SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT (TR) WCAP-16406-P, REVISION 1, "EVALUATION OF DOWNSTREAM SUMP DEBRIS EFFECTS IN SUPPORT OF GSI-191"

PRESSURIZED WATER REACTOR OWNERS GROUP

PROJECT NO. 694

1.0 INTRODUCTION AND BACKGROUND

By letter dated February 27, 2006 (Reference 1), the Pressurized Water Reactor Owner's Group (PWROG) requested U.S. Nuclear Regulatory Commission (NRC) staff review of TR WCAP-16406-P, "Evaluation of Downstream Sump Debris Effects in Support of GSI [Generic Safety Issue]-191, Revision 0." During teleconferences on March 30 and April 6, 2006, the NRC staff advised the PWROG that TR WCAP-16406-P, Revision 0, was not acceptable for review unless a marked-up copy was submitted reflecting resolution of previous NRC staff comments (Reference 2). During a telephone call with the NRC staff on April 27, 2006, the PWROG determined that due to revisions to TR WCAP-16406-P, Revision 0, a completely revised report would be issued for NRC staff review and that review of Revision 0 was no longer requested.

By letter dated May 31, 2006 (Reference 3), the PWROG requested that the NRC staff review TR WCAP-16406-P, Revision 1. The PWROG provided supplemental information for NRC review by letters dated July 13, 2006 (Reference 4), April 16, 2007 (Reference 5), May 8, 2007 (Reference 6), September 7, 2007 (Reference 7), and September 20, 2007 (Reference 8). In a letter dated August 22, 2006 (Reference 9), the NRC staff accepted TR WCAP-16406-P for review. The PWROG supplements provided additional information on TR WCAP-16406-P, Revision 1, but did not expand the scope of TR WCAP-16406-P, Revision 1, as originally submitted. By an email dated February 16, 2007, the NRC staff transmitted a request for additional information (RAI) (Reference 10) to the PWROG.

TR WCAP-16406-P, Revision 1, is intended to provide guidance and a consistent approach for pressurized water reactor (PWR) licensees to evaluate the downstream impact of sump debris on the performance of their emergency core cooling system (ECCS) and containment spray system (CSS) following a loss-of-coolant accident (LOCA). The overall issue is being driven by GSI-191, "Assessment of Debris Accumulation on PWR Sump Performance," and the subsequent NRC Generic Letter (GL) 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized Water Reactors."

Specifically, TR WCAP-16406-P, Revision 1, seeks NRC staff approval in order to be used as an acceptable reference by PWR licensees in license amendment requests. The NRC staff reviewed TR WCAP-16406-P, Revision 1, to determine whether it is an acceptable reference for use in evaluating the effects of post-LOCA fluid on ECCS and CSS operation.

The NRC staff's safety evaluation (SE) is structured according to the organization of TR WCAP-16406-P, Revision 1. A brief summary of the contents of TR WCAP-16406-P, Revision 1, is provided in Section 3.1. The NRC staff's technical evaluation is provided in Section 3.2, limitations and conditions are summarized in Section 4.0, and conclusions are summarized in Section 5.0.

The NRC staff has determined that a PWR licensee may use TR WCAP-16406-P, Revision 1, to perform an assessment of the impact of debris on various equipment required by the ECCS, CSS, and nuclear steam supply system (NSSS) to maintain the core in a coolable geometry in a post-accident condition, subject to the conditions and limitations in this SE.

A licensee using TR WCAP-16406-P, Revision 1, will need to determine its own specific sump debris mixture and sump screen size in order to initiate the evaluation. TR WCAP-16406-P, Revision 1, provides information on a common evaluation method and acceptance criteria for the components of Westinghouse Electric Company (Westinghouse), Combustion Engineering (CE), and Babcock and Wilcox (B&W) PWR NSSS designs. TR WCAP-16406-P, Revision 1, also identifies potential plant actions (based on industry evaluation) and component modifications to demonstrate compliance NRC GL 2004-02.

2.0 REGULATORY EVALUATION

This section details the regulatory requirements, associated guidance, and precedent upon which the NRC staff based its review of TR WCAP-16406-P, Revision 1.

In accordance with Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, Subsection 50.46(b)(5), licensees of domestic nuclear power plants are required to provide long-term cooling of the reactor core "after any calculated successful initial operation of the ECCS." Furthermore, the "calculated core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core." If debris collects and clogs or wears components or pathways that support operation of the ECCS or CSS, then compliance with this regulation may be in question.

NRC guidance for determining compliance with 10 CFR 50.46(b)(5) is contained in Regulatory Guide (RG) 1.82, Revision 3 (Reference 11). The NRC staff review guidance for evaluating licensee compliance with 10 CFR 50.46(b)(5) is contained in Standard Review Plan (SRP) Section 6.2.2, "Containment Heat Removal Systems." SRP Section 9.2.5, "Ultimate Heat Sink," provides review guidance from which the extended time for recirculation performance is derived.

For PWRs licensed to General Design Criteria (GDC) in Appendix A to 10 CFR Part 50, GDC-35, "Emergency core cooling," specifies additional ECCS requirements, GDC-38, "Containment heat removal," specifies heat removal systems requirements, and GDC-41, "Containment atmosphere clean-up," provides requirements for containment atmosphere cleanup. Many PWR licensees credit a CSS, at least in part, with performing the safety functions to satisfy containment-related requirements. PWRs that are not licensed to the GDC may credit a CSS to satisfy similar plant-specific licensing basis requirements. In addition, PWR licensees may credit a CSS with reducing the accident source term to meet the limits of 10 CFR Part 100 or 10 CFR 50.67.

Technical specifications (TSs) pertain to the ECCS and CSS insofar as they require the operability of these systems for the mitigation of certain design-basis accidents. Other plant-specific licensing commitments concerning the ECCS and CSS are also documented in each plant's Final Safety Analysis Report.

General guidance on evaluating the impact of debris on the ECCS and CSS and their components is provided in Nuclear Energy Institute (NEI) 04-07, Pressurized Water Reactor Sump Performance Evaluation Methodology, Revision 1 (Reference 12), and the NRC staff's SE of NEI 04-07, Pressurized Water Reactor Sump Performance Evaluation Methodology, Revision 1 (Reference 13).

NEI 04-07 provides licensees guidance on evaluating the flowpaths downstream of the containment sump for blockage from entrained debris. The guidance specified three issues yet to be addressed: (1) blockage of flowpaths in equipment, such as containment spray nozzles and tight-clearance valves, (2) wear and abrasion of surfaces, such as pump running surfaces, and heat exchanger tubes and orifices, and (3) blockage of flow clearances through fuel assemblies.

NEI 04-07 identified the starting point for the evaluation to be the flow clearance through the sump screen and stated that the flow clearance through the sump screen determines the maximum size of particulate debris for downstream analysis. It also stated that wear and abrasion of surfaces in the ECCS and CSS should be evaluated based on flow rates to which the surfaces will be subjected and the grittiness or abrasiveness of the ingested debris. NEI 04-07 also stated that abrasiveness of debris is plant-specific and therefore should be evaluated on a plant-specific basis.

The results of the NRC staff's assessment of NEI 04-07 were documented in a safety evaluation (Reference 13). Section 7.3 of the NRC staff SE for NEI 04-07 found that the guidance statements did not fully address the potential safety impact of LOCA-generated debris on components downstream of the containment sump. In its SE, the NRC staff stated that:

> The evaluation of GSI-191 should include a review of the effects of debris on pumps and rotating equipment, piping, valves, and heat exchangers downstream of the containment sump related to the ECCS and CSS. In particular, any throttle valves installed in the ECCS for flow balancing (e.g., HPSI [High Pressure Safety Injection] throttle valves) should be evaluated for blockage potential.
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> The downstream review should first define both long-term and short-term system operating lineups, conditions of operation, and mission times. Where more than one ECCS or CS configuration is used during long- and short-term operation, each lineup should be evaluated with respect to downstream effects.
>
> Evaluations of systems and components are to be based on the flow rates to which the wetted surfaces will be subjected and the grittiness or abrasiveness of the ingested debris. The abrasiveness of the debris is plant specific, as stated in the guidance, and depends on the site-specific materials that may become latent or break-jet-generated debris.
>
> Specific to pumps and rotating equipment, an evaluation should be performed to assess the condition and operability of the component during and following its required mission times. Consideration should be given to wear and abrasion of surfaces, (e.g., pumps

running surfaces, bushings, wear rings). Tight clearance components or components where process water is used either to lubricate or cool should be identified and evaluated.

Component rotor dynamics changes and long-term effects on vibrations caused by potential wear should be evaluated in the context of pump and rotating equipment operability and reliability. The evaluation should include the potential impact on pump internal loads to address such concerns as rotor and shaft cracking.

The downstream effects evaluation should also consider system piping, containment spray nozzles, and instrumentation tubing. Settling of dust and fines in low-flow/low fluid velocity areas may impact system operating characteristics and should be evaluated. The evaluation should include such tubing connections as provided for differential pressure from flow orifices, elbow taps, and venturis and reactor vessel/RCS [reactor coolant system] leg connections for reactor vessel level, as well as any potential the matting may have on the instrumentation necessary for continued long-term operation.

Valve and heat exchanger wetted materials should be evaluated for susceptibility to wear, surface abrasion, and plugging. Wear may alter the system flow distribution by increasing flow down a path (decreasing resistance caused by wear), thus starving another critical path. Or conversely, increased resistance from plugging of a valve opening, orifice, or heat exchanger tube may cause wear to occur in another path that experiences increased flow.

Decreased heat exchanger performance resulting from plugging, blocking, plating of slurry materials, or tube degradation should be evaluated with respect to overall system required hydraulic and heat removal capability.

An overall ECC or CS system evaluation integrating limiting or worst-case pump, valve, piping, and heat exchanger conditions should be performed and include the potential for reduced pump/system capacity resulting from internal bypass leakage or through external leakage. Internal leakage of pumps may be through inter-stage supply and discharge wear rings, shaft support, and volute bushings. Piping systems design bypass flow may increase as bypass valve openings increase or as flow through a heat exchanger is diverted because of plugging or wear. External leakage may occur as a result of leakage through pump seal leak-off lines, from the failure of shaft sealing or bearing components, from the failure of valve packing or through leaks from instrument connections and any other potential fluid paths leading to fluid inventory loss.

Leakage past seals and rings caused by wear from debris fines to areas outside containment should be evaluated with respect to fluid inventory, and overall accident scenario design and licensing bases environmental and dose consequences.

TR WCAP-16406-P, Revision 1, is intended to address the above comments and provide detailed guidance and a consistent approach for licensees to evaluate the downstream impact of sump debris on the performance of their ECCS and CSS following a LOCA.

TR WCAP-16406-P, Revision 1, was developed to address the issues identified in both NEI 04-07 and the NRC staff's SE of NEI 04-07. The NRC staff's technical evaluation of TR WCAP-16406-P, Revision 1, is provided in Section 3 of this SE.

3.0 TECHNICAL EVALUATION

3.1 Summary of TR WCAP-16406-P, Revision 1

TR WCAP-16406-P, Revision 1, was prepared by Westinghouse for the PWROG. It was intended to provide information to PWR licensees to support them in performing plant-specific ECCS and CSS evaluations considering the make-up of their post-LOCA process fluid. TR WCAP-16406-P, Revision1, addresses the following topics:

Sections 1, 2, 3, and 4 are informational sections. Section 1 provides an overview of the report. Section 2 presents a background and objective for evaluation of ECCS components downstream of the sump screen. Section 3 describes the scope of the program, including the affected components and the sources of data.

Section 4 discusses two elements used in evaluations. The first portion describes system information for each of the three PWR NSSS vendors. It reviews the ECCS and CSS for each NSSS designer, identifying plant alignment to be considered for a sump recirculation scenario. It then lists different critical components in those alignments that may be considered in a plant-specific evaluation. The second portion discusses component mission times.

Section 5 provides information on containment sump debris and discusses the overall types of material that may be considered when developing a plant-specific sump debris solution.

Section 6 documents and discusses the experimental and test data used in preparing the report.

Section 7 provides a discussion of component wear calculation methods. Equations and terms used to predict the wear of components introduced in Section 4 are presented. A failure modes evaluation for each component is also included.

Section 8 presents an evaluation method to evaluate each of the components for post-LOCA survivability. Acceptance criteria are identified for each component. Flow charts for each component were provided to enable a plant engineer in understanding the evaluation process.

Section 9 focuses on the reactor vessel internals and fuel evaluations.

Section 10 provides guidance on how to perform containment sump debris downstream effects evaluation for a plant-specific application. It details what pieces or groupings of information the plant engineer needs to have to begin the evaluation and how to perform an evaluation on each critical component. It also provides recommended options and fixes if the results of a plant-specific evaluation are negative.

Nineteen appendices are provided, supporting chapters one through ten and documenting inputs. Appendix F contains the detailed component wear models used to develop the methodology in Sections 7 and 8. Appendix H contains inputs on pump wear and operation. Appendix O provides a detailed discussion regarding asymmetric wear in multi-stage pumps and supports Section 8. Appendix P provides an alternate approach to Sections 7 and 8 to estimate the wear of pump internals using Archard's Wear Model. Appendix Q further discusses the concept of a bounding debris concentration to be used in conjunction with Section 8. Appendices R and S provide a discussion of pump internal wear limits considering the potential for asymmetric wear of bearing and support components.

3.2 NRC Staff Technical Evaluation

3.2.1 TR WCAP-16406-P, Revision 1: Section 1 - Report Overview, Section 2 – Background, and Section 3 - Program Scope

These sections are general in nature and provide no technical content. A technical review of these sections is not within the scope of this SE. The NRC staff understands, however, that the methodology in TR WCAP-16406-P, Revision 1, is intended to be used by Westinghouse as well as non-Westinghouse personnel. Therefore, in its letter dated February 16, 2007 (Reference 10), the NRC staff requested that the PWROG describe the measures which will be applied in terms of qualification and training to ensure that the methodology of TR WCAP-16406-P, Revision 1, is being utilized correctly. The PWROG has provided training to licensees, via webcast, to help ensure that users are familiar with the techniques described in TR WCAP-16406-P, Revision 1. Although review of the training program is outside the scope of the NRC staff's review, the PWROG has also provided NRC staff an informational copy of the training program (Reference 14). Also, NRC staff is currently conducting a series of plant audits to review licensee application and use of TR WCAP-16406-P, Revision 1. Audits are limited to a representative sampling of plants. Finally, the NRC staff plans to review licensee responses to GL 2004-02, including summaries of analysis of downstream effects. The PWROG training program, NRC staff audits, and review of licensee responses to GL 2004-02 are expected to provide reasonable assurance of correct usage of TR WCAP-16406-P, Revision 1.

3.2.2 TR WCAP-16406-P, Revision 1: Section 4 – System Descriptions and Mission Times

This section is general in nature and was included for informational purposes only. A technical review of this section was not requested (Reference 1) and is not within the scope of this SE. However, the following NRC staff comments may be of interest to the users of this section.

The system descriptions in Section 4.1 provide useful information about plant design and configuration. The ECCS descriptions provided in these sections are not suitable for use in the formal evaluation of systems, structures, and components (SSC). All system evaluations and determinations of mission times must be based on plant source documents. These source documents should be referenced in the licensees' technical evaluation of the component or system under consideration.

Reviews of Emergency Operating Procedures (EOPs), Abnormal Operating Procedures (AOPs), Normal Operating Procedures (NOPs) or other plant-reviewed alternate system line-ups are not discussed in TR WCAP-16406-P, Revision 1. A discussion of them should be included in the overall system and component evaluations as noted in the NRC staff's SE of NEI 04-07, Section 7.3 (Reference 13).

It is noted that Section 4.1.1 describes the ECCS for Babcock and Wilcox (B&W) designed plants. The ECCS for Oconee Nuclear Station, Davis Besse Nuclear Power Station, and Three Mile Island Nuclear Generating Station, Unit 1 (TMI-1) are not discussed. Table 4.2.1 is missing a reference to the McGuire Nuclear Generating Station and Wolf Creek Nuclear Operating Corporation and is, therefore, not complete.

Section 4.2 provides a general discussion of system and component mission times. It does not define specific times, but indicates that the defined term of operation is plant-specific. As stated in the NRC staff's SE of NEI 04-07, Section 7.3 (Reference 13), each licensee must define and provide adequate basis for the mission time(s) used in its downstream evaluation.

