BWROG Risk-Informed Debris Analysis—Staff Technical Evaluation
May, 2018

Background

On April 10, 2008, the Nuclear Regulatory Commission (NRC) issued a letter to the Boiling Water Reactor Owners Group (BWROG), encouraging it to develop a comprehensive evaluation plan to address potential issues related to emergency core cooling system (ECCS) performance at boiling-water reactors (BWRs) (Agencywide Documents Access and Management System [ADAMS] Accession No. ML080500540). The letter did not initiate a formal regulatory process.

The NRC identified the potential issues in ECCS performance while evaluating similar issues related to the possibility for accident-generated debris to impact ECCS performance for pressurized-water reactors (PWRs). The BWR licensees had previously addressed similar issues in responses to NRC Bulletin (NRCB) 95-02, "Unexpected Clogging of a Residual Heat Removal (RHR) Pump Strainer While Operating in Suppression Pool Cooling Mode," dated October 17, 1995, and NRCB 96-03, "Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling-Water Reactors," dated May 6, 1996. Both bulletins dealt with ensuring that debris generated during a loss-of-coolant accident (LOCA) would not clog ECCS suction strainers. Debris is considered to be any undesirable material that may affect the operation of the ECCS. Usually, most debris considered in ECCS strainer evaluations is generated from insulating materials and coatings within containment. BWRs also have iron oxide, or sludge, that is generated during operation and collects in the suppression pool. All plants also have some amount of latent debris, or debris like dust and dirt, resident in containment. Finally, debris may come from chemical reactions in the post-LOCA environment. These reactions can result in the precipitation of chemical products in the pool that can then be filtered by a debris bed on the strainer. All of these debris types are predicted to transport to (or remain in) the suppression pool and mix with the coolant due to turbulence from flows following a LOCA. ECCS suction strainer clogging caused by LOCA-generated debris could potentially prevent the ECCS from performing its safety function.

BWROG was instrumental in developing guidance for BWRs to evaluate the issue and implement plant changes as necessary to ensure adequate ECCS performance. All BWR licensees evaluated their plants and implemented modifications necessary to ensure performance, based on the BWROG Utility Resolution Guide (URG). The NRC staff concluded that all licensees had sufficiently responded to the requested action of NRCB 95-02 and NRCB 96-03, as documented in a memorandum dated October 18, 2001 (ADAMS Accession No. ML012970229).

In 1996, the NRC initiated Generic Safety Issue-191, "Assessment of Debris Accumulation on PWR Sump Performance," to evaluate the potential for debris to affect PWR ECCS performance following a LOCA. The NRC determined that PWRs could be susceptible to debris effects and ultimately issued Generic Letter 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized-Water Reactors," dated September 13, 2004. Some of the industry guidance, developed by the Nuclear Energy Institute (NEI) for evaluating PWR recirculation issues, was based on the methods and techniques previously used in the BWROG URG. NEI issued its guidance as NEI 04-07, Volume 1, "Pressurized Water Reactor Sump Performance Evaluation Methodology," in December 2004 (ADAMS Accession No. ML050550138). The staff issued a safety evaluation endorsing the NEI guidance with certain exceptions on December 6, 2004 (NEI 04-07, Volume 2, ADAMS Accession No. ML050550156).

While the NRC and industry were evaluating issues associated with the potential for debris to affect PWR ECCS performance, additional knowledge was gained about the behavior of debris and its potential effects on system function. The 2008 letter from the NRC to BWROG program addressed the increase in knowledge in the interactions between debris and ECCS systems and the possibility that the BWR closure was not conservative, based on the most recent state of knowledge.[1]

In its letter, the NRC identified issues that should be addressed to ensure that BWR treatment of each issue resulted in plant safety consistent with PWR treatment. BWROG identified the following 12 areas to be addressed in its evaluation:

(1) downstream effects—components
(2) downstream effects—fuel
(3) head loss correlations
(4) chemical effects
(5) assessment of coatings
(6) latent debris
(7) zone of influence (ZOI) adjustment for air jet testing
(8) ZOI of protective coatings
(9) debris transport and erosion
(10) debris characteristics
(11) near-field effects and scaling
(12) spherical ZOI

These 12 areas are consistent with those found by the NRC staff to be potentially important.

The discussion below addresses individually each of these issues and the approach adopted by BWROG. BWROG agreed to initiate a voluntary program to address the issues identified by the NRC. SECY-99-063, "The Use by Industry of Voluntary Initiatives in the Regulatory Process," dated March 2, 1999, contains additional information regarding the voluntary use of initiatives in the regulatory process.

BWROG used a risk-informed approach to address the identified issues. BWROG used Regulatory Guide (RG) 1.174, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis," Revision 2, issued May 2011 (ADAMS Accession No. ML100910006), to evaluate the identified issues using a risk-informed approach.[2] As stated in RG 1.174, Revision 2, "the principles, process, and approach discussed herein also provide useful guidance for the application of risk information to a broader set of activities than plant-specific changes to a plant's [licensing basis] LB (i.e., generic activities), and licensees are encouraged to use this guidance in that regard." RG 1.174, Revision 2, provides a consistent and logical framework to assess the risk significance of the identified issues.

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[1] "Evaluation of Treatment of Effects of Debris in Coolant on ECCS and CSS Performance in Pressurized Water Reactors and Boiling Water Reactors," issued May 2010 (ADAMS Accession No. ML101400088), comprehensively documents the difference in the treatment of debris effects on ECCS performance between BWRs and PWRs.

[2] The NRC issued RG 1.174, Revision 3 (ADAMS Accession No. ML17317A256), in January 2018, after the completion of the staff's review. The staff notes that the consideration of RG 1.174, Revision 3, does not change the staff's conclusions documented here.

Therefore, although the BWROG evaluation was voluntary and not a license amendment, design change, or compelled by a regulatory requirement, the staff recognized that the use of RG 1.174, Revision 2, provides the appropriate framework and improves consistency in the staff's evaluation because of the importance of the risk analyses to BWROG's evaluation.

BWROG applied the risk-informed approach and the corresponding methodology to the fleetwide issue resolution in the following five phases:

(1) Phase I—Demonstrate the proof-of-principle to determine whether it was feasible to address the issues using a risk-informed methodology.

(2) Phase II—Demonstrate the risk-informed methodology using a pilot plant as an example. A study was performed on 8 of the 12 issues using a pilot plant with a BWR/3 design and a Mark I containment. The four areas not addressed in Phase II were downstream effects—fuel/in-vessel, chemical effects, downstream effects on components, and coatings assessment.

(3) Phase III—Demonstrate the risk-informed methodology on a second pilot plant of different containment and ECCS design and use different insulation types from the Phase II plant. Phase III addressed the same eight areas that were in Phase II, using a pilot plant with a BWR/5 design and a Mark II containment.

(4) Phase IV—Apply the analysis methodology from the earlier phases to the entire U.S. BWR fleet. Phase IV also expanded the evaluation to cover the coatings assessment and the downstream effects on components. This phase included evaluation of operator actions to respond to events where ECCS pumps were assumed to be inoperable because of the effects of debris.

(5) Phase V—Address all of the 12 issues, including the two not considered in Phase IV (chemical effects and downstream effects—fuel/in-vessel) and apply the analysis methodology to the entire U.S. BWR fleet.[3] Phase V modified some of the assumptions used in Phase IV. The Phase V analysis added assumptions for core blockage and evaluated flowpaths for coolant within the core. The Phase V analysis is considered to be inclusive of all issues of concern, and appropriate to calculate the corresponding increase in risk. Phase V was an extension of Phase IV of the program and the Phase V values are considered to be final overall values for plant risk increases caused by LOCA-generated debris, including the effects addressed in Phase IV plus in-vessel and chemical effects. The Phase V approach included additional thermal-hydraulic (TH) analysis using the General Electric-Hitachi (GEH) Transient Reactor Analysis Code (TRACG) code (NEDE-33005P-A, "TRACG Application for Emergency Core Cooling Systems/Loss-of-Coolant Accident Analyses for BWR/2-6," dated February 24, 2017, ADAMS Package Accession No. ML17055A387) to predict the expected short-term response of the fuel under a wide range of LOCA scenarios (i.e., break sizes) and a range of operational conditions (e.g., ECCS pump availability), including the effects of debris inside the reactor vessel. The subsequent discussion focuses on the analyses in Phases IV and V because of the fleetwide application of those evaluations.

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[3] The Phase V evaluation excludes Oyster Creek, which was no longer a BWROG member at the time.

Overview of Methodology

The overall methodology depends on break frequency, strainer failure probability caused by debris, the probability of ECCS equipment failure, and various equipment operating states that could affect the response to a LOCA. In its evaluation, BWROG used the quantitative guidelines of the change in core damage frequency (ΔCDF) and the change in large early release frequency (ΔLERF) from RG 1.174, Revision 2. The BWROG methodology included qualitative evaluations for containment performance to justify the fact that ΔLERF would not be the limiting figure of merit. Therefore, the risk metric used for the evaluation was ΔCDF. The analysis estimated ΔCDF associated with the presence of debris in the system and its interaction with ECCS and the core.

