with the chaotic nature of the blowdown, washdown, and pool-fill debris transport modes, licensees have typically not attempted to perform detailed analyses similar to that in Appendix IV to justify exceeding this value.

**NEI-Stated Key Design Basis Conservatism:** *Accepted guidance calls for conservatively high erosion percentages for non-transportable sizes of fiberglass insulation. Accepted values range from 40% to 90% erosion of small fiberglass pieces into individual transportable fibers.*

***NEI-Stated Expected Behavior:*** *Testing shows that fibers do not "erode" from fibrous insulation under the low flow conditions present in PWR containments. Loose fibers on the surface of small pieces will be pulled away if subjected to enough velocity and turbulence. In a prototypical plant, this type of debris would transport along with other types of debris to low velocity areas on the pool floor (similar to a sand bar formation) where little or no loss of individual fibers could occur.*

**NRC Staff Response**: Guidance from the 2004 SE conservatively recommended a high erosion rate based on limited test data, but further recommended that the industry conduct testing to better define debris erosion behavior. Since then, the staff has accepted industry erosion tests as a basis for reducing conservative erosion assumptions for a number of specific materials, including calcium silicate, Nukon, and other types of fibrous insulation. The staff accepts the application of industry erosion testing provided that the test method is acceptable and that a licensee demonstrates that its plant conditions are bounded by the conditions tested.

**NEI-Stated Key Design Basis Conservatism:** *Prescribed guidance calls for uniform debris transport to and deposition on the strainer surfaces.*

**NEI-Stated Expected Behavior:** *Testing shows that debris transport to the surface of complex strainers will not be uniform, unless it is artificially induced in the testing. Some settling and uneven debris distribution is prototypical. This results in significantly lower head loss across the strainers.*

**NRC Staff Response**: The NEI statement does not accurately reflect debris accumulation on strainers. The transport analysis determines how much debris reaches the strainer but does not determine its distribution on the strainer surface. The degree of uniformity of debris accumulation expected for a given plant strainer is determined by testing of one or more prototypical strainer modules. The flow distribution across strainer surfaces typically changes as debris accumulates, and the degree of uniformity of debris accumulation is determined primarily by the specific design of a given strainer module, rather than whether or not a test permits debris settlement. Tests performed with strainer modules designed to encourage non-uniform debris accumulation show a significant degree of non-uniform accumulation of debris, and vice versa for modules designed to encourage uniform debris accumulation. The staff accepts the results of strainer testing provided that the test setup is prototypical or conservative relative to the plant strainer. Strainer testing that credits debris settlement has typically resulted in significantly reduced quantities of debris reaching the strainer, which, in many cases, has presumably reduced the debris-induced head loss. However, the staff has concluded that the debris transport modeling in these tests was generally not representative of plant conditions. Issues identified have included the adequacy of the velocity and turbulence conditions in the test flume, as well as the preparation and addition of test debris. These concerns notwithstanding, the staff has observed, on several occasions, that strainer tests that credited debris settlement have shown that having a small quantity of the finest debris accumulate on the strainer can result in a relatively uniform accumulation with head losses significantly higher than comparable tests performed with a strainer testing protocol intended to ensure full debris transport.

**Section 2.6 - Chemical Effects**

***NEI-Stated Key Design Basis Conservatism:*** *NRC accepted chemical effects modeling (WCAP-16530) relies upon short term release rates (hours) for the determination of long term releases (30 days).*

***NEI-Stated Expected Behavior:*** *Long term release rates of constituent materials are expected to be one to two orders of magnitude lower than predicted by design basis models due to surface passivation and formation of surface films.*

**NRC Staff Response**: The NRC staff agrees that the industry approach may be conservative for many materials. However, aluminum release, which accounted for 75% of the total mass released during the short-term WCAP-16530-NP tests, was developed from multiple data sets including some long-term tests. The WCAP-16530 model does not over-predict the 30-day aluminum release in Integrated Chemical Effects Testing (ICET) 1 and ICET 5. This model under-predicted aluminum release during the first 100 hours of Argonne National Lab (ANL) corrosion tests with aluminum coupons inserted into a vertical head loss test loop. Therefore, while the overall aluminum release rate determined with the WCAP-16530 model is acceptable, the staff disagrees that this model over-predicts aluminum release by one to two orders of magnitude.

