U.S. NUCLEAR REGULATORY COMMISSION

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WATER SOURCES FOR LONG-TERM RECIRCULATION COOLING FOLLOWING A LOSS-OF-COOLANT ACCIDENT

A. INTRODUCTION

Purpose

This regulatory guide (RG) describes an approach that is acceptable to the staff of the U.S. Nuclear Regulatory Commission (NRC) to meet the regulatory requirements for sumps and suppression pools that provide water sources for emergency core cooling, containment heat removal, or containment atmosphere cleanup systems. It also provides guidelines for evaluating the adequacy and the availability of the sump or suppression pool for long-term recirculation cooling following a loss-of-coolant accident (LOCA), and the use of containment accident pressure (CAP) in determining the net positive suction head (NPSH) for the emergency core cooling and containment heat removal pumps. This guide applies to both the pressurized-water reactor (PWR) and boiling-water reactor (BWR) types of light-water reactors.

Applicability

This RG applies to reactor licensees subject to Title 10 of the *Code of Federal Regulations* (10 CFR) Part 20, "Standards for Protection against Radiation" (Ref. 1), and Appendix I, "Numerical Guides for Design Objectives and Limiting Conditions for Operation to Meet the Criterion 'As Low as is Reasonably Achievable' for Radioactive Material in Light-Water-Cooled Nuclear Power Reactor Effluents," to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities" (Ref. 2). It also applies to all holders of and applicants for a power reactor combined license, design certification, standard design approval, or manufacturing license under 10 CFR Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants" (Ref. 3).

Applicable Regulations

- 10 CFR Part 50 provides regulations for licensing production and utilization facilities.
  - 10 CFR 50.46(b)(5) requires that licensees of nuclear power plants provide long-term cooling of the reactor core.

Written suggestions regarding this guide may be submitted through the NRC's public Web site in the NRC Library at https://nrcweb.nrc.gov/reading-rm/doc-collections/reg-guides/, under Document Collections, in Regulatory Guides, at https://nrcweb.nrc.gov/reading-rm/doc-collections/reg-guides/contactus.html, and will be considered in future updates and enhancements to the "Regulatory Guide" series. During the development process of new guides suggestions should be submitted within the comment period for immediate consideration. Suggestions received outside of the comment period will be considered if practical to do so or may be considered for future updates.

Electronic copies of this RG, previous versions of RGs, and other recently issued guides are also available through the NRC's public web site in the NRC Library at https://nrcweb.nrc.gov/reading-rm/doc-collections/reg-guides/, under Document Collections, in Regulatory Guides. This RG is also available through the NRC's Agencywide Documents Access and Management System (ADAMS) at http://www.nrc.gov/reading-rm/adams.html, under ADAMS Accession Number (No.) ML22152A114. The regulatory analysis is associated with a rulemaking and may be found in ADAMS under Accession No. ML21266A186. The associated draft guide DG-1385, may be found in ADAMS under Accession No. ML21266A185, and the staff responses to the public comments on DG-1385 may be found under ADAMS Accession No. ML22145A479.

- 10 CFR Part 50, Appendix A, “General Design Criteria for Nuclear Power Plants,” General Design Criterion (GDC) 1, “Quality standards and records,” requires that structures, systems, and components important to safety be designed, fabricated, erected, and tested to quality standards commensurate with the importance of the safety functions to be performed.

- 10 CFR Part 50, Appendix A, GDC 4, “Environmental and dynamic effects design bases,” requires, in part, that systems important to safety be designed to accommodate LOCAs.

- 10 CFR Part 50, Appendix A, GDC 35, “Emergency core cooling,” requires that systems be provided to perform emergency core cooling following any loss of reactor coolant.

- 10 CFR Part 50, Appendix A, GDC 36, “Inspection of emergency core cooling system,” requires that the emergency core cooling system (ECCS) be designed to permit the appropriate periodic inspection of important components.

- 10 CFR Part 50, Appendix A, GDC 37, “Testing of emergency core cooling system,” requires, in part, that the ECCS be designed to permit appropriate periodic testing to ensure its integrity and operability.

- 10 CFR Part 50, Appendix A, GDC 38, “Containment heat removal,” requires that a system be provided to perform containment heat removal following any loss of coolant accident.

- 10 CFR Part 50, Appendix A, GDC 39, “Inspection of containment heat removal system,” requires that the containment heat removal system be designed to permit the appropriate periodic inspection of important components.

- 10 CFR Part 50, Appendix A, GDC 40, “Testing of containment heat removal system,” requires, in part, that the containment heat removal system be designed to permit appropriate periodic testing to ensure its integrity and operability.

- 10 CFR Part 50, Appendix A, GDC 41, “Containment atmosphere cleanup,” requires, in part, that systems be provided to perform containment atmosphere cleanup following a postulated accident.

- 10 CFR Part 50, Appendix A, GDC 42, “Inspection of containment atmosphere cleanup systems,” requires that the containment atmosphere cleanup systems be designed to permit the appropriate periodic inspection of important components.

- 10 CFR Part 50, Appendix A, GDC 43, “Testing of containment atmosphere cleanup systems,” requires, in part, that the containment atmosphere cleanup systems be designed to permit appropriate periodic testing to ensure their integrity and operability.

- 10 CFR Part 50, Appendix B, “Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants,” applies to all components of the facility, which would include suction strainer design, fabrication, testing, and operation.

- 10 CFR Part 50, Appendix B, Section XI, “Test Control,” requires that a test program be established to assure that all testing required to demonstrate that structures, systems, and components will perform satisfactorily in service. The regulation requires that appropriate testing be identified and performed in accordance with written test procedures that incorporate the requirements and acceptance limits contained in design documents. As components the ECCS suction strainers are subject to the requirements of 10 CFR 50, Appendix B, Section XI.

For nuclear power plants licensed before the GDC were developed, the licensee's updated final safety analysis report provides the applicable design criteria.

- 10 CFR Part 52 addresses licenses, certifications, and approvals for nuclear power plants.
  - 10 CFR 52.48, "Standards for review of applications," states that the GDC and quality assurance criteria also apply to nuclear power reactor licenses issued under 10 CFR Part 52.

Related Guidance

- NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition" (Ref. 4)

Purpose of Regulatory Guides

The NRC issues RGs to describe to the public methods that the staff considers acceptable for use in implementing specific parts of the agency's regulations, to explain techniques that the staff uses in evaluating specific problems or postulated events, and to provide guidance to applicants. Regulatory guides are not substitutes for regulations and compliance with them is not required. Methods and solutions that differ from those set forth in RGs will be deemed acceptable if they provide a basis for the regulatory findings required for the issuance or continuance of a permit or license by the Commission.

Paperwork Reduction Act

This RG provides voluntary guidance for implementing the mandatory information collections in 10 CFR Parts 50 and 52 that are subject to the Paperwork Reduction Act of 1995 (44 U.S.C. 3501 et seq.). These information collections were approved by the Office of Management and Budget (OMB), under control numbers 3150-0011 and 3150-0151, respectively. Send comments regarding this information collection to the FOIA, Library, and Information Collections Branch (T6-A10M), U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001, or by e-mail to Infocollects.Resource@nrc.gov, and to the Desk Officer, Office of Information and Regulatory Affairs, NEOB-10202 (3150-0011 and 3150-0151), Office of Management and Budget, Washington, DC 20503.

Public Protection Notification

The NRC may not conduct or sponsor, and a person is not required to respond to, a collection of information unless the document requesting or requiring the collection displays a currently valid OMB control number.

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B. DISCUSSION

Reason for Revision

This revision of the guide (Revision 5) addresses new considerations identified since the NRC issued Revision 4 of this guide. These considerations concern the use of CAP in determining the NPSH margin for the ECCS and containment heat removal pumps. This revision also incorporates new information on the effects of debris on long-term core cooling. Specifically, information and references that apply to the evaluation of in-vessel effects are added. This revision applies to both PWR and BWR types of light-water reactors. This revised guide contains information specific to the use of CAP for both older plants and newer reactors licensed under 10 CFR Part 50 and 10 CFR Part 52.

Background

Long-term recirculation cooling raises four primary safety concerns following a LOCA:

(1) LOCA-generated and pre-LOCA debris materials may be transported to the ECCS strainers, the downstream components in the ECCS, the containment spray system (CSS), and the reactor core, resulting in adverse heat transfer, blockage, or wear effects, or some combination of all three,

(2) There may be post-LOCA hydraulic effects, particularly air ingestion (e.g., through vortexing or deaeration) and flashing. Gas that may exist in system piping downstream of the strainers could be a concern when recirculation is initiated. Activities in response to Generic Letter (GL) 2008-01, "Managing Gas Accumulation in Emergency Core Cooling, Decay Heat Removal, and Containment Spray Systems," dated January 11, 2008 (Ref. 5), address this issue.

(3) The combination of Items (1) and (2) may affect long-term recirculation pump operability (i.e., it may affect NPSH available at the pump inlet).

(4) CAP may be used in determining the NPSH margin for the ECCS and containment heat removal pumps.

These ECCS safety concerns extend to the CSSs for plants with containment designs in which the CSS draws suction from the water supply used for long-term recirculation. In some plant designs (e.g., PWR sub-atmospheric containments), the CSS draws from the recirculation sump much earlier than the ECCS. In other plant designs, the CSS switches the pump suction to the recirculation sump after the ECCS pumps are switched. Some designs provide CSS through the residual heat removal (RHR) system, either directly or by supplying the CSS pumps from the RHR pump discharge.

For some plant designs, high-energy line breaks (HELBs) that are not LOCAs, such as main steamline breaks, require recirculation from the long-term water source. For these plants, non-LOCA HELBs that require recirculation should be evaluated using the same criteria and methodology (as appropriate for the HELB conditions, duration, and consequences) as those for pipe breaks that result in a LOCA.

Debris that could affect long-term recirculation cooling can be divided into the following categories:

- debris generated directly by LOCA blowdown (e.g., insulation, coatings, and other materials near the break) and subject to transport by blowdown forces

- preexisting debris or debris created by adverse environmental conditions (e.g., latent debris or dirt and unqualified coatings not influenced by LOCA blowdown) that may be transported to the long-term recirculation water source primarily by washdown

- other debris that existed before a LOCA, such as debris in a BWR suppression pool or other storage tanks (e.g., suppression pool sludge), and that may become suspended in the containment sump pool or suppression pool at the start of a LOCA

- chemical reaction products generated within the containment or the reactor vessel

Licensees[1] should evaluate debris generation, debris transport, upstream and downstream effects, and blockage of ECCS strainers to ensure that they do not jeopardize the ability of the ECCS to provide long-term post-LOCA core cooling. Licensees should evaluate all potential debris sources, including, but not limited to, insulation materials (e.g., fibrous, particulate, and metallic), fire barrier materials, filters and other fiber-bearing materials, latent debris, shielding blankets, corrosion products, chemically reactive materials and their reaction products, and paints or coatings. Section C and Appendix A to this guide provide relevant information for such evaluations. Further information appears in NUREG/CR-6808, "Knowledge Base for the Effect of Debris on Pressurized Water Reactor Emergency Core Cooling Sump Performance," issued February 2003 (Ref. 6), which summarizes research conducted before 2003 on BWR and PWR ECCS suction strainers. The NRC issued an updated report, NUREG/CR-7172, "Knowledge Base Report on Emergency Core Cooling Sump Performance in Operating Light Water Reactors," in January 2014 (Ref. 7). More recent technical guidance appears in an NRC letter to the Nuclear Energy Institute (NEI), entitled "Revised Guidance for Review of Final Licensee Responses to Generic Letter 2004-02, 'Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized-Water Reactors,'" dated March 28, 2008 (Ref. 8), and in the memorandum "U.S. Nuclear Regulatory Commission Staff Review Guidance for In-Vessel Downstream Effects Supporting Review of Generic Letter 2004-02 Responses," dated September 4, 2019 (Ref. 9).

It is desirable to use ECCS suction strainers to protect the pump inlets from debris that may block restrictions in the systems served by the ECCS pumps or damage components. Suction strainers are passive devices that limit the amount of debris entering the ECCS pump suction line by capturing it on a surface with small openings that reduce the amount of debris that can pass through.

ECCS and CSS pumps are normally centrifugal pumps. For a centrifugal pump to perform its safety function, an adequate margin must exist between the available and the required NPSH[2] (NPSHr). Failure to provide and maintain adequate NPSH for the ECCS pumps could cause cavitation and subsequent failure to deliver the amount of water assumed in design-basis LOCA safety analyses. Because the safety of a nuclear power plant depends on the performance of the pumps in the ECCS and the containment heat removal system, it is important to maintain adequate margin between the available and required NPSH under all potential conditions.

The available NPSH (NPSHa) is the total suction head of liquid absolute, determined at the first-stage impeller datum, less the absolute vapor pressure of the liquid. The required NPSH, as defined

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1 Throughout this RG, the NRC uses the term "licensee" in a generic sense. The user of this document may be a nuclear power plant licensee, an applicant for a license, or a vendor performing evaluations on behalf of a licensee or applicant.

2 The term "required NPSH" does not refer to an NRC regulatory requirement. American National Standards Institute/Hydraulic Institute (ANSI/HI) 14.3-2019, "American National Standard for Rotodynamic Pumps for Design and Application" (Ref. 10), defines NPSH parameters, including required NPSH.

in ANSI/HI 14.3-2019, is the amount of suction head, over vapor pressure, required to prevent more than a 3-percent loss in total head of the first stage of the pump at a specific capacity.

The predicted performance of the ECCS and the containment heat removal pumps and their associated strainers should be independent of the calculated increases in containment pressure caused by postulated LOCAs, to ensure reliable operation under a variety of possible accident conditions. For example, if the proper operation of the ECCS or the containment heat removal system depends on containment pressure being above a specified amount, operation of these systems at a containment pressure less than this amount (e.g., resulting from impaired containment integrity or from operation of the containment heat removal systems at too high a rate) could significantly affect the systems' abilities to accomplish their safety functions.

However, for certain operating reactors, some credit for CAP may be necessary to demonstrate that adequate pump NPSH margins exist, that unacceptable deaeration will not occur at the strainer, or that sump fluid will not flash to vapor after undergoing a pressure drop at the strainer. The flashing of sump fluid to vapor should be prevented.

ANSI/HI 14.3-2019 specifies a method of accounting for the decrease in NPSHr with an increase in the temperature of the pumped fluid. This method is subject to restrictions specified in the standard that are related to pump-specific performance, the amount of air dissolved in the fluid, and the transient nature of the pressure and temperature of the pumped fluid. Because of the uncertainty in these factors, licensees should avoid taking credit for the reduction in NPSHr that results from the temperature of the pumped fluid. Transient NPSH calculations should be performed to ensure that the most limiting conditions are chosen and that the results are conservative.

The calculation of NPSH margin should include head loss caused by debris, by subtracting the total debris-laden strainer head loss from the available hydraulic head. The total debris-laden strainer head loss, including chemical reaction products, should be determined by prototypical strainer testing. The strainer testing assumptions and methodology should be similar to those used for the resolution of Generic Safety Issue (GSI)-191, "Assessment of Debris Accumulation on PWR Sump Performance" (Ref. 11), and GL 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized-Water Reactors," dated September 13, 2004 (Ref. 12). Section C of this guide and the document "NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Strainer Head Loss and Vortexing," issued March 2008 (Ref. 13), discuss this issue in more detail.

The analyses and testing for head loss effects should include all debris and chemical reaction products that are transportable to the ECCS strainer. Fine debris that is small enough to pass through the strainer should be included for head loss effects if it can be filtered by the debris bed on the strainer. ECCS components and flow restrictions inside the reactor vessel should be evaluated for erosion, wear, and blockage that may be caused by the debris and chemical precipitates that penetrate the strainers. Blockage of the ECCS strainer and other debris interceptors is a function of the types, combinations, sizes, shapes, and quantities of debris that can be transported to these components.

The size of the openings in the strainer should be appropriate for any physical restrictions in the systems supplied with coolant from the ECCS sump, including openings in the containment spray nozzles, coolant channel openings in the core fuel assemblies, fuel assembly inlet debris screens, small clearances within system flowpaths (e.g., high-pressure safety injection (HPSI) throttle valves), and pump component clearances such as seals, bearings, and impeller running clearances. The strainer opening sizes also affect clean screen head loss, the accumulation of debris passing through the sump strainer, and the wear of components in the ECCS flowpath. The amount of debris that penetrates or bypasses a strainer also depends on the strainer area, the strainer layout, the debris arrival sequence, the concentration of debris at the strainer, and the properties of the fluid field close to the strainer.

As noted above, many factors, including plant design and layout, can cause degraded pump performance. The effects of debris blockage of ECCS strainers, sump outlet configurations, and post-LOCA hydraulic conditions (e.g., air ingestion) should be considered in an integrated manner. Small amounts of ingested gas during steady-state pump operation will not lead to severe pumping degradation if the NPSHr from the pump manufacturer's curve is increased to account for the air ingestion. Thus, it is important to use the combined results of all post-LOCA effects to estimate NPSH margin at the pump inlet. Appendix A to this guide provides information on estimating NPSH margins in ECCS strainer designs in which estimated levels of air or gas ingestion are low (2 percent or less). NUREG-0897, Revision 1, "Containment Emergency Sump Performance: Technical Findings Related to Unresolved Safety Issue A-43," issued October 1985 (Ref. 14), and NUREG/CR-2792, "An Assessment of Residual Heat Removal and Containment Spray Pump Performance under Air and Debris Ingesting Conditions," issued September 1982 (Ref. 15), provide additional technical findings on NPSH effects on pumps performing the functions of RHR, emergency core cooling, containment cooling, and containment atmosphere cleanup. When air ingestion is 2 percent or less, compensation for its effects may be achieved without redesign if the NPSHa is greater than the NPSHr (as adjusted for the percentage of voiding at the pump inlet). A 2-percent limit on allowed void ingestion was selected because data show that levels above 2 percent can produce significant head degradation.

Gas intrusion and accumulation issues in plant safety systems have been an ongoing concern for many years. The NRC issued GL 2008-01 to request that each licensee evaluate its ECCS, decay heat removal system, and CSS for licensing basis, design, testing, and corrective actions for pump response to suction voids. In addition, the NRC requested that licensees demonstrate that the subject safety-related systems comply with the applicable regulatory requirements to ensure that gas void accumulation and transport arising from deaeration or air ingestion, or both, are maintained below the amount that challenges operability of these systems, and that appropriate action is taken when conditions adverse to quality are identified. In general, gas accumulation causes relatively short-term ingestion of larger amounts of gas, while vortexing and deaeration cause longer-term ingestion of smaller amounts of gas. Short-term and longer-term gas ingestion are evaluated differently because they have different effects on pump performance. Licensees should evaluate and address deaeration, flashing, and other air entrainment mechanisms as discussed in GL 2008-01 and in Appendix A to this guide.

The NRC developed this RG using insights from operating PWRs and BWRs, and the guide provides common regulatory positions applicable to both PWRs and BWRs. In certain areas, the RG gives separate guidance for PWRs and BWRs based on the design features of currently operating reactors. Adjustments may be necessary for new or advanced PWR or BWR designs whose features differ from those of currently operating reactors. For example, a plant with passive features will need adjustments for pump NPSH, and analyses of PWRs with in-containment refueling water storage tanks may need to draw on both PWR and BWR guidance.

Pressurized-Water Reactors

In PWRs, the containment emergency sumps serve as water sources to support long-term recirculation for RHR, emergency core cooling, containment cooling, and containment atmosphere cleanup. These water sources, the related pump suction inlets, and the piping between the sources and suction inlets are important safety components. In this guide, the term ECCS implicitly includes the CSS (or similar system), and the sumps or strainers (or both) servicing the ECCS and the CSS are referred to as ECCS sumps or ECCS strainers.