To avoid providing a potentially nonconservative ΔCDF calculation, the reference case was assumed to be a plant that has 100-percent probability that the design requirements prevent ECCS suction strainer blockage (i.e., a "clean" plant). This yields the maximum calculated risk change. The initiating event frequency is the frequency for various LOCA sizes. It is much more likely for small-break LOCAs (SBLOCA) to occur than large breaks while large-break LOCAs are more difficult to mitigate than smaller break LOCAs. BWROG used computer-aided design (CAD) models of the pilot plant containments to identify the locations of breaks leading to LOCAs and to automate the debris generation process. The debris source term, based on the insulation materials installed in each plant, was used as an input to a computer program called Containment Accident Stochastic Analysis (CASA) Grande. CASA Grande used plant-specific inputs for containment type, suppression pool volume, ECCS pump configurations, strainer areas, insulation types, equipment operating states, and other variables to determine how much debris would collect on the operating strainers. When a threshold value for debris bed thickness was reached, the analysis assumed that the pump associated with the strainer failed and would not provide coolant to the core. Using CASA Grande and the CAD models, a large number of breaks ranging from small breaks to double-ended guillotine breaks (DEGBs) were modeled and evaluated. By performing analyses for a range of initiating events and plant operating states, BWROG determined the probability of strainer failure under the corresponding boundary conditions. The strainer failure probabilities were then used as an input to the risk assessment to determine the increase in risk caused by the presence of debris in the coolant and the subsequent failure of the strainers.

Timing is an important factor in the analysis because time to strainer failure determines how much coolant is pumped into the reactor before the ECCS pumps fail because of strainer blockage. The more coolant that enters the reactor before pump failure the greater the likelihood of delaying core damage. More coolant from the ECCS also extends the time for operators to align, if needed, alternate water sources to the ECCS. The methodology also estimated the probability of the success of operator actions taken early enough in an event to mitigate core damage if ECCS pumps are not available or are failed because of debris effects. BWROG used software named Modular Accident Analysis Program (MAAP) to estimate the time available for operator action and defined the probability of success of the operator actions partially as a function of the time available. The detailed TH results performed using the TRACG code were then used to benchmark MAAP models used in the Phase V analysis to increase the confidence in the MAAP results, for the long-term system response, that were used for the refined risk analysis discussed later.

In evaluating the risk of debris on in-vessel effects, the Phase V analysis assumed that the reactor would capture some debris. The assumption was that the fuel filter would capture

5 grams of fiber per fuel assembly. This eliminated some debris from capture by the ECCS strainers, which increased the time to failure for ECCS pumps in some cases.

BWROG used three stages to evaluate risk for all of the plants in the program. In Stage 1, conservative assumptions were applied, and it was possible to conclude that the majority of the plants were low risk. Plants in Region I of RG 1.174, Revision 2, were subjected to a Stage 2 analysis, which included less conservative assumptions, such as reduced transport of fibrous debris for small breaks. As a result, a number of additional plants were determined to be of low risk. After Stage 2, seven plants remained in Region I, and those were examined under the Stage 3 analysis, which included operator credit to align an alternate injection source. At the end of Phase V, Stage 3, all plants were determined to have small or very small risk increases (i.e., Region II or Region III of RG 1.174, Revision 2) caused by debris effects on the ECCS and the core.

The NRC contracted with Southwest Research Institute (SwRI) to assist the staff with the review of the BWROG risk-informed analysis. SwRI performed confirmatory calculations and verification of the BWROG methods and provided additional expertise in the review of the risk-informed evaluation, including the examination of calculational methods used by BWROG. SwRI concluded that BWROG implemented technically defensible analyses to conclude that the incremental risk in all of the BWRs included in the analyses due to the debris related issues was low, and that the issues raised in the staff's April 2008 letter were adequately addressed.

The NRC staff found that, cumulatively, in the areas BWROG evaluated, small risk increases were demonstrated for the plants included in the evaluation. The NRC conclusions do not apply to other plant designs or conditions.

The NRC has not accepted the evaluation in any of the phases, or any part of those evaluations, as a basis for any change to plant designs or licensing bases outside of a formal license amendment request under Title 10 of the *Code of Federal Regulations* (10 CFR) 50.90, "Application for Amendment of License, Construction Permit, or Early Site Permit," which would be subject to a separate review by the NRC.

Several supporting requirements (SRs) in the probabilistic risk assessment (PRA) 2009 standard by the American Society of Mechanical Engineers (ASME)/American Nuclear Society (ANS), as endorsed in RG 1.200, "An Approach for Determining the Technical Adequacy of Probabilistic Risk Assessment Results for Risk-Informed Activities," Revision 2, issued March 2009 (ADAMS Accession No. ML090410014), state that the PRA should model the impact of debris (see SRs AS-B3, SY-B14 and, to a lesser extent, SY-A13, SY-A14, and SY-B8). As mentioned in the BWROG Phase V evaluation report, the probabilistic assessment of suction strainer blockage in BWR PRAs is based on judgment and reliance on the design-basis information. The BWROG Phase V evaluation quantifies such impacts and represents the best available information on the probabilistic treatment of debris-induced suction strainer blockage. Further, according to RG 1.174, Revision 2, risk-informed applications must reflect the as-built, as-operated plant and the effect of past changes to the plant need to be modeled in future applications. Therefore, the staff expects future risk-informed submittal(s) by U.S. BWRs to follow the endorsed PRA Standard and relevant staff guidance or provide adequate technical justification for any deviations.

Technical Evaluation of Issues of Concern

(1) Downstream Effects, Components and Systems

The area of downstream effects on components and systems was evaluated to determine whether debris can adversely affect components that have small clearances or could be subject to wear from debris. BWR licensees did not evaluate this area when they previously evaluated the effects of debris on long-term cooling. Fuel and in-vessel effects are evaluated in a separate area. During Phase III, BWROG performed a risk-informed analysis to determine whether the effects of debris on downstream equipment could result in significant risk to BWRs. This analysis is independent of the larger risk-informed evaluation (Phase V) that addresses most of the other 12 issues. First, BWROG ranked component importance by postulating its failure and determining the risk associated with such a failure. Only components that resulted in significant risk were further evaluated. The following systems were identified as important:

- control rod drive (CRD)
- reactor coolant isolation cooling (RCIC)
- high-pressure coolant injection (HPCI)
- high-pressure core spray (HPCS)
- (low-pressure) core spray (CS)
- RHR
- RHR-service water (RHR-SW) emergency injection
- nuclear boiler instrumentation (NBI)

Of these systems, five (CRD, RCIC, HPCI, HPCS, and RHR-SW) initially draw water from sources other than the suppression pool water so their coolant source was determined to be free of debris. Therefore, BWROG further evaluated the CS, RHR, and NBI systems using deterministic methods to assess whether debris could adversely affect their operation. BWROG evaluated the two pilot plants and determined them to be applicable to the other BWRs in the scope of the program.

The NRC staff found that the evaluation adequately demonstrated that the increase in risk of potential failure of these systems from the effects of LOCA-generated debris was not significant.

(2) Downstream Effects, In-vessel and Fuel

The area of downstream effects—fuel/in-vessel was evaluated to determine whether debris can block coolant flow such that it cannot reach the fuel or that debris is deposited on the fuel to the extent where cooling is significantly affected. BWR licensees did not address this area when they performed their evaluations of the effects of debris on post-LOCA cooling. Initially, BWROG planned to address this area deterministically. Later, it determined that an extension of the risk-informed methodology used in Phase IV might be able to address in-vessel effects. Based on this concept, Phase V of the program was initiated and ultimately used to estimate increases in plant risk, including in-vessel effects.

As part of the analysis, BWROG assumed that the fuel inlet filters become blocked with debris as soon as coolant reaches the fuel inlets during core reflood. BWROG performed TH analyses using TRACG to estimate realistic core temperatures [peak cladding temperatures (PCT)] and determine the ECCS configurations required to provide cooling under various scenarios. The TH analyses were used to determine whether core damage would occur for various conditions. The analyses found that, for some scenarios, the low-pressure coolant injection (LPCI) pumps could provide adequate cooling. This determination depended on the number of pumps available and the size of the break. Notably, the analysis found that a single CS pump could provide adequate core cooling. Based on the TH analyses, the initiating event probabilities, and the equipment response calculated by the CAD models and CASA Grande, BWROG was able to determine the increase in risk caused by core damage from the effects of debris.