Section 4.2.2 discusses mission times for CE plants. It also indicates that mission time could be related to hot-leg switchover. According to Table 4.2.1 and Figures 4.1-2 and 4.1-3, the CE plant design has limited capability for hot-leg recirculation. It is understood that these are generic discussions and simplified piping and instrumentation diagrams (P&IDs), so individual plants may have configurations that could be used/credited. As stated previously, the ECCS descriptions provided in these sections are not suitable for use in the formal evaluation of SSCs.

3.2.3 TR WCAP-16406-P, Revision 1: Section 5 – Debris Ingestion

This section provides a description of a debris ingestion model that may be used to assess the equipment in the ECCS and CSS systems. The debris considered includes fibrous insulation debris and particulate debris consisting of paint chips, concrete dust, and reflective metallic insulation shards small enough to pass through the holes of a PWR containment sump screen (typically 1/8-inch x 1/8-inch openings).

TR WCAP-16406-P, Revision 1, Section 5.1, provides an introduction stating that the TR evaluation methods are independent of sump screen design. The NRC staff agrees with this statement. No technical evaluation was required.

TR WCAP-16406-P, Revision 1, Section 5.2, states that NEI 04-07 (Reference 12) contains an alternate evaluation method for assessing sump performance and that it may, in the future, be revised to address downstream components. This section contains no technical information. If NEI 04-07 (Reference 12) is revised to address downstream components, the NRC staff will assess it separately from TR WCAP-16406-P, Revision 1.

TR WCAP-16406-P, Revision 1, Section 5.3, references GL 2004-02 and states that the debris input loadings, used for the evaluations in TR WCAP-16406-P, Revision 1, should be consistent with other GL 2004-02 evaluations. The NRC staff agrees that the evaluations in TR WCAP-16406-P, Revision 1, should be consistent with other licensee documents associated with its GL 2004-02 response.

TR WCAP-16406-P, Revision 1, Section 5.4, states that the type, size, and amount of debris that reaches a sump screen is plant-specific. For passive screens the amount of debris, both fibrous and particulate, that passes through the screen is dependent upon the size of the flow passages in the sump screen and the ratio of the open area of the screen to the closed area of the screen. There are a number of other factors affecting debris bypass through the sump screen, such as hole size, the ratio of open to closed area of the screen, the fluid approach velocity to the screen, and the screen geometry. TR WCAP-16406-P, Revision 1, also recommends that licensees with passive strainers contact their strainer designer for additional information. Section 5.4 also suggests that those licensees using an active strainer design contact their strainer vendor. This section is general information, suggesting that licensees work with their screen vendors to establish an appropriate debris mix. The NRC staff finds this section acceptable as it recommends that licensees firmly establish a basis for their debris mix. This is consistent with the NRC staff's SE of NEI 04-07 (Reference 13).

TR WCAP-16406-P, Revision 1, Section 5.5, provides a series of assumptions to be used in determining the make-up of the post-LOCA fluid. Consistent with the NRC staff's SE of NEI 04-07, Assumption 1 takes no credit for filtering of material due to a thin bed of material on a sump screen, the NRC staff finds this assumption to be conservative and therefore acceptable. Assumption 2 defines the dimensions of particulates passing through a sump screen as:

The maximum length of deformable particulates that may pass through the penetrations (holes) in passive sump screens is equal to two times (2X) the maximum linear dimension of the penetration (hole) in the sump screen.

The maximum width of deformable particulates that may pass through the penetrations (holes) in passive sump screens is equal to the maximum linear dimension of the penetration (hole) in the sump screen, plus 10 percent (10%).

The maximum thickness of deformable particulates that may pass through the penetrations (holes) in a passive sump screen is equal to one-half (½) the maximum linear dimension of the penetration (hole) in the sump screen.

The maximum cross-sectional area of deformable particulates that may pass through the penetrations (holes) in a passive sump screen is equal to the maximum cross-sectional flow area of the penetration (hole) in the sump screen, plus 10 percent (10%).

The maximum dimension (length, width and/or thickness) of non-deformable particulates that may pass through a sump screen is limited to the cross-sectional flow area of the penetration (hole) in the sump screen.

The bases for these limiting dimensions are provided in Appendix J to TR WCAP-16406-P, Revision 1. A discussion of the NRC staff review of Appendix J is provided in Section 3.2.16 of this SE. The NRC staff concludes, in Section 3.2.16, that the above assumptions are reasonable and conservative for use in the evaluation of systems and components downstream of the sump screens. In general, the assumptions account for particles larger than the screen opening size and assume all transportable material with the above dimensions or smaller passes through the sump screen unimpeded thus maximizing the calculated particulate and fibrous debris concentrations in the post-LOCA process fluid. As stated in TR WCAP-16406-P, Revision 1, the above assumptions do not apply to active strainers. Specific information from the active screen vendor should be used for debris characterization.

TR WCAP-16406-P, Revision 1, Section 5.5, Assumption 3 states that, "The particulate and fibrous debris sizes identified in the previous steps may be modified if supported by plant specific data." The NRC staff concurs with this statement. The licensee may use experiments or tests to determine downstream process fluid properties. The plant-specific evaluation would then use the particulate and fibrous debris sizes and concentrations obtained from the collected and measured size distribution of the particulate and fibrous debris. The test protocol for performing these tests and the suitability of the results for use in downstream evaluations are the responsibility of the licensee. Assumption 3 reiterates the conclusions of Appendix J and includes engineering judgment with broad assumptions that material significantly larger than a screen hole size will pass through the hole. Assumption 3 will produce larger sizes and amounts of bypass debris than would be actually expected. The NRC staff agrees that the assumption is appropriate and conservative; it does not assume any impediment from debris already on the strainer. The materials involved are relatively stiff and incompressible and account for long, thin strands, of insulation being able to pass through tight openings. Assumption 4 assumes no settling of material once in solution. The NRC staff agrees that this is a conservative assumption as material will tend to settle out in low flow areas in piping, the reactor vessel, the containment floor, or hold-up volumes. Assumption 5 assumes a homogeneous solution at the start of the event. The NRC staff agrees that this is conservative as it maximizes fluid abrasiveness early in the wear evaluations. Assumption 6 assumes no interaction of particles. Particle interaction will have the effect of wearing the particles making them less abrasive. The

NRC staff agrees that this assumption is conservative as it maximizes fluid abrasiveness. Assumption 7 assumes that transport calculations performed for other areas of a licensee's GL 2004-02 response, and used in this analysis, are conservative. The NRC staff assessment of transport calculation conservativisms is outside the scope of this evaluation. The implication for this assumption on downstream evaluations is that a conservative transport calculation, e.g. a calculation that maximizes debris transport and therefore maximizes material passing through a sump screen, will maximize the wear potential of downstream components. Assumption 8 assumes no settling of material in settle-out areas. The NRC staff agrees that this is conservative as it maximizes debris concentration in the flow stream and therefore maximizes wear of downstream components. Assumption 9 restates that concentrations assumed in this evaluation should be compared with the debris concentrations used in the TR WCAP-16406-P, Revision 1, Section 7 references. The NRC staff agrees that licensees should compare its debris composition and concentration with those of the TR references to ensure that the references are valid and applicable to their condition. Overall, the NRC staff agrees that assumptions one through nine provide a conservative approach by which material significantly larger than the screen holes goes into solution stays in solution and maximizes component wear potential.

Sections 5.6 and 5.12 of TR WCAP-16406-P, Revision 1, state that the total plant-specific debris concentration must be compared with concentration values identified in TR WCAP-16406-P, Revision 1, References 5.5-1 and 5.5-2. The NRC staff's position is that the calculated debris concentration should also be confirmed to agree with TR WCAP-16406-P, Revision 1, Assumption 5.5.7 (i.e., the debris generation and transport calculations performed to respond to GL 2004-02). TR WCAP-16406-P, Revision 1, Section 5.6, states that initial debris concentration is a plant-specific parameter that may be calculated if water volumes and debris amounts are known. This section provides a standard equation for calculating debris concentration in parts-per-million (ppm). As stated in TR WCAP-16406-P, Revision 1, calculation of water volumes and debris amounts are addressed outside of TR WCAP-16406-P, Revision 1, and should be consistent with other licensee GL 2004-02 evaluations. The NRC staff agrees that water volumes and debris amounts used should be consistent with other GL 2004-02 evaluations. The NRC staff finds that the equation is acceptable based on first principles.

TR WCAP-16406-P, Revision 1, Section 5.7, suggests that one conservative approach for wear evaluations is to assume no settling or filtering of the post-LOCA fluid. The NRC staff agrees with this since it will maximize the wear and plugging potential of ECCS and CSS components.

Section 5.8 of TR WCAP-16406-P, Revision 1, provides a methodology for calculating the reduction in particulate concentration in the recirculated coolant as a result of debris settling within the reactor vessel and elsewhere in the involved systems. Following a large LOCA, the ECCS will initially inject water into the reactor system from stored supplies. Before these supplies are exhausted, suction to the ECCS pumps will be switched to the containment sump so that the coolant spilled from the reactor system and collected from the containment spray may be recirculated back into the reactor system to provide for continued long-term cooling. During the recirculation of coolant after a LOCA, coolant will be passed through the sump screens to the ECCS pumps and to the reactor system. During the recirculation process, depending on the break location, some of the coolant will be spilled immediately on the containment floor through the break. The rest will flow into the reactor vessel.
TR WCAP-16406-P, Revision 1, assumes that the coolant which is not spilled flows into the reactor system and reaches the reactor vessel downcomer. This would be true for most PWR designs except for plants with upper plenum injection. Therefore, the methodology of

Section 5.8 may not be applicable to plants with upper plenum injection, and its use must be justified on a plant-specific basis.

During the recirculation period, the ECCS flow which reaches the reactor vessel downcomer will be transported into the lower plenum and upward into the core. Because of the large cross sectional area of the lower plenum, the flow velocity will be at a minimum. The low flow velocity in the lower plenum will provide opportunity for suspended particles to settle out of the flow stream and to remain within the lower plenum. As a result of this separation process in the lower plenum, the TR WCAP-16406-P, Revision 1, states that the recirculated coolant will become continually more dilute in suspended particles. Particles which are large and heavy are assumed to settle out in the lower plenum. Smaller and lighter particles will be swept up into the reactor core and are assumed not to settle out. Section 5.8 of TR WCAP-16406-P, Revision 1, provides equations which a licensee might use to determine particulate concentration in the coolant as a function of time. The equations are based upon a simple mass balance and incorporate the concept of debris settlement. The NRC staff finds that the equations are acceptable since they are based on the basic principles of conservation of mass. Assumptions as to the initial particulate debris concentration will be plant-specific, according to TR Section 5.8, and should be determined by the user consistent with NEI 04-07. In addition, model assumptions for ECCS flow rate, the fraction of coolant spilled from the break, and the partition of large heavy particles which will settle in the lower plenum and smaller lighter particles which will not settle must be determined and justified by the licensee.

The methodology of Section 5.8 for determining depletion of particulate debris concentration applies to both hot- and cold-leg breaks, though the section states that Equation 5.8-5 is only applicable to cold-leg recirculation. The NRC staff notes that specific guidance is not provided to evaluate particulate depletion following a hot-leg break or during hot-leg recirculation. In addition, the NRC staff notes that some of the input values utilized in the example of Section 5.9 may not be representative of what might be expected during long-term cooling for all plants. Selection of appropriate conservative input values as well as application of the methodology to conditions other than those described in TR WCAP-16406-P, Revision 1, are expected to be addressed during the PWROG training session. See Section 3.2.1 of this SE.

The methodology presented in TR WCAP-16406-P, Revision 1, Sections 5.8 and 5.9, assumes that the coolant which enters the core also flows through the core as liquid. TR WCAP-16406-P, Revision 1, then assumes that the coolant leaving the core flows into the upper plenum, into the coolant loops, and out the break to the containment floor in liquid form for continued recirculation. If the LOCA were caused by a large break in a cold leg, the flow velocity in the core would be minimal since only coolant sufficient to match the boil off in the core would flow into the core inlet. Since only steam would leave the top of the core for this process, all particulate and fibrous debris, no matter how small and light, which entered the core would remain in the core. In an e-mail dated February 16, 2007 (Reference 10), the NRC staff requested that the PWROG provide evaluations for post-LOCA buildup of debris as well as chemicals in the reactor core during long-term cooling by boiling. In a letter dated May 8, 2007 (Reference 6), the PWROG responded that the effect of debris and dissolved materials on long-term cooling is being evaluated under TR WCAP-16793-NP, “Evaluation of Long Term Cooling Considering Particulate and Chemical Debris in the Recirculating Fluid” (Reference 15). If the results of TR WCAP-16793-NP show that debris settling is not governed by force balance methods of TR WCAP-16406-P, Section 9.2.2 or Stokes Law, then the core settling term determined from TR WCAP-16793-NP should be used. This matter is discussed further in Section 3.2.7 of this SE.

Section 5.9 of TR WCAP-16406-P, Revision 1, shows a sample calculation for particulate debris depletion. The section follows the methods presented in previous sections. The NRC staff reviewed the calculation and agrees that it is mathematically correct. The NRC staff did not review the example inputs for validity.

Section 5.10 of TR WCAP-16406-P, Revision 1, provides the methodology for calculating the reduction in fibrous debris concentration in the containment sump water as a result of the fibers being captured on the containment sump screen. The governing equation consists of two components. The first is a concentration of fibers sufficiently small to travel through the sump screen, through the RCS and back into the sump without lodging anywhere. This concentration remains constant. The second component is a concentration of fibers large enough to be trapped on the sump screen with a plant-dependant screen efficiency. The concentration of these larger fibers in the flow stream decreases exponentially as the fibers are filtered with each pass through the sump screen. The referenced equation is taken directly from NUREG LA-UR-04-5416 (Reference 16), is applied appropriately; and is therefore acceptable to the NRC staff. Assumptions as to the initial fibrous debris concentration will be plant-specific and should be determined by the licensee. In addition, model assumptions for ECCS flow rate, the filtration efficiency, the initial concentrations of fibers which can be collected on the sump screen, and the concentration of fibers which are too small to be filtered should be determined and justified by the licensee. The NRC staff did not evaluate the data provided in this section for validity or applicability to PWR strainers.

Section 5.11 provides a sample calculation using the methods outlined in Section 5.10. The sample provides a useful example. The NRC staff reviewed the calculation and agrees that it is mathematically correct. However, the inputs are site- and plant-specific and the NRC staff did not evaluate their validity. The selection of appropriate conservative input values as well as application of the methodology to conditions other than those described in TR WCAP-16406-P, Revision 1, are expected to be addressed during the PWROG training session.
See Section 3.2.1 of this SE.

Section 5.13 of TR WCAP-16406-P, Revision 1, is a summary statement for Section 5. No conclusions or technical information are presented.

3.2.4 TR WCAP-16406-P, Revision 1: Section 6 – Applicable Experimental Data on Pumps

This section summarizes historical testing performed by Westinghouse and provides information gathered from open literature on Davis-Besse pump testing. Specifically, Section 6.1 is an introductory paragraph with no technical information. Section 6.2 describes a Westinghouse test performed in 1977 with a 2-stage vertical pump. Section 6.3 describes the Davis-Besse testing performed in 2003. Section 6.4 provides a comparison of the debris concentrations used in the Westinghouse testing versus a debris mix from a 1996 study on PWR pump performance. The information in Sections 6.2, 6.3, and 6.4 was provided as reference material and is used in various Appendices to TR WCAP-16406-P, Revision 1. The application of this information in support of these appendices is discussed on a case-by-case basis within the context of the particular Appendix. A specific technical review of these references is not within the scope of this SE and was not performed. Prior to using this data in the evaluation of their systems and components, a licensee should ensure that the tests and experiments are applicable to, or bound its specific situation.

3.2.5 TR WCAP-16406-P, Revision 1: Section 7 – Wear Rate and Component Evaluation Methods

Section 7 of TR WCAP-16406-P, Revision 1, provides a summary of the wear and analysis models used for evaluating pumps and valves in plant ECC and CS systems.

Section 7.1 of TR WCAP-16406-P, Revision 1, introduces Section 7 and contains no technical information.

Section 7.2 of TR WCAP-16406-P, Revision 1, specifically addresses pumps. Debris-laden fluid may impact the operability of ECC and CS pumps used during long-term recirculation following a LOCA. These pumps are intended to provide adequate core cooling and maintain safe shutdown of the reactor. TR WCAP-16406-P, Revision 1, assumes a mission time of 720 hours (720 hours is used as a base time limit for evaluation throughout TR WCAP-16406-P, Revision 1) for pump operations. The NRC staff's review concludes that licensees should confirm that: 720 hours bounds their mission time or provide a basis for the use of a shorter period of required operation.