The design of PWR strainers and their outlets should consider the avoidance of air ingestion, gas void intrusion, flashing, accumulation of air from deaeration, and other undesirable hydraulic effects (e.g., circulatory flow patterns and outlets leading to high head losses). The location and size of the sump outlets within ECCS sumps are important to minimize air ingestion caused by vortexing at the pump suction inlets, because this phenomenon depends on the submergence level and velocity in the outlet piping. Experiments for PWRs have determined that air ingestion and gas void intrusion caused by vortexing at the pump suction inlets can be minimized by following the sump hydraulic design considerations in Appendix A to this guide. NUREG-0897, Revision 1, and NUREG/CR-2758, "A Parametric Study of Containment Emergency Sump Performance," issued July 1982 (Ref. 16), provide additional technical information relevant to ECCS sump hydraulic performance and original design guidelines. The hydraulic design guidelines in Table A-1 of Appendix A apply to designs that do not have a complete water seal over the strainer or that otherwise could have a free surface inside the strainer volume. For example, the sump design could include a vent, the strainer might not be fully submerged, or a pocket of gas could accumulate inside the strainer. For fully submerged, unvented strainers, licensees should use other analytical or empirical means to evaluate the possibility of vortex formation at the strainer surface.

Air or gas voids can also be generated downstream of the strainer surface if dissolved gas comes out of solution within the sump fluid after undergoing a pressure drop across the debris bed on the strainer or across flow restrictions within the ECCS piping. Excessive deaeration resulting from the passage of flow through the debris bed or internal system flow restrictions could significantly increase the head loss and impair pumping performance. A similar increase in head loss could occur if sump fluid flashes to vapor upon undergoing a differential pressure drop at the strainer or inside the ECCS. Both the flashing of sump fluid and the generation of air or gas voids through deaeration should be prevented by providing sufficient strainer submergence relative to the expected pressure drop. In general, flashing across or within the strainer should be avoided.

Placement of the ECCS strainers at the lowest floor level practical ensures maximum use of available recirculation coolant. Areas within the containment in which coolant could accumulate during the containment spray period should be provided with drains or flowpaths to the sumps to prevent coolant holdup. Debris may also block the drains or flowpaths themselves, either totally or partially, thus preventing water from reaching the active sump region. If drains or other upstream flowpaths necessary to ensure adequate performance of the ECCS sumps are susceptible to debris blockage, they should be protected by trash racks or other design features to ensure that they will fulfill their intended function. Because debris can migrate to the ECCS strainers through these drains or paths, they are best terminated in a manner that will prevent debris from being transported to and accumulating on the strainers.

Containment drainage sumps collect and monitor normal equipment leakage flow for leakage detection systems within containments. They are typically separated from the ECCS water sources and are located at an elevation lower than the ECCS pools to minimize inadvertent spillover into the ECCS from minor leaks or spills within containment. The general floor area adjacent to the ECCS strainers normally slopes away from the ECCS strainers, toward the drainage collection sumps. This slope reduces the tendency for debris to collect against the ECCS strainers. Another way to reduce the accumulation of larger pieces of debris on the strainer may be to elevate the sump strainers slightly above the floor level, on a pedestal. NUREG/CR-6772, "GSI-191: Separate-Effects Characterization of Debris Transport in Water," issued August 2002 (Ref. 17), provides test results on the transport of various types, sizes, and shapes of debris with variables of flume water depth, turbulence intensity, flow patterns, fluid temperature, simultaneous presence of combinations of debris, types of obstructions, extent of congestion, and height of curbs. NUREG/CR-6916, "Hydraulic Transport of Coating Debris," issued December 2006 (Ref. 18), provides test results on the transport of protective coating debris.

Flow during pool fill or longer -term recirculation may sweep debris pieces too large or dense to remain in suspension along the floor toward the ECCS strainer. Trash racks, debris curbs, and debris interceptors upstream of the ECCS strainers may decrease the amount of debris reaching the strainer. Some debris interceptor designs may also reduce the transport of fine, suspendable debris; however, it can be difficult to demonstrate the effectiveness of such interceptors in capturing fine debris.

ECCS strainers and any trash racks, debris interceptors, or similar design features credited in the strainer performance analysis should be strong enough to withstand seismic events, resist jet impingement loads, resist impact loads that could be imposed by missiles generated by a LOCA and withstand the differential pressure loads imposed by the accumulation of debris. Materials for ECCS strainers, debris interceptors, and other design features should be able to withstand long periods of inactivity (i.e., no submergence) and periods of operation involving partial or full submergence in fluids that may contain chemically reactive materials.

It is important to isolate the ECCS strainers from high-energy pipelines to protect against internally generated missiles, and it is necessary to shield the ECCS strainers, debris interceptors, and other credited design features from impacts of ruptured high-energy piping and associated jet impingement loads.

ECCS strainers should be designed to minimize or prevent blockage by large pieces of debris (e.g., partially torn insulation blankets or damaged reflective metallic insulation cassettes). For example, despite their large and complex surface area, ECCS strainers located in pits below the containment floor grade could be susceptible to blockage by large debris pieces that accumulate at the relatively restricted pit openings. The installation of trash racks, curbs, or interceptors may prevent this type of accumulation.

Consistent with the plant licensing-basis single-failure criterion, redundant ECCS strainers should be separated to the extent practicable to reduce the probability that a single event will render more than one train inoperable.

It is generally expected that the water surface will be above the top of the ECCS strainer after completion of the injection phase and before the start of the ECCS recirculation phase. However, because of uncertainties about the time-dependent water coverage on the strainer and the amount of floating debris that may accumulate, horizontally oriented strainer surfaces may become significantly blocked. Therefore, in the computation of available strainer surface area, no credit may be taken for horizontal strainer surfaces unless plant evaluations that account for water level changes and uncertainties demonstrate that the horizontal surface will be submerged at the time of recirculation. For certain sump designs, the top of the sump structure should preferably be a solid cover plate that will provide additional protection from LOCA-generated loads and the direct impact of water drainage. If a cover plate is installed, it should be designed to vent any trapped air. It is possible that ECCS sump strainers in some plants may not be submerged completely at the time of recirculation, either because of unique designs or because of uncertainties in water level estimates. ECCSs and CSSs with partially submerged strainers may be subject to failure criteria other than NPSH margin, as discussed in Section C.1.3.11.3 and Appendix A of this guide. For partially submerged strainers, calculations should consider only the portion of the strainer that is expected to be submerged as a function of time.

A complex geometry and location at the containment floor level will reduce the deposition or settling of debris on strainer surfaces, ensuring the greatest possible free flow through the strainer.

Boiling-Water Reactors

In BWRs, the suppression pool, also referred to as the wetwell, serves as the water source for long-term recirculation cooling. This source, the related pump suction inlets, and the piping between them are important safety components. Figure 1 shows the features and relationships of the suppression pool or wetwell pertinent to this guide.

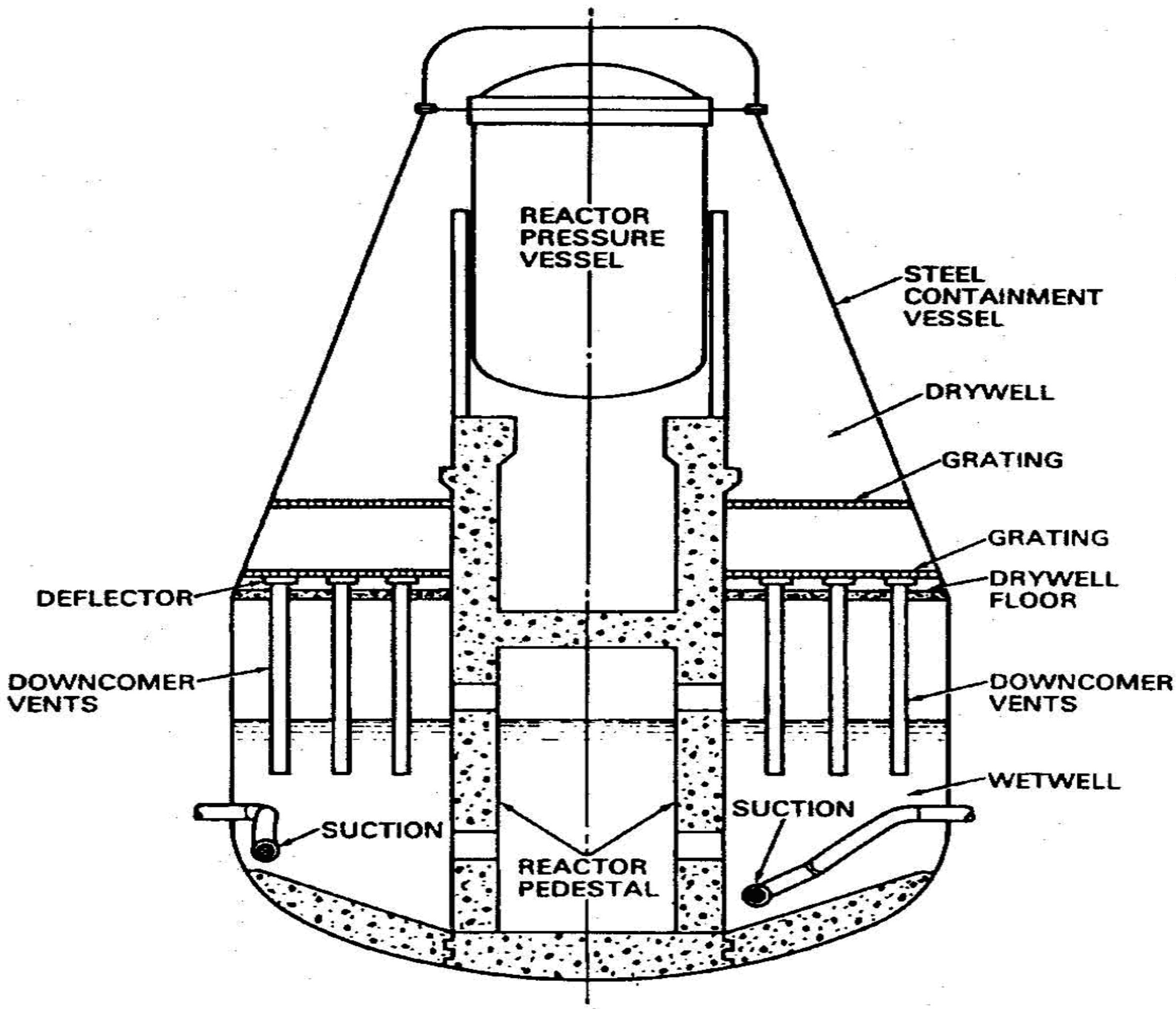

Figure 1: Conceptual features of a BWR Mark II containment (other BWR containments are similar in function)

Concerns related to the performance of the suppression pool hydraulics and ECCS pump suction strainers include air ingestion effects, blockage of suction strainers by debris, and the combined effects of these items on the operability of the ECCS pumps (e.g., the impact on NPSHa at the pump inlets). NUREG-0897, Revision 1, provides data on the performance and air ingestion characteristics of some types of BWR suction strainer configurations. Currently operating BWR strainer designs are based on guidance from sources such as the Boiling Water Reactor Owners' Group (BWROG) Utility Resolution Guide (URG), issued October 1998 (Ref. 19), the accompanying safety evaluation (SE) found in Volume 1 of the URG, and NUREG/CR-6224, "Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris," issued October 1995 (Ref. 20). For future evaluations, BWR strainer designs should consider subsequent guidance developed during the resolution of GSI-191 and GL 2004-02, including chemical and downstream effects and strainer head loss and vortexing. For details, the reader should consult the recent NUREG-series publications, several industrial topical reports and their accompanying SEs, and other technical guidance listed in the reference section of this guide. During the PWR work on GSI-191, staff determined that some lessons learned from PWRs should be evaluated for application to BWRs. NUREG/CR-7011, “Evaluation of Treatment of Effects of Debris in Coolant on ECCS and CSS Performance in Pressurized Water Reactors and Boiling Water Reactors,” issued May 2010 (Ref. 21), documents these findings. The BWROG undertook a voluntary program to evaluate the differences that the NRC staff had identified as potentially significant. The NRC and the industry had numerous interactions on these topics. On November 20, 2017, the BWROG submitted a letter, “Final Resolution of Potential Issues Related to Emergency Core Cooling Systems (ECCS) Strainer Performance at Boiling Water Reactors” (Ref. 22), stating that it had finished evaluating the differences and had identified no safety concerns warranting further action. The NRC reviewed the BWROG letter and agreed that no further action was required. This was documented in the NRC letter entitled “Closure of Potential Issues Related to Emergency Core Cooling Systems Strainer Performance at Boiling Water Reactors,” dated June 29, 2018 (Ref. 23). The BWROG analysis included an evaluation of the potential for in-vessel effects. The NRC staff reviewed the BWROG work and determined that it had reached acceptable conclusions. The NRC documented its findings in a staff technical evaluation issued May 2018 (Ref. 24).

Safety analyses, including analyses of debris transport in and to the suppression pool, should include the effects of the LOCA progression, because LOCAs of different sizes will affect the duration of LOCA-related hydrodynamic phenomena (e.g., condensation oscillation, chugging, and blowdown). These phenomena and long-term recirculation hydrodynamic conditions will affect the transport of debris in the suppression pool.

Debris that is transported to the suppression pool during a LOCA or that is present in the suppression pool before a LOCA could block or damage the suction strainers; head loss effects should therefore be evaluated through prototypical strainer testing. (See Information Notice (IN) 94-57, “Debris in Containment and the Residual Heat Removal System,” dated August 12, 1994 (Ref. 25); IN 95-06, “Potential Blockage of Safety-Related Strainers by Material Brought inside Containment,” dated January 25, 1995 (Ref. 26); and IN 95-47, “Unexpected Opening of a Safety/Relief Valve and Complications Involving Suppression Pool Cooling Strainer Blockage,” dated October 4, 1995 (Ref. 27).) The strainer testing methodology should be similar to that used for the resolution of GSI-191 and GL 2004-02, as discussed in Section C.1.3 of this guide. The head loss evaluation should consider the filtration of particulate, fibrous, chemical, and coating debris by the accumulated debris bed. The head loss characteristics of a debris bed depend on the types and quantities of the debris, strainer approach velocities, and LOCA-related hydrodynamic phenomena in the suppression pool. The determination of the total debris load should also consider chemical reaction products (e.g., precipitates) that may form from interaction between the post-LOCA environment and plant materials. Plants that credit the standby liquid control system or equivalent to inject boron into the primary system should include the potential chemical reaction products resulting from the use of that system.

The flowchart (Figure 2) on the following page illustrates the input logic and information considered during head loss testing and design of an ECCS suction strainer. Guidance for each step in the process can be found in the applicable regulatory positions in Section C.

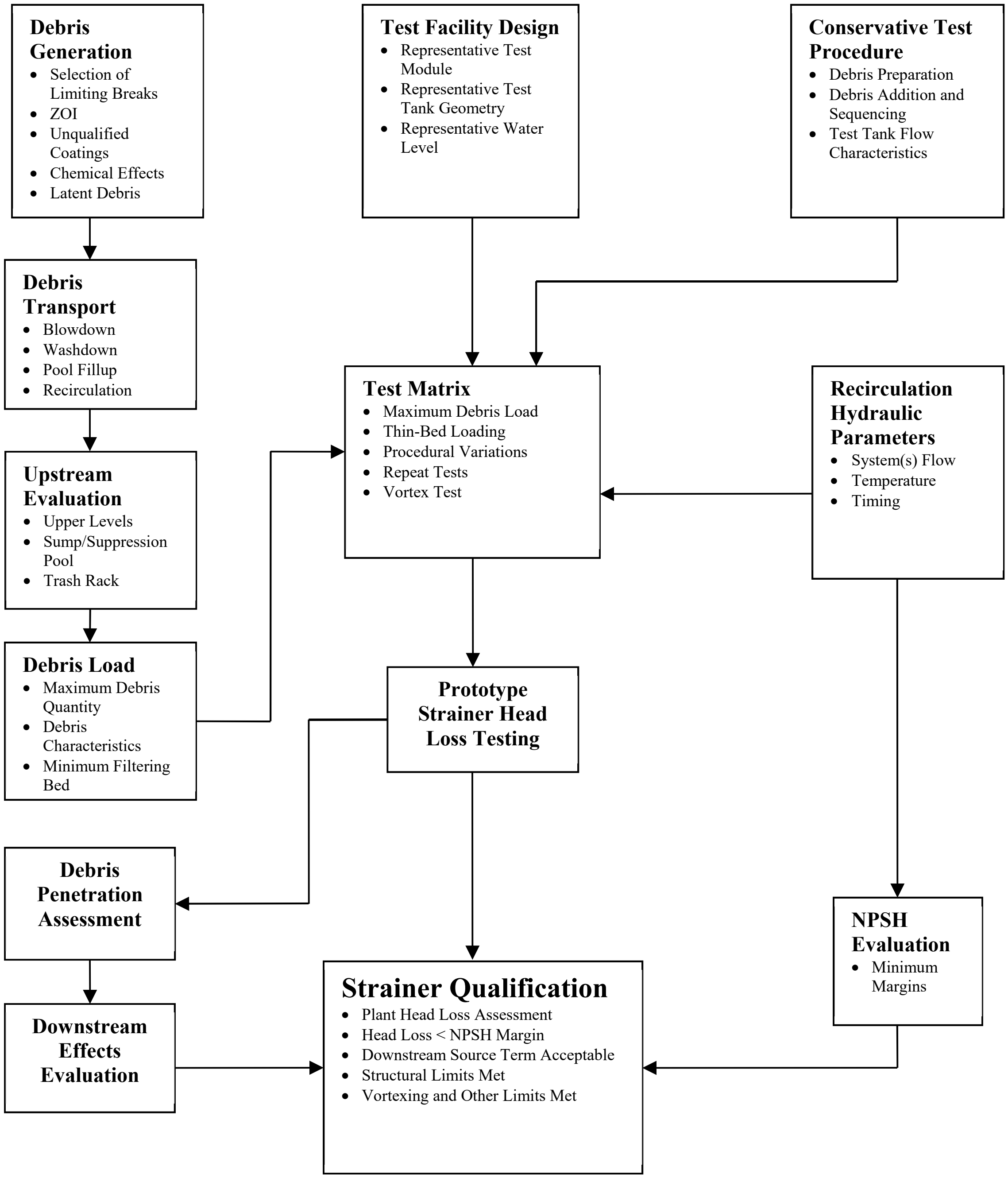

Figure 2: Flowchart for steps in qualification of a suction strainer

Consideration of International Standards

The International Atomic Energy Agency (IAEA) works with member states and other partners to promote the safe, secure, and peaceful use of nuclear technologies. The IAEA develops Safety Standards and Safety Guides for protecting people and the environment from harmful effects of ionizing radiation. This system of safety fundamentals, safety requirements, safety guides, and other relevant reports reflects an international perspective on what constitutes a high level of safety. To inform its development of this RG, the NRC considered IAEA Safety Requirements and Safety Guides pursuant to the Commission's International Policy Statement (Ref. 28) and Management Directive and Handbook 6.6, "Regulatory Guides" (Ref. 29).

The following IAEA Safety Requirements and Guides were considered in the update of the Regulatory Guide:

- IAEA Specific Safety Guide SSG-56, "Design of the Reactor Coolant System and Associated Systems for Nuclear Power Plants," issued in 2020 (Ref. 30), Sections 7 and 8.

Documents Discussed in Staff Regulatory Guidance

This RG endorses, in part, the use of one or more codes or standards developed by external organizations, and other third-party guidance documents. These codes, standards and third-party guidance documents may contain references to other codes, standards or third-party guidance documents ("secondary references"). If a secondary reference has itself been incorporated by reference into NRC regulations as a requirement, then licensees and applicants must comply with that standard as set forth in the regulation. If the secondary reference has been endorsed in a RG as an acceptable approach for meeting an NRC requirement, then the standard constitutes a method acceptable to the NRC staff for meeting that regulatory requirement as described in the specific RG. If the secondary reference has neither been incorporated by reference into NRC regulations nor endorsed in a RG, then the secondary reference is neither a legally-binding requirement nor a "generic" NRC-approved acceptable approach for meeting an NRC requirement. However, licensees and applicants may consider and use the information in the secondary reference, if appropriately justified, consistent with current regulatory practice, and consistent with applicable NRC requirements.