The NRC staff noted that the assumption that blockage would not occur at the upper tie plate (UTP) was not justified quantitatively. This assumption leads to the conclusion that CS will pump coolant to the top of the core and provide adequate core cooling. In response to NRC questions about the assumption, BWROG stated that the dynamic circulation in the area of the UTP would prevent debris from depositing in a continuous layer on top of the fuel bundles. Additionally, BWROG calculated the amount of debris that could reach the UTP on a per-fuel-assembly basis and showed that the amount was relatively small for most plants, so that blockage was considered unlikely. The NRC staff's evaluation concluded that the blockage is unlikely but still a possibility. BWROG's risk analysis included a small probability that the UTP might block. BWROG performed a sensitivity study that increased this probability by an order of magnitude and demonstrated that the increase in risk remained small.

The ECCS suction strainer Phase V analysis used information obtained from TH analyses to determine whether certain break sizes and locations can be successfully mitigated when the effects of debris are considered. These analyses were performed using the GEH proprietary version of TRACG. The analyses assumed various combinations of mitigating ECCS subsystem availability. Analyses were performed for ECCS representative of the BWR/3-4 reactor design and the BWR/5-6 reactor design.

The NRC has approved the use of the TRACG code to evaluate ECCS performance in accordance with the requirements contained in 10 CFR 50.46, "Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors." NRC-approved applications use a specific set of modeling assumptions and include a statistical method to determine the uncertainty associated with the analytic methods. BWROG used TRACG in a manner that was generally consistent with the approved methodology, with some noteworthy exceptions:

- The analyses assumed generally nominal conditions, and no attempt was made to quantify the uncertainties associated with the analyses.
- The core spray was modeled using a realistic distribution, rather than the bounding, conservative approach that is delineated in NEDE-33005P-A. The NRC staff accepted this approach for modeling postulated LOCAs in BWR/2s only.
- BWROG modeled the debris by assuming that the debris filter at the bottom of the fuel assembly was blocked.

Analyses were performed by BWROG to demonstrate ECCS capability for a spectrum of break sizes with differing combinations of LPCI subsystem availability. Analyses were also performed with a single CS subsystem available. These analyses were used to establish a cutoff break size for each of the equipment availability assumptions. The cutoff break size was the break size above which it could not be assured that the predicted peak cladding temperature would remain below 2,200 degrees Fahrenheit (F), given the specific ECCS availability analyzed.

Although no attempt was made to quantify and bound uncertainties associated with the results, it should be noted that the nominal TRACG predictions for various ECCS availability combinations indicated that the BWR ECCS could mitigate the consequences of much larger break sizes than were assumed to lead to core damage in CASA Grande. Because of this, the TRACG predictions generally indicate that the CASA Grande modeling applies a somewhat conservative break-size distribution. Although the NRC would not accept a TRACG analysis for use in a specific licensing action unless it produced an upper tolerance limit result that bounds the applicable uncertainties, the BWROG analysis provides a reasonable confirmation of the CASA Grande conservatism. Further, the agency considers the use of mean or best estimate values appropriate in the context of the risk assessment use to support risk-informed decisionmaking in accordance with the guidance in RG 1.200, Revision 2, and RG 1.174, Revision 2.

The assumption that the fuel inlet filters are blocked as soon as coolant reaches the level of the lower tie plate (LTP) (fuel inlet) is conservative. It is likely that a significant mass of coolant would enter the core through the normal fuel inlet flow path before blockage occurs. This would decrease the amount of coolant from other flowpaths that may be required to prevent core damage. The conservative assumption also decreases the time that operators have to align alternate water sources. The assumption of fuel inlet filter blockage is also applied for all break sizes in the risk assessment.

BWROG assumed that the fuel inlet filters would become fully blocked with a small amount of fibrous debris and that the remaining debris that arrived at the core inlet returned to the suppression pool and became available for collection on the pump suction strainers. This is conservative, because it would likely take more debris than assumed to fully block the filters, and the debris would remain trapped at the filters.

Based on the BWROG evaluations, the NRC staff concluded that the effects of debris on fuel would not contribute significantly to increases in risk caused by the failure of long-term cooling for BWRs.

(3) Debris Head Loss Correlations

The debris head loss issue was evaluated to determine whether debris that is generated or transported to ECCS strainers following a LOCA can form a debris bed and increase the resistance of flow to the ECCS pumps such that the function of the pumps could be challenged. Many BWRs used semiempirical correlations when calculating the potential head losses associated with debris on ECCS strainers. During the resolution for PWRs, the NRC staff determined that correlations may not provide accurate predictions of head loss, especially when problematic materials, like calcium silicate or Microtherm, are present in the debris bed.

BWROG initially attempted to address this issue by using more refined correlations and information on the effects of various types of debris on head loss. The NRC staff did not accept the refined head loss predictions because the concerns observed by the staff during the PWR resolution and raised by the staff in the 2008 letter to BWROG remained unaddressed. Therefore, BWROG proposed that a strainer would be assumed to fail (be blocked) when a debris bed of 1/8-inch thickness was calculated to be deposited on the strainer. The debris bed thickness was based on the mass of debris at the strainer, the strainer surface area, and the density of the materials in the debris bed. The density used was the as-manufactured density of the insulating material. The NRC has observed and evaluated the results of many strainer head loss tests that include many types of debris, amounts of debris, and ratios of particulate to fibrous debris. The NRC determined that the use of a 1/8-inch bed threshold was reasonable, and for many materials conservative, based on the results of the head loss tests conducted on BWR and PWR strainers, as documented in NUREG/CR-6244, “Parametric Study of the

Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris," issued October 1995 (ADAMS Accession No. ML083290498).

The NRC noted that, in some cases, in beds without problematic debris but thinner than 1/8 inch, tests resulted in measurable head loss, but the head losses in these tests were less than expected to adversely affect net positive suction head (NPSH) margin. The NRC concluded that debris beds that did not include problematic debris and remained below the acceptance criteria would not likely result in significant head losses, even if chemical precipitates occurred and were deposited on the debris bed. Issue 4 discusses chemical effects.

The NRC was concerned that debris beds that include problematic debris types could result in significant head losses, even if they were below the acceptance limit of 1/8 inch. To address this concern, BWROG conducted a sensitivity study in the Phase V analysis that multiplied the volume of any problematic debris calculated to reach the strainer by a factor of 3. Under the assumptions used for the Phase V analysis, the sensitivity study showed that the strainer failure probability did not increase significantly when the weighting factor was applied. It also showed that larger breaks, especially medium-break LOCAs, were more likely to have a conditional failure. However, such breaks are significantly less likely to occur than smaller breaks, so their overall contribution to the increase risk calculated by the sensitivity study is small.

The NRC staff concluded that the 1/8-inch bed thickness limit was a reasonable criterion for determining strainer failure in the risk-informed analysis. Although there is some uncertainty associated with the limit, it is conservative for most conditions likely to occur throughout the BWR fleet. A sensitivity study on the issue of most concern, head loss caused by problematic debris types, showed a low impact on overall risk.

(4) Chemical Effects

The chemical effects area was evaluated to determine whether materials interacting with the post-LOCA environment can result in the production of chemical species that may collect in a debris bed and increase head loss or collect on the fuel, increasing fuel clad temperatures.

To address chemical effects on strainer head loss, BWROG made a simplifying assumption. It assumed that any time a filtering bed (1/8-inch calculated bed criterion), as described under Issue 3, is present, the strainer fails. The NRC staff has observed testing that has shown that chemical precipitates collected on a strainer in the absence of a fiber bed do not result in significant head loss. The NRC has also observed that debris beds with limited amounts of fiber will not sustain high head losses because the structural stability of the bed becomes compromised by increasing differential pressure. Since bench testing performed by BWROG did not identify any chemical precipitates worse than were observed with the PWR Owners Group testing, and the strainer is assumed to fail when the strainer bed reaches a theoretical thickness able to sustain high head losses, the staff concludes the BWROG chemical precipitates are accounted for on the strainers within the context of this specific evaluation. This staff conclusion is not intended to be applied to other post-LOCA environments or other plant designs.

Similarly, the BWROG assumption that the core inlet is blocked when coolant reaches the LTP negates the need to address the effects of chemical products on head loss at the core inlet.

The NRC staff did not perform a detailed review of BWROG's "Evaluation of LOCA Deposit Thickness and Impact on Cladding Temperature." Therefore, the staff is not able to reach a conclusion related to the BWROG treatment of chemical precipitates on fuel temperatures following a LOCA. However, the NRC staff received a calculation package for LOCA deposit thickness for information and notes the following:

- The suppression pool concentrations of the various chemical species was developed from bench testing that was performed with and without adding sodium pentaborate. For the fuel deposit calculation, the maximum concentration of each element was taken considering all bench testing independent of the sodium pentaborate addition. For example, maximum aluminum occurred during tests with pentaborate while maximum iron and zinc occurred in tests without pentaborate. The deposit thickness was calculated using the maximum 30-day bench test concentrations at time zero. These assumptions provide a bounding chemical source term, assuming all BWR plant material debris quantities are bounded by the scaled bench testing that was based on BWR plant material surveys.