***NEI-Stated Key Design Basis Conservatism:*** *100% of chemical species of interest are assumed to precipitate. These precipitates are further assumed to be present at the beginning of the event when flow margins are at a minimum.*

***NEI-Stated Expected Behavior:*** *When solubility limits are taken into account, the predicted precipitation is reduced by 1-2 orders of magnitude. Further, precipitates will form during periods when flow margins are greater.*

**NRC Staff Response**: The WCAP-16530 model assumes that all aluminum precipitates. The NRC staff agrees that this can be quite conservative for aluminum, depending on the post-LOCA pool pH. For plants that maintain pH slightly above 7, only small quantities of aluminum would be expected to remain in solution. Solubility increases with increasing pH. Plants that use trisodium phosphate (TSP) or sodium tetraborate as buffers to control post-LOCA pH typically range from pH 7 (little solubility) to 8 (greater solubility). At pH values greater than 9, more typical of plants using sodium hydroxide to control pH, overprediction of aluminum precipitation increases. For example, the long term analysis of fluid from ICET Test 1 indicated that about one-half the aluminum remained dissolved. It is important to remember, however, that the NRC staff used the conservative assumption on aluminum precipitation to balance uncertainties that remain in other aspects of chemical effect evaluations. These uncertainties (e.g., potential effects from radiation) are discussed in NUREG/CR-6988, "Final Report – Evaluation of Chemical Effects Phenomena in Post-LOCA Coolant."

ANL tests in support of NUREG/CR-6913, "Chemical Effects Head-Loss Research in Support of Generic Safety Issue 191," issued December 2006, indicate that assuming all dissolved calcium precipitates in the presence of a TSP buffer is reasonable. The staff also notes that many plants have been given credit for delayed precipitation of aluminum and therefore do not assume all precipitates are present at the time of recirculation. The staff further notes that head loss testing has shown that a little precipitate can cause high head loss, given the "right" filtering bed, and, therefore, a chemical precipitate load that is 3X or 10X higher does not necessarily equate to an increase of 3X or 10X times in total differential pressure across the test strainer fiber bed. Depending on the debris bed characteristics, this difference may be insignificant. In other words, large overpredictions in precipitate amounts do not always translate into excess conservatism in the measured head loss during integrated strainer testing.

***NEI-Stated Key Design Basis Conservatism:*** *The current models call for chemical precipitate formation in a form readily transported to the sump screen.*

***NEI-Stated Expected Behavior:*** *A significant portion of precipitate formation will occur on the large surface areas in containment and will not be readily transported to the strainer.*

**NRC Staff Response**: The precipitate type, location of precipitate formation, and precipitate transport properties are difficult to predict. While the staff acknowledges that some precipitate may form and not be transported to the strainer, it is not aware of any reliable method to predict where precipitates will form and the transport of precipitates once formed. Therefore, based on NRC staff observations of amorphous, slow-settling precipitate developed during ICET, the staff's position is that the precipitate developed as part of the WCAP-16530 methodology is appropriate for strainer testing. The staff also notes that some licensees have used alternate chemical effects methodologies that do not rely on pre-mixed chemical precipitate.

## 2.7 - Debris Accumulation and Headloss

### Thin Bed Testing

***NEI-Stated Key Design Basis Conservatism:*** *During strainer thin bed testing, the full particulate load is introduced to the test tank/flume first, followed by fiber fines and finally small and large fiber pieces. This debris introduction sequence is non-prototypical and results in the highest strainer head loss.*

***NEI-Stated Expected Behavior:*** *During DBA, particulate debris, fiber fines, and larger fibrous debris are expected to reach the strainer at the same time resulting in lower headloss across the debris bed.*