C. STAFF REGULATORY GUIDANCE

1. General

This section includes regulatory positions on design criteria, performance standards, and analysis methods that relate to all water-cooled reactor types (Section C.1.1) and to specific light-water reactor types (PWRs in Section C.2 and BWRs in Section C.3). As stated in the introduction to this guide, the purpose of the guidance is to identify information and methods that the NRC staff considers acceptable for use in evaluating analytical techniques and implementing regulations related to water sources for long-term cooling of both existing and future reactor systems.

1.1 Regulatory Positions Common to All Water-Cooled Reactors

Research, analysis, and lessons learned have shown that in many areas, similar approaches to performing the long-term recirculation capability evaluation are appropriate for all water-cooled reactors. These areas include NPSH evaluation, selection of limiting pipe breaks, debris generation, debris transport, coating debris, latent debris, sump structure, downstream effects, chemical effects, structural analyses, and head loss testing.

1.1.1 Emergency Core Cooling System Sumps, Suppression Pools, Suction Strainers, and Debris Interceptors

ECCS sumps and suppression pools should contain an appropriate combination of the features and capabilities listed below to ensure the availability of the water sources for long-term cooling.

1.1.1.1 A minimum of two independent ECCS suction strainers should be provided, each with sufficient capacity to accommodate the full plant debris loading while providing sufficient flow to one train of the ECCS and containment heat removal pumps. To the extent practicable, the redundant suction strainers should be physically separated from each other by structural barriers to preclude damage resulting from a LOCA, such as whipping pipes or high-velocity jet impingement.

1.1.1.2 The containment floor near floor-mounted ECCS strainers should slope gradually downward away from the strainers to retard floor debris transport and reduce the fraction of debris that might reach the suction strainer. Similar floor sloping should be used near a sump pit if the ECCS strainers are installed in a pit configuration. Debris interceptors or curbs can also be used to retard debris transport.

1.1.1.3 The inlet of pumps required for long-term cooling should be protected by a suction strainer placed upstream of the pumps to prevent the ingestion of debris that may damage components or block restrictions in the systems served by the pumps.

1.1.1.4 All drains from the upper regions of the containment should terminate so that streams of water will neither directly impinge on nor discharge close to the ECCS strainers. Streams of drainage from upper containment may contain entrained debris; they can also cause air ingestion and other issues if they directly impinge on the strainers. The drains, drain piping internal clearances, and other pathways that connect containment compartments with potential break locations to the sump or suppression pool should be designed so as not to become blocked by debris; this will ensure that water needed for an adequate NPSH margin will not be held up or diverted from the pool.

1.1.1.5 Trash racks, suction strainers, and debris interceptors should be able to withstand the loads imposed by expanding jets, missiles, debris accumulation, and pressure differentials caused by post-LOCA blockage under design-basis or realistic flow conditions, whichever cause the greatest loads. When evaluating the impacts from potential expanding jets and missiles, licensees should justify credit for any protection offered by surrounding structures or credit for remoteness of trash racks and strainers from potential high-energy sources.

1.1.1.6 ECCS strainers, trash racks, and debris interceptors should be designed to withstand the inertial and hydrodynamic effects of the vibratory motion of a safe-shutdown earthquake following a LOCA without loss of structural integrity.

1.1.1.7 Licensees should select materials for debris interceptors, trash racks, and suction strainers that do not degrade during periods of inactivity or operation, and that have low sensitivity to stress-assisted corrosion or general corrosion that may be induced by chemically reactive spray or by the containment or suppression pool liquid.

1.1.1.8 Licensees should choose a suction strainer design (i.e., size and shape) that will prevent unacceptable loss of NPSH margin from debris accumulation during the period that the ECCS and CSS are required to operate to maintain long-term cooling.

1.1.1.9 Licensees should assess the possibility of debris clogging narrow flow passages downstream of the ECCS strainer, to ensure adequate long-term recirculation cooling, containment cooling, and containment pressure control capabilities. The size of the openings in the strainer should be determined by considering the flow restrictions of systems served by the containment pool. Licensees should consider the possibility that long, thin debris pieces will pass axially through the suction strainer, then reorient and clog downstream flow restrictions.

1.1.1.10 Licensees should consider the effects of debris and chemical reaction products at downstream locations, including containment spray nozzle openings, HPSI throttle valves, coolant channel openings in fuel assemblies, fuel assembly inlet debris screens, ECCS pump seals, bearings, and pump impeller clearances. The design of the ECCS pumps is a significant factor in the sensitivity of the pump operability to debris ingestion. Three aspects of pump operability—hydraulic performance, mechanical shaft seal assembly performance, and pump mechanical performance (vibration)—should be considered when evaluating the ECCS pumps for operation with debris-laden water. Westinghouse Commercial Atomic Power (WCAP)-16406-P-A, Revision 1, "Evaluation of Downstream Sump Debris Effects in Support of GSI-191,"[3] issued March 2008 (Ref. 31), and its SE (Ref. 32) provide evaluation methods and criteria that the NRC considers acceptable for ex-vessel downstream evaluations. If wear or internal blockage evaluations indicate that a component may not be able to fulfill its design function throughout its mission time, and that it is not practicable to install a suction strainer with openings small enough to filter out the debris that would cause the predicted failure, the licensee should take action to ensure that the ECCS pumps will operate long-term under the postulated conditions. WCAP-16793-NP-A, Revision 2, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid," issued July 2013 (Ref. 33), discusses a method for evaluating the downstream impact of debris on fuel assemblies. Additional guidance on PWR in-vessel debris evaluations can be found in "U.S. Nuclear Regulatory Commission Staff Review Guidance for In-Vessel Downstream Effects Supporting Review of Generic Letter 2004-02

3 WCAP-16406-P-A, Revision 1, contains information proprietary to Westinghouse Electric Company, LLC, and is not publicly available.

Responses" (Ref. 9). The NRC evaluation of PWR in-vessel effects used extensive information from WCAP-17788-P, Revision 1, "Comprehensive Analysis and Test Program for GSI-191 Closure (PA-SEE-1090)," dated July 17, 2015 (Ref. 34). For BWRs, the in-vessel issue was evaluated by the BWROG and the NRC staff. The NRC evaluation of the BWR in-vessel issue appears in a staff technical evaluation dated May 2018 (Ref. 24). The reader should refer to Section C.1.3.8.2 for additional discussion of in-vessel effects. WCAP-16530-NP-A, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," issued March 2008 (Ref. 35) and its SE (Ref. 36), provides one approach to conducting chemical effects evaluations, as discussed in Section C.1.3.10 of this guide.

1.1.1.11 ECCS strainers and suction inlets for pumps required for long-term ECCS, CSS, or suppression pool cooling functions should be designed to prevent degradation of pump performance through air ingestion, flashing, and other adverse hydraulic effects (e.g., circulatory flow patterns, high-intake head losses, and gas void intrusion).

1.1.1.12 Advanced strainer designs have demonstrated capabilities that simple flat plate and basket-type strainers and screens do not have. The performance characteristics and effectiveness of such designs should be supported by appropriate test data for the intended application.

1.1.1.13 Prototypical head loss testing should be performed to verify suction strainer designs. Section C.1.3.12 provides guidance on prototypical head loss testing.

1.1.2 Minimizing Debris

The debris and chemical reaction products (see Sections C.1.3.3 and C.1.3.10) that could accumulate on the suction strainer should be minimized. This is most easily accomplished during the design process and maintained through administrative controls.

1.1.2.1 Licensees should maintain debris source terms below the amount assumed in the strainer performance and other associated analyses. For example, cleanliness programs should ensure that the assumed latent debris and suppression pool sludge loading is not exceeded, and controls should be maintained to ensure that problematic debris (e.g., insulations, signage, coatings, foreign materials, and chemically reactive materials) is not introduced into containment to an extent that would exceed the analytically assumed values. In addition, permanent plant changes that may affect materials inside containment should be programmatically controlled so as not to change the analytical assumptions and numerical inputs of the licensee analyses.

1.1.2.2 When latent debris is a significant source (i.e., contributes more than a minimal amount to strainer head loss) that can affect strainer performance or create downstream effects, periodic containment surveys or sampling should be performed to verify that the amount of latent debris is within the assumed limits. Such periodic monitoring may not be necessary if the latent debris evaluation incorporates sufficient conservatism to account for uncertainties associated with latent debris sampling (see Section C.1.3.6 for more information on latent debris).

1.1.2.3 Licensees should assess any new or unanalyzed potential debris sources (e.g., fiber and coatings) resulting from equipment modifications or discoveries to ensure that the post-accident sump/pool analysis is bounding of the plant condition.

1.1.2.4 Licensees should assess tags and labels that may fail and be transported to the strainer and should determine a sacrificial strainer area to account for the area that could become fully blocked by such transportable tags and labels and by other miscellaneous debris.

1.1.2.5 Licensees should consider using insulation types (e.g., reflective metallic insulation) that are less readily transported and would cause less severe head losses if deposited onto the strainer, in place of insulation types (e.g., fibrous and microporous insulation) that are more readily transported to the strainer and would cause higher head losses. If insulation is replaced or otherwise removed during maintenance, abatement procedures should be established to avoid generating latent debris in the containment.

1.1.2.6 To minimize the potential for debris created by the chemical reaction of the pool water with metals in the containment, licensees should reduce the exposure of bare metal surfaces (e.g., aluminum and uncoated carbon steel) to containment cooling water through spray impingement or immersion. These materials may be removed or protected by chemical-resistant systems (e.g., qualified coatings or jacketing).

1.1.3 Instrumentation and Operator Actions

If a licensee relies on operator actions to mitigate the consequences of the accumulation of debris on the ECCS suction strainer, it should ensure that safety-related instrumentation that provides operators with an indication and audible warning of impending loss of NPSH for ECCS pumps is available in the control room.

If a licensee relies on operator actions to prevent the accumulation of debris on ECCS suction strainers or to mitigate the consequences of the accumulation of debris on the ECCS strainers, it should evaluate whether operators have adequate indications, training, time, procedural guidance, and system capabilities to perform the necessary actions.

1.1.4 Inspection

To ensure the operability and structural integrity of the ECCS strainers and associated structures, access openings may be necessary to permit their inspection, as well as that of the sump pits and pump suction piping inlets. Licensees should perform regular inspections (including visual examinations) of strainers, trash racks, vortex suppressors, and pump suction piping inlets for evidence of structural degradation, potential for debris bypass, and presence of corrosion or debris blockage. Licensees should conduct similar inspections for drainage flowpaths (e.g., refueling cavity drains and floor drains), debris interceptors, trash racks, and other design features upstream of the ECCS strainers that are credited in the strainer performance analysis. Inspection of the ECCS strainer, associated structures, and upstream components should be conducted late in a refueling outage to ensure the absence of debris generated by nearby construction or maintenance.

1.2 Evaluation of Alternative Water Sources

Licensees should establish emergency operating procedures to use alternative water sources, either safety-related or non-safety-related, that will be activated if unacceptable head loss renders the ECCS strainers inoperable. For some plant designs, the use of alternative water sources may involve replenishing the inventory of the water storage tank that served as the source of inventory for core cooling during the injection phase of a LOCA. In this case, if the flow rate of the makeup supply to the alternative water source is not larger than the core boiloff rate, procedures should direct replenishment of the water storage tank with alternative water sources relatively soon after the switchover to recirculation. The makeup supply should have a sufficient flow rate to ensure that adequate water will be available in the storage tank if excessive debris blockage subsequently renders the ECCS strainers inoperable. Licensees should periodically inspect and maintain the valves needed to align the ECCS, CSS, and suppression pool cooling pumps from the recirculation water source to an alternative water source. The impact of adding water volume to containment should be evaluated if this step is to be used.

1.3 Evaluation of Long-Term Recirculation Capability

a. To demonstrate that a combination of design features and operator actions is adequate to ensure long-term cooling and that the criteria of 10 CFR 50.46(b)(5) will be met following a LOCA, licensees should evaluate the long-term recirculation capability. The techniques, assumptions, and guidance described below should be used in a plant-specific evaluation to ensure that any implementation of a combination of the features and capabilities listed in Section C.1.1 is adequate to ensure the availability of a reliable water source for long-term recirculation following a LOCA. These assumptions and guidance can also be used to develop conditions for suction strainer testing.

b. To ensure that long-term recirculation cooling can be accomplished following a LOCA, licensees should evaluate (1) ECCS strainer hydraulic performance (e.g., geometric effects, air ingestion, flashing, and gas void accumulation), (2) debris effects (e.g., break selection, debris generation, debris transport, latent debris, chemical precipitation, upstream effects, downstream effects, interceptor blockage, strainer head loss, and structural integrity), and (3) the combined impact on NPSHa at the pump inlet. Such an evaluation should demonstrate adequate strainer and pumping performance (e.g., adequate pump NPSH margins, adequate strainer structural strength, and no excessive air ingestion). Licensees should also assess the susceptibility of the containment drainage flowpaths to the recirculation sump or suppression pool to debris blockage. A holdup of water assumed to reach the pool could affect the NPSHa, flashing, and/or air ingestion evaluations. In addition, licensees should assess the structural adequacy of any interceptors or trash racks used to prevent debris blockage of these flowpaths to protect against a reduction in NPSHa if substantial amounts of water are held up or diverted away from the sump or suppression pool. Licensees should also assess the potential for failure of the flowpaths and components downstream of the strainers, to ensure that debris blockage and particulate ingestion do not prevent the components from performing their required functions. The assessment should include abrasive effects to ensure that long-term degradation of the equipment does not occur.

1.3.1 Net Positive Suction Head of the Emergency Core Cooling System and Containment Heat Removal Pumps

1.3.1.1 The design of the ECCS and containment heat removal system should ensure that sufficient NPSHa is provided to the system pumps, assuming the maximum expected temperature of the pumped fluid and no increase in containment pressure from that present before the postulated LOCA. Appendix B implements the staff requirements memorandum for SECY-11-0014, “Staff Requirements—SECY-11-0014—Use of Containment Accident Pressure in Analyzing Emergency Core Cooling System and Containment Heat Removal System Pump Performance in Postulated Accidents,” dated March 15, 2011 (Ref. 37), by providing guidance on the use of CAP for determining the NPSH margin for the ECCS and containment heat removal pumps in BWRs and PWRs.

a. It is conservative to assume that the containment pressure equals the vapor pressure of the pool water. This ensures that credit is not taken for containment pressurization during the transient.

b. For PWR sub-atmospheric containments, this guidance should apply after termination of the injection phase. For these sub-atmospheric containments, before termination of the injection phase, NPSH analyses should include conservative predictions of the containment atmospheric pressure and sump water temperature as a function of time.

1.3.1.2 For certain operating reactors in which it is not practicable to alter the design, conformance with Section C.1.3.1.1 may not be possible. In these cases, the determination of NPSHa should not include containment pressure above that which is necessary to preclude pump cavitation. In the determination of NPSHa for this situation, the calculation of available containment pressure and sump/pool water temperature as a function of time should underestimate the expected containment pressures and overestimate the sump/pool water temperatures.

1.3.1.3 If credit is taken for operation of an ECCS or containment heat removal pump in cavitation, licensees should conduct prototypical pump tests, along with a posttest examination of the pump, to demonstrate that pump performance will not be degraded and that the pump will continue to meet all of the performance criteria assumed in the safety analyses. The time period in the safety analyses during which the pump may be assumed to operate while cavitating should not be longer than the time period for which the performance tests demonstrate that the pump meets the performance criteria.

1.3.1.4 Because high water temperatures reduce NPSHa and can affect the potential for flashing and impact fluid properties, such as density and viscosity, the determination of the water temperature should include the decay and residual heat produced following accident initiation. This calculation should include uncertainty in the determination of the decay heat (uncertainty in decay heat is typically included at the 2-sigma level). The licensee should calculate the residual heat with margin.

1.3.1.5 Licensees should not use the correction factor for pumping high-temperature fluid discussed in ANSI/HI 14.3-2019 to determine the margin between the available and required NPSH for the ECCS and the containment heat removal systems.

1.3.1.6 The calculation of NPSHa should consider the minimum calculated height of water above the pump suction and strainer surfaces. The calculated height of water should not consider quantities of water that do not contribute to the sump or suppression pool (e.g., atmospheric steam, pooled water on floors and in refueling canals, spray droplets and other falling water, holdup in containment coolers, water held up by upstream obstructions, and the volume of empty system piping). In determining the minimum level, licensees should not credit non-leak-tight structures, such as ducting for heating, ventilation, and air conditioning, for the displacement of water. The calculated height should not include the amount of water in enclosed areas that cannot readily be returned to the sump or suppression pool. Minimum water level calculations should consider worst-case break locations (e.g., breaks at high elevations) that could lead to a minimum quantity of reactor coolant reaching the sump or suppression pool. Licensees should consider volume reduction of the reactor coolant inventory as it cools when crediting the contribution of spilled coolant to the sump or suppression pool. The volume of the coolant remaining in the primary system will also decrease as it cools. Therefore, it will be necessary to add more inventory to the primary system before it is filled. Licensees should explicitly consider the limiting small-break LOCA water level, because elevated break locations may be possible and certain sources of inventory (e.g., PWR accumulators) may not inject.

1.3.1.7 Licensees should calculate the pipe and fitting resistance and the nominal strainer resistance without blockage by debris in a recognized, defensible method or determine it from applicable experimental data. Calculations of the clean strainer head loss (i.e., the friction head loss caused by the passage of flow through the strainer and any associated connecting pipes and plenums) should consider the distribution of flow through the strainer that produces the highest head loss. For some curvilinear-type strainer designs, this occurs with a filtering debris bed near the strainer outlet and a clean strainer where the unobstructed flowpath is longer. If the strainer were partially covered with a filtering debris bed, much of the strainer flow could occur through the unblocked strainer surfaces, which could be more limiting for some designs.

1.3.1.8 Licensees should refer to Sections C.1.3.10 and C.1.3.11 for guidance on determining strainer head loss caused by blockage from LOCA-generated debris and its chemical reaction products or from foreign material in the containment that is transported to the suction intake screens.

1.3.1.9 Licensees should calculate NPSHa as a function of time until it is clear that the NPSHa will not decrease further.

1.3.2 Pipe Break Selection

a. Licensees should consider a sufficient number of high-energy pipe break locations that could result in ECCS recirculation, so that variations in debris size distributions, quantity, and types are bounded. The objective of the break selection process is to identify the break location and size that results in debris generation that produces the maximum head loss across the sump screen. Licensees should consider all aspects of the accident scenario for each postulated break location, including debris generation, debris transport, latent debris, coating debris, chemical effects, upstream and downstream effects of debris accumulation, and sump screen head loss.

b. The objective of strainer head loss testing is to simulate the debris from the break location that transports the maximum amount of debris or the combination of debris types that produces the maximum head loss to the sump strainer. At a minimum, licensees should consider the postulated break locations and pipe break characteristics described in the following sections.

c. Sections 3.3.3 to 3.3.5 of NEI 04-07, "Pressurized Water Reactor Sump Performance Evaluation Methodology," issued December 2004 (Ref. 38), the associated SE (Ref. 39), and Section 3.2.1.1 of the URG provide additional guidance on break selection criteria.

1.3.2.1 Licensees should consider breaks where debris is most easily transported to the suction strainer (e.g., breaks in areas with the most direct path to the sump strainer or suppression pool).

1.3.2.2 Licensees should consider a spectrum of breaks, including the breaks with the largest amount and greatest variety of debris within the expected zone of influence (ZOI).