- The limiting LOCA deposit thickness and clad temperatures were calculated for the hottest fuel rods. Limiting axial and radial power multipliers were applied to the calculated decay heat to account for local power peaking before the LOCA. As the boiling moves up the fuel rods over time so does the deposition, resulting in a nonuniform deposit thickness over the height of a given rod.

- The BWR fuel deposit temperature calculation used the same value for chemical deposit thermal conductivity that the NRC staff accepted for the PWR LOCA chemical deposit analysis.

- The calculated total fuel rod deposit thickness and clad temperatures for the hot channel retained significant margin to the acceptance criteria for the entire 30-day calculation.

- The NRC staff did not perform a detailed review of the calculations contained in the evaluation package.

Although the staff could not confirm that the BWROG assumptions were valid in all potential BWR conditions and did not perform a detailed review of the chemical effects calculations contained in the BWROG evaluation, the staff concluded that the overall treatment of chemical effects was reasonable. The staff noted that there are considerable unknowns and uncertainties in the chemical effects evaluations. The staff conclusion is based on (1) the use of the 1/8-inch bed criterion for strainer head loss failure, (2) the assumption that the fuel inlet filters completely block instantaneously upon debris arrival, and (3) the conservatism contained in the fuel deposition and fuel temperature calculations.

(5) Coatings Programmatic Assessments

Coatings were assessed for potential strainer blockage because they can result in a significant amount of particulate debris that may transport to the strainers and into other downstream equipment, including the reactor. The NRC found that BWR licensees may not have adequately identified limiting amounts of coatings that could degrade or be damaged following a LOCA and contribute to the debris source term. This concern was based on the premise that BWRs may not have had programs in place to adequately monitor degradation of coatings within their containments or have adequately tracked changes in unqualified coatings inventories.

To address this issue, BWROG developed a survey to determine whether plants had implemented programs for tracking the identified issues and whether the plant strainer evaluations had included adequate source terms for unqualified coatings. BWROG determined that all plants have programs that track degraded and unqualified coatings. The plants also track degraded conditions and their remediation in corrective action programs. BWROG agreed to notify plants that did not provide a link between the coatings assessment program and tracking the design-basis coating loads to follow up on the issue. The NRC staff noted that, for the evaluation of the BWROG risk-informed analysis, the use of the 1/8-inch bed criterion described above, under debris head loss correlations, and below, under coatings ZOI, negates the need to evaluate the coatings source term when determining strainer head loss.

As for the concern that the plant source terms used in the strainer analysis were too small, the risk-informed evaluation addressed the effects of additional particulate source terms by setting the failure criteria for strainer debris beds based on the theoretical thickness of the bed, regardless of the constituents in the bed. The staff discusses this above, under the debris head loss correlation area.

Based on the information provided by BWROG, and the use of the bed thickness criterion for strainer failure, the NRC staff concluded that the issues associated with unqualified coatings do not contribute significantly to the risk associated with debris effects on long-term cooling for BWRs.

(6) Latent Debris

The issue of latent debris was evaluated to determine how much debris may reside in containment, including dust and dirt, before any LOCA event. Latent debris is added to the accident-generated debris to arrive at the total debris source term used in the strainer analysis.

The latent debris source term comprises fibrous and particulate portions. The NRC staff found that the initial BWR strainer evaluations did not include any fibrous latent debris source term. The NRC staff did not identify any issues with the BWR miscellaneous debris source terms. PWR studies found that a source term of 200 pounds (lb) of latent debris comprising 85-percent particulate and 15-percent fibrous was bounding for most plants. The particulate portion is not important in the BWR risk analysis because of the adoption of the 1/8-inch bed limit. However, the fibrous term from the latent debris can be significant for some plants. The initial BWR analyses included a 150-lb latent source term but considered it to be 100 percent particulate. The NRC staff considered the 150-lb total source term to be adequate for BWRs because of their smaller containment sizes but determined that 15 percent of the total should be assumed to be fibrous.

To evaluate the contribution of latent fibrous debris to plant risk, the BWROG performed sensitivity studies that included latent fibrous debris. In the evaluations, the analyses assumed either 150 lb or double a plant-specific amount determined by individual plant sampling programs. Whether a plant-specific value or the default values were used, it was assumed that 15 percent of the latent debris was fiber (in addition to the fiber amount predicted to be generated by the breaks). The Phase V risk analysis generally showed that the inclusion of fibrous latent debris in the source term did not affect risk significantly under the assumptions of the Phase V analysis. However, for a few plants, risk increased when it was included in the baseline (Stage 1) analysis (the PRA logic model discussion contains additional details of the different stages in the Phase V analysis). BWROG performed refined analyses to show that the affected plants could accommodate the increase in fibrous debris from the latent term. There are few plants affected by the issue caused by the refined analysis as described below.

One of the changes made in the refined analysis was to assume that, for small breaks, only 10 percent of the latent debris washed down into the suppression pool. The NRC determined that this assumption was not justified. The NRC accepts 10-percent washdown for fine debris (including latent debris) if containment sprays do not actuate and the break does not contribute significantly to washdown. For a small break, the break flow would not contribute significantly to washdown. However, BWROG stated that, even for small breaks, the drywell sprays would be initiated, likely between 30 minutes and 3 hours after the break occurs, depending on the location of the break. No analysis was conducted to determine the effects of such delayed washdown, nor was the estimated spray initiation timing confirmed.

To assist in the quantification of risk from the 10-percent washdown assumption for the affected plants, BWROG performed sensitivity analyses that assumed a washdown of 50 percent and 75 percent, with the washdown occurring at the initiation of recirculation. For the sensitivity study that assumed 50-percent washdown, BWROG stated that the change in the result as compared to the 10-percent case was negligible. The 75-percent washdown sensitivity study suggested that four plants could have significantly higher strainer failure probabilities for SBLOCAs. BWROG noted that, for SBLOCAs, the assumptions in the analysis resulted in ignoring the surface area of redundant strainers in the plants, or about half of the strainer area. The assumptions were that the other redundant pumps were secured and not available for mitigation of the LOCA. In reality, it is probable that these pumps would be available and would be started by the operator if the operating pumps did not perform their functions. BWROG also stated that the analysis did not credit high-pressure systems like the HPCI and RCIC. These systems would provide makeup before depressurization of the reactor, and the normal source for these systems is the condensate storage tank, which is not affected by debris. The potential for injection from the condensate and feedwater systems was also neglected.

For the higher risk plants, small LOCA breaks below the top of the active fuel (TAF) dominated the risk. Based on the reduced inventory replenishment requirements and the increased time for operators to take action for SBLOCAs, it becomes much more likely for the operators to successfully align alternate cooling sources to provide long-term cooling. The NRC staff also recognizes that the coolant flow requirements are reduced as time progresses following the event initiation because the heat produced by the fuel is constantly decreasing. Therefore, as would be the case for the SBLOCAs, cooling requirements will be reduced by the time operator action might be necessary.

It is noteworthy that BWROG, while still addressing the 12 issues using deterministic methods, had stated that BWRs would use the default value of 150 lb of latent debris with 15 percent of the latent debris as fiber. BWROG also noted that plant-specific values for latent debris could be used if justified by individual licensees, as stated in a letter to the NRC on February 3, 2015 (ADAMS Accession No. ML15035A551). The NRC accepted this disposition in a letter dated March 25, 2015 (ADAMS Accession No. ML15062A365). However, it has not been documented that any BWR licensee has individually reevaluated its debris source term using the agreed-upon assumptions in a deterministic calculation. Therefore, although the methodology exists for a deterministic resolution to this issue, it has yet to be implemented. The BWR risk-informed analysis did incorporate similar appropriate latent debris assumptions, but the reduced transport assumption was not sufficiently justified.

Although the NRC disagrees with the assumption of 10-percent washdown for SBLOCAs, it recognizes that the analysis had some unquantified conservatisms and included assumptions that result in added conservatism. The staff concluded that, although the assumption of 10-percent washdown of latent debris was not sufficiently justified, the significance of the issue is expected to be mitigated to some extent by conservative assumptions in the analysis. Therefore, the issue of latent debris is considered to be addressed adequately for the purposes of the BWROG risk-informed analysis and does not contribute significantly to BWR plant risk associated with debris effects on long-term cooling.

(7) Zone of Influence

The ZOI area was evaluated to determine the extent of damage that will occur to various materials within volumes surrounding a LOCA break location. Materials that are more robust have smaller ZOIs, while materials that are more fragile have larger ZOIs. Debris amounts generated by a LOCA break are determined by considering the materials in containment, their distance from the break location, and the damage pressure assumed for the material. The damage pressure for each material was determined by placing a sample of the material in a jet at a known distance from the jet nozzle. Based on pressure measurements taken during the tests and jet modeling, pressures were identified for materials at which damage would begin to occur. In addition, many materials were subjected to tests at locations closer to the nozzle to enable the extent of damage to the material at higher pressures to be measured. Pressures closer to the break are higher and result in greater destruction or fragmentation of debris than those further from the break. These tests allow the debris to be characterized into size distributions based on the location of debris with respect to a break.