Section 7.2 of TR WCAP-16406-P, Revision 1, states that when considering long-term pump operation and performance, it is necessary to consider how wear of internal pump components will affect the pump hydraulic performance (total dynamic head and flow), the mechanical performance (vibration), and pressure boundary integrity (shaft seals). The wear of the close running clearances may impact the hydraulic performance because of increased internal or bypass leakage. Multistage pumps, designed for high head service, usually operate at speeds above the first natural frequency of the rotating assembly. The running clearances of the suction side and discharge side of each impeller stage are designed and manufactured to provide hydrostatic support and damping for the rotating assembly, thus allowing operation at super-critical speeds without dynamic instability. Increasing the close running clearances due to wear may reduce the overall shaft support stiffness at each impeller location, thus affecting the dynamic stability of the pump. Debris in the pumped fluid may affect the sealing capability of mechanical shaft seals. These seals are dependent on seal injection flow to cool the primary seal components. Debris in the pumped flow has the potential of blocking the seal injection flow path or of limiting the performance of the seal components due to debris buildup in bellows and springs. These effects may lead to primary seal failure. Graphite safety bushings (disaster bushings) may fail if exposed to high pressure fluid with debris following a primary seal failure thus providing an outside containment path for post-LOCA fluid. The NRC staff agrees with these statements as they are based on standard, accepted pump design practices.

The NRC staff concludes that two types of wear of close running clearances within the pump may occur; 1) free-flowing abrasive wear and 2) packing-type abrasive wear. Wear within close-tolerance, high-speed components is a complex analysis. The actual abrasive wear phenomena will likely not be either a classic free-flowing or packing wear case, but a combination of the two. Licensees should consider both in their evaluation of their components.

The PWROG describes the free-flowing abrasive wear model in TR WCAP-16406-P, Revision 1, Appendix F. The NRC staff's review of this Appendix is addressed in SE Section 3.2.12. TR WCAP-16406-P, Revision 1, Appendix F, discusses the relationship between the rate of wear of the running clearance surfaces and the debris concentration in the bulk fluid, the hardness of the wear surfaces, and the mission time for the pump.

The PWROG describes the packing type abrasive wear in TR WCAP-16406-P, Revision 1, Appendix P. The model is based on the Archard wear equation for abrasive wear, relating the volume of material removed to contact load on the wear surface, total wear distance, and a material/surface finish parameter called "wear index." The NRC staff's review of Appendix P is addressed in SE Section 3.2.22.

Abrasive wear in the close running clearances may result from free-flowing abrasive wear or packing type abrasive wear as described by the Archard model. As stated in the TR WCAP-16406-P, Revision 1, Section 7.2.1:

The principal differences between the Archard wear model and the free-flowing abrasive wear model are:

1. The wear associated with the Archard model is single-sided. The debris packing adheres to the stationary surface (wear rings), and wear only the rotating surface (impeller hub). The free-flowing abrasion model wears both the rotating and the stationary surfaces individually at rates determined by the fluid debris concentration and the hardness of the wear surfaces.

2. The wear rate of Archard's model is constant. Once the packing is established, debris depletion in the bulk fluid does not affect the rate of wear. For the free-flowing abrasive wear model, the rate of wear is a direct result of the debris concentration in the fluid at any time during the pump duty cycle.

The NRC staff finds that the Archard model can be implemented in the same way as the free-flowing model because both methods calculate suction and discharge wear clearances which are then used as inputs into the overall pump evaluation. Both models are considered valid because both will reasonably predict abrasive wear in close tolerance components. The wear predictions from both models match the results from field testing. The Archard model can also be adjusted to reflect changes in debris concentration.

A flow chart, TR WCAP-16406-P, Revision 1, Figure 7.2-1, is provided showing how these models are used for evaluating the wear of the close running clearances in the centrifugal pumps. Figure 7.2-1, Note 1, assumes that packing is assumed to be expelled from the running clearance when the running clearance exceeds 50 mils. As stated elsewhere in TR WCAP-16406-P, Revision 1, assuming the packing is expelled when wear ring clearances are greater than 50 mils will cause greater pump instability versus the packing remaining in place due to loss of support load and is therefore conservative. Figure 7.2-1, Note 2, states that the free flowing abrasive wear calculation for the discharge wear ring should be performed taking no credit for debris depletion. The NRC staff finds that this is conservative as it maximizes the calculated wear to the discharge wear ring. The NRC staff finds that the flowchart and accompanying notes are conservative and consistent with the information contained in other TR WCAP-16406-P, Revision 1, sections and are therefore acceptable.

Section 7.2.1.1 of TR WCAP-16406-P, Revision 1, states: "The free flowing abrasive model takes into account debris depletion over time. The initial debris concentration in the sump and characteristics are specific to each plant. Debris heavier than the reactor coolant will tend to settle out in the low velocity regions, such as in the sump and the reactor lower plenum. Therefore, the recirculation flow will tend to "clean up" the debris over time." The NRC staff finds that this is a realistic assumption based on sound fluid engineering principles.

TR WCAP-16406-P, Revision 1, also states that the concentration of depletable debris as a function of time will follow an exponential decay curve with a depletion coefficient (λ) that is plant-specific. The NRC staff finds the depletion equation acceptable because it is based on accepted fluid and fluid mechanics principles.

The NRC staff agrees with the TR statements that some debris below certain sizes are not subject to depletion, and should be assumed to remain suspended in the fluid throughout a components' mission time. The NRC staff concludes that this is conservative since it will maximize the potential for free-flowing wear over time.

The depletion coefficients in Table 7.2-1 are illustrative, and plant-specific values are determined from their plant-specific calculations, bypass testing, and other applicable sources. The value may be greater or less than those listed in the table. Licensees should consider both hot-leg and cold-leg break scenarios to determine the worst case conditions for use in its plant-specific evaluations.

A sample calculation, using the free-flowing abrasive wear model developed in TR WCAP-16406-P, Revision 1, Appendix F, is provided in Section 7.2.2. The NRC staff's review of the sample calculation confirms that the methods developed in other sections and appendices of TR WCAP-16406-P, Revision 1, are appropriately applied. The NRC staff concludes that licensees may use the sample calculation as a guide in performing their specific evaluation. The NRC staff did not review the input data for the calculation for validity or applicability to PWR strainers.

Section 7.2.3 of TR WCAP-16406-P, Revision 1, provides a general discussion of debris build-up in running clearances and refers to a series of tests performed at Wyle laboratories (TR WCAP-16406-P, Revision 1, Reference 7.2.5). The reference testing was performed with non-abrasive paint chips. The testing showed the possibility of clogging tight clearance areas and demonstrated and confirmed wear patterns observed in other tests. Section 7.2.3 of TR WCAP-16406-P, Revision 1, also states that there is no increase in motor current as a result of packing debris build-up, and concludes that increased drag on the rotating assembly was therefore low and shaft seizure unlikely. The NRC staff acknowledges the testing observations detailed in Section 7.2.3 and based upon a review of the references in TR WCAP-16406-P, Revision 1, agrees that shaft seizure is an unlikely due to debris buildup in the close running pump clearances for the reason stated in Section 7.2.3 of TR WCAP-16406-P, Revision 1.

Section 7.2.4 of TR WCAP-16406-P, Revision 1, introduces the Archard Wear Equation and states that it is further developed in Appendix O of TR WCAP-16406-P, Revision 1. The NRC staff's review of Appendix O is detailed in SE section 3.2.21.

Section 7.2.5 of TR WCAP-16406-P, Revision 1, concludes that suction-side wear ring running clearance should be calculated using the free flowing abrasive wear model documented in Appendix F. The discharge-side wear ring clearances should be calculated using both the free flowing abrasive wear model developed in Appendix F and the Archard abrasive wear model for packing type wear developed in Appendix O. The results of the wear calculations must be used to evaluate the effects on the hydraulic performance and the dynamic performance of the pump during containment recirculation conditions. The NRC staff finds this approach acceptable since it considers worst-case wear conditions and is consistent with published test observations. The approach is also consistent with the NRC staff SE of NEI 04-07 (Reference 13).

Section 7.3 of TR WCAP-16406-P, Revision 1, specifically addresses valves and notes that valves may degrade via two main modes; by erosive wear or by plugging. A comprehensive list of valves, design features, and failure modes is presented in Section 7.3.1. The NRC staff reviewed the general failure modes listed in TR WCAP-16406-P, Revision 1, Table 7.3.1. The NRC staff finds that the table is in accordance with standard, industry-accepted failure modes, and effects principles and is therefore acceptable for general use. However, the NRC staff notes that the list is not intended to be all-inclusive, and that licensees should verify its applicability to their plant.

Section 7.3.2 of TR WCAP-16406-P, Revision 1, recognizes that the debris mix and concentration in the post-LOCA fluid contribute to erosive wear. Erosive wear is a free-flowing erosion model. Valves subjected to debris-laden water experience erosive wear. Erosive wear is caused by particles that impinge on a component surface and remove material from the surface due to momentum effects. The wear rate depends on a number of factors: the debris type, debris concentration, material hardness, flow velocity, and valve position. The wear rate models used in Section 7.3.2 were developed in Appendix F. Section 7.3.2 applies the equations of Appendix F in a systematic fashion to determine overall wear rates. The NRC staff finds that the equations of Appendix F are appropriately transcribed into and described in this section. The NRC staff's review of TR WCAP-16406-P, Revision 1, Appendix F, is addressed in SE Section 3.2.12.

Section 7.3.2.1 of TR WCAP-16406-P, Revision 1, presents a constant debris size model for use in free-flowing wear evaluations. The NRC staff's review concludes that the wear equation presented is a standard engineering equation used in erosion calculations. It assumes that all erosive media contribute equally to wear rate and at the rate expected for large particles. This is a conservative assumption and will estimate wear rates larger than assuming that some erosive media will contribute less to the overall wear rate and is therefore acceptable.

Section 7.3.2.2 of TR WCAP-16406-P, Revision 1, presents a modified wear rate model based upon a distribution of wear particles. The NRC staff's review concludes that the wear equation presented is a standard engineering equation used in erosion calculations. It recognizes that that not all erosive media contribute equally to wear rate. The NRC staff concludes, that while the equation is less conservative than the approach of TR WCAP-16406-P, Revision 1, Section 7.3.2.1, it is still a standard, industry-accepted method to evaluate free-flowing erosive wear and is therefore acceptable for use.

Section 7.3.2.2.1 of TR WCAP-16406-P, Revision 1, refers the licensee to TR WCAP-16406-P, Revision 1, Appendix I, for classification of particulate distribution. The NRC staff agrees that this is the appropriate reference based on a review of TR WCAP-16406-P, Revision 1, Appendix I.

Section 7.3.2.2.2 of TR WCAP-16406-P, Revision 1, provides the written steps to follow when performing an erosive wear evaluation. The NRC staff finds that the steps presented are acceptable because they are logical and based on good, standard, engineering evaluation practices.

Section 7.3.2.3 of TR WCAP-16406-P, Revision 1, recognizes that material hardness has an effect erosive wear. TR WCAP-16406-P, Revision 1, suggests that "For elastomers, the wear rate is at least one order of magnitude less than steel. Therefore, for soft-seated valves, divide the estimated wear rate of steel from above equations by 10 per Appendix F." The NRC staff agrees that the wear rates of elastomers are significantly less than for steels. However, the wear coefficient should be determined by use of a suitable reference, not by dividing the steel rate by a factor of 10. The NRC staff reviewed the method for adjusting the wear rates of stellite and hardened steels presented in Section 7.3.2.3 of TR WCAP-16406-P, Revision 1, and finds that the approach is consistent with standard, industry-accepted tribological wear rate calculations and modeling methods and is therefore acceptable.

Section 7.3.2.3 of TR WCAP-16406-P, Revision 1, discusses the wear value to be used in the evaluation of valves and provides the written steps to follow when performing an erosive wear evaluation. The NRC staff finds the steps presented to be acceptable because they are logical and based on good, standard engineering evaluation practices. The NRC staff finds the free flowing erosive wear equation presented to be mathematically correct because it re-iterates the free-flowing wear equation developed in TR WCAP-16406-P, Revision 1, and adjusts it by combining the wear rate of the valve body or seat with that of the valve plug. TR WCAP-16406-P, Revision 1, Section 7.3.2.3, also states that for small, less than three percent, area losses, the result will have minimal effect on system flow. TR WCAP-16406-P, Revision 1, recommends that if wear is greater than three percent, a licensee should contact the vendor to assess the effects on valve flow rate. The NRC staff agrees that a less than three percent wear of valve opening size will not significantly affect system flow. The three percent value is well within nominal valve manufacturing tolerances and well within standard fluid flow calculation tolerances, and is therefore acceptable.

Section 7.3.3. of TR WCAP-16406-P, Revision 1, discusses a flow area evaluation method for use in valve assessments. Typical valve configurations are presented, and TR WCAP-16406-P, Revision 1, states that evaluations are to be performed in accordance with the guidance in NRC Information Notices (IN) 97-76, “Degraded throttle Valves in Emergency Core Cooling System Resulting from Cavitations – Induced Erosion during a Loss-of-Coolant Accident,” October 30, 1997 and IN 96-27, “Potential Clogging of High Pressure Safety Injection Throttle Valves during Recirculation,” May 1, 1996. This is consistent with the NRC staff’s SE of NEI 04-07 (Reference 13) requiring that valves be evaluated to the referenced INs and is therefore acceptable. The NRC staff’s review concludes that the descriptions of the typical valves and their failure mechanisms (susceptibility to debris-induced clogging) are in accord with industry descriptions and with typical failure modes and effects evaluations and are therefore acceptable.

Section 7.4 of TR WCAP-16406-P, Revision 1, refers the licensee to TR WCAP-16406-P, Revision 1, Appendix F, and states that the erosive wear rate evaluation method for heat exchangers, orifices, and spray nozzles should be the same as that developed for valves as discussed in Section 7.3 of TR WCAP-16406-P, Revision 1. The NRC staff agrees with this conclusion on the basis that the wear mechanisms in a free-flowing stream are similar for these components and are therefore applicable.

3.2.6 TR WCAP-16406-P, Revision 1: Section 8 – Auxiliary Equipment Evaluation

Section 8 discusses the evaluation and acceptance criteria used to assess auxiliary components subjected to debris-laden post–LOCA fluid. Other sections and appendices in TR WCAP-16406-P, Revision 1, are referred to throughout this section. The NRC staff’s assessments of those sections are covered in the applicable sections of this SE.

Section 8.1 specifically addresses ECCS and CSS pumps. The ECCS and CSS pumps are required to operate during recovery from LOCA and steam line break (SLB) accidents. The post-accident duty for these components varies depending on the assumed accident, break size, and design of the plant including pump/system alignment.

TR WCAP-16406-P, Revision 1, notes that the physical characteristics and design of an ECCS or CSS pump are large factors in determining the ability of a pump to perform its intended function in a post-LOCA environment. Vertical and horizontal single-stage pumps, in general, do not require internal water-lubricated bearings, and use a single shaft seal assembly. Horizontal multistage pumps usually have two shaft seal assemblies or a single shaft seal assembly combined with an internal water-lubricated outboard bearing (or bottom bearing for a vertical multistage pump). Some multistage pumps use internal sleeves or journal bearings to support the shaft along its length, or may use the inter-stage wear rings for shaft support. These pumps may employ internal water-lubricated carbon (graphite) or rubber sleeve bearings. Carbon bearings when exposed to a combination of abrasive debris in the process fluid, and a pressure drop across the bearing (to bring the debris into the bearing) may experience high wear rates. The NRC staff has reviewed this general information and concludes that the statements are reasonable and in accordance with general pump industry information.

The evaluations contained in Section 8.1 consider ECCS and CSS pump hydraulic performance, mechanical shaft seal assembly performance, and pump mechanical performance (vibration). This set of evaluations is consistent with the expectations noted in Reference 13.

Section 8.1.1 of TR WCAP-16406-P, Revision 1, provides a general discussion of ECCS pump operation with debris-laden water from the containment sump. TR WCAP-16406-P, Revision 1, states that: "For pumps tested by Pacific Pumps/Westinghouse, it was shown that the debris that entered the suction piping will pass through the pumps without measurable short-term impact on pump performance (up to 12 hours). This is expected to be generally true for pumps selected for ECCS and CSS service. However, for pumps not tested for sensitivity to debris in the pumped fluid, the pump and seal manufacturers must be consulted as part of an assessment of both short and long term impact on their equipment designs." The NRC staff reviewed the TR-referenced tests and agrees with the observations stated. As stated in other sections of this SE, licensees should review these tests to determine their applicability to their SSC and perform additional evaluations, as appropriate.