1.3.2.3 Licensees should consider medium and large breaks that can generate and transport enough fiber to form a thin filtering bed and that have the greatest potential ratio of particulate to fibrous insulation debris by weight. These breaks could form a thin layer that would subsequently filter sufficient particulate debris to create a relatively high head loss (called the "thin-bed effect"). A "thin bed" is a relatively thin layer of debris on a screen or strainer that has a high particulate-to-fiber ratio and causes a large flow resistance.

1.3.2.4 Licensees should disregard break exclusion zones in their evaluations (i.e., pipe breaks should be postulated in break exclusion zones).

1.3.2.5 Licensees should exclude NRC Branch Technical Position (BTP) 3-4, Revision 2, "Postulated Rupture Locations in Fluid System Piping inside and outside Containment," issued March 2007 (Ref. 40), as a basis for selecting break locations, because limiting conditions for ECCS strainer performance are not related to the pipe vulnerability issues addressed in BTP 3-4.

1.3.2.6 Licensees should consider locations that result in unique debris source terms (i.e., not multiple, identical locations). Particular consideration should be given to breaks that result in the destruction of materials known to cause high head loss, such as microporous insulation (e.g., calcium silicate, Min-K, and Microtherm).

1.3.2.7 If the LOCA blowdown does not generate a significant amount of fibrous debris, the contribution of latent debris sources may become the limiting factor in ECCS strainer and downstream evaluations.

1.3.2.8 If long-term cooling requires recirculation flow through the ECCS strainer for non-LOCA HELBs (e.g., main steam and feedwater line breaks), then licensees should use the same selection criteria for break locations on that piping as those specified for a LOCA.

1.3.3 Debris Generation/Zone of Influence

The energy associated with jet impingement can generate debris from the blowdown of a ruptured pipe. The jet can damage insulation, coatings, fire barriers, shielding blankets, and other materials located close to the break. The distance from the break within which a material may be damaged depends on the robustness of the material. The material-specific volume of space affected by the jet, or ZOI, is modeled to define and characterize the debris generated.

1.3.3.1 Zone of Influence Model

a. The size of the ZOI should be consistent with experiments performed for specific debris sources (e.g., insulation, coatings, and fire barrier materials). The ZOI should extend until the jet pressures decrease below the experimentally determined damage pressures appropriate for the debris sources.

b. Licensees should use the volume of material contained within the ZOI to estimate the amount of debris generated by a postulated break. The size distribution of debris created in the ZOI should be determined from applicable experiments. It is noted that if robust barriers intersect the postulated jet zone, the extended volume may be truncated within the limitations of NEI 04-07, Section 3.4.2.3, and its associated SE.

c. Licensees should use jet pressure isobars from the jet generated from the postulated pipe break as the basis for estimating the amount and the size or size distribution of the debris generated within the ZOI. The pressure distribution within the jet will vary depending on the pressure and temperature of the fluid and the size of the break.

d. Licensees should use the results of debris generation testing to determine the ZOI in a manner that is prototypical of the plant condition. Test scaling is complicated because material destruction may result from both pressure waves and jet impingement. Scaling considerations for debris generation testing include the test fluid used (e.g., air or saturated water), the initial thermodynamic conditions of the test fluid, the rupture disk opening time, the blowdown period, the size and orientation of the test nozzle relative to the target, and the specific configuration of the target material compared to the various plant materials to which the testing is being applied (e.g., insulation jacketing seam, jacketing thickness, and banding and latching strength). The staff has not developed specific guidance for the performance of ZOI testing. Methods and results are reviewed case by case. One example is the Air Jet Impact Tests documented in Section 3.2.1 of the URG. More recent testing and analyses to refine ZOIs for some materials are documented in WCAP-17561-P, Revision 0, "Testing and Analysis to Reduce Debris Generation Zones of Influence for GSl-191," issued May 2012 (Ref. 41), and FAI/12-058, Revision 0, "A Methodology to Calculate the Zones of Influence of Different Insulation Materials for a Flashing and Freely Expanding Two-Phase Critical Flow Jet," issued April 2012 (Ref. 42).

e. The shape of the ZOI should be consistent with the break configuration and accepted jet models. For typical evaluations, the ZOI shapes are simplified to allow reasonable estimates of debris generation at each break location.

f. If the evaluation uses simplified ZOI models, such as the spherical ZOI models discussed in Section 3.2.1 of the URG and Section 3.4.2 of NEI 04-07, licensees should apply sufficient conservatism to account for simplifications and uncertainties in the model. For example, a spherical ZOI model assumes that the blowdown from a LOCA is evenly distributed in all directions radiating from the break location. Although, with sufficiently conservative inputs, a spherical model may be appropriate for estimating the loadings of debris within a ZOI, such a model does not account for nonuniform blowdown that could create damage in a particular direction at much greater distances from the break. Therefore, a spherical model may be nonconservative when specifying a ZOI for particularly problematic materials (e.g., calcium silicate insulation for a PWR with a trisodium phosphate buffer, or fibrous debris for a plant with a limited strainer area where the licensee intends to demonstrate that a fibrous debris bed cannot be formed).

1.3.3.2 Analysis can demonstrate that certain types of material used in small quantities inside the containment contribute only marginally to the debris loading for the ECCS sump. If debris generation and debris transport data have not been determined experimentally for a specific material, the material may be grouped with another material with similar physical and chemical characteristics existing in large quantities. For example, a small quantity of fibrous filtering material may be grouped with a substantial quantity of fibrous insulation debris, in which case the debris generation and transport data for the filter material need not be determined experimentally. However, such analyses are valid only if the small quantity of material does not have a significant effect when combined with other materials (e.g., it may not be valid to combine a small quantity of calcium silicate with fibrous debris).

1.3.3.3 All insulation (e.g., fibrous, calcium silicate, microporous, and reflective metallic); painted surfaces; fire barrier materials; and fibrous, cloth, plastic, or particulate materials within the ZOI should be considered as potential debris sources. Licensees should use applicable test data as the basis for predicting the size distributions of the postulated debris. For breaks postulated in the vicinity of the containment penetrations, licensees should also consider the potential for debris generation from the packing materials used in the penetrations. In addition, licensees should consider breaks that could destroy the insulation installed on the reactor vessel and steam generators. Finally, licensees should consider the potential for particulate debris to be generated by the action of pipe rupture jets damaging paint or coatings and erosion of concrete at the point of impact.

1.3.3.4 In addition to debris generated by jet forces from the pipe rupture, the analyses should consider (1) debris existing before the pipe rupture that is transported to the suppression or containment pool, (2) debris created by the reactor pressure vessel environment (i.e., thermal and chemical), (3) debris created by the atmospheric environment (i.e., thermal and chemical), and (4) debris created by the environment of the submerged containment or suppression pool, as appropriate. Examples of debris created by the environment include unqualified coatings that fail in the form of chips and particulates, and the formation of chemical products caused by chemical reactions occurring anywhere within the containment, including the ECCS pool or the suppression pool and the reactor vessel (see Sections C.1.3.5 and C.1.3.10).

1.3.3.5 The analyses should consider debris erosion that results from continued degradation of insulation and other debris when subjected to turbulence caused by cascading water flows from upper containment, containment spray, or flows in the sump or suppression pool. Chemical decomposition or environmental conditions may also damage materials so that they can erode and become transportable to the pool. The determination of eroded quantities for various types of debris should be based on testing that is prototypical of plant conditions. In the absence of applicable testing, demonstrably conservative assumptions should be used. (For example, Appendix III to the SE for NEI 04-07 recommends a bounding value of 90-percent erosion for fibrous debris.)

1.3.4 Debris Transport

The debris transport evaluation determines the fraction of containment debris that is transported to the ECCS strainer.

1.3.4.1 The calculation of debris quantities transported to the ECCS strainers should comprise all modes of debris transport, including blowdown transport, spray transport, washdown transport, and transport within the containment pool. Consideration of containment pool debris transport should address (1) debris transport during the pool fill phase, as applicable, and during the recirculation phase, (2) the velocity and turbulence in the sump, suppression pool, or storage tank (i.e., turbulence caused by the flow of water to the ECCS strainers, water splashing down from the break, containment spray drainage, and the discharge of pressure-relief flowpaths such as from downcomers, vents, and safety/relief valve spargers), and (3) the density, characteristic size, and other properties of the debris. Section 3.2.3 of the SE for NEDO-32686-A (the URG) and Section 3.6 of the SE for NEI 04-07 discuss staff-accepted methods to evaluate debris transport. NUREG/CR-6369, "Drywell Debris Transport Study," issued September 1999 (Ref. 43), is also a useful reference for debris transport evaluations. Section 3.6.4 of NEI 04-07 contains a sample calculation for debris transport that the staff finds acceptable.

1.3.4.2 Transport analyses within the containment pool should include debris that may be transported through the following modes: (1) floating along a water surface, including debris that may float temporarily because of air entrapment, (2) traveling with the containment flow (i.e., debris suspended within the flow) because of neutral buoyancy or turbulence (e.g., individual fibers and fine particulates), and (3) settling to the floor and tumbling along the floor to reach the strainer.

1.3.4.3 The debris transport analyses should consider each type of insulation (e.g., fibrous, calcium silicate, and reflective metallic), as well as other debris such as chemical precipitates, coatings, and latent debris. The debris size (e.g., fine, readily suspendable, small, large, or intact) should also be considered. The analyses should also consider the potential for further decomposition of the debris as it is transported to the ECCS strainers.

1.3.4.4 An acceptable analytical approach to predict debris transport resulting from fluid flows caused by long-term recirculation or pool fill is to use appropriately verified computational fluid dynamics (CFD) simulations in combination with experimental debris transport data. The CFD simulations can be used to predict fluid flows, while debris transport thresholds can be determined experimentally. Section 4.2.4 of NEI 04-07 and Section 4.2.4 and Appendix III in the associated SE provide guidance and an example of this approach. Alternative methods for debris transport analysis are also acceptable, provided that analytical techniques are adequately validated using experimental data to ensure that estimates are conservative with respect to the quantities and types of debris transported to the strainer.

1.3.4.5 The analysis may credit curbs for removing heavier debris that has been analytically or experimentally shown to travel by sliding or tumbling along the containment floor, and that cannot be lifted off the floor within the calculated water velocity range. Curbs around the ECCS strainers may reduce or prevent the transportation of some types of debris to floor- or pit-mounted strainers during the pool fill phase (see NUREG/CR-6772 for limitations).

1.3.4.6 If transported to the containment pool, all debris that would remain suspended because of turbulence (e.g., fine fibrous and particulates) should be considered to reach the ECCS strainers. If settlement of fine fibrous or particulate debris is credited during recirculation or pool fill, licensees should provide an adequate theoretical and experimental basis to demonstrate that such settling is prototypical of plant conditions. This settlement analysis should account for the possibility that natural convection through the water column will provide a motive force to keep the material in suspension.

1.3.4.7 Rather than perform detailed analyses for each transport mode, licensees may conservatively assume that 100 percent of the debris being considered during a specific transport phase is transported. For example, they may assume that all debris generated is transported to the pool, or that all debris entering or originating in the sump or suppression pool is transported to the ECCS strainers.

1.3.4.8 The effects of floating or buoyant debris on the integrity of the ECCS strainers and on strainer head loss should be considered during the initial filling of the sump (if applicable) and during recirculation. For strainers that are not fully submerged or are only shallowly submerged, floating debris could contribute to the debris bed head loss. Floating debris could be deposited onto the strainer and remain there because of the flow through the strainer surface. Entrapped air may cause some types of debris to float temporarily; the debris may then be transported by surface currents to the vicinity of the ECCS strainers, where it may sink or be drawn to the top surface of the strainers. A design feature (e.g., use of trash racks and solid cover plate) that keeps floating debris from reaching the sump or suppression pool strainer could reduce head loss caused by floating or buoyant debris.

1.3.4.9 Use of Debris Interceptors

a. Credit for the performance of debris interceptors upstream of the ECCS strainers should be based on results of tests that are demonstrated to be either conservative or representative of the plant conditions.

b. If the interceptors are credited with capturing fine debris to reduce the ECCS strainer debris load, licensees should perform time-dependent analyses and tests that consider the conditions that would lead to minimum debris capture fractions. The analysis should include the potential for trapped debris further eroding into fines that could then pass through the interceptors. Iterative analyses of the flow in the sump or suppression pool (e.g., multiple CFD simulations that have been acceptably verified) may be necessary if the blockage of the interceptors significantly affects the containment pool flow pattern.

1.3.5 Coating Debris

Coating debris is generated from the postulated failure of both design basis accident (DBA)-qualified and unqualified coatings within the ZOI and from the postulated failure of unqualified coatings outside the ZOI. Generally, qualified coatings fail because of jet impingement, and unqualified coatings fail because of environmental conditions. Failure of unqualified coatings within the ZOI is assumed to be due to jet impingement. NRC reports entitled “NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Coatings Evaluation,” issued March 2008 (Ref. 44), and “Revised Guidance Regarding Coatings Zone of Influence for Review of Final Licensee Responses to Generic Letter 2004-02, ‘Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized-Water Reactors,’” dated April 6, 2010 (Ref. 45), provide a general approach to conducting plant-specific coatings evaluations.

1.3.5.1 Licensees should use a ZOI for coatings that is determined by applicable testing and plant-specific analysis. The fluid used for the test (steam, air, or two-phase water) should be representative of the plant exposure conditions.

1.3.5.2 All (100 percent of) unqualified coatings should be assumed to fail. However, licensees may also be able to demonstrate the performance of their unqualified coatings through plant-specific and coating-specific testing. Generally, unqualified coatings should be assumed to fail as fine particulate. However, if a filtering fibrous bed does not form on the strainer, it may be conservative to treat the unqualified coatings as chips.

1.3.5.3 Licensees should determine the debris characteristics (e.g., size, shape, density) of failed coatings separately for each coating system within containment.

1.3.5.4 Licensees may determine coating chip debris transportability in flowing water by using the results from NUREG/CR-6916, to the extent that they apply to a licensee’s plant-specific coating types.

1.3.6 Latent Debris

1.3.6.1 Latent debris present in containment during operation may contribute significantly to head loss across the ECCS strainers. Licensees must determine the types, size, quantities, and locations of latent debris. NEI 04-07 and its associated SE provide general considerations for the potential impact of latent debris on strainer blockage. In collecting latent debris samples for analysis, licensees should use a sampling technique with demonstrated collection efficiency for fine particulate and fibrous debris. NEI 02-01, Revision 1, “Condition Assessment Guidelines: Debris Sources inside PWR Containments,” issued September 2002 (Ref. 46), provides an accepted approach for determining latent debris quantities.

1.3.6.2 Licensees should not assume that their foreign material exclusion programs have entirely eliminated latent debris. Results from plant-specific walkdowns should be used to determine a realistic amount of latent debris in containment and to monitor cleanliness programs for consistency with committed estimates. Evaluation of the results of latent debris walkdowns should include sufficient conservatism to account for uncertainties inherent in the debris sampling and collection process. In lieu of plant-specific walkdowns, 10 CFR Part 52 applicants may perform conservative analyses based on latent debris measurements made for operating plants.

1.3.7 Upstream Effects

1.3.7.1 Section 7.2 of the staff’s SE on NEI 04-07 provides guidance on evaluating the flowpaths upstream of the PWR containment sump for the holdup of inventory, which could limit flow to, and possibly starve, the suction strainer. A similar approach may be used for BWRs.

1.3.7.2 Licensees should use the results of their debris assessments to assist in the evaluation of water inventory holdup. Based on these assessments and the mapping of probable flowpaths, licensees should determine whether trash racks or debris interceptors are necessary to protect flowpaths in upper containment to prevent the holdup of water upstream of the sump, storage tank, or suppression pool. Licensees should also evaluate how the placement of curbs and debris interceptors may affect the holdup of water flow to the sump, storage tank, or suppression pool.

1.3.8 Downstream Effects

1.3.8.1 Debris may be carried downstream of the ECCS strainer, thus causing downstream blockage or wear and abrasion. The three areas of concern identified are (1) blockage of system flowpaths at narrow flow passages (e.g., containment spray nozzles, some pump internal flow passages, and tight-clearance valves), (2) wear and abrasion of surfaces (e.g., pump running surfaces) and heat exchanger tubes and orifices, and (3) blockage of flowpaths through fuel assemblies.

1.3.8.2 The quantity and size characteristics of debris that penetrates the strainer will be unique to each strainer design and plant-specific debris mixture and should be determined during strainer head loss tests. WCAP-16406-P-A and the staff SE (Ref. 32) provide a method that the NRC considers acceptable for PWR licensees to use in evaluating the downstream impact of sump debris on the performance of their ECCSs, CSSs, and other components following a LOCA. Section C.1.3.12.7 discusses methods for evaluating the amount of debris that may pass downstream of the strainer. The NRC-approved Westinghouse report WCAP-16793-NP-A, Revision 2, gives a method for evaluating the impact of debris on fuel in the reactor vessel following a LOCA for PWR licensees whose plants are bounded by its assumptions, subject to the conditions and limitations specified in the NRC SE. The acceptance criteria for WCAP-16793-NP-A as originally approved by the NRC SE had a relatively low fiber limit. Some PWR licensees could not demonstrate that the amount of fiber entering the core was bounded by this acceptance limit. The Pressurized-Water Reactor Owners’ Group conducted a program of testing and analysis, which it submitted to the NRC for review and approval, to justify an increase the in-vessel fiber limits based on plant-specific parameters. This program was ultimately documented in WCAP-17788-P, Revision 1. The NRC did not approve the topical report but considered that it provided significant information and understanding of the phenomena associated with debris in the reactor vessel. Based on the topical report and extensive staff analysis, the NRC developed guidance on PWR in-vessel debris evaluations, provided in "U.S. Nuclear Regulatory Commission Staff Review Guidance for In-Vessel Downstream Effects Supporting Review of Generic Letter 2004-02 Responses" (Ref. 9). For BWRs, the BWROG and the NRC staff performed deterministic and risk-informed analyses of the in-vessel issue. The NRC evaluation of the BWR in-vessel issue can be found in a staff technical evaluation issued May 2018 (Ref. 24).

1.3.9 Strainer Structural Analysis

(This regulatory position also applies to trash racks and debris interceptors, if used.)

1.3.9.1 Items that should be considered in the structural analyses include (1) verification of maximum differential pressure caused by the combined clean strainer and worst-case debris scenario at rated flow rates or maximum realistic flow rates, whichever are greater, (2) geometry concerns (i.e., mesh and frame versus perforated plate), (3) ECCS strainer material selection for the post-accident environment (i.e., corrosion-resistant materials that can withstand the post-LOCA environment), and (4) hydrodynamic loads.

1.3.9.2 Licensees should compute structural loads on a strainer using the maximum pressure drop across the strainer. This is accomplished by evaluating the limiting conditions corresponding to the break location and debris source term that induce the maximum total head loss at the ECCS strainer.

1.3.9.3 For some licensees, the minimum structural design criterion for the ECCS strainer may depend on the plant's NPSH margin. That is, the crush pressure of the strainer must support the required NPSH margin by ensuring that the strainer does not fail structurally before other parameters result in a failure. Plant-specific licensing bases may dictate the structural capacity of the ECCS strainer to support water flow through the strainer and debris bed under limiting flow rates. The criteria will depend on strainer geometry (i.e., fully submerged versus partially submerged or vented designs).

1.3.9.4 Load combinations (e.g., safe-shutdown earthquake, deadweight, crush pressure, thermal, and live loads) used for structural analysis should be selected in accordance with the specific plant licensing-basis requirements and the applicable design code of record. Licensees should also refer to RG 1.92, Revision 3, "Combining Modal Responses and Spatial Components in Seismic Response Analysis," issued October 2012 (Ref. 47), when analyzing the seismic loading conditions during the structural analyses of the strainers.

1.3.9.5 Licensees should include the effects of the fluid temperature and containment ambient temperature (e.g., restrained thermal growth, temperature-dependent material properties) in determining the structural integrity of the strainer.