It was postulated that an air jet (used for material testing) may not have been as destructive as an actual steam jet in a plant. Therefore, the NRC reduced the destruction pressures for some materials for PWRs. The NRC position is that there is not adequate empirical evidence to determine whether air jets or steam jets result in greater degrees of destruction of materials, given that the pressure at the material is equal. However, the NRC has concluded that the destruction pressures used by the BWRs for some materials may have been too high, based on the air jet test results.

To address this issue, the BWROG risk-informed analysis included a 10-percent increase in the ZOI diameter, which results in a 33-percent increase in the ZOI volume. This increases the amount of debris generated for the analysis and provides conservatism above that used in the original plant analyses. This increase in ZOI is also used to address Issue 12 below.

While BWROG was working on dispositioning the 12 issues deterministically, the staff determined that Issue 7 was not a significant issue for almost all materials identified as potential debris sources for BWRs. The NRC staff transmitted its conclusions in a letter dated March 25, 2015 (ADAMS Accession No. ML15062A365) (the same letter referenced above under Issue 6). The NRC based its conclusions on an analysis described in an enclosure (ADAMS Accession No. ML15062A367) to the letter. The NRC evaluation compared several cases to determine ZOIs for various materials. The evaluation determined that the ZOIs used for BWRs were conservative or equivalent to PWR ZOIs for all materials with a destruction pressure of 6 pounds per square inch gauge, or greater. The bottom line of the NRC evaluation of this issue was that the BWR destruction pressures were generally acceptable but that licensees should evaluate potential debris sources for problematic debris types that are outside their calculated spherical ZOI but potentially in a path of a directed jet that could cause damage outside the ZOI. BWROG agreed to include guidance for treating problematic materials and directed jets in their guidance. The staff discusses this further under Issue 12.

Based on the BWROG assumption that increased the destruction zone diameters by 10 percent, and on the deterministic evaluations completed earlier, the NRC staff concluded that the area of ZOI does not contribute significantly to BWR plant risk associated with debris effects on long-term cooling.

(8) Coatings Zone of Influence

The coatings ZOI was evaluated to determine how much coating material may be damaged directly by the LOCA jet and become debris that could contribute to the debris source term. For this area, a destruction pressure was estimated from jet destruction testing of coatings systems, and a ZOI associated with the destruction pressure was assigned. The BWROG guidance originally assigned a generic value of 85 lb. for the break-generated coatings source term. PWRs used ZOIs based on destruction pressure and calculated plant-specific coatings amounts based on the coatings installed within the ZOI.

BWROG, when working toward a deterministic resolution of these issues, calculated equivalent ZOI sizes based on destruction pressures developed from PWR conditions and coatings jet destruction testing. The BWR ZOIs were determined to be somewhat smaller than the PWR ZOIs because the lower temperature and pressure conditions within the BWR reactor coolant system (RCS) result in less energetic jets. BWROG developed proprietary report BWROG-ECCS-TA08-001, “Damage Pressure and Zone of Influence for BWR Coatings,” dated April 19, 2013, to document the calculations. The staff concluded that the ZOI sizes calculated by the BWROG were acceptable but questioned whether coatings that could be generated within the calculated ZOIs were bounded by the assumption of 85 lb used in the initial BWR evaluations. Further work was not performed to quantify the potential amount of coatings that could be generated within the BWR-calculated ZOIs before the deterministic methodology was replaced by the risk-informed analysis.

In the risk-informed analysis, BWROG addressed the amount of coatings that may be available in the source term by assuming that a strainer will fail when a 1/8-inch debris bed builds on the strainer. This methodology was found acceptable, as discussed under Issue 3 related to head loss correlations. Therefore, the NRC staff found that the treatment of coatings within the ZOI did not contribute significantly to increases in BWR plant risk associated with debris effects on long-term cooling.

(9) Debris Transport and Erosion

The debris transport and erosion area was evaluated to determine how much of the debris generated by a LOCA, or present in the containment before a LOCA, reaches the strainer because of various transport mechanisms that occur following the pipe break. The NRC staff questioned whether the amounts of debris that were assumed to transport to the strainers may have been underestimated, based on several assumptions in the initial BWR analyses. The major parameters identified by the NRC to potentially affect transport were debris characterization (debris assumed too large) and inadequate consideration of the erosion of materials in the post-LOCA pool.

To address these issues, BWROG used larger transport fractions and a faster washdown time assumption in sensitivity study S403 in Phase IV of the analysis. S404, a cumulative sensitivity study that included sensitivity studies on other parameters, also considered the increased transport and washdown assumptions. The cumulative sensitivity became the baseline for Phase V and therefore contains the more conservative assumptions that the Phase IV sensitivity studies included. The transport sensitivity assumptions increase the amount of debris transporting to the strainer and decrease the strainer failure timing. Both of these result in increased risk compared to the original assumptions; however, the Phase IV analyses concluded that those increases would be negligible.

(10) Debris Characteristics

The debris characteristics area was evaluated to assess how various debris types and sizes will behave in the post-LOCA environment and how the characteristics affect the debris transport and head loss behavior. The NRC staff was concerned that the initial BWR determination of head loss may not have evaluated the debris characteristics appropriately. Issue 9, debris transport and erosion, discussed the effect of debris characteristics on transport.

During reviews and observations of tests conducted for PWRs, the NRC staff recognized the potential for relatively high head loss caused by relatively small amounts of calcium silicate and other microporous types of insulation. BWROG addressed this issue by using a 1/8-inch bed thickness criterion for strainer failure as described in Issue 3 on head loss correlations. Also, as discussed in Issue 3, the NRC staff was concerned that the 1/8-inch bed criterion did not capture the potential for problematic debris types to result in high head losses from smaller debris amounts. The sensitivity study discussed previously, which multiplied volumes of problematic debris arriving at the strainer by a factor of 3, found little effect on changes in BWR plant risk.

As concluded under Issue 3, the NRC determined that the treatment of debris characteristics does not contribute significantly to BWR plant risk.

(11) Near-Field Effect and Scaling

The area of near-field effects was evaluated to ensure that, during strainer testing, the amount of debris that settles in the test is less than or equal to that predicted to settle in the plant. That is, the test should be designed so that all of the debris that is predicted to arrive at the plant strainer actually deposits on the strainer during testing. Scaling was evaluated to ensure that test conditions account for actual plant conditions. The NRC staff did not identify concerns with scaling other than those that might affect near-field settling of debris. The NRC staff was concerned that BWR strainer testing may not have accounted for near-field settling of debris during tests performed to validate the design of the strainers.

BWROG addressed this issue, as discussed above, by using a predetermined 1/8-inch bed thickness as an acceptance limit for ECCS strainers. Use of the 1/8-inch criterion negates the need to evaluate for debris settlement during testing because justification of the criterion is based on a body of tests, many of which verified that excessive near-field settling did not occur. Therefore, the issue of near-field effect and scaling was determined not to increase the risk of debris effects on long-term cooling at BWRs.

(12) Spherical Zone of Influence

The area of spherical ZOI was evaluated to determine whether there are significant amounts of problematic insulation within a plant's containment but outside the normally considered spherical ZOI for that material. The concern is that these material sources could contribute to head loss if a directed jet damaged a significant amount of the material. The initial BWR methodology did not evaluate for the effects of directed jets on problematic materials. In contrast, PWR licensees performed qualitative analyses to demonstrate that sources of problematic debris outside normally accepted ZOIs were not likely to contribute significantly to debris head loss.

It should be noted that the NRC and BWROG agreed to close this issue deterministically before the risk-informed evaluation began. This agreement is documented in a letter dated March 25, 2015 (ADAMS Accession No. ML15062A365) and was contingent on BWR licensees evaluating whether problematic debris could significantly affect their existing strainer evaluations, as described in a letter dated February 3, 2015 (ADAMS Accession No. ML15035A551). The NRC has not received any indication that this reevaluation was completed, so deterministic resolution of this issue was not achieved. However, the methodology for deterministic resolution of this issue is documented.

This issue was considered to be less significant for most BWRs. The small volume containments meant that most debris sources were included within ZOIs, since the piping is confined to a relatively small volume. For a few BWRs with Mark III containments, the issue could be more significant.

BWROG stated that this issue was addressed by increasing the ZOI diameter by 10 percent (increasing the volume by 33 percent). This sensitivity is also used to evaluate Issue 7 and is discussed there. The staff found the increase in ZOI volume, considering the limited volumes of most BWR containments, a reasonable method to account for debris that might reside outside the spherical ZOI and be damaged by a directed jet.