The TR states that: "The debris recipe is a result of a specific plant containment design and type of insulation used on piping and equipment and must be evaluated by the individual plant according to the guidelines given in Section 5." It also states that hydraulic performance, mechanical shaft seal assembly performance, and pump mechanical performance must be considered. The NRC staff agrees with these evaluation criteria. The stated criteria are in agreement with Appendix 9.

Section 8.1.1.1 of TR WCAP-16406-P, Revision 1, refines the scope of hydraulic performance by noting that a pump must consider degradation due to pump internal parasitic flows and operation with changing different system resistances due to system component wear. The NRC staff finds the stated conclusions acceptable because they are consistent with Reference 13.

Section 8.1.1.2 of TR WCAP-16406-P, Revision 1, refines the scope of the mechanical shaft seal assembly evaluation. It provides a general discussion and notes that a leakage evaluation is required by Reference 13. The NRC staff disagrees with the TR conclusion that seal failure is unlikely based on a single test, TR WCAP-16406-P, Revision 1, Reference 8.1.3. Section 8.1.3

provides a method to determine shaft seal leakage. While Section 8.1.1.2 of TR WCAP-16406-P, Revision 1, concludes that seal leakage is unlikely, it does state that, "Sufficient time is available to isolate the leakage from the failed pump seal and start operation of an alternate ECCS or CSS train." Also, Section 8.1.3, "Mechanical Shaft Seal Assembly," states: "Should the cooling water to the seal cooler be lost, the additional risk for seal failure is small for the required mission time for these pumps." The NRC staff concludes that these statements refer only to assessing seal leakage in the context of pump operability and 10 CFR Part 100 concerns. A licensee also should evaluate leakage in the context of room habitability and room equipment operation and environmental qualification, if the calculated leakage is outside that which has been previously assumed.

Section 8.1.1.3 of TR WCAP-16406-P, Revision 1, provides a general discussion on mechanical pump evaluations (vibration). Only a general technical discussion is provided, and no guidance for use of the information is included. Therefore, no NRC staff assessment was performed. A vibration evaluation is specified as being needed per Reference 13.

Section 8.1.2 of TR WCAP-16406-P, Revision 1, discusses pump hydraulic performance and concludes that the increased internal flows due to internal wear, (e.g. impeller, volute, wear rings, bushings, etc.,) do not impact the required net positive suction head (NPSH) for the pumps. The NRC staff agrees that there will be a minimal impact on NPSH required. The impact is minimal because the fluid density of debris-laden post-LOCA fluid is close to that of the density of non-debris-laden post-LOCA fluid. The NRC staff finds the conclusion acceptable because it is consistent with pump industry engineering and design methods regarding the determination of conditions under which a pump begins to cavitate.

Section 8.1.2 of TR WCAP-16406-P, Revision 1, also discusses the effect of debris loading in the pumpage on the hydraulic performance of pumps. TR WCAP-16406-P, Revision 1, states that: "Pumpage with high debris loading and high abrasive content will, over an extended period of time, cause abrasion and erosion of the pump internals. This can include roughening and pitting of the hydraulic surfaces, and wear of the close running clearances. Both of these effects will reduce the hydraulic efficiency of the pump." The NRC staff agrees with these conclusions because they are consistent with Reference 13.

TR WCAP-16406-P, Revision 1, notes that high debris loading in the process fluid can cause increased parasitic flows due to the erosion of pump running clearances. Reference 8.1-10 of TR WCAP-16406-P, Revision 1, documents test results by Worthington Pump International, Inc., on the effect of increased wear ring clearances on the hydraulic performance of centrifugal pumps (single and multistage). The NRC staff reviewed the reference for technical adequacy and concludes that the results are reasonable and are representative of what may be expected in representative PWR ECCS and CS pumps and therefore may be used in a licensee's assessment of hydraulic performance. The NRC staff agrees that Figure 8.1-3 of TR WCAP-16406-P, Revision 1, showing the plot of the changes in hydraulic performance (percent of the values at the best efficiency point (BEP)) versus percent of design wear ring gap based on test data, accurately represents the test data from Reference 8.1-10 of TR WCAP-16406-P, Revision 1.

Section 8.1.2 of TR WCAP-16406-P, Revision 1, consistent with Reference 13, performs a generic evaluation of wear ring gap on hydraulic performance is performed using published text book data. The reference information is provided for licensee use and emphasizing that a pump must not be operating at run-out condition considering the worst-case operating profile. The operating profile includes "the effect of changing resistance in the ECCS due to wear of valves, orifices, and so forth." The NRC staff concludes that is consistent with the NRC staff position (Reference 13) that an overall system evaluation should be performed considering the combined effects of all analyses.

Section 8.1.3 of TR WCAP-16406-P, Revision 1, discusses a mechanical shaft seal assembly evaluation. Debris buildup in the shaft seal package may interfere with the normal operation of the seal, in that spring and bellow movement may be restricted and actual wear of the seal surfaces may increase. TR WCAP-16406-P, Revision 1, states that the possibility of a seal failure due to debris damaging the seal surfaces, or increased seal leakage due to debris interfering with the seal operation, must be considered. The NRC staff concludes that this is consistent with the NRC staff's position in Reference 13.

Section 8.1.3 of TR WCAP-16406-P, Revision 1, also discusses cyclone separator operation. TR WCAP-16406-P, Revision 1, generically concludes that cyclone separators are not desirable during post-LOCA operation of HHSI pumps. The NRC staff does not agree with this generic statement. If a licensee's pump contains a cyclone separator, it should be evaluated within the context of both normal and accident operation. The evaluation of cyclone separators is plant-specific and depends on cyclone separator design and the piping arrangement for a pump's seal injection system. This concern is specifically mentioned in Reference 13.

Section 8.1.4 of TR WCAP-16406-P, Revision 1, refers to pump vibration evaluations. The section refers to and summarizes numerous other sections and appendices in TR WCAP-16406-P, Revision 1. No additional technical data is presented. However, the NRC staff notes that the effect of stop/start pump operation is addressed only in the context of clean water operation, as noted in Section 8.1.4.5 of TR WCAP-16406-P, Revision 1. The NRC staff concludes that if an ECCS or CSS pump is operated for a period of time and builds up a debris "packing" in the tight clearances, stops and starts again, the wear rates of those areas may be different due to additional packing or imbedding of material on those wear surfaces. Licensees who use stop/start operation as part of their overall ECCS or CSS operation plan should address this situation in their evaluation.

Section 8.1.4 of TR WCAP-16406-P, Revision 1, states: "should the multistage ECCS pumps be operated at flow rates below 40% of BEP during the containment recirculation, one or more of the pumps should be secured to bring the flow rate of the remaining pump(s) above this flow rate." The NRC staff does not agree with this statement. System line-ups and pump operation and operating point assessment are the responsibility of the licensee. Licensees must ensure that its ECCS pumps are capable of performing their intended functions and NRC has no requirements as to its operating point during the recirculation phase of a LOCA.

Section 8.1.5 of TR WCAP-16406-P, Revision 1, provides additional discussion regarding example evaluations of a standard pump design. The NRC staff concludes that licensees must perform a similarity analysis showing that their condition is similar to or bounded by the examples shown if they are to be used in their evaluations.

Section 8.1.5 of TR WCAP-16406-P, Revision 1, makes a generic statement that all SI pumps have wear rings that are good "as new" based solely upon "very little service beyond inservice testing." TR WCAP-16406-P, Revision 1, also states: "The Westinghouse experience with the CCPs wear rings is that the amount of wear in most cases is negligible and seldom exceeds 3 mils on the diameter for those rings that show wear." The NRC staff notes, through discussion with the PWROG, that these pumps were pumping clean water and not debris laden fluid. The NRC staff concludes that anecdotal information and engineering judgment regarding inservice testing is not an adequate justification. A stronger basis is needed to validate the assumption that the wear rings are "as good as new", if used (e.g., maintenance, test and operational history and/or other supporting data).

The evaluation template and flowcharts contained in Section 8.1.6 are consistent with the information contained in other subsections of Section 8 and its referenced sections and appendices. No additional information is provided. The NRC staff finds the flowcharts and template acceptable based upon a review of Section 8 and its referenced sections and appendices.

Section 8.1.7 of TR WCAP-16406-P, Revision 1, is a listing of references used in Section 8.1. No specific technical review of each reference was performed.

Section 8.2 of TR WCAP-16406-P, Revision 1, provides a functional flowchart and process description summarizing the analyses presented in Section 7 and supporting Appendices. The flowcharts and guidance are consistent with the TR WCAP-16406-P, Revision 1, guidance in those sections. The NRC staff concludes that the flowchart provides a reasonable approach to organizing and evaluating the data previously determined. This is based on the NRC staff's review of Section 7 and supporting Appendices.

Section 8.3 of TR WCAP-16406-P, Revision 1, reiterates the need to perform standard heat exchanger wall thinning calculations using industry standard methods and to evaluate the consequences of wall thinning. As stated, the methods referenced are standard industry practice. The NRC staff finds the guidance presented acceptable as it represents widely accepted, standard industry practice. Section 8.3 also identifies criteria for consideration of tube plugging. It states that a plant-specific tube plugging evaluation is needed if a heat exchanger tube inner diameter (ID) is smaller than the largest expected particle. The NRC staff finds this criterion acceptable because particles smaller than the large (as compared to expected debris particle size) heat exchanger tubes will tend to pass through without causing blockage. Licensees should confirm that the fluid velocity going through the heat exchanger is greater than the particle settling velocity and evaluate heat exchanger plugging if the fluid velocity is less than the settling velocity.

Sections 8.4 and 8.5 of TR WCAP-16406-P, Revision 1, provide standard, industry-accepted, orifice and containment spray nozzle wear evaluation methods. As noted previously, in TR WCAP-16406-P, Revision 1, Section 8.1.2, the effect of orifice and containment spray nozzle wear must be incorporated into the overall system evaluation(s). The methods and criteria referenced for plant-specific evaluations are standard industry practice. The NRC staff finds the guidance presented acceptable as it represents widely accepted standard industry practice.

Section 8.6 of TR WCAP-16406-P, Revision 1, refers to evaluation of instrumentation tubing. Plugging evaluations of instrument lines may be based on system flow and material settling velocities as stated in TR WCAP-16406-P, Revision 1, Section 8.6. The NRC staff finds that this is a reasonable approach, but it must consider local velocities and low-flow areas due to specific plant configuration. The NRC staff finds the criterion for determining whether settling in instrument sensing lines occurs (transverse velocity less than 7 times the settling velocity) is acceptable because it calculates a higher minimum settling velocity than would be expected in a free-flowing, fully-developed, turbulent line, thus maximizing the potential for settling in a bottom mounted instrument line. The transverse velocity settling criterion was developed in TR WCAP-16406-P, Appendix L. The NRC staff's review of Appendix L is contained in Section 3.2.18.

Sections 8.6.7, 8.6.8, 8.6.9, and 8.6.10 of TR WCAP-16406-P, Revision 1, describe, in general terms, the Westinghouse, CE, and B&W reactor vessel level indication systems (RVLIS). TR WCAP-16406-P, Revision 1, recommends that licensees evaluate their specific configuration to confirm that a debris loading due to settlement in the reactor vessel does not effect the operation of its RVLIS. TR WCAP-16406-P, Revision 1, recommends that licensees specifically review their plant-specific EOPs, sensing line design, and system operation. The NRC staff finds that the general approach TR WCAP-16406-P, Revision 1, to evaluation is reasonable because it considers both formal design and operation of the system. The evaluation of specific RVLIS design and operation is outside the scope of this SE and should be performed in the context of a licensee's reactor fuel and vessel evaluations.

Section 8.7 of TR WCAP-16406-P, Revision 1, refers to evaluation of system piping. The NRC staff finds that plugging evaluations of system piping should be based on system flow and material settling velocities. Licensees should consider the effects of local velocities and low flow areas due to specific plant configuration. A piping wear evaluation using the free-flowing wear model outlined in Section 7 should be performed for piping systems. The evaluation should consider localized high-velocity and high-turbulence areas. A piping vibration assessment should be performed if areas of plugging or high localized wear are identified.

3.2.7 TR WCAP-16406-P, Revision 1: Section 9 – Reactor Internals and Fuel Blockage Evaluation

Section 9 of TR WCAP-16406-P, Revision 1, deals with the possibility that the reactor vessel internals or the reactor fuel might be blocked or partially blocked by problematic insulation and debris. In this context, "problematic" insulation is taken to mean insulation that may result in flow path blockage in the reactor vessel or nuclear fuel, should it be ingested into the ECCS beyond the containment sump screen. The discussions in Section 9 are general in nature and provide a starting point from which more detailed evaluations might be formulated. The PWROG has provided more detailed generic evaluation methodology in TR WCAP-16793-NP, which was submitted for NRC staff review in June 2007 (Reference 15).

For the majority of PWRs, if a large break LOCA were to occur, the ECCS pumps would be aligned to inject into the reactor cold legs or directly into the reactor vessel downcomer from an external water source. Once the external water source became exhausted, the ECCS pumps would be aligned to take suction from the containment sump for continued recirculation of coolant so as to provide for long term core cooling. If the break were in a reactor system hot leg, the ECCS water would be forced through the reactor core toward the break. Core flow, including a small amount of core bypass flow, during the long-term cooling period would be equal to the total ECCS flow. If all ECCS pumps were assumed to operate, ECCS flow into the reactor system through the reactor vessel and into the core would be maximized. The maximum flow condition should be evaluated since it provides the greatest potential for debris transport to the reactor core and subsequent lodging within flow restrictions.

Following a large cold-leg break with ECCS flow into the reactor cold legs or directly to the downcomer, flow into the reactor core will eventually be limited to the replacement of that boiled away. The excess will be spilled out of the break, including any water injected into the intact cold-legs which will flow around the upper elevations of the downcomer to reach the break without passing through the core. The NRC staff requested that the PWROG provide a methodology to evaluate the consequences from long-term boiling in the core following a large cold-leg break. The long-term cooling period following a large cold-leg break represents a minimum core flow condition. Core blockage by debris under these conditions would add to the resistance which must be overcome for the ECCS water to reach the core and lead to additional spillage from the break. The methodology presented in TR WCAP-16793, “Evaluation of Long-Term Cooling Considering Particulate and Chemical Debris in the Recirculating Fluid,” (Reference 15) addresses these issues. TR WCAP-16793 is currently under review by the NRC staff, therefore no conclusions regarding it are presented in this SE.

The low pressure injection pumps at two-loop plants designed by Westinghouse inject directly into the upper plenum. These plants are known as upper plenum injection (UPI) plants. During the period when sump water is re-circulated following a large break LOCA, all operating ECCS pumps may be aligned to provide flow into the reactor vessel upper plenum. If the break were in a reactor system cold leg, the ECCS water would be forced through the reactor core toward the break. Core flow, including a small amount of core bypass flow, during the long-term cooling period would be equal to the total ECCS flow. If both low-pressure ECCS pumps were assumed to operate, ECCS flow into the reactor system through the reactor vessel and into the core would be maximized. The maximum flow condition should be evaluated since it provides the greatest potential for debris transport to the reactor core and subsequent lodging within flow restrictions.

Following a large hot-leg break with ECCS flow directed into the reactor upper plenum, water will flow into the core from above at a rate needed to replenish that boiled away. The excess will be spilled out of the break. The long-term cooling period following a large hot-leg break represents a minimum core flow condition for a UPI plant. With water only being added above the core, the NRC staff expects that the water in the reactor system cold leg piping will be stagnant since for flow to be established through the cold legs, water would have to be pushed over the tops of the U-bends of the steam generator tubing. Both excess ECCS flow and steam from the core would be expected to flow out of the broken hot-leg because of its lower elevation relative to the top of the steam generator tubes. Without a net flow through the core, boiling in the core would continue for an indefinite period, causing debris and chemicals to be concentrated. The NRC staff requested that the PWROG provide a methodology to evaluate the consequences from long term boiling in the core following a large hot leg break at a UPI plant. The methodology presented in Reference 15 addresses these issues.