1.3.9.6 Licensees should perform an evaluation to determine the possibility of dynamic loading on the strainers caused by HELBs and other structures, systems, and components that could produce missiles, pipe whipping, or jet impingement loads. Chugging and condensation oscillation loads can be a significant factor in some BWR designs. This evaluation should conform to GDC 4 and should be based on the plant's design basis for postulated dynamic effects within the region of the strainers. Based on the SE for NEI 04-07, in general, if a postulated pipe break is located more than 10 pipe diameters away from the strainer, the dynamic effects of such a break on the structural integrity of the strainer may be neglected.

1.3.10 Chemical Reaction Effects

1.3.10.1 Chemical reaction products in the containment post-LOCA environment can contribute to blockage of the ECCS strainers and increase the associated head loss. The final SE by the Office of Nuclear Reactor Regulation on WCAP-16530-NP-A, issued December 2007 (Ref. 36), and the NRC report entitled “NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Plant-Specific Chemical Effect Evaluations,” issued March 2008 (Ref. 48), provide a general approach to conducting plant-specific evaluations of chemical effects.

1.3.10.2 During a LOCA, materials in the ZOI can become debris that may be transported to the containment pool, where spray solution, spilled reactor coolant, and water from other sources accumulate. Subsequently, the combination of spray chemicals, insulation, corroding metals, and submerged and unsubmerged materials may lead to the formation of chemical substances that could impede the flow of water through the ECCS suction strainers or downstream components in the ECCS, CSS, or reactor coolant system.

1.3.10.3 New reactors with configurations different from those of operating PWRs (e.g., different containment materials and lack of buffering agents) may require additional evaluation.

1.3.11 Debris Accumulation, Head Loss, and Vortexing

a. In a letter to NEI dated March 28, 2008 (Refs. 8 and 13), the NRC provided guidance for evaluating the potential for debris accumulation and its impact on strainer head loss following a LOCA.

b. Testing and analyses performed to address GL 2004-02 indicate that the maximum head losses for the ECCS strainers in some plants can occur when a layer of fiber just thick enough to fully cover the strainer accumulates on the strainer along with a bounding quantity of fine particulate matter. This may produce a thin, dense debris bed with low porosity that maximizes head loss. The thickness of the fiber layer necessary to filter fine particulate has not been generally defined, because it depends on several factors, including the strainer design, the strainer geometry and orientation, the approach velocity, the type and size of the fibrous debris, the type of particulate debris, and the presence of chemical effects. Appendix A, Section 6, in Ref. 13 provides testing methods acceptable to the NRC staff for evaluating thin-bed effects.

c. Other testing and analyses have shown that the maximum debris loading case can also be a limiting head loss condition for strainers. Therefore, licensees should test for both the thin-bed and the maximum loading cases. If the maximum debris loading case could result in circumscribed debris accumulation, licensees should ensure that the strainer design and head loss test scaling account for this type of debris bed, which reduces the area through which the coolant flows.

1.3.11.1 Debris accumulation on the ECCS strainers for the head loss evaluation should be based on the amount of debris generated and the formation of different combinations of fibers and particulate mixtures (e.g., a fiber bed with a minimum thickness necessary to effectively filter particulate debris, as well as maximum debris loading), using the guidelines in

Section C.1.3.3, and on the debris transported to the strainers, in accordance with Section C.1.3.4. The evaluation should be based on plant-specific debris loads determined in accordance with these regulatory positions.

1.3.11.2 The degree of ECCS strainer submergence (full or partial) at the time of switchover to recirculation should be considered in calculating the available (wetted) screen area. For plants in which certain pumps take suction from the ECCS strainers before the switchover of other pumps, the NPSHa for these pumps should consider the submergence of the strainers at the time these pumps initiate suction through the strainers. Unless experiments show otherwise, licensees should assume that debris is uniformly distributed over the available strainer surface.

1.3.11.3 Strainer submergence should be adequate to preclude vortexing, sump fluid flashing, and deaeration induced by differential pressure. Vortexing can cause the ingestion of unacceptable quantities of air into the ECCS and CSS pumps, resulting in unacceptable pump performance. If the pressure drop across the strainer and debris bed is large enough, the coolant will flash to steam. For partially submerged strainers, licensees should evaluate the potential for vortex formation internal to the strainer. Deaeration can similarly cause ingested air and unacceptable pump performance. Both deaeration and sump fluid flashing can result in an unacceptable increase in strainer head loss caused by the increased resistance associated with two-phase flow.

1.3.11.4 Licensees should validate the adequacy of ECCS strainer designs through testing applicable to plant-specific conditions. Analytical or empirical head loss correlations should not be used to validate plant-specific debris bed head losses. However, correlations may be useful in conducting scoping evaluations for conditions and debris loads within the range of applicable test data.

1.3.12 Prototypical Head Loss Testing

1.3.12.1 The methodology for predicting the key inputs to head loss testing has been conservatively developed and documented in NEI 04-07, referred to as the guidance report, and its associated SE (Refs. 37 and 38). Additionally, the NRC staff review guidance (Ref. 13) provides a general approach to plant-specific head loss testing. This guidance document discusses the staff positions on various aspects of head loss testing, including scaling of the plant strainer to the test strainer module, considerations for debris transport and debris accumulation on the strainer during testing, surrogate debris similitude requirements, and posttest data processing extrapolation.

1.3.12.2 The objective of prototypical head loss testing is to determine the potential peak or bounding head loss that could occur across a suction strainer debris bed during a postulated LOCA scenario. If the test facility is scaled properly and the testing procedures and inputs are conservative, the measured head loss is also expected to be conservative. To ensure adequate strainer function, licensees should design the test facility properly and follow conservative procedures for testing. The conditions within the test tank should be prototypical or conservative with respect to the plant, including the postulated debris loading, the recirculation system hydraulics, and key aspects of various accident scenarios. The primary scaling parameters are the screen area, the dimensions of the strainer elements (e.g., disks), the submergence level, the number of strainer elements, the debris amounts, and the local fluid flow conditions, as applicable. These parameters affect the flow velocities approaching the test strainer and the velocities through accumulated debris.

1.3.12.3 The test specifications should be designed to determine a reasonably bounding head loss from all possible types of debris beds that could accumulate on the strainer, considering the plant-specific debris quantities transported from various break scenarios. In some cases, more than one scenario will need to be modeled during a plant test program. This may be necessary if a plant has various debris types that are not uniformly distributed throughout containment and if the inclusion of all potential debris types results in unacceptable head loss.

1.3.12.4 Posttest evaluations are required to validate the head loss results, apply the results to the proposed strainer, and ensure that the debris penetrating the strainer cannot cause adverse effects to downstream equipment. Licensees wishing to scale the results of head loss tests conducted using colder water to the plant water temperatures should ensure that boreholes, bed degradation, open strainer area, and other phenomena that could affect the head loss response of the debris bed do not have a nonconservative effect when the head loss is scaled. The NRC does not recommend scaling of head loss results to alternate approach velocities or debris loadings, because the theoretical debris bed head loss behavior is not well understood and the results of experiments examining these parameters have varied.

1.3.12.5 Licensees may need to extrapolate the results of head loss testing for a time period matching the mission time of the ECCS. The method of extrapolation should conservatively fit the data (e.g., linear, log, quadratic) over the time period of interest.

1.3.12.6 Because it is difficult to model and scale multiple complex physical phenomena in a single test, licensees should conduct head loss tests in a manner that ensures complete transport of debris (as determined by transport analysis) to the test strainer. Agitation of the test fluid may be necessary to achieve conservative debris transport. The agitation should not disturb the debris bed. Licensees may conduct separate tests to credit reductions in debris transport to the strainer (i.e., settling) under conditions that are conservatively or prototypically scaled to the plant conditions. Head loss or debris settlement testing which credits or evaluates lack of transport due to settling should include careful evaluation of the flow characteristics (e.g., velocity and turbulence) in the test to ensure that the simulated flows are prototypical or conservative with respect to the plant conditions. In evaluating how potential accumulation of debris in areas of flow restrictions may affect debris transport, licensees should consider scaling of debris per unit area of floor in the flume versus debris per unit floor area of the plant. The quantity of debris per unit width of the flume relative to the flow passages in the plant is another important scaling parameter. Licensees should also consider the adequacy of other aspects of the test protocol, such as debris preparation, addition sequencing, debris concentration in the flume, and test flume geometry, when designing tests. They should ensure that the amounts of debris settling in the plant containment will be similar to or larger than the amounts in the test. They should also consider how debris settlement during a head loss test could affect other aspects of the analysis. For example, allowing debris settlement in the test tank may not account for erosion of the settled debris in the analysis. Because it is impractical to simultaneously scale the multiple complex phenomena associated with debris transport and head loss in a rigorous way, licensees should apply conservatism to tests that model both transport and head loss. Section 5.7.4 of NUREG/CR-7172 provides more details on this topic.

1.3.12.7 Licensees may sample the flows downstream of the test strainer to determine the amount of debris passing through the strainer. The sampling should be performed with a frequency that ensures adequate characterization of the total bypass content. This debris could damage or clog components, such as pumps, throttle valves, or components within the reactor core. Licensees may use the downstream debris characteristics to determine the likelihood that downstream blockage or wear and abrasion could threaten long-term core cooling or affect heat transfer of the fuel cladding. The conditions for the limiting downstream sampling tests will typically differ from the conditions for the limiting debris bed head loss tests because a filtering debris bed will reduce the quantity of debris that passes through the strainer. A larger strainer surface area, higher flow rates, a low rate of introduction of debris into the water, or thinner debris beds can result in greater debris penetration. Licensees may need to conduct separate strainer penetration tests for fibrous and particulate debris, to avoid crediting filtration caused by one debris type that might affect the other debris type. Another method that has been successfully used to characterize the bypass content is to collect bypass debris in a filter with very small pore size, downstream of the strainer. The NRC staff has not accepted sampling of downstream fluid samples for quantification of penetrated debris. However, sampling results may help determine debris characteristics and trends in the amount of penetration over time. The NRC has not issued guidance on performing strainer penetration testing. However, the NRC has observed penetration testing conducted by some vendors and has concluded that the test results are conservative with respect to penetration that could occur in the plant. Penetration testing is conducted only for fibrous debris. In general, head loss testing guidance applies to penetration testing. Penetration testing usually involves only fine fibers, which are introduced in small batches to prevent formation of a filtering bed faster than might occur in the plant. If larger debris is included, it should be introduced after the fines. Particulate debris is generally excluded, because it is difficult to separate it from fibrous debris when quantifying penetration. A test may attempt to determine the maximum amount of fiber that may penetrate the strainer, or to determine a load-dependent fiber penetration curve. The latter is done by batching in fiber while collecting fiber downstream of the strainer, allowing time for the system to stabilize, collecting the penetrated fiber from that batch, aligning a new collection filter, then repeating the process. These steps may be iterated several times; the results can be used to generate a penetration model that is dependent on fiber load at the strainer. Load-dependent models may be useful in determining the amount of fiber that reaches the core if credit is taken for flow through the CSS, if different fiber load cases are considered, or if other scenarios require analysis of penetrated fiber. Penetrated debris should be collected in full flow filters. If incremental penetration data are desired, the system and test procedure should allow for swapping of collection filters without perturbing the flow rate through the test strainer. Filters should be fine enough to collect all penetrated fiber. Penetration testing and its extrapolation to the plant strainer should consider flow velocity through the strainer and the velocity profile through the strainer. Testing and extrapolation to the plant scale should also consider sacrificial strainer area, the number of strainers in service, and the flow through each strainer. In general, testing demonstrates that increasing strainer area and approach velocity increases penetration. Observations have also shown that penetration decreases significantly with fiber load on the strainer. Penetration testing should account for all fiber that was added to the test. In tests observed by the NRC staff, fiber penetration amounts were measured by careful drying and weighing of the filters used to collect the fiber, with filters dried and weighed both before and after use to ensure consistent results. The drying and weighing process can significantly affect results and constitutes a critical step in testing. Any fiber that did not reach the strainer should be accounted for and evaluated in the test report. Licensees may use test results that were not performed for their specific strainer design if they can justify that the results are prototypical or conservative with respect to their plant. Penetration testing and evaluation should consider strainer hole size, strainer geometry, flow profile across the strainer, flow conditions, fiber type, water chemistry, licensee actions that may change flow rates, and sacrificial strainer area.

1.3.12.8 The analyses and testing should consider worst-case single failures. For example, licensees with plant designs that include low-pressure safety injection (LPSI) pumps that shut down during the switchover from the refueling water storage tank to the sump should consider one LPSI train failure to stop. This assumption leads to a conservatively calculated maximum flow rate to and through the screen. Alternatively, licensees may demonstrate that the pump can be secured by operator action before significant effects on debris transport and strainer performance occur.

1.3.12.9 The time dependence of debris arrival at the strainer is difficult to model in a practical number of head loss tests. A conservative assumption is that all of the LOCA debris is present on the strainer at the beginning of recirculation. This debris should include that generated from the LOCA blowdown, failed unqualified coatings, eroded fine debris, chemical precipitates, and all other debris predicted to be transported to the strainer. Licensees may be able to demonstrate that the arrival of some debris will be delayed and account for this in the analyses.

1.3.12.10 In some cases, head loss testing for complex combinations of debris that typically result from limiting plant debris loads has shown significant variation for the same debris loading. Licensees should therefore ensure that head loss test results have been demonstrated to be sufficiently repeatable, in light of known margins, uncertainties in debris quantities, the collective body of knowledge from tests on similar strainers, and other relevant information.

1.3.12.11 Debris introduction procedures should consider the fact that variations in the sequence and rate of debris introduction can affect the head loss measurement. One acceptable approach is to introduce the debris slowly into the test tank with the pump running and prototypical hydraulic conditions established. The most transportable debris should be added first and the least transportable last. Licensees may also use other approaches, if justified. Testing that takes credit for nearfield settlement should either realistically or conservatively simulate the strainer upstream flow and turbulence conditions. Licensees should conduct a proper analytical evaluation of the similarity of the test tank and the actual plant conditions. The NRC staff considers CFD codes to be useful tools in such evaluations. Surrogate debris materials used in head loss testing should be either the actual plant materials or suitable substitutions. Licensees should justify substitutions by comparing the important characteristics of the plant debris sources and the surrogate, to verify that the debris preparation creates prototypical or conservative debris characteristics. NEI has developed a fibrous debris preparation procedure that has been used in strainer head loss and penetration testing. This procedure is described in "ZOI Fibrous Debris Preparation: Processing, Storage and Handling," Revision 1, issued January 2012 (Ref. 49). In a letter dated April 26, 2012 (Ref. 50), the NRC recognized that the NEI protocol could produce the intended surrogate debris for testing, but that the results depended on human actions not fully controlled by the procedure. The NRC staff has observed debris produced using the NEI procedure and has found it acceptable for use in head loss and penetration testing. However, because of the human factors involved, the NRC expects licensees to verify that the surrogate materials have the desired characteristics.

2. Regulatory Positions Specific to Pressurized-Water Reactors

Evaluations of the susceptibility of a PWR to debris blockage should address the considerations and events shown in Figure 3.

2.1 Emergency Core Cooling System Sumps, Strainers, and Debris Interceptors

Distribution of water sources and containment spray between the sumps should be considered in the calculation of boron concentration in the sumps for evaluating post-LOCA subcriticality and shutdown margins. Typically, these calculations are performed assuming minimum boron concentration and maximum dilution sources. Similar considerations should also be included in the calculation of time for hot-leg switchover, which assumes maximum boron concentration and a minimum of dilution sources.

The evaluation of debris transport to the sump screen should account for the time to switch over to sump recirculation and the operation of containment spray.

2.1.1 The ECCS strainers should be located on the lowest elevation in the containment, exclusive of the reactor vessel cavity and the normal drainage sump, to maximize the pool depth relative to the strainers. Recirculation strainers should protect the pump inlets for which they supply water. A curb may be provided upstream of the strainers to prevent high-density debris from being swept along the floor into the sump strainer. The height of the curb should be appropriate for the pool flow velocities and plant debris types, because flows of sufficiently high velocity can carry debris over a curb. Estimation of pool flow velocities should include both the pool fill (as applicable) and the recirculation phases of the event. Licensees should also consider that turbulence in the pool may keep some debris in suspension that would otherwise settle. Experiments documented in NUREG/CR-6772 and NUREG/CR-6916 demonstrated that at typical containment pool velocities, some types of settled debris will slide or tumble across the containment pool floor to the suction strainer.

The ECCS strainers should include access openings and other design features, as required, to facilitate inspection of the strainer structures, vortex suppressors, and pump suction piping inlets. Where consistent with overall design and functionality, the top of the ECCS strainer structures should be a solid cover plate that is designed to be fully submerged after a LOCA and completion of the ECCS injection phase. The cover plate protects the strainer from LOCA-generated loads and from water drainage from upper containment. The design should also provide a means for venting any air trapped under the cover.

2.2 Chemical Reaction Effects

2.2.1 For PWRs, the Westinghouse report WCAP-16530-NP-A and the limitations discussed in the associated SE (Ref. 36) provide an acceptable approach to evaluating chemical effects that may occur in a post-accident containment sump pool.

2.2.2 Plant-specific information should be used to determine the projected post-LOCA chemical precipitate quantity. The plant-specific chemical effects evaluations should use a conservative analytical approach. The report "NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Plant-Specific Chemical Effect Evaluations" (Ref. 48) provides a general approach to these evaluations for PWR licensees.

2.2.3 WCAP-16793-NP-A and its SE (Ref. 33) provide guidance for evaluation of chemical debris within the reactor for those PWRs in which a limited amount of fibrous debris reaches the core inlet. In addition to the acceptance criterion for fiber mass limit per fuel assembly, evaluations using WCAP-16793-NP-A also determine deposition thickness on the fuel rods and the resulting peak clad temperature. Another method of evaluating the effects of fibrous debris, particulate, and chemical precipitates in the reactor vessel can be found in WCAP-17788-P, Revision 1. Volume 5 of WCAP-17788-P, Revision 1, was not approved by the NRC but nevertheless contains considerable information on the timing of chemical precipitates based on simulated plant-specific post-LOCA environments. The memorandum "U.S. Nuclear Regulatory Commission Staff Review Guidance for In-Vessel Downstream Effects Supporting Review of Generic Letter 2004-02 Responses" (Ref. 9) provides updated guidance on chemical effects as they relate to fuel.

In its work on the in-vessel issue, the NRC staff determined that chemical effects timing was the most important factor related to effects on long-term core cooling.