PRA Logic Model and Development

The PRA logic development was evaluated to determine its technical appropriateness as well as its ability to capture the cause-effect relationship of the issues under consideration.

The risk analyses need to consider all hazards and scenarios that can lead to the generation of debris and the subsequent failure of suction strainers. The staff found that BWROG did not consider all such hazards (e.g., seismic events) and scenarios (e.g., anticipated transients without scram (ATWSs)). As a result, BWROG, as part of the Phase III analyses, qualitatively evaluated the impact of initiating events other than LOCAs in the internal events PRA model on the suction strainer blockage issues. Based on the qualitative evaluation, BWROG concluded that such initiators do not significantly impact the risk. In response to the staff's question, BWROG provided a quantitative argument in conjunction with the risk insights from the Phases II and III PRA analyses to justify not including in the analysis ATWS events in plants with "unpiped" safety valves that discharge into the containment. Further, external event hazards, including seismic and fire events, as well as the risk contribution during plant shutdown, were either quantitatively or qualitatively considered to conclude that neither of those hazards contribute significantly to the calculated risk. The staff's evaluation of this information resulted in its determination that BWROG provided appropriate justification for determining the hazards and initiating events to be considered in the risk analysis for the issues of concern.

Although the risk analyses used the acceptance guidelines in RG 1.174, Revision 2, the staff determined that BWROG inadequately addressed the ΔLERF metric. As a result, BWROG provided qualitative arguments supporting its conclusion that ΔLERF would likely not be limiting as compared to ΔCDF in the Phases III and IV analyses. A primary LERF consideration for BWRs with a Mark I containment design is the steel shell liner melt-through following core melt and reactor pressure vessel (RPV) breach if water is not present on the drywell floor. However, for the LOCA scenarios that represent significant challenges to the effectiveness of ECCS suction strainers during recirculation, the CASA Grande analysis that determines the suction strainer failure probability results show ECCS injection being initially available before suction strainer clogging under the corresponding analysis assumptions. Therefore, a substantial amount of water is expected on the drywell floor from spillover as well as from the initial break flow. The existence of water on the drywell floor significantly reduces the likelihood of early shell failure leading to a large early release.

The different design of the Mark II and Mark III containments, as compared to the Mark I design, means they are less susceptible to large releases caused by core damage scenarios in the risk analysis. The above discussion is applicable to the analysis in all phases, including Phase IV and Phase V. The staff's evaluation concluded that sufficient justification has been provided for ΔLERF likely not being limiting when compared to ΔCDF. The information available in NUREG/CR-6595, "An Approach for Estimating the Frequencies of Various Containment Failure Modes and Bypass Events," issued October 2004 (ADAMS Accession No. ML043240040), and the NRC's significance determination process guidance from Inspection Manual Chapter 0609, Appendix H, "Containment Integrity Significance Determination Process," dated May 6, 2004, support the staff's conclusion. To avoid providing a potentially nonconservative ΔCDF calculation, the reference case was assumed to be a plant that has 100-percent probability that the design requirements prevent ECCS suction strainer blockage (i.e., a "clean" plant). This yields the maximum calculated risk change.

The Phase II and Phase III analyses used the pilot-plant-specific PRA models to quantify the impact of strainer failure under the assumptions used for those analyses. The Phase II and Phase III analyses found that the ΔCDF from post-LOCA debris impacts was dominated by scenarios involving loss of RPV makeup with the RPV at low pressure. The dominant scenarios involved cutsets that included the LOCA initiating event, failure of ECCS suction strainers under the corresponding analyses assumptions, and failure of alternate injection for long-term RPV makeup. Other scenarios (e.g., loss of decay heat removal) were found to have a negligible contribution to the ΔCDF associated with post-LOCA debris impacts. Based on the risk insights from the Phase II and Phase III results, the accident sequence analyses for Phase V focused on loss of RPV makeup scenarios.

BWROG performed the risk evaluation in a staged manner for the Phase IV and V analyses. The Phase V analysis approach is discussed further, because the staff's final determination of the risk evaluation approach is based on that analysis. BWROG used the staged approach to incrementally add further refinement to the analysis in each subsequent stage, depending on the determination in the preceding stage. The determination for additional refinement was based on meeting the Region II or III acceptance guidelines in RG 1.174, Revision 2. If a plant did not meet those acceptance guidelines in a particular stage, further stages of refinement were used. The staged risk evaluation approach can be summarized as follows:

- Stage 1: Used the following assumptions for ECCS suction strainer and LTP failure:
  - evaluated ECCS suction strainer failure probability based on 100-percent filtration (i.e., no debris bypass)
  - assumed that ECCS suction strainer failure leads directly to core damage

   - assumed guaranteed debris filter clogging failure at the LTP

   - assumed no credit for LPCI, given potential uncertainty for success with early LTP failure

   - assumed minor probability for potential debris clogging of UTP

   - did not credit operator action to align alternate injection

- Stage 2: Used the following assumptions for ECCS suction strainer and LTP failure for plants remaining in Region I of RG 1.174, Revision 2, after the Stage 1 PRA analysis:

   - applied the minimum ECCS suction strainer penetration function

   - applied 10-percent latent debris transport fraction for small LOCAs (note that the staff's evaluation of this assumption is provided in the latent debris section of this document)

   - assumed sequential strainer failure with the risk being controlled by the last core spray strainer to form the threshold bed (i.e., 1/8-inch fibrous debris bed).

   - modeled the in-vessel debris impacts in the same way and under the same assumptions as for Stage 1 (as listed from bullet 3 onwards in the Stage 1 assumptions above)

   - assumed that a certain amount (5 grams) of debris is sequestered at the debris filter of each fuel assembly (note that this assumption does not affect the in-vessel debris modeling in the risk analysis but does affect the debris inventory being tracked by CASA Grande and, therefore, the probability of ECCS suction strainer failure)

- Stage 3: Used the same assumptions for ECCS suction strainer and LTP failure for plants remaining in Region I of RG 1.174, Revision 2, after the Stage 2 PRA analysis with the following exceptions:

   - For the sequences where the ECCS suction strainer did not fail but CS did, LPCI was credited, based on the LOCA size as supported by the TRACG analyses.

   - Operator action was credited to align one alternate injection path. The human error probability (HEP) for the operator action was based on accident sequence timing from MAAP analyses. The exception to this assumption was that no operator action was credited for large water LOCAs (i.e., large LOCAs in locations that are below the TAF).

Each stage used the debris source term from the cumulative sensitivity, which included sensitivity studies for different parameters, as discussed in this document. Further, in each stage for the sequences where the ECCS suction strainer did not fail, two CS systems were credited for mitigation and their probabilistic failures (e.g., fail to start, fail to run, system in maintenance) were modeled.

Of the 27 plants evaluated, 16 were calculated to be in Region II or III of RG 1.174, Revision 2, in the Stage 1 PRA analysis and 11 plants remained in Region I. Of the 11 plants remaining in Region I after the Stage 1 analysis, 4 were calculated to move to Region II after the Stage 2 analysis and 7 plants remained in Region I for further evaluation in the Stage 3 PRA analysis. All seven plants remaining in Region I after the Stage 2 PRA analysis were calculated to move to Region II after the Stage 3 analysis.

In the Stage 1 analysis, the first strainer to reach the threshold bed (i.e., 1/8-inch fibrous debris bed) was considered to be representative of the failure of all strainers. As listed above, for the evaluation in Stages 2 and 3, BWROG relaxed that assumption and considered the sequential strainer failure with the risk being controlled by the last CS strainer to form the threshold bed. Both the RHR and CS pumps are assumed to lose NPSH and fail with zero flow at the moment of accumulation of the threshold bed on the bounding strainer (for Stage 1) or on the respective suction strainer (for Stages 2 and 3). In response to the staff's questions, BWROG also determined that, given the similarities in the CS strainers, CASA Grande predicts the failures of the first and last CS strainer to occur at the same time with the same probability.

The Phase V risk evaluation selects a single representative operator action for aligning long term, alternate external RPV injection for each plant. BWROG used information from a survey of its members, which included details of the human reliability analysis (HRA), based on the existing HRA documentation from the member plant-specific PRA model. For example, the HRA documentation provided operator action timelines associated with aligning alternate external injection to the RPV in response to the loss of RPV makeup scenarios. Based on the survey information, a single representative operator action for aligning long-term, alternate external RPV injection was selected for each plant, based on key factors such as time required for alignment ("relatively short," or less than 30 minutes), injection capacity, and suction source (high-volume source). The characteristics of the selected representative operator action (e.g., time to align, execution failure probability) were then incorporated into the Phase V HRA methodology to determine the corresponding HEPs. The HEP development considered qualitative attributes of cue identification, procedure availability, and training. In addition, the timing window for execution was determined using the time to failure as predicted by CASA Grande, as well as the time to core damage predicted by representative MAAP cases as discussed below. It should be noted that the BWROG Phase IV and V analyses did not credit any operator action(s) to align flexible and diverse coping strategies (FLEX) equipment. The guidance regarding HRA methods for FLEX actions and its acceptance by the NRC is evolving. In addition, BWROG indicated that the time required to align FLEX equipment (e.g., 2 or more hours) is generally much longer than the time to align existing installed alternate injection systems. Therefore, the staff concludes that not crediting FLEX equipment for mitigation in the Phase V risk analysis is appropriate.