**NRC Staff Response**: The NEI paper states that the staff guidance for thin bed testing is nonprototypical and conservative, because the debris arrival sequence is biased to promote the formation of a thin bed and to produce the highest strainer head loss. NEI asserts that all types of debris would reach the strainer at the same time and that lower head loss would result when fiber fines and larger fiber pieces accumulate simultaneously with particulate debris. The staff agrees that the order of debris arrival would be more homogeneous, but the finer debris would likely arrive sooner. The staff notes that its 2008 guidance on this subject (ML080230038) includes two allowable debris addition methods. Industry has used the method referenced in the NEI paper because conservatisms in the test protocol allow the staff to conclude that the head loss has been bounded by a smaller number of tests than would be the case for the alternative method. The alternative method would result in a more prototypical debris addition sequence. Some licensees have used this method.

### Treatment of Eroded Fiber

***NEI-Stated Key Design Basis Conservatism:*** *During testing, fiber fines produced by erosion are assumed to arrive at the strainer at time t=0, instead of hours or days later when flow margin is greater.*

***NEI-Stated Expected Behavior:*** *Fiber fines created by erosion will arrive at the strainer over a period of hours or even days. A significant portion of these fines will arrive after flow margin has increased to the point where additional strainer headloss can be readily accommodated.*

**NRC Staff Response**:  The NEI paper states that, during thin bed and thick bed head loss testing, fiber fines eroding from larger pieces is assumed to occur at time t=0, whereas NEI asserts that the erosion will take place over a period of hours or even days.  The staff agrees that there is some time dependence to erosion, but testing has shown that most erosion occurs relatively early in the event.  The staff agrees that the test with erosion products reaching the strainer at the very beginning of the scenario would result in a higher head loss at a time when minimum head loss margin exists for most plants, but it also expects that any conservative effect is likely to be small, because testing has shown that a significant amount of erosion occurs relatively early.  The staff also notes that no licensees or vendors have attempted to perform a time-dependent head loss test (except for chemical debris arrival) and finds the test, as performed now, is acceptable, since the objective of the test is to determine the maximum head loss across the strainer, given a specific plant's inputs.

<u>Treatment of Chemical Precipitates</u>

***NEI-Stated Key Design Basis Conservatism:*** *During testing, a full 30-day chemical precipitate load is assumed to arrive at the strainer at the earliest possible time with no credit for settling or nucleation on containment surfaces.*

***NEI-Stated Expected Behavior:*** *The quantity of precipitate arriving at the strainer surface is expected to be significantly lower than tested amounts.  In addition, the precipitate is expected to arrive gradually and resultant headloss would be compensated by increased headloss margins.*

***NEI-Stated Key Design Basis Conservatism:*** *During testing, all fiber and particulate debris is collected on the strainer prior to addition of chemical precipitates.*

***NEI-Stated Expected Behavior:*** *The chemical precipitate coating on the strainer would be less uniform than that achieved during testing since some fiber and particulate debris would arrive along with the precipitates, producing a less uniform deposit.*

**NRC Staff Response**:  The NEI paper states that chemical precipitates would be gradually generated in the sump pool over time and the head loss contribution from the precipitates arriving later in the sequence will provide increased net positive suction head (NPSH) margin to the ECCS pumps because of sump subcooling and lower ECCS flow rates.  The staff agrees that this could be the case and notes that many plants have credited (and the NRC staff has accepted) delayed arrival of precipitates.

<u>Treatment of Bypassed Debris</u>

***NEI-Stated Key Design Basis Conservatism:*** *All debris predicted to reach the strainer is assumed to contribute to debris bed development; no credit is taken for debris that reaches the strainer but does not contribute to strainer headloss because it passes through the strainer and settles somewhere else in the recirculation flow path.*

***NEI-Stated Expected Behavior:*** *Some debris reaching the strainer will pass through the strainer, collecting elsewhere in the recirculation flow path and therefore would not contribute to strainer headloss.*

**NRC Staff Response**: The NEI paper states that bypassed debris is not treated realistically in sump strainer testing because, once the debris passes through the strainer, a significant portion of it will collect in other areas of the recirculation loop. The staff agrees that this could happen to some extent, but any debris that passes through the strainer is relatively small, and has already shown the potential to transport by the fact it got to the strainer and, therefore, is less likely to settle.