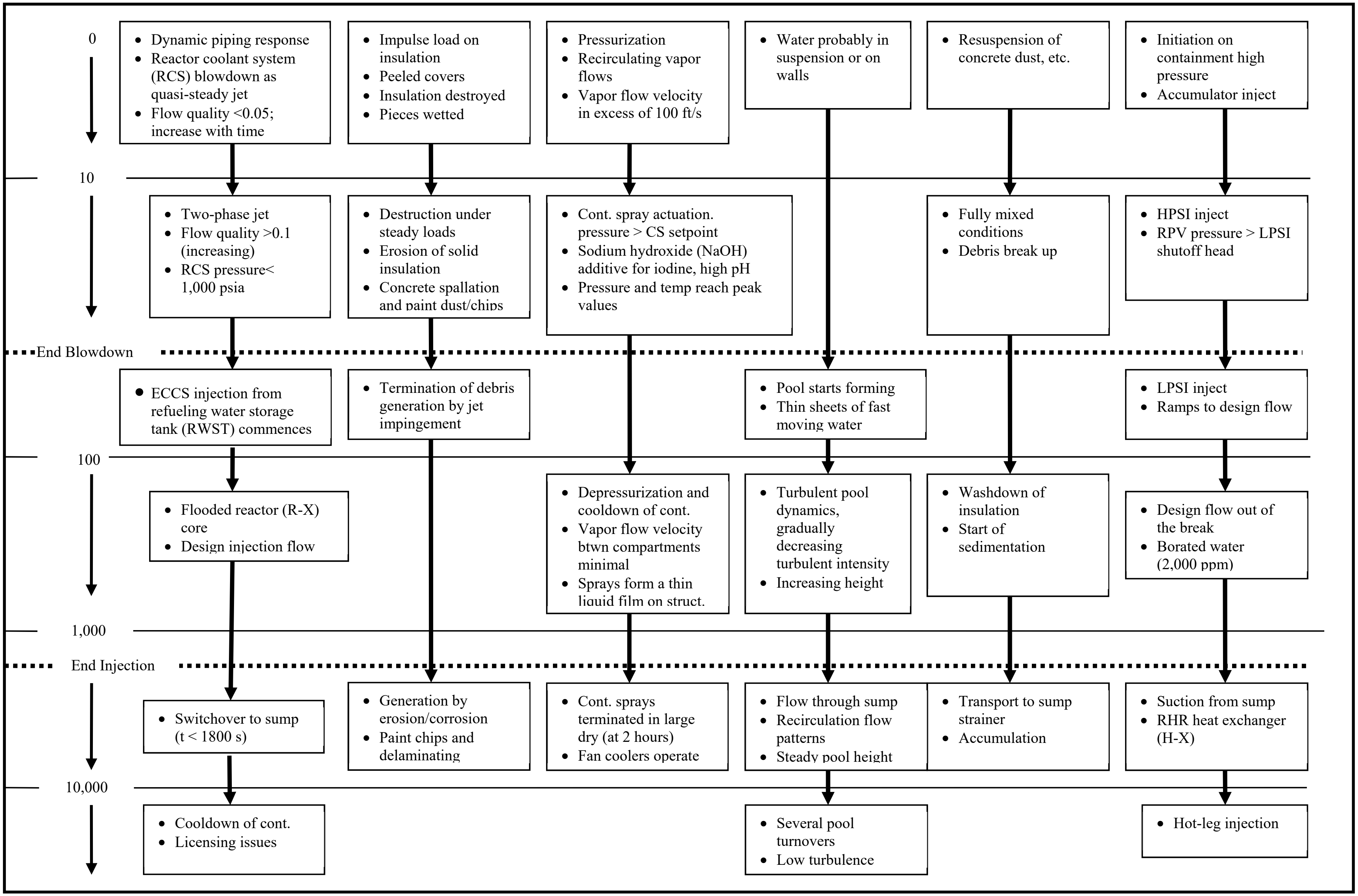

Figure 3: PWR large-break LOCA accident progression in a large, dry containment (from NUREG/CR-6762, Figure 2-2)

3. Regulatory Positions Specific to Boiling-Water Reactors

Evaluations of the susceptibility of a BWR to debris blockage should address the considerations and events shown in Figures 4 and 5. These figures are from NUREG/CR-6224, which gives more detail on the information in the figures. The URG and the associated NRC staff SE (Ref. 19) contain additional guidance.

3.1 Suppression Pools and Debris Interceptors

3.1.1 For the purposes of evaluating strainer performance, licensees should assume that the level of water in the suppression pool or wetwell is the minimum value given in the technical specifications, reduced by the drawdown caused by suppression pool water in the drywell and the sprays.

3.1.2 Debris interceptors in the drywell in the vicinity of the downcomers or vents may reduce debris transport to the suppression pool. Debris interceptors between the drywell and wetwell should not reduce the suppression capability of the containment.

3.2 Debris Sources, Generation, and Transport

3.2.1 Licensees should assume the amount of particulates in the suppression pool before a LOCA is the maximum amount of corrosion products (i.e., sludge) expected to be generated since the last time the pool was cleaned. The size distribution and amount of particulates should be based on plant samples. The quantity and size distribution of suppression pool sludge has been analyzed for BWRs participating in the URG.

3.2.2 Licensees should not take credit for debris settling until LOCA-induced turbulence in the suppression pool has ceased. This should include the effect of the automatic depressurization system for small-break LOCAs. Sections C.1.3.4.6 and C.1.3.4.7 apply to the settlement of fine debris.

3.3 Chemical Reaction Effects

3.3.1 The post-LOCA containment conditions for BWRs may lead to different chemical interactions from those analyzed in WCAP-16530-NP-A and in other experimental and analytical studies of chemical interactions for operating PWRs. Therefore, the chemical effects for BWRs require additional evaluation. The BWROG described its evaluation of chemical effects in a letter dated November 20, 2017 (Ref. 22). The BWROG adopted a simplified approach for chemical effects related to the ECCS suction strainer, assuming negligible impact preceding the accumulation of a 1/8-inch-thick debris bed, but assuming NPSH failure if a debris bed over 1/8 inch thick forms. The NRC reviewed the BWROG letter and agreed that no further action was required, as documented in a letter dated June 29, 2018 (Ref. 23). The BWROG analysis included an evaluation of the potential for in-vessel effects. The NRC staff reviewed the BWROG work and determined that it reached acceptable conclusions. The NRC documented its findings in a staff technical evaluation issued in May 2018 (Ref. 24).

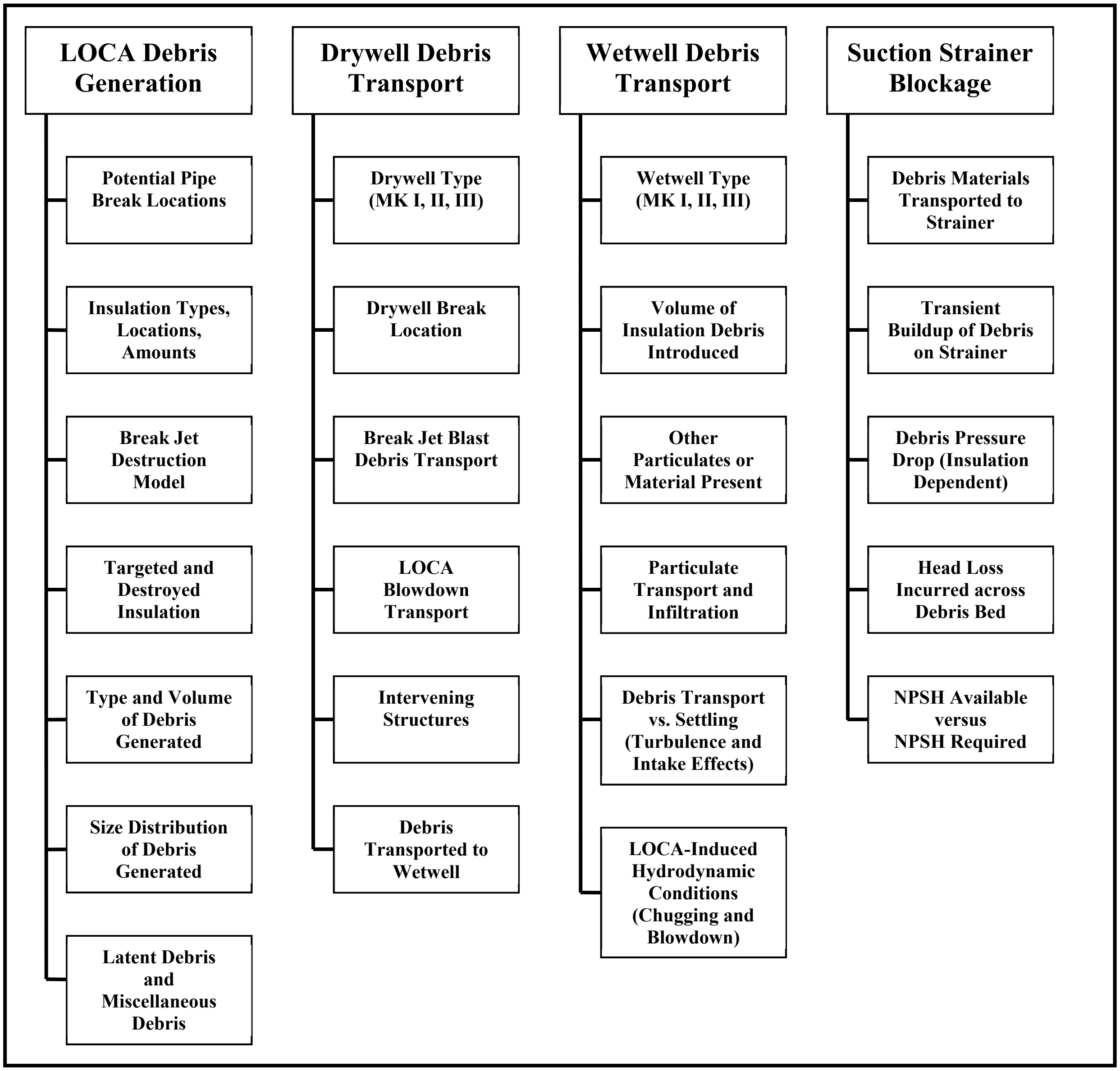

Figure 4: Debris blockage considerations for BWR LOCA sequences (see NUREG/CR-6224, Figure 1-1)

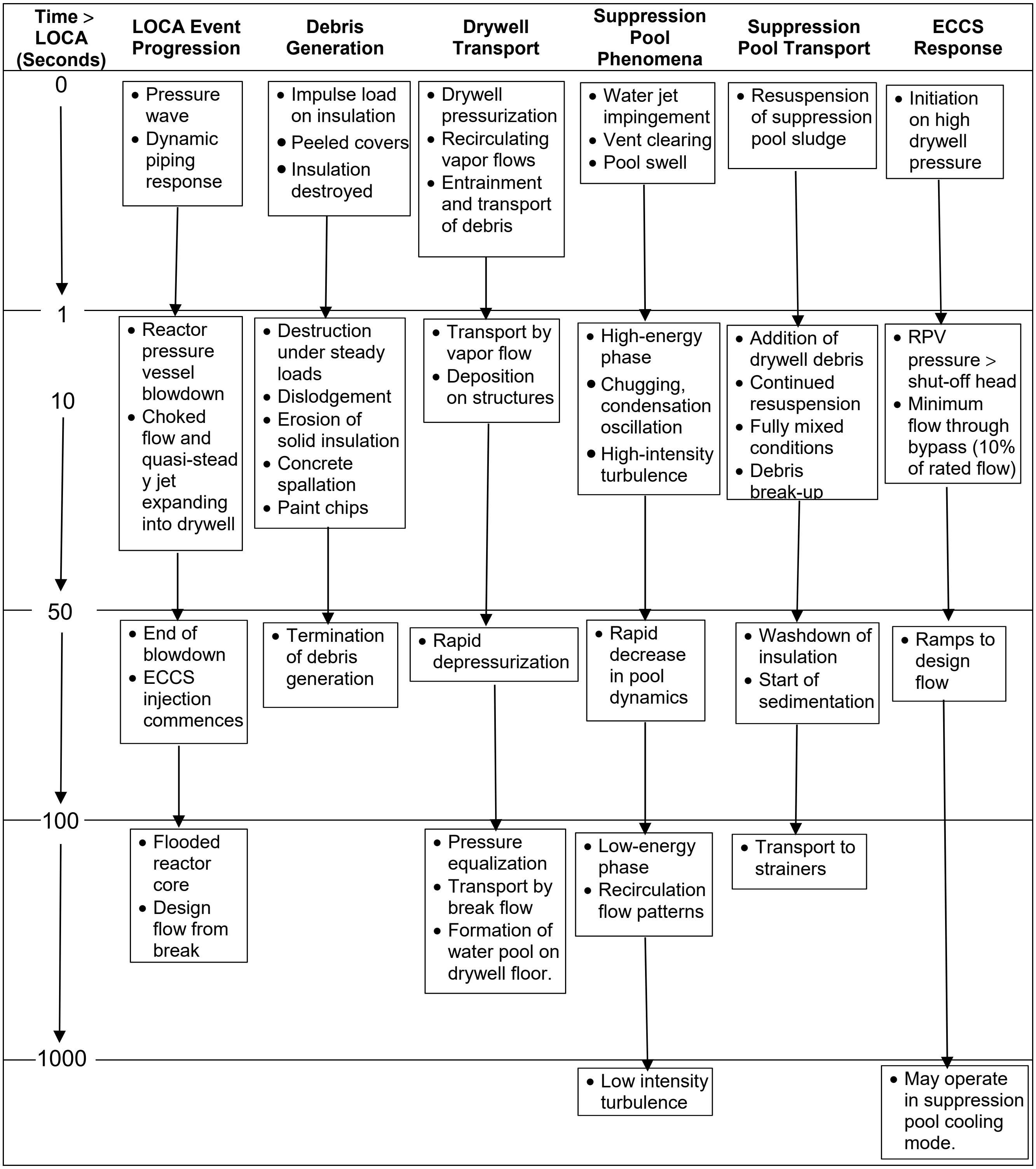

Figure 5: Events that may affect debris blockage for BWR LOCA sequences (see NUREG/CR-6224, Figure B-1)

D. IMPLEMENTATION

The NRC staff may use this regulatory guide as a reference in its regulatory processes, such as licensing, inspection, or enforcement. However, the NRC staff does not intend to use the guidance in this regulatory guide to support NRC staff actions in a manner that would constitute backfitting as that term is defined in 10 CFR 50.109, "Backfitting," and as described in NRC Management Directive 8.4, "Management of Backfitting, Forward Fitting, Issue Finality, and Information Requests," dated September 20, 2019 (Ref. 51), nor does the NRC staff intend to use the guidance to affect the issue finality of an approval under 10 CFR Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants." The staff also does not intend to use the guidance to support NRC staff actions in a manner that constitutes forward fitting as that term is defined and described in Management Directive 8.4. If a licensee believes that the NRC is using this regulatory guide in a manner inconsistent with the discussion in this Implementation section, then the licensee may file a backfitting or forward fitting appeal with the NRC in accordance with the process in Management Directive 8.4.

ACRONYM LIST

10 CFR	Title 10 of the *Code of Federal Regulations*
ADAMS	Agencywide Documents Access and Management System
ANSI	American National Standards Institute
BWR	boiling-water reactor
BWROG	Boiling Water Reactor Owners' Group
CAP	containment accident pressure
CFD	computational fluid dynamics
CS	core spray or containment spray
CSS	containment spray system
DBA	design-basis accident
ECCS	emergency core cooling system
GDC	general design criterion (criteria)
GL	Generic Letter
GSI	Generic Safety Issue
HELB	high energy line break
HI	Hydraulic Institute
HPSI	high pressure safety injection
HX	heat exchanger
IAEA	International Atomic Energy Agency
IN	Information Notice
LPSI	low pressure safety injection
LOCA	loss-of-coolant accident
LWR	light water reactor
NEI	Nuclear Energy Institute
NPSH	net positive suction head
NPSHa	net positive suction head available
NPSH margin	net positive suction head margin (NPSHa – NPSHr)
NPSHr	net positive suction head required

NRC	U.S. Nuclear Regulatory Commission
PDR	public document room
PWR	pressurized-water reactor
RCS	reactor coolant system
RG	Regulatory Guide
RHR	residual heat removal
RPV	reactor pressure vessel
RWST	refueling water storage tank
SE	safety evaluation
URG	Utility Resolution Guide
WCAP	Westinghouse Commercial Atomic Power
ZOI	zone of influence

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2. *U.S. Code of Federal Regulations*, "Domestic Licensing of Production and Utilization Facilities," Part 50, Chapter I, Title 10, "Energy."

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APPENDIX A

ADDITIONAL GUIDELINES FOR THE REVIEW OF HYDRAULIC PERFORMANCE OF WATER SOURCES FOR EMERGENCY CORE COOLING SYSTEMS

Water sources for long-term recirculation should be evaluated under possible conditions after a loss-of-coolant accident (LOCA) to determine the adequacy of their design for providing long-term recirculation. Areas for technical evaluations can be subdivided into (1) emergency core cooling system (ECCS) strainer hydraulic performance, (2) pump suction inlet hydraulic performance, (3) LOCA-induced debris effects, and (4) impacts of ingested air on pump performance. Figure A-1 identifies specific considerations within these categories and the combination thereof. The primary acceptance criterion is that adequate net positive suction head (NPSH) margin exists at the pump inlet under all postulated post-LOCA conditions such that the required coolant flow is delivered to the reactor. However, other potential failure modes, such as structural failure, flashing or deaeration as coolant flows through the strainer, and insufficient flow (for partially submerged or vented strainers), should also be considered as applicable, as discussed in the regulatory positions.

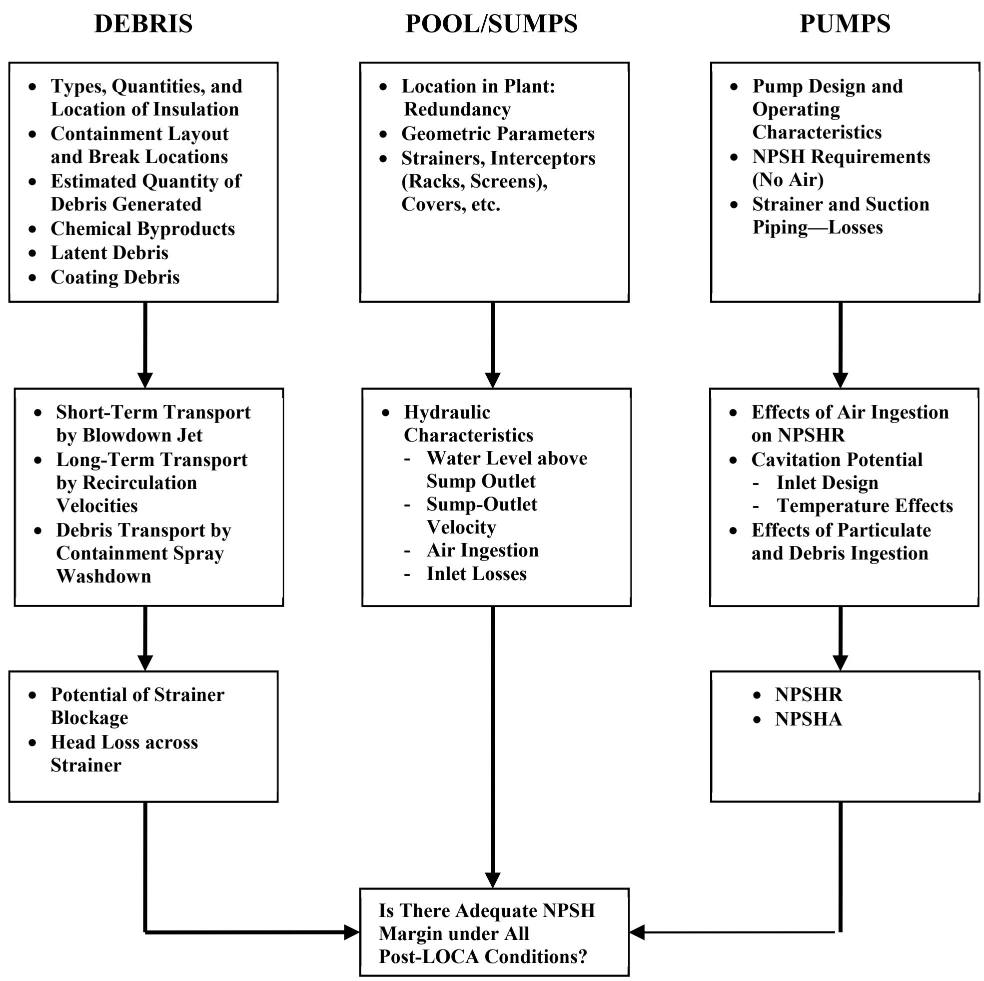


Figure A-1: Technical considerations relevant to ECCS suction strainer performance

A-1 Emergency Core Cooling System Strainer Hydraulic Performance

ECCS strainer hydraulic performance is primarily affected by the potential for air ingestion and for flashing or deaeration of the recirculating coolant across ECCS strainer surfaces, including the debris bed, and internal flow restrictions. Air ingestion could occur in several ways, including (1) through vortex formation, (2) through the release of gas dissolved in the recirculating coolant via deaeration after undergoing a pressure drop, and (3) through entrainment with water drainage that splashes down onto, or in the direct vicinity of, the strainer. Flashing could occur if the strainer pressure drop is sufficiently large that the recirculating coolant undergoes a transition to the vapor phase anywhere in the system. Deaeration may occur if the differential pressure across the strainer is large enough to liberate entrained gases from the fluid. These phenomena may be evaluated by considering factors such as the strainer submergence, the strainer approach velocity, the strainer debris bed head loss, the temperature of the recirculating coolant, and the properties of the containment atmosphere.