BWROG performed MAAP simulations to determine the success criteria as well as the time available for operator action to support the HRA under the assumptions of the Phase IV and V analyses. Further, as noted above, all the stages of the risk analysis performed in the Phase V evaluation assumed guaranteed debris filter clogging failure at the LTP. That assumption resulted in an increase in the necessary flow requirements to support successful alternate external injection by refilling the bypass region. For example, the flow from the CRD mechanisms was found to be effective in delaying core damage and, therefore, increasing the time available for operator action in the Phase IV evaluation. However, when blockage of the fuel inlet was considered in the Phase V analysis, CRD flow was unimportant. Similar unique considerations resulted in BWROG making Phase V-specific MAAP calculations for various large, medium, and small LOCA events, assuming 100-percent reactor power for the seven plants that were included in the Stage 3 analysis. MAAP models for two of the seven plants were used as surrogates to perform the calculations with adjustments made to reflect each of the seven plants' core power, core flow area, and bypass flow area.

The onset of core damage in the MAAP calculations was defined as a peak core nodal temperature greater than 1,800 degrees F for more than 10 minutes in conjunction with the water level being below one-third core height and falling. The 10-minute duration criterion was chosen to address very short-term temperature spikes. The staff's evaluation concludes that the definition of core damage used by BWROG for the MAAP calculations in support of the Phase V analysis is consistent with typical industry practice and industry PRA models. Further, in response to the staff's question, BWROG confirmed that the 10-minute duration criterion is not invoked for the MAAP calculations supporting the Phase V analysis. The staff also noted that containment venting was not explicitly modeled in any of the MAAP calculations. The containment venting function would not be adversely impacted by LOCA-generated debris in the suppression pool and is expected to remain available to control containment pressure, if required.

In Services Information Letter (SIL)-636, dated May 24, 2001, General Electric indicated that its use of the American National Standards Institute/American Nuclear Society standard ANSI/ANS-5.1-1979, "Decay Heat Power in Light Water Reactors," may not include the impact of additional actinide and activation products. This could represent a potential nonconservatism in the calculated decay heat determined from the MAAP calculations, because MAAP uses the 1979 decay heat standard. The staff requested details about the impact of SIL-636 on calculations performed to support the BWROG risk-informed analysis, including the Phase V analysis. In response, BWROG stated that it judged the uncertainties associated with MAAP decay heat evaluations to have no significant impact on the BWROG risk-informed analysis and that industry evaluations have found that the impacts of SIL-636 on PRA success criteria and HRA have a small-to-negligible overall quantitative impact on the risk analysis. BWROG also provided the results of an evaluation of the risk impact of SIL-636 for a PWR site and noted that the risk insights from it are judged to be generally applicable to both PWRs and BWRs, as well as to the BWROG analysis. The risk impact evaluation concluded that long-term time to boil calculations for refuel outages could be impacted by SIL-636, but the time to core damage and time to reach ultimate containment failure pressure would be minimally impacted. However, to address some of the uncertainty associated with the issue raised in SIL-636, BWROG reduced the total time to core damage as determined by MAAP calculations by 5 minutes. The staff's evaluation of the BWROG response concluded that the impact of SIL-636 is primarily on the long-term decay heat prediction and that BWROG has adequately incorporated the impact of the uncertainty in the decay heat caused by SIL-636 in the Phase V risk analysis by applying a penalty to the time of core damage.

The risk analyses in each stage also consider configurations in which one or more ECCS pumps are unavailable. For such cases, the strainer failure probability is determined using CASA Grande and provided as input to the risk calculation. Further, the risk calculations assume that configurations with four or more pumps unavailable lead directly to core damage. The calculated ΔCDF that is compared against the RG 1.174, Revision 2, acceptance guidelines includes the risk contribution from all evaluated ECCS pump unavailabilities.

As noted earlier, the risk insights and dominant sequences from the Phase II and III analyses found that the ΔCDF from post-LOCA debris impacts was dominated by scenarios involving loss of RPV makeup with the RPV at low pressure. Based on those insights, BWROG constructed "streamlined" event trees for the sequential risk analysis performed in Stages 1 through 3 of the

Phase V evaluation. The Phase V report provided to the staff contained these "streamlined" event trees, along with a description of each "top event" in the event tree. The Phase V report also included the functional fault trees that provide the logic input to the "streamlined" event trees. The LPCI success criteria applied in the risk analysis were generally more conservative when compared to the TRACG results. This level of conservatism for the LPCI success criteria in the PRA model could be afforded with respect to the in-vessel risk impacts because the TRACG results, given the more realistic models and assumptions used relative to the NRC-approved ECCS evaluation model, showed that the availability of CS alone could mitigate the entire range of LOCA sizes, thus significantly reducing the risk significance of LPCI. The staff evaluates the TRACG results supporting the Phase V risk analysis in the downstream effect, in-vessel and fuel section of this document.

BWROG vetted plant-specific PRA input used in the evaluations to ensure that the technical adequacy and quality is commensurate with the risk-informed decision process. BWROG vetted selected plant-specific data from individual site full power internal events (FPIE) PRA models (e.g., HRA information for operator alignment of alternate injection) that was used in the analysis to ensure that its pedigree was consistent with the ASME/ANS PRA standard as confirmed by corresponding peer reviews. Detailed PRA models were used for a more refined risk evaluation for selected plants. BWROG ensured that the PRA models used for the refined evaluations have been peer reviewed in accordance with the guidance in RG 1.200, Revision 2. In addition, for each of the detailed PRA models, BWROG confirmed that there were no open FPIE peer-reviewed facts and observations that would impact its evaluation.

The staff's evaluation of the "streamlined" event trees and fault trees was informed by its review of the Phase II and III reports, as well as the dominant hazards and sequences. The staff's evaluation concluded that the logic model, including the event trees and fault trees, captured the progression of the event and the system response adequately to determine their risk impact under the assumptions of the Phase V evaluation. Further, the staff evaluated the dominant cutsets for the plants that were part of the Stage 3 analysis and concluded that they were logically coherent.

The Phase V risk analysis assumed that the fuel was always blocked at the elevation of the LTP (i.e., a probability of 1.0). The failure probability for the UTP and the bypass holes in the fuel assemblies were assigned based on expert opinion. Based on the dimensions of the UTP openings relative to the assumed debris size and amounts, BWROG judged the probability for UTP clogging to be negligible based on expert opinion. The staff evaluates BWROG's judgment of UTP blockage, along with the outcome of a sensitivity study to determine the amount of debris available for deposition on the UTP in the downstream effects, in-vessel and fuel section of this report. Given the dimensions of the bypass openings between the lower plenum and the bypass region relative to the assumed debris size, BWROG judged the probability for their clogging to have a negligible probability.

The staff indicated that sensitivity analyses would be beneficial to determine the risk impact of the expert-judgement-based failure probabilities for the UTP and bypass holes. BWROG performed such sensitivity analyses. The first sensitivity was similar to the Stage 1 approach but with an increase in the probability for clogging the UTP by an order of magnitude. The sensitivity resulted in some of the plants moving from Region III to Region II and one plant that was in Region II slightly exceeding the Region I threshold. BWROG stated that, if a Stage 2 evaluation were performed for the plant that was in Region I because of the sensitivity, minor credit for operator action would cause the plant to fall under Region II.

Principles of Risk-Informed Decisionmaking

Since the evaluation was within the framework of RG 1.174, Revision 2, BWROG addressed all five principles of risk-informed decisionmaking from that guidance. The staff used the information presented for each of the five principles in RG 1.174, Revision 2, in its evaluation.

The 2008 letter from the NRC to BWROG did not constitute a formal regulatory action. Therefore, the currently installed ECCS suction strainers were and are currently considered to meet applicable NRC regulations.

The BWROG evaluation recognized that it is prudent to have additional mitigation capabilities to supplement the primary mitigating systems, which can be challenged because of the issues under consideration, and thereby maintain adequate defense-in-depth. The BWROG evaluation report summarizes various defense-in-depth measures that are implemented or are under consideration in the unlikely event that ECCS suction strainers become blocked during an accident response. BWROG also evaluated the effectiveness and viability of those defense-in-depth measures. In addition, certain conservative assumptions used in the analysis, such as the exclusion of high-pressure injection systems, which are unaffected by strainer blockage, and restrictive success criteria in the PRA, as compared to the TH analysis, result in additional defense in depth. The BWROG evaluation meets the seven examples of adequate defense-in-depth provided in RG 1.174, Revision 2. The variety and the feasibility of the defense-in-depth measures considered as part of this evaluation provide reasonable assurance that options to ensure long-term core coolability remain available, even if suction strainers become blocked by debris.