Treatment of Settled Debris

***NEI-Stated Key Design Basis Conservatism:*** *During headloss testing, repeated attempts are made to get debris that has settled in the intermediate vicinity of the strainer back onto the strainer.*

***NEI-Stated Expected Behavior:*** *The conservatism of debris transport calculations is clearly demonstrated in testing where non-prototypic "mixing" must be employed to prevent natural settling of debris. Much of the debris that is predicted to transport to the strainer will settle in the immediate vicinity of the strainer and not become part of the strainer debris bed.*

**NRC Staff Response**: Although consistency with the accepted debris transport guidance leads to a conservative transport evaluation, the use of agitation during head loss testing does not demonstrate that debris transport calculations are overly conservative. Rather, agitation is used to maintain debris in suspension during strainer head loss testing because, lacking agitation, the debris transport conditions in typical test tanks would be much more favorable to settlement than would actual plant conditions. The use of agitation in these tests is a conservative approach that avoids the need to perform challenging scaling and fluid dynamics analyses to validate the similarity of debris transport conditions in the test relative to realistic plant conditions. A small number of licensees that have attempted to perform these complex analyses have been unable to demonstrate that the test conditions were adequately prototypical of the plant. Therefore, although significant debris settlement has been observed in non-agitated tests, the staff has concluded that the test conditions were not prototypical of the plant and does not consider the observed settlement to be representative of transport behavior in the plant. So the staff cannot conclude that minimization of settling in tests is extremely conservative.

Treatment of Reflective Metal Insulation (RMI)

***NEI-stated Key Design Basis Conservatism:*** *During testing, metallic insulation debris is excluded from the tested debris in order to conservatively bound headloss.*

***NEI-Stated Expected Behavior:*** *Some of the smaller metallic insulation debris will transport to the strainer and disrupt formation of a uniform fiber/particulate debris bed. This results in lower strainer headloss.*

***NEI-Stated Key Design Basis Conservatism:*** *Metallic insulation debris that is predicted to enter the sump pool but not reach the strainer is excluded from testing to prevent capture of finer debris before it reaches the strainer.*

***NEI-Stated Expected Behavior:*** *Under DBA conditions any debris that enters the sump pool but does not transport to the strainer would capture some of the fine debris before it reaches the strainer.*

**NRC Staff Response**: The NEI paper states that exclusion of reflective metallic insulation (RMI) from head loss testing is nonprototypical because the RMI would mix with other debris, providing open flow paths through the debris bed and reducing the head loss. In addition, NEI claims that, for strainer testing crediting settlement, RMI, as well as small and large fiber debris predicted not to transport to the strainers, is excluded from the testing to avoid potential capture of any fine particulate and fiber before it reaches the strainer. Based on the incipient tumbling and curb lift velocity thresholds for RMI, it is unlikely RMI could transport and "climb" onto a floor mounted strainer. Therefore, the effects of RMI would likely be limited to a small portion of the lower strainer and would likely not have a significant effect on head loss. Nonprototypical transport of RMI during head loss testing could result in a nonconservative value. Regarding NEI's statement that debris that does not transport to the strainer would capture some of the fines; the staff agrees that it is possible but unquantifiable. In addition, the staff notes that this type of capture is less likely in larger-volume sump pools than under test conditions, where the debris-to-volume ratio is much higher.

<u>Assumed Strainer Flow Rate</u>

***NEI-Stated Key Design Basis Conservatism:*** *Higher-than-expected flow rates are conservatively used during strainer headloss testing.*

***NEI-Stated Expected Behavior:*** *Flow rates will generally be lower than as-tested flow rates and operator actions to further reduce flow would be expected following indications of significant strainer headloss.*

**NRC Staff Response**: The NEI paper states that during strainer testing, the ECCS pumps are assumed to be operating at worst-case maximum flows. NEI states that maximum flow would be lower than the worst case and that operator actions would be taken to secure unneeded pumps upon first indications of increased strainer head loss. The staff expects the licensees to determine the design strainer head loss using design basis flow rates. Some licensees have justified reduced flow rates later in the event. The staff has evaluated these reduced flow rates and approved them where appropriate.