Licensees should perform prototypical testing to ensure that an ECCS strainer is not subject to vortex formation. Consistent with the range of possible plant-specific values, the testing should consider conservatively low submergence levels and conservatively high flow rates. If the potential exists for a nonuniform flow distribution among the various modules in a strainer array, a conservatively high flow rate should be used to account for this nonuniformity and ensure that vortexing does not occur. Some work has been performed to determine analytically whether vortex formation will occur under various hydraulic conditions for specific types of strainers; NUREG/CR-2758, "A Parametric Study of Containment Emergency Sump Performance," issued July 1982 (Ref. A-1), provides details. However, these evaluations were based on empirical data and are not generically applicable. Therefore, licensees should conduct properly scaled testing to determine the potential for vortex formation under plant-specific conditions. In some plant designs, the flowpath upstream of the strainers may cause significant vorticity in the flow approaching the strainers. Computational fluid dynamics simulations may be useful in identifying this situation. If significant, the strainer vortex tests should account for vorticity in the flow upstream of the strainer.

Licensees should conduct an analysis to ensure that deaeration (or off-gassing) caused by the pressure drop at the strainer surface, including the debris bed, or at internal flow restrictions does not lead to air void formation within or downstream of the strainer that could adversely affect safety pump performance. The accumulation and transport behavior of air voids inside a strainer is not well understood. Therefore, it is difficult to demonstrate that gas voids generated at or inside the strainer surface through deaeration will not eventually reach the pump suction inlet. Furthermore, excessive deaeration could lead to increases in differential pressure across the strainer because of the presence of two-phase flow. Therefore, licensees should ensure that strainer submergence is sufficient, relative to the strainer head loss and other parameters of interest, to minimize deaeration across the strainer debris bed or internal flow restrictions. If the strainer submergence is not sufficient to ensure zero deaeration under the potential post-LOCA conditions, then licensees should follow the guidance below for increasing the required NPSH to account for gas voids. Air ingestion greater than 2 percent by volume (or 1 percent by volume if the ratio of the flow rate to the best efficiency flow rate is over 120 percent or under 40 percent) should be avoided, to ensure that the pumps perform adequately and to prevent a significant increase in pressure drop across the strainer.

Strainers should be designed so that water drainage does not splash down directly onto their surfaces or in their vicinity. Drainage splashing onto a water surface above or directly adjacent to the strainer can cause air entrainment and transport downstream of the ECCS strainer by the recirculation flow. As discussed above, this entrained air could adversely affect the performance of the pumps taking suction from the strainer. For designs in which water drainage near the strainer cannot be avoided, a solid cover plate should be provided so that entrained air is not drawn into the strainer.

Licensees should conduct an analysis to ensure that the pressure drop at the strainer surface or at internal flow restrictions does not cause flashing of the recirculating coolant. Head loss tests are typically not conducted at design post-LOCA fluid temperatures, so the strainer tests do not model head loss increases caused by two-phase flow. Therefore, licensees should perform an analysis to demonstrate that they have prevented any flashing resulting from a pressure drop at the strainer surface or internal flow restrictions, or that they have analyzed the effects conservatively.

A-2 Pump Suction Inlet Hydraulic Performance

In addition to the ECCS strainer hydraulic performance, licensees should evaluate the pump suction inlet hydraulic performance. This may be particularly important for partially submerged strainer configurations, vented strainer designs with a free surface above the pump suction inlets, and strainers that could have an interior free surface formed by gas voids caused by accumulated gas from vortexing or deaeration. (See NUREG/CR-6762, "GSI-191 Technical Assessment," issued August 2002 (Ref. A-2).)

Pump suction inlet hydraulic performance (with respect to air ingestion potential) can be evaluated on the basis of submergence level (water depth above the pump suction inlet piping) and necessary pumping capacity (or pipe inlet velocity). The ratio between the water depth above the pipe centerline and the pipe inlet velocity based on the effective pipe flow area can be expressed non-dimensionally as the Froude number (see Figure A-2):

$$\text{Froude number} = \frac{U}{\sqrt{gs}}$$

where g is the acceleration due to gravity, s is the submergence, and U is the pipe inlet velocity.

Extensive experiments have shown that the hydraulic performance of pump suction inlets (particularly the potential for air ingestion resulting from vortex formation) is strongly dependent on the Froude number. Perturbations in the geometry of the flow approach path, such as a sharp turn just before the sump, can also influence vortex formation. Where these sharp turns exist, quiescent flume testing may not accurately predict vortex formation or behavior. Other nondimensional parameters (e.g., the Reynolds number and the Weber number) are of secondary importance.

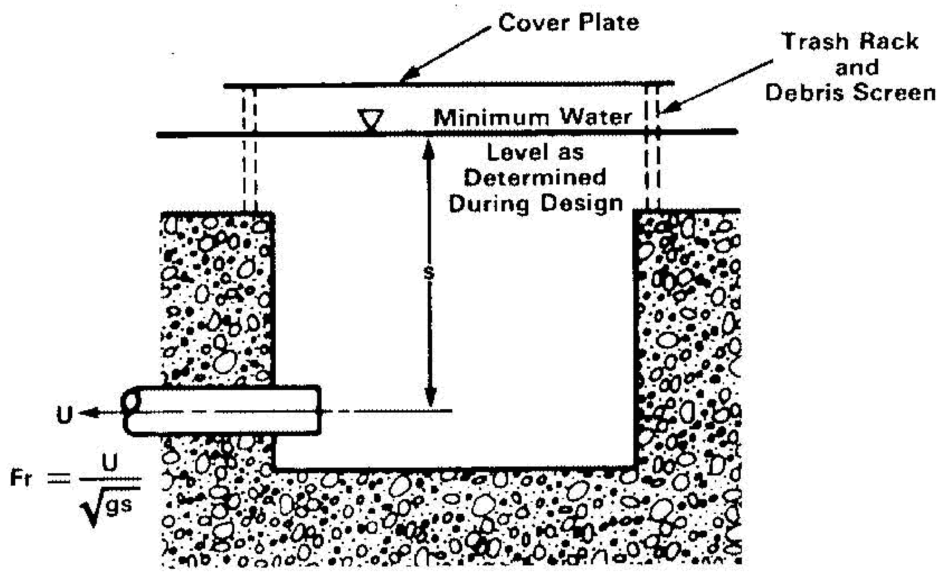


Figure A-2: Submergence level

Pump suction inlet hydraulic performance can be divided into the following categories:

a. For zero air ingestion (α) caused by vortexing at the pump suction inlets, there is no need for vortex suppressors or increases in the required NPSH above that from the pump manufacturer's curves.

b. If air ingestion (α) caused by vortexing at the pump suction inlets is 2 percent or 1 percent (depending on flow rate) or less, this is a conservative level at which degradation of pumping capability is not expected, provided that an increase in the required NPSH is accounted for as noted below.

c. Vortex suppressors are used to reduce air ingestion caused by vortexing at the pump suction inlets to zero.

d. For pressurized-water reactors (PWRs), the correlations in Table A-1 can be used to determine which pump suction inlet designs have ingestion levels of 2 percent or less. Table A-1 applies only to PWR sump screens without a complete water seal (e.g., screens are not fully submerged) and with the sump geometry described in the table. However, it should be noted that most strainers have the potential to generate and accumulate air in the long term, which could lead to the formation of a free surface inside the strainer volume. If long-term generation and accumulation of air cannot be ruled out, licensees should continue to consider the design guidance in Table A-1, even if the strainers are fully submerged. Some plant designs have open or vented sumps downstream of the strainers. Table A-1 also applies in these cases. If the PWR pump suction inlet design deviates significantly from the bounding values of design parameters in the table, licensees should use plant-specific data to verify adequate hydraulic performance.

e. For boiling-water reactors (BWRs), full-scale tests of pump suction inlet designs have shown that air ingestion is zero for Froude numbers less than 0.8, with a minimum submergence of 1.83 meters (6 feet). Operation up to a Froude number of 1.0 with the same minimum submergence may be possible before air ingestion levels of 2 percent occur. The reader should refer to NUREG-0897, Revision 1, “Containment Emergency Sump Performance: Technical Findings Related to Unresolved Safety Issue A-43,” issued October 1985 (Ref. A-3), and NUREG/CR-2772, “Hydraulic Performance of Pump Suction Inlets for Emergency Core Cooling Systems in Boiling Water Reactors,” issued June 1982 (Ref. A-4).[1]

1 See also NEI 09-10, Revision 1a-A, “Guidelines for Effective Prevention and Management of System Gas Accumulation,” issued April 2013, and the NRC staff SE (Ref. A-6).

Table A-1: PWR Hydraulic Design Guidelines for Air Ingestion (Tables 5.1 and 5.2 in NUREG-0897, Revision 1)

Zero Air Ingestion

Item	Horizontal Outlets	Vertical Outlets
Minimum submergence, s (ft)	9	9
(m)	2.7	2.7
Maximum Froude number, Fr	0.25	0.25
Maximum pipe velocity, U (ft/s)	4	4
(m/s)	1.2	1.2

NOTE: These guidelines were established using experimental results from NUREG/CR-2758 and other sources, and are based on sumps having a right rectangular shape.

Air Ingestion Less than 2 Percent

	HORIZONTAL OUTLETS		VERTICAL OUTLETS	
ITEM	**DUAL**	**SINGLE**	**DUAL**	**SINGLE**
Coefficient α_0	−2.47	−4.75	−4.75	−9.14
Coefficient α_1	9.38	18.04	18.69	35.95
Minimum submergence, s (ft)	7.5	8.0	7.5	10.0
(m)	2.3	2.4	2.3	3.1
Maximum Froude number, Fr	0.5	0.4	0.4	0.3
Maximum pipe velocity, U (ft/s)	7.0	6.5	6.0	5.5
(m/s)	2.1	2.0	1.8	1.7
Maximum screen face velocity (blocked and minimum submergence) (ft/s)	3.0	3.0	3.0	3.0
(m/s)	0.9	0.9	0.9	0.9
Maximum approach flow velocity (ft/s)	0.36	0.36	0.3	0.36
(m/s)	0.11	0.11	0.11	0.11
Maximum sump outlet coefficient, C_L	1.2	1.2	1.2	1.2

* Air ingestion (α) is empirically calculated as $\alpha = \alpha_0 + (\alpha_1 \times Fr)$, where α_0 and α_1 are coefficients derived from test results as given in the table.

This table applies to pump suction inlet geometry. The guidance developed to resolve Generic Letter 2008-01, "Managing Gas Accumulation in Emergency Core Cooling, Decay Heat Removal, and Containment Spray Systems," dated January 11, 2008 (Ref. A-5), which appears in the Nuclear Energy Institute (NEI) document NEI 09-10, Revision 1a-A, "Guidelines for Effective Prevention and Management of System Gas Accumulation," issued April 2013 (Ref. A-6), addresses gas accumulation downstream of the inlet.

A-3 Effects of Ingested Air on Pump Performance

Table A-2 presents the guidance limits for air or gas ingestion. Higher levels than those listed have been shown to degrade pumping capacity. Independently of pumping capacity, NPSH can be affected by air or gas void ingestion from vortex formation, deaeration, and entrainment from splashing. These gas sources are included in the limits and in the calculation to adjust the required NPSH described in the next paragraph. Further details can be found in NEI 09-10, Revision 1a-A, including the U.S. Nuclear Regulatory Commission staff safety evaluation.

The limit on sump air or gas ingestion for pumping capacity and the NPSH criteria are applied independently. As stated in NUREG-0897, Revision 1, steady-state air or gas ingestion levels less than 2 percent can also affect NPSH margin. If air or gas ingestion is indicated, then the following relationship can be used to correct the required NPSH from the pump curves for steady-state operating conditions:

$$NPSH_{required(\alpha p < 2\%)} = NPSH_{required(liquid)} \times \beta,$$

where $\beta = 1 + 0.50\alpha_p$, and α_p is the volumetric percentage of air in the fluid at the pump inlet flange.

For transient operation, it is not necessary to consider the effect of gas on NPSH if the Table A-2 transient conditions are met, because the conservatism associated with the void fraction Φ adequately covers the short-term effects. For steady-state operation (periods longer than those defined in the table) with voids present at the pump suction, the required NPSH is adjusted as described above.

Table A-2: Impact of Ingested Air on Pump Performance (Taken from Staff Safety Evaluation in NEI 09-10, Revision 1a-A)

Condition	$\% \frac{Q}{Q_{BEP}}$	Φ for BWR Typical Pumps	Φ for PWR Typical Pumps		
			Single-Stage	Multistage Stiff Shaft	Multistage Flexible Shaft
Steady-State Operation	40–120%	0.02	0.02	0.02	0.02
Steady-State Operation	<40% or >120%	0.01	0.01	0.01	0.01
Transient Operation	70–120%	0.10 for ≤5 s	0.05 for ≤20 s	0.20 for ≤20 s	0.10 for ≤5 s
Transient Operation	<70% or >120%	0.05 for ≤5 s	0.05 for ≤20 s	0.05 for ≤20 s	0.05 for ≤5 s

Notes: Q = water volumetric flow rate.
BEP = best efficiency point.
Transient Φ is averaged over the specified time span.
Instantaneous Φ is less than 1.7 times the listed value.[2]

A-4 Criteria for Evaluating Emergency Core Cooling System Strainer Failure

The applicable ECCS strainer failure criteria depend on several factors, including submergence and structural strength, and may be pump or system dependent. Figures A-3a, A-3b, and A-3c illustrate the three basic strainer configurations for fully submerged, partially submerged, and vented strainers. Although these figures show only vertical strainers with configurations that appear more consistent with PWR plants, the same designations generally apply to other strainer designs, including those used for BWRs. The key distinction between the fully and partially submerged configurations is that partially submerged or vented strainers allow equal pressure above the water surface on both sides of the strainer. Fully submerged strainers have a complete seal of water between the pump inlet and the containment atmosphere along all water paths passing through the sump screen. The following sections describe the effect of this difference on the evaluation of the sump failure criterion. (The reader should also refer to NUREG/CR-6762, Volume 1, Section 1.4.) For all of these configurations, entrainment of gases or voids at the pump suction should be evaluated. Note that vortexing may occur inside a vented or partially submerged strainer.

2 The value of 1.7 represents the mutual judgment of industry and Office of Nuclear Reactor Regulation staff representatives. See Section 1.4 of "Guidance to NRC/NRR/DSS/SRXB Reviewers for Writing Temporary Instruction (TI) 2515/177 Suggestions for the Region Inspections," Revision 11, dated May 23, 2011 (Ref. A-7), for additional information and qualification.

A-4.1 Fully Submerged Sump Strainers

Figure A-3a presents a schematic of a fully submerged strainer. Potential failure modes considered for systems with this strainer configuration include (1) structural failure of the strainers caused by excessive differential pressure and (2) cavitation of the pump when head loss caused by debris accumulation exceeds the pump NPSH margin. (Note that in a fully submerged configuration, a strainer structural failure, rather than cavitation, may occur, because containment accident pressure may increase the available NPSH, allowing the required flow for the pump to continue to pass through the strainer until a structural failure occurs.) For plants in which ECCS strainers are fully submerged at the time of switchover, the onset of cavitation is determined by comparing the NPSH margin, which is part of the plant's licensing basis, with the screen head loss calculated in the plant evaluations performed in accordance with Section C.1.3 of this regulatory guide. For this case, therefore, the ECCS strainer failure criterion is assumed to be met when one of the following occurs:

- Head loss across the debris bed results in loss of NPSH margin.
- Head loss across the debris bed is greater than or equal to the structural limit.

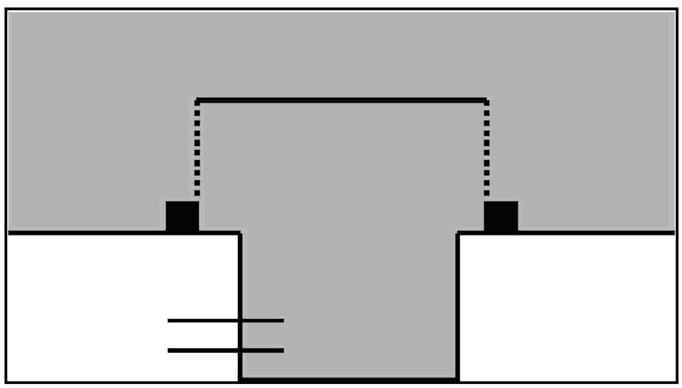


Figure A-3a: Fully submerged strainer configuration showing solid water from the pump inlet to the containment atmosphere

Note that one pump could undergo cavitation while a different pump with a different NPSH margin does not. In certain conditions (see Section C.1.3.1.3), credit may be taken for continued operation under conditions with negative NPSH margin. If justified, short-term operation may be credited to provide an opportunity for recovery action.

A-4.2 Partially Submerged Sump Strainers

Figure A-3b presents a schematic of a partially submerged strainer. Failure modes for systems with this strainer configuration include (1) pump cavitation, (2) structural failure, and (3) insufficient water entering the strainer because of head loss caused by debris buildup (i.e., flow starvation). The latter failure mode occurs when water infiltration through a debris bed on the strainer can no longer satisfy the volumetric demands of the pump or pumps taking suction from the strainer. Because the volumes inside and outside the strainer are at equal atmospheric pressures, the only force available to move water through the debris bed is the static pressure head of the water in the pool.

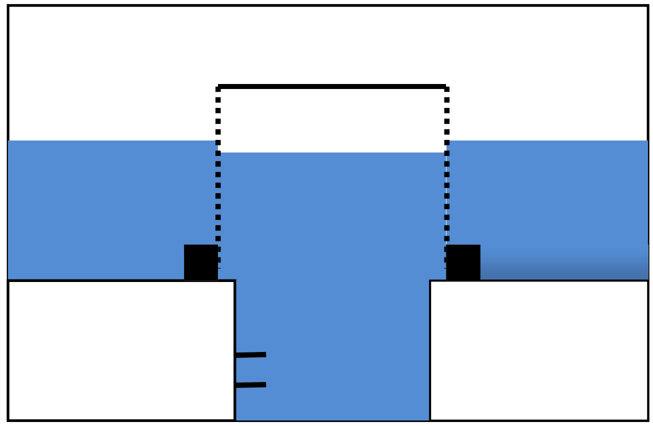


Figure A-3b: Partially submerged strainer configuration, with containment atmosphere over both the external pool and the strainer internal water surface

Numerical simulations confirm that head loss across a debris bed equal to approximately one-half the submerged strainer height can be sufficient to prevent adequate water flow (i.e., the pressure available to move water through the debris bed is approximately the average of the gravitational head at the existing depth of the pool and zero head at the pool surface). For strainers with more complex geometries, the calculation of the pressure available to move water through the debris bed may require more complicated evaluations and additional testing. For all partially submerged strainers, failure is assumed to be reached when one of the following occurs:

- Head loss across the debris bed is greater than or equal to NPSH margin.
- Head loss across the debris bed is greater than or equal to one-half of the submerged screen height.
- Head loss across the debris bed is greater than or equal to the structural limit.

When the flow starvation failure criterion is met, the water level on the downstream side of the screen will drop rapidly, and all pumps taking suction from the sump will have insufficient flow for continued operation.