RG 1.174, Revision 2, states that safety margins are maintained when codes and standards or their alternatives approved for use by the NRC are met and when the safety analysis acceptance criteria in the licensing basis (e.g., updated final safety analysis report, supporting analyses) are met, or proposed revisions provide sufficient margin to account for analysis and data uncertainty. The BWROG evaluation does not change or include any changes to codes and standards or their alternatives approved for use by the NRC for any BWROG member. Further, any programs and processes that ensure that the codes and standards are being met remain unaltered. The BWROG evaluation methodology includes conservatisms, as summarized in the conclusion section of this report, which are expected to preserve safety margins.

In its evaluation, BWROG used the RG 1.174, Revision 2, criteria for ΔCDF as acceptance guidelines. All plants included in the evaluation were demonstrated to be in Region II or Region III of RG 1.174, Revision 2, based on the ΔCDF from the ECCS suction strainer clogging by debris. Further, based on an industry survey, BWROG determined that the plants that were in Region II of RG 1.174, Revision 2, acceptance guidelines had a total (all hazards; at power) CDF below the 10^{-4} per reactor year guideline in RG 1.174, Revision 2.

Based on the evaluation and its assumptions, BWROG anticipates existing monitoring programs will be sufficient to maintain plant conditions within the bounds of the analysis. Examples of existing monitoring programs cited by BWROG include (1) coatings maintenance and degradation monitoring, (2) plant cleanliness procedures for suppression pool sludge and drywell latent debris, (3) containment configuration control of foreign material, problematic insulation, and exposed metal corrosion sources, (4) emergency operating procedures change control, (5) operator training standards for accident response time and operational readiness, and (6) technical specifications for pH control.

The staff's evaluation concludes that BWROG adequately addressed each of the five principles of risk-informed decisionmaking in RG 1.174, Revision 2, even though the Phase IV and V analyses neither constitute nor should be considered license amendment requests.

Based on the results of the evaluation, BWROG identified certain risk insights that can be useful for continued safe operation of its member plants. Examples of such insights are that the CS system provides diversity for core cooling in the event of debris accumulation at the fuel inlet filter and that the majority of the risk from suction strainer blockage caused by debris is from scenarios involving a loss of sufficient RPV inventory makeup caused by failure of operators to align alternate external injection.

Conclusions

The NRC staff concluded that the BWROG risk-informed evaluation shows that the differences in treatment of the evaluation of debris effects on long-term cooling between BWRs and PWRs does not have a significant effect on risk for the BWRs included in the study. Based on these conclusions, there are no regulatory actions required.

BWROG used NRC staff guidance for risk-informed licensing applications (RG 1.174, Revision 2) in performing the evaluation. As stated in RG 1.174, Revision 2, "the principles, process, and approach discussed herein also provide useful guidance for the application of risk information to a broader set of activities than plant-specific changes to a plant's [licensing basis] LB (i.e., generic activities), and licensees are encouraged to use this guidance in that regard." RG 1.174, Revision 2, provides a consistent and logical framework to assess the risk significance of the identified issues.

BWROG stated that none of the specific numerical results from the Phase IV or Phase V reports should be used in any future applications for any individual plant. The NRC staff position, as articulated in RG 1.200, Revision 2, is that the PRA results used to support a risk-informed application must be derived from a baseline PRA model that represents the as-built, as-operated plant. Several SRs in the 2009 ASME/ANS PRA standard, as endorsed in RG 1.200, Revision 2, state that the PRA should model the impact of debris (see SRs AS-B3, SY-B14 and, to a lesser extent, SY-A13, SY-A14, and SY-B8). The BWROG Phase V evaluation report stated that, while most BWRs already have a probabilistic assessment of suction strainer blockage in their PRAs, these probabilities are generally based on judgment and reliance on the design basis to provide adequate protection. The BWROG Phase V evaluation quantifies such impacts and represents the best available information on the probabilistic treatment of debris-induced suction strainer blockage. Further, according to RG 1.174, Revision 2, risk-informed applications must reflect the as-built, as-operated plant, and future applications need to model the effect of past changes to the plant.

The use of a generic and "conservative" approach, as opposed to a plant-specific or more "refined" approach, was a conscious choice made during the analysis. Such a choice does not override established regulatory guidance or provide a basis for a deviation from such guidance. Based on the cited regulatory guidance, the staff expects future risk-informed submittal(s) by U.S. BWRs to follow the endorsed PRA standard and relevant staff guidance or provide adequate technical justification for any deviations.

Because the study was a fleetwide evaluation and because of the methodology used, the study is not truly plant specific. Not all of the uncertainties, conservatisms, models, or assumptions used in the evaluation apply equally to all plants in the fleet. Therefore, the results of the analyses in any of the phases, or any part of those analyses, may not be used for plant-specific justification of equipment operability, design-basis changes, or licensing changes outside of a formal license amendment request under 10 CFR 50.90, subject to a separate review by the NRC.

The NRC staff conclusions presented here do not apply to other plant designs or conditions.

The staff identified uncertainties and conservatisms used in the risk-informed methodology. Significant issues not discussed in a specific area above are described here.

The NRC staff was concerned that significant uncertainty could be introduced by mapping debris from plants onto the pilot plant geometries for determination of debris generation amounts. The NRC staff asked BWROG to provide a basis for the determination that the results for the nonpilot plants would be adequately representative of plant-specific evaluations. BWROG stated that the large number of weld locations modeled resulted in a diversity of ZOI sizes and locations so that adequate sampling of debris generation scenarios was performed for every plant. The NRC staff considered the BWROG response and determined that, by modeling breaks at all reactor coolant system welds in the pilot plants, it is reasonable to conclude that all potential debris sources within containment would be challenged and sampled. The staff also considered that the 1/8-inch bed criterion is conservative under most conditions, making accuracy of the debris generation amounts less critical.

During the review of the BWROG risk-informed evaluation, the NRC staff noted that the debris source terms, especially those provided to the NRC that were used to estimate the effects of chemical interactions following a LOCA, appeared to be inaccurate for some plants. Although the NRC considered that the evaluations were performed on a voluntary basis, it was apparent that some of the plant information was incomplete or that some plants did not understand what information BWROG requested. Although some of the information provided to BWROG in support of the analyses was incomplete or inaccurate, the calculations were of a bounding nature. It is likely that the plants that provided more accurate data provide a representative cross section of the source terms in BWR containments. The source term information and resulting calculations cannot be considered bounding.

BWROG has included conservatism in the analysis. Some of the conservative aspects of the evaluation are listed here, if not discussed above:

- The BWROG did not credit any settling of debris in the suppression pool. It is likely that at least some debris would settle and not transport to the strainers. The use of a 1/8-inch bed is an acceptable simplification to eliminate the need to use correlations to calculate head loss. In most cases, the NRC considers the 1/8-inch criterion to be conservative.

- The evaluations did not credit the HPCI and RCIC systems. For the smaller, more likely breaks, these systems would provide some coolant inventory to the RCS from a clean source such as the condensate storage tank. The HPCS was credited only when necessary to refine risk results. The HPCS provides injection directly to the top of the core from a clean water source. The high-pressure systems available at each plant are based on a plant-specific design, and, therefore, not all of these systems are installed in every plant. No credit was taken for makeup from condensate or feedwater, which can be available, at least for an appreciable duration, and can especially help mitigate the smaller, more likely, breaks. Credit for makeup from the CRD system was also limited.

- Redundant pumps were secured and not available to mitigate LOCAs, especially SBLOCAs, whereas it is probable that these pumps would be available and would be started by the operator if the operating pumps did not perform their functions.

- The risk evaluation also took only limited credit for operator action to mitigate strainer blockage issues by assuming that only a single alternate injection source can be used. The time available for operator action (for example, delayed washdown fibrous debris is expected for small breaks, which was dismissed in the analyses) was also estimated using conservative estimates, including the random failure of the alternate injection equipment. Further, only a single alternate injection source was considered for each plant.

- The latent debris amounts used in the evaluation are considered to be conservative, except as described above in the discussion on the latent debris issue. BWROG used the smallest strainer penetration function to maximize the amount of debris on the strainers while also assuming that the fuel inlet filters become blocked, regardless of break size and, therefore, debris load.

- The assumption for the blockage of the fuel inlet filters was applied to both the TH and the risk analysis. The LPCI success criteria applied in the risk assessment were generally more conservative when compared to the TRACG results.

- The risk assessment assumed that all debris was transported to the suppression pool within 1 minute and immediately began collecting on the ECCS strainers, based on the flow through them. Some debris would be retained above the suppression pool and take time to wash down into the suppression pool.

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