Following a large cold-leg break at most operating PWRs or a large hot-leg break at a UPI plant, continued boiling in the core will act to concentrate the debris and chemicals in the water between the core coolant channels. Chemical reaction of the debris with the containment spray buffering agents and boric acid from the ECCS water in the presence of the core radiation field might change the chemical and physical nature of the mixture. Heat transfer might be affected by direct plate out of debris on the fuel rods or by accumulation of material within the fuel element spacer grids. During a February 7, 2007, public meeting (Reference 17), the NRC staff provided the PWROG representatives a list of considerations which should be addressed to resolve GSI-191 for the reactor core:

1. Methodology should account for differences in PWR RCS and ECCS designs
   Examples:
   - CE plants with smaller recirculation flows may produce extended core boiling long after hot leg recirculation begins. The extended boiling period may impact concentration of debris in core, plate-out, etc. Use of pressurizer spray nozzles for hot-leg recirculation should be evaluated for the potential of clogging with debris.
   - UPI plants with no cold leg recirculation flow may have no means of flushing the core following a large hot-leg LOCA and may need special consideration.

2. Hot spots may be produced from debris trapped by swelled and ruptured cladding.
   - Debris may collect in the restricted channels caused by clad swelling, and at the rough edges at rupture locations.
   - FLECHT tests have shown that swelled and ruptured cladding may not detrimentally affect the cladding temperature profile. The FLECHT tests did not include post-LOCA debris.

3. Long-term core boiling effects on debris and chemical concentrations in the core should be accounted for.
   - The evaluations should be similar to post-LOCA boric acid precipitation evaluations.
   - They should account for the change in water volume available to mix with constituents concentrated by the core from debris accumulation.
   - Partial blockage of the core creates alternate circulation patterns within the reactor vessel and will affect the concentration analysis.
   - Will the solubility limits be exceeded for any of the material dissolved in the coolant that is being concentrated by boiling in the core?
   - The lower plenum is often credited as part of the mixing volume to determine the timing for precipitation. Partial filling of the lower plenum by debris may reduce its effectiveness.

4. Debris and chemicals which might be trapped behind spacer grids could potentially affect heat transfer from the fuel rods and should be evaluated.
   - Analyses show that a partially filled spacer grid produces only a moderate cladding temperature increase even if only axial conduction down the cladding is considered.
   - Similar analyses show that a completely filled spacer grid with only axial conduction will result in unacceptable temperatures.
   - A physical basis for determining to what extent the spacer grids can trap debris, and the ability for the debris to block heat transfer needs to be provided.
   - The evaluation needs to include all the chemical and physical processes which may occur in the core during the long term cooling period.

5. Consideration should be included for plating out of debris and/or chemicals on the fuel rods during long-term boiling.
   - Long-term boiling in the core following a large LOCA may last for several weeks for some designs depending on the ECCS flow and core inlet temperature.
   - The concentration of materials in the core, and the potential for plate out on the fuel rods (boiler scale) from this material should be determined.
   - When the composition and thickness of the boiler scale has been determined, the effect on fuel rod heat transfer should be evaluated.

6. The PWROG needs to address whether high concentrations of debris and chemicals in the core from long-term boiling can affect the natural circulation elevation head which causes coolant to enter the core.
   - For a large cold leg break, the density difference between the core and the downcomer determines the hydrostatic driving head, and consequently the flow rate into the core.
   - As boiling continues, a high concentration of debris and chemicals in the core may increase the core density and reduce the flow into the core.

7. If hot spots are found to occur, the PWROG should address cladding embrittlement. Applicable experimental data for the calculated condition and type of the cladding should be presented to demonstrate that a coolable geometry is maintained.

The methodology presented in Reference 15 addresses the above seven issues. The NRC staff's SE for TR WCAP-16793-NP (Reference 15), will address the seven issues and NRC staff's assessment of them. Therefore the NRC staff has not reached any conclusions regarding the information presented in TR WCAP-16406-P, Revision 1: Section 9.

3.2.8 TR WCAP-16406-P, Revision 1: Section 10 – Plant Implementation

This section discusses system assessments, debris concentration, duty cycles, pumps, valves, heat exchangers, orifices, containment spray nozzles, piping and instrumentation tubing, reactor internals, and fuel. Discussions provide general guidance on how to evaluate SSCs. In all cases, sub-sections refer back to the specific section where the component or system was evaluated. Logic diagrams are provided showing the various steps needed to evaluate ECCS and CSS components. The logic diagrams refer to the different sections of TR WCAP-16406-P, Revision 1, for specific technical guidance.

Section 10.1 of TR WCAP-16406-P, Revision 1, introduces the section and provides no technical information. No NRC staff review was performed.

Section 10.2 of TR WCAP-16406-P, Revision 1, provides "Evaluation Flow Diagrams" for each reactor design. The NRC staff's review concludes that the flow charts are useful, logical and provide adequate general guidelines for evaluating the performance of a particular system or component. The TR WCAP-16406-P, Revision 1, sections referenced in the flowcharts should be used in the performance of specific component and systems evaluations. Most topical areas are addressed with the exception of reactor internals and fuel. This is acceptable since this area will be addressed in the context of TR WCAP-16793-NP (Reference 15).

Section 10.3 of TR WCAP-16406-P, Revision 1, repeats the inputs, from Section 5 of TR WCAP-16406-P, Revision 1, to be considered in calculating a time-dependent concentration. The NRC staff's review concludes that the information was correctly transcribed and is therefore, acceptable. The section contains no technical information and is a summary of useful information contained elsewhere in TR WCAP-16406-P, Revision 1.

Section 10.4 of TR WCAP-16406-P, Revision 1, provides a series of flow charts to assist licensees in their evaluation of pump mission time. Table 4.2-1 of TR WCAP-16406-P, Revision 1, defines a plant Category based on its Low-Head / Pressure Safety Injection to RCS Hot-Leg Capability. Figure 10.4-2 implies that Category 2 and 4 plants can justify low-head safety injection (LHSI) for hot-leg recirculation. However, these categories of plants only have one hot-leg injection pathway. The NRC staff concludes that Category 2 and Category 4 plant licensees should confirm that taking credit for the single hot leg injection pathway for their plant is consistent with their current hot leg recirculation licensing basis. The NRC staff also concludes that the evaluation method presented in Section 10.4 of TR WCAP-16406-P, Revision 1, does not alter or modify the current licensing basis of plants with regard to hot-leg recirculation. Thus, the current licensing basis of plants with only one hot leg injection pathway is not altered by the evaluation of downstream effects. Therefore, the evaluation method presented in Section 10.4 of TR WCAP-16406-P, Revision 1, is acceptable.

Figure 10.4-3 requires licensees of Category 5 plants to determine if the HPSI pump is required for hot-leg recirculation. The NRC staff notes, however, that Category 5 plants, by definition, have no hot-leg switchover capability. Therefore, the answer to the question, "Is HPSI pump required for hot leg recirculation?" is always "NO", which leads the licensee to note that the mission time is the time at which the LHSI pump meets boil-off requirements. This is acceptable since it has no effect on the HPSI pump evaluation.

The flow charts contained in TR Section 10.4 are an aid in determining an appropriate component mission time. The NRC staff review concluded that they do not alter or change, in any way, a plant's licensing basis. Consistent with Reference 9, appropriate plant-specific mission times for component evaluations should be established.

Section 10.5 of TR WCAP-16406-P, Revision 1, states that with the exception of shaft seal assembly, failure of the pressure boundary in a pump is not considered a possible consequence. The NRC staff accepts this statement. The expected post-LOCA fluid properties are not such to cause significant damage to a pump casing. TR WCAP-16406-P, Revision 1, also notes that wear affecting the structural integrity of pump hydraulic surfaces (impeller, diffuser, and volute) is not likely to be affected by more than a slight roughening or local pitting since the maximum debris loading expected in the post-LOCA fluid is limited to much less than 1 percent (such as 0.1 percent). The NRC staff accepts this statement. The expected post-LOCA fluid properties are not such to cause significant damage to pump hydraulic surfaces.

Section 10.5 of TR WCAP-16406-P, Revision 1, notes that, "The WCAP wear model does not require the same determination of bearing loads because the WCAP wear model was developed empirically." This statement applies to the free-flowing wear model and not to the Archard wear model. This is further clarified by the TR statement that "Plants who wish to use the Archard's wear model should obtain the bearing loads from their pumps suppliers." The NRC staff accepts these statements as they are consistent with other sections of TR WCAP-16406-P, Revision 1, which the NRC staff has accepted as documented elsewhere in this SE.

Section 10.5.1 of TR WCAP-16406-P, Revision 1, provides a narrative of the steps a licensee might go through in assessing hydraulic performance of a pump. TR WCAP-16406-P, Revision 1, states: "The first step in the evaluation process is to determine what flow margin exists for the pumps being evaluated during the recirculation phase, based on the minimum performance curves applicable for these pumps and the most conservative break location for the large break LOCA. The performance data are verified by the plant IST Program. The pump performance must be reconciled against the minimum acceptable performance developed by the plant's engineering staff based on a thorough review of the design basis (DB) and licensing basis (LB) for the plant." The NRC staff accepts this approach. It is consistent with Reference 9 and with good engineering practice. It calls for licensees to validate the appropriate and conservative operating characteristics prior to beginning any evaluation. Section 10.5.1 further summarizes the evaluation methods of TR WCAP-16406-P, Revision 1, Section 8.1. This section discusses loss of hydraulic efficiency and acceptance criteria due to the possible wear ring gap increases caused by abrasive wear. The NRC staff evaluation of Section 8.1 of TR WCAP-16406-P, Revision 1, in addressed in SE Section 3.2.6.

Section 10.5.2 of TR WCAP-16406-P, Revision 1, addresses cyclone separators and backup seal bushings (disaster bushings). Cyclone separators typically include orifices that have been shown susceptible to plugging with debris, and are especially sensitive to fibrous insulation. TR WCAP-16406-P, Revision 1, states: "Plants that are using cyclone separator should work with the seal manufacturer to determine if removing the cyclone separators would increase the seal package reliability for operation with debris in the pumpage." The NRC staff's assessment is that if a licensee pump contains a cyclone separator, it should be evaluated within the context of both normal and accident operation. The evaluation of cyclone separators is plant-specific and depends on cyclone separator design and the piping arrangement for a pump's seal injection system.

Seal packages used for the ECCS and CSS pumps may be equipped with disaster bushings to limit the leakage should the primary seal fail. TR WCAP-16406-P, Revision 1, recommends that licensees using pump seals equipped with carbon material disaster bushings should re-evaluate their use unless it can be shown that the leakage will be acceptable for the pump with a completely worn carbon bushing. The NRC staff agrees with this statement. This is consistent with Reference 9 and will both minimize leakage into pump rooms and enhance the safety and performance of ECCS and CSS pumps.

Section 10.5.3 of TR WCAP-16406-P, Revision 1, states that multistage pumps without a stiff rotating assembly require a rotor-dynamic evaluation. The NRC staff agrees that such an evaluation is needed. This expectation is consistent with Reference 13.

Section 10.6 of TR WCAP-16406-P, Revision 1, evaluates instrument lines or tubing as generally not being susceptible to blockage from debris ingested in the ECCS flow. The exception to this statement is side or bottom mounted instruments. Appendix L of TR WCAP-16406-P, Revision 1, is provided to aid licensees in this determination. TR WCAP-16406-P, Revision 1, suggests that instrument line and tubing routing be confirmed on a plant-specific basis. This confirmation may be via review of as-built drawings and, or if appropriate, plant walk-downs. The NRC staff finds that a licensee's evaluation should also consider local velocities and low flow areas due to specific plant configuration. With that exception, the NRC staff agrees with this section because it is consistent with Reference 13.

Section 10.7 of TR WCAP-16406-P, Revision 1, defers to Section 9 of TR WCAP-16406-P, Revision 1, for the review of reactor internals and fuel. No technical information was provided in this section and therefore, no NRC staff review was performed. As noted in Section 3.2.7 of this SE, the NRC staff has not reviewed in detail or accepted TR WCAP-16406-P, Revision 1, Section 9.

TR WCAP-16406-P, Revision 1, Section 10.8, Valves states: "See Section 8.2." No NRC staff review was performed.

3.2.9 TR WCAP-16406-P, Revision 1: Appendix A – Generic Letter 2004-02

Appendix A is a copy of GL 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized Water Reactors," dated September 13, 2004. This was provided in TR WCAP-16406-P, Rev. 1 for information only. A technical review of the GL 2004-02 is not within the scope of this SE.

3.2.10 TR WCAP-16406-P, Revision 1: Appendix B – Westinghouse ECCS and CSS Components, Appendix C – CE ECCS and CSS Components and Appendix D – B&W ECCS and CSS Components

The information included in Appendices B, C, and D was compiled from a variety of sources, and is not assumed by NRC staff to be 100 percent accurate. For each plant-specific evaluation, plant personnel should not rely on these appendices but rather should verify their current configuration. This information was provided for information only. A technical review of these appendices is not within the scope of this SE.

3.2.11 TR WCAP-16406-P, Revision 1: Appendix E – Reactor Internals and Fuels Considerations

This section of TR WCAP-16406-P, Revision 1, is empty of content.

3.2.12 TR WCAP-16406-P, Revision 1, Appendix F – Component Wear Models

Two wear rate models are developed in Appendix F, an abrasive wear model and an erosive wear model. The wear models are tools for determining the effects of debris-laden fluid on ECCS and CSS components downstream of the containment sump. The models are empirical in nature and were developed from data collected by Westinghouse from testing and from open literature that are provided in Appendix F.

TR WCAP-16406-P, Revision 1, Appendix F, Section F.1 provides a brief background on component wear models. No technical information is provided and therefore no NRC staff evaluation was performed.

As stated in Section F.2 of TR WCAP-16406-P, Revision 1, "Abrasive wear is the removal of material due to hard or sharp particles that get in between two close-proximity surfaces that are in motion; that is, the wear from an abrasive particle trapped between two surfaces in motion. In pumps, abrasive wear affects the wear rings, impeller hubs, bushings, and diffuser rings." The NRC staff agrees that this is a reasonable statement and in accord with widely accepted industry definitions.

TR WCAP-16406-P, Revision 1, Appendix F, Section F.3, describes a 1977 Westinghouse test of a two-stage vertical pump. Information on the test and test results is provided. The NRC staff considers the information reference material and did not perform a technical review of the test or data.

TR WCAP-16406-P, Revision 1, Appendix F, Section F.4, develops a free-flowing abrasive wear model to be considered in the evaluation of pump internal components. TR WCAP-16406-P, Revision 1, Section F.4, refers to two technical papers: "Effects of Surface Hardness and Other Material Properties on Erosive Wear of Metals by Solid Particles," by Sherdon and "Abrasive Wear of Steels in Handling of Bulk Particulates: An appraisal of wall friction measurement as an indicator of wear rate," by Bradley, Bingley, and Pitman (TR WCAP-16406-P, Revision 1, References F.4-1 and F.4-2). The equations and relationships used and cited in Section F.4 are from these two references. The NRC staff reviewed these papers and find that they appropriately address the abrasive wear of metal components similar to those found in nuclear power plant components.

TR WCAP-16406-P, Revision 1, Section F.4, manipulates the equations therein and compares the results with test data from Westinghouse testing performed in 1977 on a two-stage vertical pump. The NRC staff's review concludes that the analytical results agree reasonably well with the 1977 test results. The PWROG then compares the Westinghouse data to generic publicly available data from the Davis-Besse pump wear rate testing performed in 2003. The NRC staff's review confirms that the analytical results compare reasonably well with the Davis-Besse data.

TR WCAP-16406-P, Revision 1, Section F.4.4, performs a sample calculation using the limited Davis-Besse/MPR data to show that the free-flowing abrasive wear model is a reasonable approach. From the Davis-Besse/MPR data, the TR example assumes 920 PPM abrasive material. This concentration is the concentration assumed in the 1977 Westinghouse test and was used because no Davis-Besse/MPR concentration data was available. The example also uses an average stellite 6B hardness. The NRC staff finds that the concentration and hardness assumptions are nominal values and therefore reasonable for use in a sample calculation. Using the free-flowing equations developed in Appendix F, the TR calculates a wear rate of the Davis-Besse HPI pump wear rings. The results show that the free-flowing model calculates a wear-rate 25 percent greater than the published Davis-Besse data. The NRC staff concludes that the free-flowing wear model can calculate reasonable wear rates based on appropriate inputs. The NRC staff also concludes that, while the method may be applicable to conditions mirroring the 1977 test, they may not be generically applicable to all pumps. The free-flowing model does not take into account such parameters as bearing loads, stage-to-stage pressure, pump speed etc. As discussed in TR WCAP-16406-P, Revision 1, Section 7.2.5, and Appendices O, P, and R, this method may not be applicable to discharge wear ring evaluations. Prior to using the free-flowing abrasive model for pump wear, the licensee should show that the benchmarked data is similar to or bounds its plant conditions.