<u>Extrapolation of Measured Head Loss</u>

***NEI-Stated Key Design Basis Conservatism:*** *Measured strainer headloss from testing is extrapolated to the full 30-day mission time.*

***NEI-Stated Expected Behavior:*** *Strainer headloss will reach a peak value and then decrease over time due to natural settling (sloughing) of the debris bed or other changes in debris bed morphology.*

**NRC Staff Response**: The NEI paper states that strainer head losses are extrapolated to the full 30 days from tests run for a period of several hours to several days. NEI claims that head loss through the strainer may actually peak and then diminish with time. The staff agrees that some strainers and associated debris loads have exhibited this behavior. However, the staff also notes that other testing has shown constantly increasing head loss over several days. The staff has allowed plants to use peak measured head loss as design head loss, when plant-specific testing run for extended periods indicated no further increase in head loss over the peak measured value. For such plants, the staff did not require extrapolation. A 30-day test could be run to avoid the need to extrapolate.

## 2.8 - Downstream Effects

### LOCADM

***NEI-Stated Key Design Basis Conservatism:*** *Evaluations for in-vessel responses assume a worst case debris generation scenario where all debris is homogeneously distributed throughout the recirculation phase of the event. All material transported by boiling is assumed to deposit on the fuel. Deposits, once formed are not allowed to be thinned by flow attrition or by dissolution.*

***NEI-Stated Expected Behavior:*** *Only some material will be transported to the core, less will accumulate on the rods themselves; fibrous debris will get caught in a debris bed and the debris will not be homogeneously distributed. Deposits, once formed, will be thinned by flow attrition or by dissolution. The resulting deposit thickness is expected to be much less than what is currently predicted by approved models (LOCADM).*

**NRC Staff Response**: The NEI paper states that there are significant conservatisms in the way debris deposition onto fuel assemblies is calculated, because debris is double counted by assuming that it is captured at the core inlet to block coolant flow, but it is also assumed to enter the core and plate out/deposit on the fuel surface. The paper also says that debris is assumed to be homogeneously distributed in the recirculating fluid, whereas, in NEI's opinion, some of the debris will tend to move to locations not actively involved in the flow path. The staff's response is that the double counting conservatively serves two different phenomena with different effects (i.e., ensure adequate flow gets to the core, and prevent fuel cladding from exceeding the temperature limit, thus becoming brittle). For a cold-leg break, all debris that enters the core will remain in the core. Therefore, it is reasonable to assume that debris suspended in the coolant will deposit when the water boils away. The staff agrees that robust boiling may dislodge some debris from the fuel but quantifying that effect would require relatively complex high-temperature testing.

### Fuel Assembly Testing

***NEI-stated Key Design Basis Conservatism:*** *During fuel assembly testing, uniform flows were used and lacked anticipated complex mixing patterns that would preclude the formation of a uniform debris bed. Debris constituents were introduced in a non-prototypic fashion (i.e., introduction of particulate debris followed by fibrous debris) to promote a higher pressure drop. Additionally, all debris that passes the sump screens is assumed to reach the fuel assembly and is used in the fuel tests, allowing for no settling and no plating on the hot fuel rods despite LOCADM assumptions to the contrary.*

***NEI-Stated Expected Behavior:*** *The probability for the formation of a uniform debris bed is low; a non-uniform bed is more likely and less limiting, as only a few locations without blockages* *in the core are required to allow for coolant flow to remove heat from the fuel. The simultaneous arrival of fiber and particulate will also result in a lower pressure drop.*

**NRC Staff Response**: The NRC staff does not agree that turbulence would cause the distribution of debris across the bottom of the core to be significantly non-uniform, because the flow velocity in the lower plenum during ECCS circulation from the sump is relatively low, and the core support plate would tend to distribute flow evenly across the core inlet. Further, if debris began to build up in one area, the increase in flow resistance in that area would tend to redistribute flow to other areas. The outcome would be a relatively even distribution of debris across the bottom of the core inlet or first spacer grid.

The sequence of debris introduction provides a representative post-LOCA mixture. Considering the difference in filtration efficiency at the sump strainer, the debris-laden coolant passing through the core would typically have an initial concentration of suspended particulate that is significant relative to the quantity of suspended fine fibers. Thus, particulate was added first to the test to create a homogeneous mixture of suspended particulate that would be present when fiber was added. Because particulate is not captured in the fuel assembly without the presence of fiber, this practice is not considered to affect the test results. After particulate, fiber was added in small increments to represent the small quantity of fiber passing through the sump strainer. Chemical precipitate was added last, because it is expected to form in containment after some time, as the containment pool cools.

The staff agrees that fiber and chemical precipitates that enter the core region may deposit on the fuel and, therefore, may not contribute to core blockage. However, fuel assembly testing, using particulate and fiber debris mixtures in near equal proportions, has shown that much of the fiber is captured at the core inlet or first spacer grid and, therefore, cannot be depleted by crediting deposit on the fuel. With regard to chemical precipitate depletion, testing has shown that a small quantity of chemical precipitate, combined with a fibrous debris bed, can cause significant resistance to flow. Therefore, the deposition of precipitates on the fuel will not remove sufficient precipitate from the circulated coolant to prevent core blockage.

<u>Hot-Leg Break Testing</u>

***NEI-Stated Key Design Basis Conservatism:*** *Fuel assembly testing ignored expected debris attrition mechanisms, lack of consideration of filtration, settling, or boiling results in conservatively high pressure drops.*

***NEI-Stated Expected Behavior:*** *The debris-laden water, once passed though the core, will return to the sump. The debris will settle and/or be filtered out before it returns to the RCS. The simultaneous arrival of fiber and particulate will also result in a lower pressure drop. Boiling in the core will provide a more turbulent environment which will end to remove debris from the spacer grids.*

**NRC Staff Response**: The staff agrees that initial testing using debris mixtures of high particulate content with respect to fiber content may have been conservative, because the test did not have provisions for removing, from the test loop, the fiber that exited the fuel assembly. This created a nonprototypical situation where more debris was passed through the fuel than that represented by the acceptance criteria. However, testing using debris mixtures having nearly equal proportions of particulate and fiber has shown that nearly all of the fiber is captured on the first pass at the fuel inlet nozzle or at the spacer grids. The staff does not agree that turbulent boiling in the core will dislodge and remove the debris, because tests have shown that a nearly impervious layer of debris can build at the core inlet with relatively small quantities of fiber present in the circulated fluid. During a LOCA, the degree of boiling in this region would be minimal, because the fuel is inactive in this region, and the entering circulating coolant is expected to be well below the boiling point. Therefore, boiling cannot be relied upon to disrupt the debris bed at the core inlet and does not represent a realistic conservatism.

Cold-Leg Break Testing

***NEI-Stated Key Design Basis Conservatism:*** *Fuel assembly testing was performed with quantities of debris greater than that expected to reach the core.*

***NEI-Stated Expected Behavior:*** *Fuel assembly debris buildup will be considerably lower than seen in the tests with low likelihood of extensive blockages at any one spacer grid. The flow rate to the core will not remain constant – it will decrease which results in a lower pressure drop. Therefore, the pressure drop at the core inlet and spacer grids for a cold-leg break will be considerably less than observed in the tests.*

**NRC Staff Response**: The staff has accepted the argument that the quantity of debris that is expected to be transported to the core inlet will be proportional to the flow entering the core to replenish boiloff. However, the staff is not aware of a basis to show that, once a debris bed is formed, the resistance to flow will diminish as the rate of makeup flow to the core is reduced with time. Further, as the core decay heat diminishes, the core void fraction will decrease, resulting in a decrease in available driving head. Therefore, an equilibrium point will be reached among available head, flow resistance, and boil-off. As a result, a gain in available head caused by the reduction in flow rate with decreased decay heat cannot be credited to demonstrate conservatism.