The erosive wear model developed in Appendix F.5 is not applicable to pumps. It is intended to be used for valve surfaces, heat exchangers, piping, tubes, orifices, and other similar components. This section develops a general wear model for components based on technical literature published in the coal and slurry pumping industries. The NRC staff finds that the methods presented are well founded, complete, and based on standard and widely accepted technical practice. The NRC staff reviewed the references and equations finds that the information has been appropriately represented. The NRC staff reviewed the data supporting Equation F.5-8 and finds that this linear equation reasonably predicts wear rates at debris concentrations below 18 mass percent. For any value above 18 percent, the equation predicts wear rates greater than that associated with a 46 percent mass slurry. This is well above any concentration postulated in post-LOCA fluid. Therefore, the NRC staff finds its application acceptable.

The wear rate for carbon steel component calculations other than pumps in erosive media is defined by F.5-11a and F.5-11b. These equations were extracted from TR WCAP-16406-P, Revision 1, Reference F.5-2, Goddard, J. B., “Abrasion Resistance of Piping Systems,” ADS-Pipe Technical Note 2.116, November 1, 1994. The NRC staff finds these equations to be acceptable because they are widely-used, industry accepted equations.

The wear models developed in Sections F.4 and F.5 are based on the assumption that all debris particulates contribute equally to erosive wear regardless of their size. This is conservative as smaller particles will cause less wear than larger particles. By assuming that the wear contribution of small particles applies equally to that of large particles, wear rate is maximized. The NRC staff, therefore, finds the wear models described in Appendix F, Sections F.4 and F.5 acceptable.

TR WCAP-16406-P, Revision 1, Section F.5.2, Attachments F.1 and Attachment F.2, present a sampling of industrial data on wear rates of metals under abrasive slurries, hardness values and wear resistant materials. Staff did not review the data for accuracy. The NRC staff concludes that licensees should confirm the composition of their components and abrasive debris mix prior to using this information.

In Sections F.6, F.7, and F.8 the approaches of Sections F.4 and F.5 are refined. Debris mix is a plant-specific input. Specifically, Section F.6 adjusts the wear rate equation for carbon steel components. Equation F.6-1 separates out the mass fractions to account for the distribution of small medium and large particles. This would allow a licensee to account for actual distribution of material sizes. The NRC staff finds that the refinements are consistent with the approaches detailed in F.4 and F.5. Section F.7 defines small, medium, and large particles and refers to a licensee's debris generation and transport analysis to define the mass fractions. The NRC staff finds that this approach agrees with Reference 9 and is therefore acceptable. Section F.8 provides the steps to incorporate the mass fractions into the equations of Appendix F. The NRC staff review finds that the steps do not change the bases, assumptions, or use of the equations and are therefore acceptable. The refinements in TR Sections F.6, F.7 and F.8 do not change the analytical methods or basic assumptions and are, therefore, acceptable. The NRC staff also concludes that assumptions regarding the constituents of post-LOCA fluid should be consistent with those identified in other analysis supporting the response to GL 2004-02.

3.2.13 TR WCAP-16406-P, Revision 1, Appendix G: Proceedings of the Eighth NRC/ASME Symposium on Valve and Pump Testing

Appendix G is a copy of a NUREG/CP-0152, Volume 5 paper, "Design, Testing, and Implementation of Modifications to the Davis-Besse HPI Pumps for Debris Laden Water Operation," presented at the Eighth NRC/ASME Symposium on Valve and Pump Testing, July 12, 2004. The information was provided as reference material and is used in various Appendices to TR WCAP-16406-P, Revision 1. The application of this paper in support of these appendices is discussed on a case-by-case basis within the context of the particular Appendix. A specific technical review of this paper is not within the scope of this SE and was not performed. The NRC staff finds that prior to using the information and data from this paper in the evaluation of their systems and components, a licensee should ensure that the tests and experiments are applicable to, or bound their specific situation.

3.2.14 TR WCAP-16406-P, Revision 1: Appendix H – Vendor Inputs

Appendix H summarizes the inputs received from equipment vendors. Flowserve (Pump Division) provided information on pumps manufactured by Flowserve. Copes Vulcan and Flowserve (Flow Control Division) provided information on the types of materials used to resist valve wear. A technical review of this section was not requested and is not within the scope of this SE. However, the following NRC staff comments apply to the users of this section.

In Section H.2.1, Flowserve - Pump Input, pages H-3 thru H-7, Flowserve provides comments and observations regarding the PWROG wear models. The results of these comments and observations were revisions to Sections 7, 8, and Appendix F. The text is provided for reference and background information only. Validation of the methods in Sections 7, 8 and Appendix F is further discussed in TR WCAP-16406-P, Revision 1, Appendices O, P, Q, R, and S.

A Flowserve paper entitled the "Effect of Erosion due to Contamination on Pump Life for Nuclear Safety Pumps" is presented on pages H-8 thru H-19. The paper presents standard Department of Energy (DOE) methods to estimate impeller wear based upon a sand-like contamination. It considers an 11-stage, 4850 revolutions per minute (rpm), Flowserve Type RLIJ Pump operating at approximately 350 gallons per minute (gpm) at 4500 feet total developed head (TDH) at its best efficiency point (BEP). This style pump is representative of a HHSI pump common to the nuclear industry. The paper considers the hardness and concentration of hard sand-like contaminates and shows that pump impellers wear and provides a method to determine pump life based on impeller wear only. The wear and resulting pump inefficiencies should be factored into the pump and system hydraulic analyses.

The Flowserve, Lateral Rotor Dynamic Analysis, pages H-21 thru H-34, uses American Petroleum Institute (API) Standard 610, Annex 1 eighth edition in the evaluation of a 2.5 inch RLIJ 11 stage pump and an 3.0 inch JHF 10 Stage Pump. This Standard is for newly manufactured pumps not pumps with worn or damaged bearings, damaged rotors, damaged impellers, etc. It is appropriate in the context of rotor dynamic analysis. API-610 provides a standard analysis method for severe service pumps. The NRC staff finds that API-610 is a standard, widely-used, industry-accepted standard used in the manufacture and test of heavy-duty, centrifugal pumps and is therefore acceptable for use in the evaluation of PWR ECCS and CS pumps. Licensees should verify that their pumps are “as good as new” prior to using the analysis methods of API-610. This validation may be in the form of maintenance records, maintenance history, or testing that documents that the as-found condition of their pumps.

If a licensee uses the results of the TR WCAP-16406-P, Revision 1, Appendix H, analysis rather than performing its own specific analysis, it must show how these conditions match or bound its conditions. Further guidance on assessing rotor dynamic stability and acceptance is contained in Sections 7, 8, and Appendices O, R, and S.

TR WCAP-16406-P, Revision 1, Section H.3, provides a list of typical hard facing material for valves in abrasive service. This is an informational list only. The licensee should evaluate its specific materials for suitability.

3.2.15 TR WCAP-16406-P, Revision 1: Appendix I – Mass Distribution of Failed Coatings vs. Debris Particle Size for Use in Evaluation of Sump Debris during Containment Recirculation following a LBLOCA

This Appendix provides guidelines for the treatment, categorization and amount of DBA Qualified, DBA Acceptable, Indeterminate, DBA Unqualified and DBA Unacceptable coatings to be used in a licensee’s downstream sump debris evaluation.

A technical review of coatings generated during a DBA is not within the scope of this SE. For guidance regarding this subject see the NRC staff’s SE of NEI-04-07 (Reference 13), Section 3.4 "Debris Generation." The SE discusses acceptable sizing of coatings debris. The text from the SE (p.43) is reproduced below.

> **Staff Conclusions Regarding GR Section 3.4.3.6 -** The staff concludes that acceptance of this section depends upon each plant-specific evaluation properly determining that the parameters selected for the analysis adequately reflect the insulation types actually used in that containment, and that the specific surface area used in the head loss calculation is properly determined.
>
> The staff did not independently verify all the data contained in GR Tables 3-2 and 3-3, however, the values presented agree with analyst perceptions for these materials.

Failed Coatings

The GR assumes that all failed coatings generate debris sizes equivalent to the coatings' basic constituent or pigment sizes which the methodology identifies as 10μm. The GR chose this value because experimental evidence was lacking regarding coating debris size generation during a postulated event. The industry pressure wash testing detailed in Appendix A to the GR provided some insight that coatings within the ZOI will likely fail by erosion resulting in debris sized in the range of 10μm−50μm spheres. The testing also provided insight that the "qualified" epoxy and "qualified" IOZ coatings that were tested would not fail as chips or sheets during simulated jet-impingement testing. Coatings outside the ZOI that fail are also assumed to generate debris in sizes equivalent to their basic constituents or pigment sizes. This debris is on the order of 10μm spheres.

Staff Conclusions Regarding Failed Coatings: For plants that substantiate a thin bed, use of the basic material constituent (10 μm sphere) to size coating debris is acceptable. For those plants that can substantiate no formation of a thin bed that can collect particulate debris, the staff finds that coating debris should be sized based on plant specific analyses for debris generated from within the ZOI and from outside the ZOI, or that a default area equivalent to the area of the sump screen openings should be used. Such an analysis should conservatively assess the coating debris generated with appropriate justification for the assumed particulate size or debris size distribution. Degraded, "qualified" coatings that have not been remediated should be treated as "unqualified" coatings.

3.2.16 TR WCAP-16406-P, Revision 1: Appendix J – Characterization of Debris Size

Appendix J derives an approach to determining a generic characteristic size of deformable material that will pass through a strainer hole. The approach in TR WCAP-16406-P, Revision 1, concludes that a deformable material with a diameter of 110 percent of strainer hole diameter, a material length of 200 percent of strainer hole diameter or with a thickness of 50 percent or less of hole diameter may reasonably pass through. This is based, in part, on the deformability of small particles. The NRC staff finds this approach reasonable and conservative for use in determining the amount of deformable material that passes through a sump screen for the following reasons: Reference 9 notes that material larger than a sump screen hole may pass through. Assuming that material 110 percent of screen size passes through the hole accounts for deformable material. The bulk of hard particles and fibrous insulation are not deformable in small sizes and under small driving forces. Therefore the NRC staff finds the assumption of 110 percent criterion for deformable material acceptable. Current screen designs minimize pressure drop across a screen. TR WCAP-16406-P, Revision 1, assumes that deformable material with a length twice (200 percent) or less of the strainer hole diameter passes through. The NRC staff finds that this is conservative as it accounts for a complete bending in half and passing through of a deformable particle. TR WCAP-16406-P, Revision 1, also assumes that any deformable strand with a thickness 50 percent or less of the strainer hole diameter passes through. The NRC staff finds that this is conservative as it accounts for the potential of a complete bending in half of a strand and allowing the bent strand to completely pass through the strainer. Assuming material significantly larger than the strainer hole size, and that all deformable material can fully bend in half and can therefore pass through is conservative in that it maximizes plugging and wear potential of downstream components. The NRC staff notes that these parameters are only applicable to screens and are not applicable to determining material that will pass through other close tolerance equipment.

TR WCAP-16406-P, Revision 1, Appendix J, states that all non-deformable material smaller in diameter and length than the screen hole size passes through. The NRC staff accepts this statement because it is consistent with the NRC staff's SE on NEI 04-07 (Reference 13).

3.2.17 TR WCAP-16406-P, Revision 1: Appendix K – Depletion Coefficients for Fibrous and Non-fibrous Debris

Appendix K documents the basis for the depletion coefficient (λ=0.07) for fibrous and non-fibrous debris when performing plant specific evaluations.

The TR states that two broad categories of debris can exist in the containment sump at the start of containment recirculation; non fibrous (abrasives, paint chips, etc.) with specific gravities significantly greater than that of water, and fibrous debris (from fibrous insulation) with specific gravities close to that of water. The first type will tend to settle out in low flow velocity regions, while the second type will tend to be carried along with the flow to be captured by the sump screen.

The depletion of the fibrous or non-fibrous debris is an exponential function as described in report Section 5.8, "Particulate Debris Concentration Depletion," and Section 5.10, "Fibrous Debris Concentration Depletion." The NRC staff's evaluation of these sections is contained in SE Section 3.2.3.

The NRC staff notes that for fibrous debris, the debris depletion rate is primarily determined by the capture efficiency of the containment sump screen. This is because, once in solution, debris will stay in solution and depletion will be governed by Stokes law and settling velocities. Containment sump screens may act as filter beds filtering out debris in solution.
Section 5.10 of TR WCAP-16406-P, Revision 1, lists the test results of the fibrous debris capture efficiency of screens with different mesh size (from 1/4 inch to 1/16 inch) and sump screen approach velocities from 0.208 ft/sec to 1.065 ft/sec. The results show that, for approach velocities less than 1 ft/sec, the screen capture efficiency was 95 percent or better for screen sizes 1/4 inch to 1/16 inch. The approach flow velocities for most current PWR sump screens during containment recirculation are 0.2 ft/s or less, with some approach flow velocities expected to be as low as 0.005 ft/sec. Report Figure 5.11-1 shows that a 95 percent capture efficiency would result in a fibrous debris depletion half-life much less than four hours. Therefore, the NRC staff agrees that using a half-life of 10 hours (λ=0.07) is conservative for fibrous debris.

TR WCAP-16406-P, Revision 1, states that for non-fibrous debris, the debris depletion rate is primarily determined by the settling rate in the low fluid velocity regions of piping, the containment floor, or in the reactor vessel core inlet plenum. Appendix K ignores the potential for settling in containment or in system piping. This is conservative because it assumes that all material that passes through a sump screen will pass through to the reactor vessel and core, thus maximizing debris concentrations in the vessel and core. From report Section 5.9, a representative fluid velocity in the reactor vessel lower plenum, just below the core, is approximately 0.1 ft/s during the containment recirculation phase of a postulated LBLOCA accident. The fluid velocity of 0.1 ft/s was in a sample calculation in TR WCAP-16406-P, Revision 1, Section 7.2.1. The NRC staff did not evaluate the implications or validity of this number, as in-vessel effects will be addressed in the staff's review of TR WCAP-16793-NP (Reference 15).

The NRC staff reviewed the use of the methods in Section 5 of TR WCAP-16406-P, Revision 1, which provide a sample calculation in Section 7.2.1. Table 7.2-1 shows that the debris depletion half-life for a cold leg break with 1 or 2 RHR pumps is approximately three hours. Using this same method, the two hot-leg breaks were shown to have debris depletion half-lives of one and two hours. The NRC staff reviewed the sample calculation, TR Reference 8.1-13, that concluded that a reasonable depletion half-life for a cold-leg break was three hours and found it acceptable based on its use of the methods of TR Section 7 (accepted by the NRC staff in Section 3.2.5 of this SE) and representative hot and cold-leg flow-rates. Therefore, the NRC staff concludes that using a debris depletion half-life of 10 hours (λ=0.07) is conservative for non-fibrous debris in the containment sump.

Based upon the above, the NRC staff also concludes that a debris depletion half-life of 10 hours (λ=0.07) is reasonable for use for an overall depletion rate for both fibrous and non-fibrous debris. However, as stated in Section 3.2.3 of this SE, licensees should validate that the examples used in Section 5 bound their configuration. The licensee may use experiments or tests to determine a more representative depletion coefficient. The test protocol for performing these tests and the suitability of the results for use in downstream evaluations is the responsibility of the licensee.

3.2.18 TR WCAP-16406-P, Revision 1: Appendix L – Basis for Settling Velocity Multiplier for Bottom Mounted Instrument Lines

Appendix L provides the basis for using a settling velocity multiplier of seven to determine a minimum local system flow velocity at entrained debris will not settle out in bottom mounted instrument lines. A bottom mounted instrument line is defined as a line installed below the horizontal plane. There is no settling on debris in a line installed above the horizontal plane. The Appendix references a technical paper on the subject and then applies a slight conservatism. The NRC staff reviewed the paper and agrees that it is appropriate and conservative. The assumption that the Richardson number is assumed to be zero is appropriate since the analysis is being applied to tubing where there is expected to be negligible temperature difference across the tubing length and therefore the assumption of a Richardson Number of zero is appropriate. The NRC staff finds the criterion for determining whether settling in instrument sensing lines occurs (transverse velocity less than seven times the settling velocity) is acceptable because it calculates a higher minimum settling velocity than would be expected in a free-flowing, fully-developed, turbulent line, thus maximizing the potential for settling in a bottom mounted instrument line.

The NRC staff notes that this setting factor is only applicable for bottom-mounted instrument taps and may be applied to the various types of entrained debris. The determination of initial settling velocities of the entrained material may be based on standard textbook reference or by test.

3.2.19 TR WCAP-16406-P, Revision 1: Appendix M – Bibliography

This section is general in nature and was included for informational purposes only. A technical review of this section was not performed and is not within the scope of this SE.

3.2.20 TR WCAP-16406-P, Revision 1: Appendix N – Basis for 1/8-Inch Fiber Bed Thickness Acceptance Criterion for GSI-191 Downstream Effects Fuel Evaluation

This appendix addresses the possibility that sufficient fibrous debris could pass through the sump screen to collect at fuel element flow restrictions, such as the inlet debris strainers or the fuel bundle support grids so as to make a continuous blanket across a core plane. Maximum core inlet head loss from these evaluations was compared with the head loss from the tests described in NUREG/CR-6224 (Reference 11) and the NRC SER on NEI 04-07 (Reference 9). A review of this comparison is not considered part of this SE. In-vessel effects will be addressed in the NRC staff's SE of TR WCAP-16793-NP (Reference 12).

3.2.21 TR WCAP-16406-P, Revision 1: Appendix O – Asymmetric Wear of Close Running Clearances in Multistage Pumps due to Debris in the Pumped Fluid

Appendix O provides a method to determine the running clearances within a pump operating with debris-laden fluid. Archard's wear model is presented with clarifying sections on a method to determine shaft centering load. The Archard wear model is primarily a two-body analysis tool. The NRC staff review concludes that the two-body method is reasonable and provides conservative results when compared to a three-body, or free-flowing wear model. The two-body method more closely models pump operation and calculates higher wear rates.

TR WCAP-16406-P, Revision 1, Appendix O, Section 1.1, contains a discussion of Westinghouse/Pacific Pumps testing showing that softer materials (graphite) would wear rapidly at debris concentrations of 92 ppm and 920 ppm when a pressure drop caused flow in the running clearance. The data from the test was used to develop a free flowing abrasive wear model described in Appendix F. This section summarizes test data and provides no additional technical information. Therefore, no NRC staff review was performed.

TR WCAP-16406-P, Revision 1, Appendix O, Section 1.2, contains a discussion of the Davis-Besse wear results. The wear of the stellited rings was mentioned but nothing was said of the tungsten carbide wear rings. Tungsten carbide hard coating comes in a number of grades with varying amounts of carbide in the cobalt or nickel matrix. The hardness of these grades varies significantly depending on the concentration of tungsten carbide. The NRC staff notes that the hardness of the wearing material is important compared to the hardness of the debris. The difference in the hardness provides the abrasive wear driving force. Therefore, users should ensure that appropriate hardness numbers are selected for use in their evaluations as discussed in Sections 3.2.12 and 3.2.14.

TR WCAP-16406-P, Revision 1, Appendix O, Section 1.3, contains a discussion of testing at Wyle Laboratories performed with coating debris in a simulated wear ring fixture. TR WCAP-16406-P, Revision 1, states the results showed a type of wear characteristic of the Archard model. This section summarizes test data and provides no additional technical information. Therefore, no NRC staff review was performed.

The testing described in TR WCAP-16406-P, Revision 1, Appendix O, Sections 1.1, 1.2, and 1.3 indicates that abrasive wear in the close running clearances may result from free flowing abrasive wear (see Appendix F) or packing type abrasive wear as described by the Archard model. As stated in TR WCAP-16406-P, Revision 1, Appendix O, Section 1.4, describes the principal differences between the Archard wear model and the free flowing abrasive wear model as:

1. The wear associated with the Archard model is single sided. The debris packing adheres to the stationary surface (wear rings), and wear only the rotating surface (impeller hub). The free flowing abrasion model wears both the rotating and the stationary surfaces individually at rates determined by the fluid debris concentration and the hardness of the wear surfaces.

2. The wear rate of Archard's model is constant. Once the packing is established, debris depletion in the bulk fluid does not affect the rate of wear. For the free flowing abrasive wear model, the rate of wear is a direct result of the debris concentration in the fluid at any time during the pump duty cycle.

3. The packing type wear, as described by the Archard wear model, may be limited to a diametric clearances up to 0.050 inch based on limited data from the testing at Wyle Laboratories. The debris packing can be expelled from the running clearance due to the increased axial load on the packing caused by the increased running clearance.

The NRC staff finds that the three principal differences between the free-flowing model and the Archard wear model are accurately stated and in agreement with the descriptions of the models in the TR WCAP-16406-P, Revision 1. TR WCAP-16406-P, Revision 1, also states: "For the evaluation of the dynamic stability of multistage pumps, the analysis must consider the most conservative wear model of the running clearances." The NRC staff finds this statement acceptable as it requires a user to determine the worst-case wear and to evaluate the pump based on this worst-case wear.

A recommended process for evaluating the wear of the close running clearances in multistage pumps is depicted in TR Figure O-1. The process is based on observations from the Westinghouse, Davis-Besse, and Wyle testing. The NRC staff finds that flow chart is logical and consistent with the Sections and Appendices of TR WCAP-16406-P, Revision 1, and is therefore acceptable.

The NRC staff concludes that the Archard model can be implemented in the same way as the Westinghouse model because Archard can be adjusted to reflect change in debris concentration. Further, abrasive debris in the bulk fluid can be intermixed with the packing type plug and continue to produce wear during this period of blockage.

TR WCAP-16406-P, Revision 1, Appendix O, Section 2, notes that wear rates of discharge wear rings and the suction wear rings are different. Therefore, before a rotor dynamic, dynamic stability, analysis of multistage pumps can be performed; appropriate wear ring clearances must be calculated. The analysis must consider the most conservative wear model of the running clearances. The NRC staff agrees that this approach is appropriate and in concert with good engineering practice.

As discussed in TR WCAP-16406-P, Revision 1, Appendix O, discharge wear rings may be subject to a packing type wear, where debris packing builds up in the running clearance and partially shuts off the flow across the discharge wear rings. Once a "debris packing" is developed, the wear rate is not reduced by the debris depletion of the bulk fluid. The NRC staff agrees with this discussion. Reviews of the referenced test results support this concept. This assumption maximizes the wear rate in close tolerance components.

TR WCAP-16406-P, Revision 1, Appendix O, Section 2.1, describes engineering considerations for use in the review of multi-stage pumps. It provides a narrative of the physical actions occurring and briefly discusses the Davis-Besse testing results. The narrative and discussion are general in nature and reach no technical conclusions. TR WCAP-16406-P, Revision 1, does state that at some point, the material packed into the tight clearance locations of a multistage pump may expel when the worn opening becomes large enough. The method described in TR Appendix O assumes that all packing at all tight clearance locations expels at the same time. The NRC staff agrees that this is a conservative assumption since simultaneous expulsion of material, while unlikely, would cause maximum shaft support instability.

TR WCAP-16406-P, Revision 1, Appendix O, Section 2.2 states, "The packing type wear is best modeled by the Archard general equation for abrasive wear:

$$W = K * load * length/hardness$$

where:

W = volume of worn material
K = wear coefficient (For values of wear coefficient)"

TR WCAP-16406-P, Revision 1, states that load (L) may be obtained from the pump vendor based on design data or the maximum hydrostatic centering load may be calculated by the Lomakin effect (hydrostatic shaft support). An alternate method to estimate the load is to use the packing pressure distribution, as discussed in Appendix P. The wear coefficient, K, in the Archard Model is determined from testing. The NRC staff agrees that the centering load approach provides a reasonable way to estimate the Archard's model load parameter (L) and is in accordance with accepted tribological methods. The wear coefficient (K) is more uncertain and may vary widely. Therefore, licensees should provide a clear basis, in their evaluation, for their selection of a wear coefficient.

The NRC staff notes that this centering load is pump-specific, based on wear ring pressure drop, running clearance, running clearance diameter, and width of wear ring. The load represents the maximum hydraulic load that can be generated in the running clearances during pump operation. The NRC staff concludes that the methods presented (i.e., Archard's Wear equation and the calculation of the Lomakin effect) are standard, widely accepted pump design, and evaluation methods and are therefore acceptable.

TR WCAP-16406-P, Revision 1, Appendix O, Sections 3 and 5, use the centering loads, the Archard model and the Westinghouse 'free-flowing' abrasive model to calculate the suction and discharge wear ring clearances of a representative pump. Section 3 provides a comparison to the Davis-Besse data. The NRC staff reviewed the calculation and the Davis-Besse data and finds that it adequately validates the approach. Section 5 provides an example assuming a standard HHSI pump design and representative fluid and material properties. The NRC staff reviewed the example for mathematical accuracy and agrees with the sample results. As stated in previous SE sections, the design inputs are plant and component specific and should be validated prior to use.

TR WCAP-16406-P, Revision 1, Appendix O, Section 4, acknowledges the possibility of asymmetric wear conditions and refers licensees to TR WCAP-16406-P, Revision 1, Appendix R. The NRC staff agrees that asymmetric wear should be evaluated. The NRC staff's review of Appendix R is located in SE Section 3.2.24.

The NRC staff concludes that the methods provided in Appendix O are based on standard pump designer and manufacturer methods and offer a valid and reasonable approach to the calculation of suction and discharge wear ring clearances. This information is used as inputs to the rotor dynamics and internal bypass analysis discussed in other sections of TR WCAP-16406-P, Revision 1.

3.2.22 TR WCAP-16406-P, Revision. 1: Appendix P – An Estimation of Packing Load for Archard's Wear Model across a Rotating Pump Shaft

Appendix P provides a method to estimate the load (L) in Archard's Wear model in a packed shaft where the packing is exposed to high pressure on one side and low pressure on the other side. This situation is representative of wear at wear rings or bearing surfaces in a multi-stage pump. In Appendix O, a packing load (L), using the centering load approach, was developed. Appendix P presents an alternate approach to estimating the packing load, L, using the pressure distribution in a packed system.

The method in TR WCAP-16406-P, Revision 1, assumes that the debris wedged in the pump running clearances acts similar to valve packing in a standard valve stuffing box orientation. As in valve packing design, the value of the coefficient of friction depends on a number of parameters, such as the surface finish, the abrasiveness of the debris mix (packing), the debris concentration and the lubricity of the process fluid.

The method in TR WCAP-16406-P, Revision 1, was benchmarked against the data from the Davis-Besse testing of the discharge wear rings. While Davis-Besse specific data was not available, TR WCAP-16406-P, Revision 1, assumed a debris concentration of 1000 parts per million (ppm) consisting primarily of abrasives. Using Archard's model for packing type wear, the required contact load was determined.

The NRC staff notes that Archard's wear coefficients can vary widely and Archard's model does not specifically address debris concentration. The wear coefficient (K) can be adjusted to account for the abrasivity of the mix of debris concentrations (i.e., coatings, fibers, and particulates).

The NRC staff's review of TR WCAP-16406-P, Revision 1, Appendix P, concludes that, while the method presented provides a reasonable estimate of the load needed for discharge wear ring estimation with packing, it is dependent on component-specific and plant-specific parameters such as the inter-stage differential pressures, the wear surface dimensions, and material hardness. The licensee should incorporate the appropriate design parameters of the specific pump of interest. The method was benchmarked for a single situation. Licensees would be expected to provide a discussion as to the similarity and applicability to their conditions.

3.2.23 TR WCAP-16406-P, Revision 1: Appendix Q – Bounding Debris Concentration

TR WCAP-16406-P, Revision 1, Appendix Q discusses bounding debris concentration for use in evaluating component wear. The wear model for free flowing abrasive wear in TR WCAP-16406-P, Revision 1, Sections 7 and 8, were based on a debris concentration of 920 PPM by weight. The debris mix for this concentration was: 600 PPM abrasive particulates, 120 PPM fibrous, 200 PPM failed coatings. Free flowing abrasive wear is a linear relationship, assuming the ratio of abrasive to fibrous particulate remains constant. Failed coatings are generally softer debris than particulates, and expected to be significantly less abrasive than the other two components. TR WCAP-16406-P, Revision 1, scaled the abrasive wear factor, 9.02E-5 (mils/hr)/10 PPM, to account for concentrations greater than 720 ppm abrasive. The NRC staff review concludes that this is conservative and reasonable as long as the ratio of abrasive to fibrous debris is less than the 5 to 1 ratio assumed for the examples in TR WCAP-16406-P, Revision 1.

As stated in previous SE sections, the NRC staff notes that debris concentrations are plant-specific. If 9.02E-5 (mils/hr)/10 PPM is to be used as the free flowing abrasive wear constant the licensee must show how it is bounding or representative of its plant.

3.2.24 TR WCAP-16406-P, Revision 1: Appendix R - Wear Limits for Asymmetric Wear

The purpose of Appendix R is to evaluate wear limits for the asymmetric wear condition. The results of Appendices O and P are reviewed against the criteria in Appendix R.

In evaluating pump vibrations, TR WCAP-16406-P, Revision 1, refers to API-610, to define wear limits based on separation margin and damping ratio. These limits are shown in API-610, Annex I, Figure I-1. The figure shows an acceptable region where no further evaluation is needed, and an unacceptable region where further evaluation is necessary.

TR WCAP-16406-P, Revision 1, states that if the dynamic analysis shows operation within the unacceptable region, increased pump vibrations can be expected. Further evaluation of the pump (such as response analysis, evaluation of required residual mission time, or other evaluations) is then required to determine the acceptability of the pumps. As stated earlier in this SE, API-610 is a recognized design standard for the design and operation of centrifugal pumps for petroleum, heavy duty chemical and gas industry services. The NRC staff finds that evaluating a pump's post-LOCA condition to 'new' pump design specifications provides reasonable assurance that the pump will operate acceptably and perform its intended function(s).

Based on API-610, a wear limit of 2X is generally applied. TR Appendix R states: "However, it should be noted that the dynamics analysis performed (WCAP-16406-P, Section 8.1.4) shows that symmetric wear limit(s) of up to 2.5X and 2.8X are acceptable for the pumps that were analyzed. Using these limits, for the ECCS multistage pumps, a total support stiffness for each impeller location (included both suction and discharge centering loads) should be 6.12 lbf/mil for pumps not analyzed (2X limit) or 3.51 lbf/mil for the pumps that have been analyzed (2.8X). As long as the sum of the suction and discharge support stiffness, based on asymmetric wear conditions meet or exceed these values, the dynamic analysis based on symmetric wear is considered bounding." The NRC staff finds that these stated conditions coincide with limits as shown in API-610, Annex I, Figure I-1, in the acceptable region where no further evaluation is needed. Therefore, the NRC staff finds that use of these criteria represents a bounding, analyzed condition.

Support stiffness and centering loads are as calculated in other Sections of TR WCAP-16406-P, Revision 1. The 'analyzed' results included in TR WCAP-16406-P, Revision 1, are those of a Pacific 11-stage 2.5" RLIJ pump. The analysis was performed by the PWROG using specific inputs. The NRC staff concludes that ECCS pumps with running clearance designs and dimensions significantly different than those covered by the analysis may require pump-specific analysis to determine the support stiffness based on asymmetric wear. The NRC staff also concludes that if licensees use the aforementioned example, a similarity evaluation should be performed showing how the example is similar to or bounds their situation.

3.2.25 TR WCAP-16406-P, Revision 1: Appendix S – Flowserve Report SR-1205, Revision 1, Parametric Rotor Dynamic Evaluation for Asymmetric Clearance Enlargement

Appendix S provides a Flowserve analysis on a Pacific 2.5" RLIJ 11 Stage Centrifugal Pump with a coupling weight of 29.6 lb. The purpose of the analysis was to investigate the effect of asymmetric wear of close running clearance components on the dynamic characteristics of the rotor bearing system with the goal of determining an upper limit on critical clearance enlargement of the pump wear rings. This report was provided as technical background and is referenced throughout TR WCAP-16406-P, Revision 1. The NRC staff notes that this style pump is similar to pumps used for HHSI in US PWRs. The NRC staff concludes that licensees should compare the design and operating characteristics of the Pacific 2.5" RLIJ 11 to their specific pumps prior to using the results of this Appendix in their component analyses.

4.0 LIMITATIONS AND CONDITIONS

The NRC staff reviewed TR WCAP-16406-P, Revision 1, and finds that a licensee may use TR WCAP-16406-P, Revision 1, to perform an assessment of the impact of debris on various equipment required by the ECCS, CSS, and nuclear steam supply system (NSSS) to maintain the core in a coolable geometry in a post-accident condition, subject to the following conditions and limitations.

1. Where a TR WCAP-16406-P, Revision 1, section or appendix refers to examples, tests, or general technical data, a licensee should compare and verify that the information is applicable to its analysis.

2. A discussion of EOPs, AOPs, NOPs or other plant-reviewed alternate system line-ups should be included in the overall system and component evaluations as noted in the NRC staff's SE of NEI 04-07, Section 7.3 (Reference 13).

3. A licensee using TR WCAP-16406-P, Revision 1, will need to determine its own specific sump debris mixture and sump screen size in order to initiate the evaluation.

4. TR WCAP-16406-P, Revision 1, Section 4.2, provides a general discussion of system and component mission times. It does not define specific times, but indicates that the defined term of operation is plant-specific. As stated in the NRC staff's SE of NEI 04-07, Section 7.3 (Reference 13), each licensee should define and provide adequate basis for the mission time(s) used in its downstream evaluation.

5. TR WCAP-16406-P, Revision 1, Section 5.8, assumes that the coolant which is not spilled flows into the reactor system and reaches the reactor vessel downcomer. This would be true for most PWR designs except for plants with UPI. Therefore, the methodology of Section 5.8 may not be applicable to plants with UPI and its use should be justified on a plant-specific basis.

6. TR WCAP-16406-P, Revision 1, Section 5.8, provides equations which a licensee might use to determine particulate concentration in the coolant as a function of time. Assumptions as to the initial particulate debris concentration are plant-specific and should be determined by the licensee. In addition, model assumptions for ECCS flow rate, the fraction of coolant spilled from the break and the partition of large heavy particles which will settle in the lower plenum and smaller lighter particles which will not settle should be determined and justified by the licensee.

7. TR WCAP-16406-P, Revision 1, Sections 5.8 and 5.9, assumes that debris settling is governed by force balance methods of TR Section 9.2.2 or Stokes Law. The effect of debris and dissolved materials on long-term cooling is being evaluated under TR WCAP-16793-NP (Reference 12). If the results of TR WCAP-16793-NP show that debris settling is not governed by force balance methods of TR Section 9.2.2 or Stokes Law, then the core settling term determined from TR WCAP-16793-NP should be used.

8. TR WCAP-16406-P, Revision 1, Section 7.2, assumes a mission time of 720 hours for pump operation. Licensees should confirm that 720 hours bounds their mission time or provide a basis for the use of a shorter period of required operation.

9. TR WCAP-16406-P, Revision 1, Section 7.2, addresses wear rate evaluation methods for pumps. Two types of wear are discussed: 1) free-flowing abrasive wear and 2) packing-type abrasive wear. Wear within close-tolerance, high-speed components is a complex analysis. The actual abrasive wear phenomena will likely not be either a classic free-flowing or packing wear case, but a combination of the two. Licensees should consider both in their evaluation of their components.

10. TR WCAP-16406-P, Revision 1, Section 7.2.1.1, addresses debris depletion coefficients. Depletion coefficients are plant-specific values determined from plant-specific calculations, analysis, or bypass testing. Licensees should consider both hot-leg and cold-leg break scenarios to determine the worst case conditions for use in their plant-specific determination of debris depletion coefficient.

11. TR WCAP-16406-P, Revision 1, Section 7.3.2.3, recognizes that material hardness has an effect on erosive wear. TR WCAP-16406-P, Revision 1, suggests that “For elastomers, the wear rate is at least one order of magnitude less than steel. Therefore, for soft-seated valves, divide the estimated wear rate of steel from above equations by 10 per Appendix F.” The NRC staff agrees that the wear rates of elastomers are significantly less than for steels. However, the wear coefficient should be determined by use of a suitable reference, not by dividing the steel rate by a factor of 10.

12. TR WCAP-16406-P, Revision 1, Section 8.1.1.2, “Evaluation of ECCS Pumps for Operation with Debris-Laden Water from the Containment Sump,” states that “Sufficient time is available to isolate the leakage from the failed pump seal and start operation of an alternate ECCS or CSS train.” Also, Section 8.1.3, “Mechanical Shaft Seal Assembly,” states: “Should the cooling water to the seal cooler be lost, the additional risk for seal failure is small for the required mission time for these pumps.” These statements refer only to assessing seal leakage in the context of pump operability and 10 CFR Part 100 concerns. A licensee should evaluate leakage in the context of room habitability and room equipment operation and environmental qualification, if the calculated leakage is outside that which has been previously assumed.

13. TR WCAP-16406-P, Revision 1, Section 8.1.3, discusses cyclone separator operation. TR WCAP-16406-P, Revision 1, generically concludes that cyclone separators are not desirable during post-LOCA operation of HHSI pumps. The NRC staff does not agree with this generic statement. If a licensee pump contains a cyclone separator, it should be evaluated within the context of both normal and accident operation. The evaluation of cyclone separators is plant-specific and depends on cyclone separator design and the piping arrangement for a pump’s seal injection system.

14. TR WCAP-16406-P, Revision 1, Section 8.1.4, refers to pump vibration evaluations. The effect of stop/start pump operation is addressed only in the context of clean water operation, as noted in Section 8.1.4.5 of TR WCAP-16406-P, Revision 1. If an ECCS or CSS pump is operated for a period of time and builds up a debris "packing" in the tight clearances, stops and starts again, the wear rates of those areas may be different due to additional packing or imbedding of material on those wear surfaces. Licensees who use stop/start operation as part of their overall ECCS or CSS operational plan should address this situation in their evaluation.

15. TR WCAP-16406-P, Revision 1, Section 8.1.4, states: "should the multistage ECCS pumps be operated at flow rates below 40% of BEP during the containment recirculation, one or more of the pumps should be secured to bring the flow rate of the remaining pump(s) above this flow rate." The NRC staff does not agree with this statement. System line-ups and pump operation and operating point assessment are the responsibility of the licensee. Licensees must ensure that their ECCS pumps are capable of performing their intended function and the NRC has no requirements as to their operating point during the recirculation phase of a LOCA.

16. TR WCAP-16406-P, Revision 1, Section 8.1.5, makes a generic statement that all SI pumps have wear rings that are good "as new" based solely upon "very little service beyond inservice testing." A stronger basis is needed to validate this assumption, if used (e.g., maintenance, test and operational history and/or other supporting data).

17. TR WCAP-16406-P, Revision 1, Section 8.3, identifies criteria for consideration of tube plugging. Licensees should confirm that the fluid velocity going through the heat exchanger is greater than the particle settling velocity and evaluate heat exchanger plugging if the fluid velocity is less than the settling velocity.

18. TR WCAP-16406-P, Revision 1, Section 8.6, refers to evaluation of instrumentation tubing and system piping. Plugging evaluations of instrument lines may be based on system flow and material settling velocities, but they must consider local velocities and low-flow areas due to specific plant configuration.

19. TR WCAP-16406-P, Revision 1, Sections 8.6.7, 8.6.8, 8.6.9, and 8.6.10 describe, in general terms, the Westinghouse, CE, and B&W RVLIS. TR WCAP-16406-P, Revision 1, recommends that licensees evaluate their specific configuration to confirm that a debris loading due to settlement in the reactor vessel does not effect the operation of its RVLIS. The evaluation of specific RVLIS design and operation is outside the scope of this SE and should be performed in the context of a licensees reactor fuel and vessel evaluations.

20. TR WCAP-16406-P, Revision 1, Section 8.7, refers to evaluation of system piping. Plugging evaluations of system piping should be based on system flow and material settling velocities. Licensees should consider the effects of local velocities and low-flow areas due to specific plant configuration. A piping wear evaluation using the free-flowing wear model outlined in Section 7 should be performed for piping systems. The evaluation should consider localized high-velocity and high-turbulence areas. A piping vibration assessment should be performed if areas of plugging or high localized wear are identified.

21. TR WCAP-16406-P, Revision 1, Section 9, addresses reactor internal and fuel blockage evaluations. This SE summarizes seven issues regarding the evaluation of reactor internal and fuel. The PWROG indicated that the methodology presented in TR WCAP-16793-NP (Reference 15) will address the seven issues. Licensees should refer to TR WCAP-16793-NP and the NRC staff's SE of the TR WCAP-16793-NP, in performing their reactor internal and fuel blockage evaluations. The NRC staff has reached no conclusions regarding the information presented in TR WCAP-16406-P, Section 9.

22. TR WCAP-16406-P, Revision 1, Table 4.2-1, defines a plant Category based on its Low-Head / Pressure Safety Injection to RCS Hot-Leg Capability. Figure 10.4-2 implies that Category 2 and 4 plants can justify LHSI for hot-leg recirculation. However, these categories of plants only have one hot-leg injection pathway. Category 2 and Category 4 plant licensees should confirm that taking credit for the single hot-leg injection pathway for their plant is consistent with their current hot-leg recirculation licensing basis.

23. TR WCAP-16406-P, Revision 1, Appendix F, discusses component wear models. Prior to using the free-flowing abrasive model for pump wear, the licensee should show that the benchmarked data is similar to or bounds its plant conditions.

24. TR WCAP-16406-P, Revision 1, Appendix H, references American Petroleum Institute (API) Standard 610, Annex 1 eighth edition. This standard is for newly manufactured pumps. Licensees should verify that their pumps are "as good as new" prior to using the analysis methods of API-610. This validation may be in the form of maintenance records, maintenance history, or testing that documents that the as-found condition of their pumps.

25. TR WCAP-16406-P, Revision 1, Appendix I, provides guidelines for the treatment, categorization and amount of DBA Qualified, DBA Acceptable, Indeterminate, DBA Unqualified, and DBA Unacceptable coatings to be used in a licensee's downstream sump debris evaluation. A technical review of coatings generated during a DBA is not within the scope of this SE. For guidance regarding this subject see the NRC staff's SE of NEI-04-07 (Reference 13) Section 3.4 "Debris Generation."

26. TR WCAP-16406-P, Revision 1, Appendix J, derives an approach to determining a generic characteristic size of deformable material that will pass through a strainer hole. This approach is only applicable to screens and is not applicable to determining material that will pass through other close tolerance equipment.

27. TR WCAP-16406-P, Revision 1, Appendix O, Section 2.2, states that the wear coefficient, K, in the Archard Model is determined from testing. The wear coefficient (K) is more uncertain than the load centering approach and K may vary widely. Therefore, licensees should provide a clear basis, in their evaluation, for their selection of a wear coefficient.

28. TR WCAP-16406-P, Revision 1, Appendix P, provides a method to estimate a packing load for use in Archard's wear model. The method presented was benchmarked for a single situation. Licensees are expected to provide a discussion as to the similarity and applicability to their conditions. The licensee should incorporate its own specific design parameters when using this method.

29. TR WCAP-16406-P, Revision 1, Appendix Q, discusses bounding debris concentrations. Debris concentrations are plant-specific. If 9.02E-5 (mils/hr)/10 PPM is to be used as the free flowing abrasive wear constant, the licensee should show how it is bounding or representative of its plant.

30. TR WCAP-16406-P, Revision 1, Appendix R, evaluates a Pacific 11-Stage 2.5" RLIJ pump. The analysis was performed by the PWROG using specific inputs. ECCS pumps with running clearance designs and dimensions significantly different than those covered by the analysis should be subjected to pump-specific analysis to determine the support stiffness based on asymmetric wear. If licensees use the aforementioned example, a similarity evaluation should be performed showing how the example is similar to or bounds their situations.

31. Licensees should compare the design and operating characteristics of the Pacific 2.5" RLIJ 11 to their specific pumps prior to using the results of Appendix S in their component analyses.

5.0 CONCLUSIONS

The NRC staff has reviewed TR WCAP-16406-P, Revision 1 and the supplemental information provided in letters dated July 13, 2006, April 16, 2007, May 8, 2007, and September 7, 2007, and finds that TR WCAP-16406-P, Revision 1, as modified and clarified to incorporate the NRC staff's limitations and conditions, provides an acceptable method and reference for licensees to use in evaluating the downstream impact of sump debris on the performance of their ECCS and CSS and components following a LOCA. TR WCAP-16406-P, Revision 1, as modified by the NRC staff limitations and conditions listed in Section 4.0 of this SE, is acceptable for licensee use at any time during either a facility's current operating term or extended license period. The use of TR WCAP-16406-P, Revision 1, will not endanger public health and safety.

6.0 REFERENCES

1. WOG Letter OG-06-71, Submittal of WCAP-16406-P Revision 0, "Evaluation of Downstream Sump Debris Effects in Support of GSI-191 (PA-SEE-0195), dated February 27, 2006 (ADAMS Accession No. ML060600457).

2. NRC Letter dated May 4, 2006, Response to Westinghouse Owners Group Letter No. WOG-06-71, dated February 27, 2006 requesting NRC Staff Review of Topical Report WCAP-16406-P, Draft Revision 0, "Evaluation of Downstream Sump Debris Effects in Support of GSI-191" (ADAMS Accession No. ML061220255).

3. WOG Letter OG-06-173, Submittal of WCAP-16406-P Draft Revision 1, "Evaluation of Downstream Sump Debris Effects in Support of GSI-191 (PA-SEE-0195), dated May 31, 2006 (ADAMS Accession No. ML061580182).

4. PWROG Letter OG-06-184, Submittal of Westinghouse Proprietary Reference Supporting WCAP-16406-P Draft Revision 1, "Evaluation of Downstream Sump Debris Effects in Support of GSI-191 (PA-SEE-0195), dated July 13, 2006 (ADAMS Accession No. ML061990194).

5. PWROG Letter OG-07-172, Submittal of Westinghouse Proprietary Reference Supporting WCAP-16406-P Draft Revision 1, “Evaluation of Downstream Sump Debris Effects in Support of GSI-191 (PA-SEE-0195), dated April 16, 2007 (ADAMS Accession No. ML071070557).

6. PWROG WCAP-16406-P, Draft RAI Responses, Revision 1, dated May 08, 2007 (ADAMS Accession No. ML072880563).

7. PWROG Letter OG-07-404, Submittal of WCAP-16406-P Revision 1, “Evaluation of Downstream Sump Debris Effects in Support of GSI-191 (PA-SEE-0195), dated September 7, 2007 (ADAMS Accession No. ML072550227).

8. PWROG WCAP-16406-P, Draft RAI Responses, Revision 1, dated September 20, 2007 (ADAMS Accession No. ML072880588).

9. NRC Letter dated August 22, 2006, Acceptance for Review of Topical Report WCAP-16406-P, Draft Revision 1, “Evaluation of Downstream Sump Debris Effects in Support of GSI-191”(PA-SEE-0195) (ADAMS Accession No. ML062150229).

10. Email from Sean Peters, USNRC to Thomas J. Laubham, Westinghouse PWR Owners Group, “WCAP-16406 Draft RAIs dated February 16, 2007” (ADAMS Accession No. ML072880614).

11. NRC Regulatory Guide 1.82, Water Sources for Long-Term Recirculation Cooling following a Loss-of-Coolant Accident, Revision 3, November 2003 (ADAMS Accession No. ML033140347).

12. NEI 04-07, Pressurized Water Reactor Sump Performance Evaluation Methodology, Revision 1 (ADAMS Accession No. ML050550138).

13. USNRC Safety Evaluation of NEI 04-07, Pressurized Water Reactor Sump Performance Evaluation Methodology, Revision 1 (ADAMS Accession No. ML043280641).

14. PWROG Web Cast, WCAP-16406, Revision 1 “Evaluation of Downstream Sump Debris Effects in Support of GSI-191” dated October 3, 2007 (ADAMS Accession No. ML072880600).

15. WCAP-16793-NP, “Evaluation of Long-Term Cooling Considering Particulate and Chemical Debris in the Re-circulating Fluid,” Westinghouse Electric Company LLC, May 2007. (ADAMS Accession No. ML071580139).

16. NUREG/CR-6885, “Screen Penetration Test Report”, Los Alamos National Laboratory, Submitted to US NRC, October. (ADAMS Accession No. ML053000064).

17. NRC Presentation GSI-191 Resolution Status Meeting, February 7, 2007, In-Vessel Downstream Effects (ADAMS Accession No. ML072890320).

18. NRC Generic Letter 2004-02, Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized-Water Reactors (ADAMS Accession No. ML042360586).

19. NUREG/CR-6916 Hydraulic Transport of Coating Debris, December 2006 (ADAMS Accession No. ML0702200610).

20. NUREG/CR-6224, “Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris, Final Report,” Science and Engineering Associates, Inc. (ADAMS Accession No. ML051590366).

21. American Petroleum Institute, API, Standard 610 (ISO 13709), Centrifugal Pumps for Petroleum, Heavy Duty Chemical and Gas Industry Services. September 2005 Edition.

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