After switchover to ECCS recirculation, the configuration may change from partially submerged to fully submerged. This can occur for several reasons, including the accumulation of containment spray water, the continued melting of ice condenser reservoirs, and the continued addition of the refueling water storage tank inventory to the containment pool. As the containment pool depth changes during recirculation, the "wetted area" (or submerged area) of the strainers may also change. The wetted area determines the average approach velocity of water that may carry debris and the amount of debris that may accumulate per unit of strainer area. Both of these variables affect head loss. The gravitational head of the containment pool across the strainer also varies with the water level. For cases where the strainer submergence varies with time, the containment pool water level should be calculated as a function of time, and a conservative assessment should be made of debris transport and the accumulation of debris on the strainer. For plants that have systems initiating recirculation for containment spray and ECCS at different times, evaluations should consider the containment pool water level and strainer debris loading appropriately in view of this timing.

A-4.3 Vented Submerged Strainers

A flow starvation failure mode may occur with vented submerged strainers, as illustrated in Figure A-3(c). The potential for this to occur and the subsequent impact on pump performance should be evaluated in the same manner as for a partially submerged strainer, above.

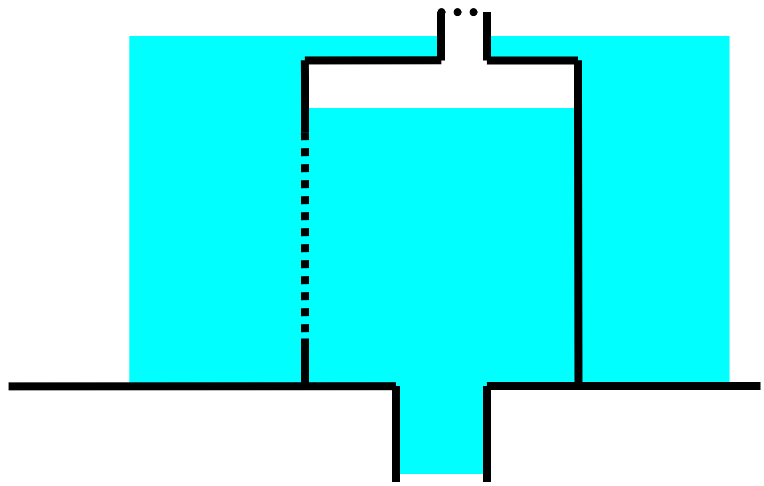


Figure A-3c Vented submerged strainer

A-4.4 Partial Suction Line Uncovery

Unlike earlier strainer designs, the new generation of suction strainer designs that consist of a series of modules connected by piping may be susceptible to uncovery of piping internal to the strainer. For such a strainer design, uncovery of internal piping is possible if a complete water seal does not exist over all strainer surfaces; this represents an additional failure criterion that should be analyzed or addressed in some other manner. Figure A-3d illustrates the partial uncovery of suction piping for a partially submerged strainer. Failure could occur if the internal suction pipes connecting different strainer modules become uncovered. Such uncovery could severely affect the head loss and could lead to air or gas ingestion. This scenario should be avoided by ensuring that strainers with designs similar to that shown in Figure A-3d are fully submerged whenever there is flow through the strainer.

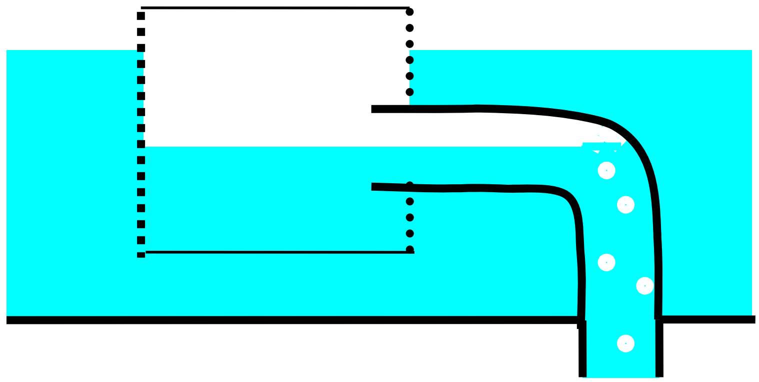


Figure A-3d Internal suction line uncovery

ACRONYM LIST

ADAMS	Agencywide Documents Access and Management System
BWR	boiling-water reactor
ECCS	emergency core cooling system
GSI	Generic Safety Issue
LOCA	loss-of-coolant accident
NEI	Nuclear Energy Institute
NPSH	net positive suction head
NPSHa	net positive suction head available
NPSH margin	net positive suction head margin (NPSHa – NPSHr)
NPSHr	net positive suction head required
NRC	U.S. Nuclear Regulatory Commission
PWR	pressurized-water reactor

REFERENCES

A-1. U.S. Nuclear Regulatory Commission (NRC), “A Parametric Study of Containment Emergency Sump Performance,” NUREG/CR-2758, July 1982, Agencywide Documents Access and Management System (ADAMS) Accession No. ML112440059.

A-2. U.S. NRC, “GSI-191 Technical Assessment,” NUREG/CR-6762, Vols. 1–4, August 2002, ML022470077 (package), ML022470093, ML022480182, and ML022480262.

A-3. U.S. NRC, “Containment Emergency Sump Performance: Technical Findings Related to Unresolved Safety Issue A-43,” NUREG-0897, Rev. 1, October 1985, ML112440046.

A-4. U.S. NRC, “Hydraulic Performance of Pump Suction Inlets for Emergency Core Cooling Systems in Boiling Water Reactors,” NUREG/CR-2772, June 1982, ML112440074.

A-5. U.S. NRC, “Managing Gas Accumulation in Emergency Core Cooling, Decay Heat Removal, and Containment Spray Systems,” Generic Letter 2008-01, January 11, 2008, ML072910759.

A-6 Nuclear Energy Institute, “Guidelines for Effective Prevention and Management of System Gas Accumulation,” NEI 09-10, Rev. 1a-A, April 2013, ADAMS Accession No. ML13136A129.

A-7 U.S. NRC, “Guidance to NRC/NRR/DSS/SRXB Reviewers for Writing Temporary Instruction (TI) 2515/177 Suggestions for the Region Inspections,” Rev. 11, May 23, 2011, ML111660748 (package).

APPENDIX B

GUIDANCE FOR THE USE OF CONTAINMENT ACCIDENT PRESSURE IN DETERMINING THE NET POSITIVE SUCTION HEAD MARGIN FOR EMERGENCY CORE COOLING SYSTEM PUMPS AND CONTAINMENT HEAT REMOVAL PUMPS IN BOILING-WATER REACTORS AND PRESSURIZED-WATER REACTORS

The purpose of this guidance is to ensure that emergency core cooling system (ECCS) and containment heat removal pumps will perform their safety functions during postulated design-basis accidents (DBAs) and certain postulated non-DBAs. Specifically, this guidance addresses the use of containment accident pressure (CAP) to ensure adequate suction conditions for these pumps. This appendix refers to the pertinent non-DBAs collectively as "special events."

B-1 Pump Net Positive Suction Head and Cavitation

Cavitation is defined as the occurrence of vapor-filled cavities in a liquid (Grist, *Cavitation and the Centrifugal Pump: A Guide for Pump Users* (Ref. B-1)). In a pumped liquid, cavitation is the formation of vapor-filled cavities in the liquid flow due to a decrease in the local static pressure below its vapor pressure. The formation of vapor cavities and the vapor's subsequent rapid condensation can damage and adversely affect the operation of a centrifugal pump. Cavitation is nearly always accompanied by the release of gases previously dissolved in the liquid. The first appearance of cavitation is called "cavitation inception." In pumps, cavitation is most likely to occur at the inlet to the blades of the impeller, where the static pressure is lowest. Cavitation in pumps is undesirable not only because it can alter the flow pattern and thus degrade pump performance, but also because collapsing cavities can cause vibration and mechanical damage to the impeller.

Directly related to cavitation is the net positive suction head (NPSH). The NPSH is the difference between the inlet absolute total head (which includes the velocity head in the inlet pipe) and the head equivalent to the vapor pressure of the liquid being pumped. The available NPSH (NPSHa) is defined as the NPSH at the pump inlet. The NPSHa is a function of the flow rate, head loss in the suction piping, liquid temperature, absolute pressure above the liquid surface, and liquid elevation relative to the pump for the system in which the pump is located.

The required NPSH (NPSHr) depends on the pump design. It is the NPSH value that limits cavitation within the pump to a specified amount (or prevents it entirely). The American National Standards Institute/Hydraulic Institute standard ANSI/HI 14.6-2016, "American National Standard for Rotodynamic Pumps for Hydraulic Performance Acceptance Tests" (Ref. B-2), defines NPSHr as the value of NPSH that results in cavitation sufficient to reduce the pump total dynamic head (TDH) by 3 percent. This guidance will denote this value by $NPSHr_{3\%}$.

NPSHr as a function of flow rate is typically obtained by testing the pump in question or a similar pump at the pump vendor's facility in accordance with ANSI/HI 14.6-2016. Figure B-1 shows the HI constant flow rate test for the determining $NPSHr_{3\%}$. The test begins with a large value of NPSHa in the test loop, which is gradually reduced. The flow rate and the pump speed are held constant. As the test loop NPSHa is reduced, a value of NPSHa is reached at which the pump TDH can no longer be maintained and decreases. The value of NPSHr is the value of the measured NPSHa corresponding to a given measured decrease in the TDH. The value of $NPSHr_{3\%}$ corresponds to a TDH 3 percent below the TDH at the higher values of NPSHa for which the TDH is constant. Other quantities could also be obtained (e.g., $NPSHr_{1\%}$). These are the most accurate test methods for determining the $NPSHr_{3\%}$ of a pump. For best accuracy, the test should be conducted at the rated speed and impeller diameter, with the NPSHa controlled by a vacuum pump.

The NPSH margin is defined as the difference between NPSHa and NPSHr. The NPSH margin should be greater than or equal to zero. Another useful parameter is the NPSH margin ratio, which is defined as the ratio NPSHa/NPSHr.

When the suction pressure or the NPSHa is decreased from the value corresponding to cavitation inception, the region of cavitation grows. If the decrease in NPSHa is significant, then noise, cavitation erosion of pump parts (mainly the impeller), and pump performance degradation will occur.

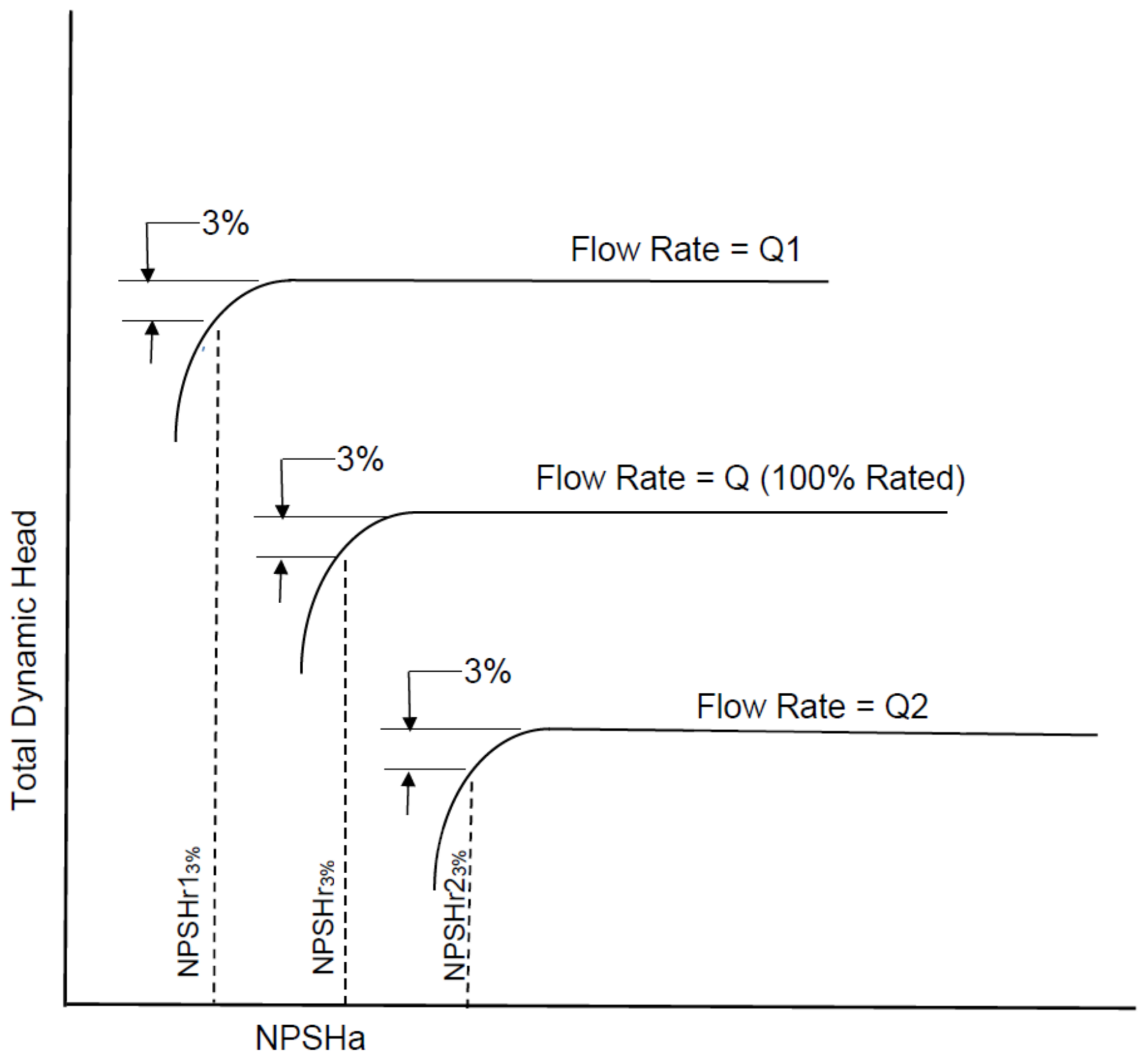


Figure B-1: Illustration of NPSH test with flow rate held constant

B-2 The Role of Emergency Core Cooling System and Containment Heat Removal Pumps

Boiling-Water Reactor Pumps

The boiling-water reactor (BWR) pumps for which licensees may use CAP in determining the NPSH margin are the residual heat removal (RHR) system and low-pressure core spray (LPCS) system pumps. The RHR pumps are typically single-stage, high-capacity, low-discharge-head pumps. They have several modes of operation, including but not limited to the following:

- cooling of the reactor coolant system during normal reactor shutdown

- suppression pool cooling during normal plant operation if heat is added to the suppression pool

- emergency coolant injection into the reactor vessel following a loss-of-coolant accident (LOCA)

- suppression pool cooling following a postulated accident (e.g., LOCA) or special event (e.g., Appendix R fire, station blackout (SBO), or anticipated transient without scram (ATWS))

- Containment spray (CS) (drywell spray and wetwell spray) for containment cooling and fission product removal

During normal operation, the RHR pumps are in standby and configured for safety injection. They may be operated for suppression pool cooling during normal operation and for surveillance testing in accordance with the American Society of Mechanical Engineers (ASME) Code and the plant's technical specifications (TS).

BWR CS pumps are typically single-stage, low-head, high-flow-rate pumps. Their function is to spray water from the suppression pool into the core following a LOCA. During normal operation, they are in standby except for surveillance testing in accordance with the ASME Code and the plant's TS.

Pressurized-Water Reactor Pumps

The pressurized-water reactor (PWR) pumps for which licensees may use CAP in determining the NPSH margin are the RHR and CS pumps. The RHR pumps are typically single-stage, low-head, high-capacity pumps. The functions of the RHR system are the following:

- emergency coolant injection following a LOCA
- cooling of the reactor coolant system during normal reactor shutdown

The PWR CS pumps are single-stage, low-head, high-flow-rate pumps. The function of the CS system is to cool the containment and also to remove fission products from the containment for some PWRs by spraying water following a LOCA. The pumps are in standby during normal plant operation.

B-3 Regulatory Requirements and Guidance

As part of reactor safety analysis, licensees must demonstrate that the ECCS pumps and containment heat removal pumps will perform their safety functions of delivering flow for emergency core cooling and containment cooling respectively, as required by Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, "Domestic Licensing of Production and Utilization Facilities," Appendix A, "General Design Criteria for Nuclear Power Plants," General Design Criterion (GDC) 35, “Emergency core cooling,” and of rapidly reducing the containment pressure and temperature following a LOCA, as required by GDC 38, “Containment heat removal.” The ECCS pumps must perform their safety functions during a LOCA to satisfy the requirements of 10 CFR 50.46, “Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors.”

In this regulatory guide, Position C.1.3.1.1 states the following:

> The design of the ECCS and containment heat removal system should ensure that sufficient NPSHa is provided to the system pumps, assuming the maximum expected temperature of the pumped fluid and no increase in containment pressure from that present before the postulated LOCA.

Also in this regulatory guide, Position C.1.3.1.2 states the following:

> For certain operating reactors in which it is not practicable to alter the design, conformance with Section C 1.3.1.1 may not be possible. In these cases, the determination of NPSHa should not include containment pressure above that which is necessary to preclude pump cavitation. In the determination of NPSHa for this situation, the calculation of available containment pressure and sump/pool water temperature as a function of time should underestimate the expected containment pressures and overestimate the sump/pool water temperatures.

In a letter dated March 18, 2009 (Ref. B-3), to the U.S. Nuclear Regulatory Commission (NRC) Executive Director for Operations, the Advisory Committee on Reactor Safeguards (ACRS) questioned the use of containment pressure higher than the containment pressure before the accident in determining the NPSHa. This letter also references previous correspondence from the ACRS on this subject. In discussions with the NRC staff, the ACRS recommended quantifying the uncertainty in the calculations used to verify the acceptability of using CAP in determining NPSH margin.

As part of the safety analysis to confirm that the pumps will perform their safety functions, licensees should demonstrate that the ECCS and containment heat removal pumps will have adequate NPSH margin following the occurrence of a postulated accident.

The use of CAP is acceptable to the NRC if the licensee demonstrates that the CAP used in the calculation of NPSH margin is less than or equal to the calculated CAP available at that time in the postulated accident. For the postulated DBA, the calculated CAP includes conservative inputs and assumptions intended to minimize the NPSH margin. For BWR special events (e.g., Appendix R fire, SBO, or ATWS), nominal inputs may be used.

This guidance is intended to apply to using CAP to determine the NPSH margin of ECCS and containment heat removal pumps in reactor safety analysis, including the ACRS recommendation to include uncertainty in the NPSH calculations.

In the staff requirements memorandum for SECY-11-0014, “Staff Requirements—SECY-11-0014—Use of Containment Accident Pressure in Analyzing Emergency Core Cooling System and Containment Heat Removal System Pump Performance in Postulated Accidents,” dated March 15, 2011 (Ref. B-4), the Commission directed the staff to continue to permit credit for CAP and to include the guidance in Enclosure 1 of SECY-11-0014, dated January 31, 2011 (Ref. B-5).

Uncertainty Analysis

The current approach to calculating NPSH margin assigns bounding values to the parameters used. These bounding values and assumptions are typically based on historically high or low values or on TS limiting conditions for operation (LCOs). The chosen accident scenario is also limiting. For example, the worst pipe break (giving the most limiting NPSH margin) is assumed for the LOCA, and the worst single failure is assumed. It is also assumed that all these limiting conditions occur simultaneously.

For the DBA (the LOCA), the Boiling Water Reactor Owners' Group (BWROG), in its topical report NEDC-33347P-A/NEDO-33347-A, Revision 2, "Containment Overpressure Credit for Net Positive Suction Head (NPSH)," issued March 2017 (Ref. B-6), has proposed an alternate method of calculating the NPSH margin, in which the CAP is determined by a Monte Carlo calculation. For some parameters, input values are sampled from statistical distributions; for others, conservative (bounding) values are used. An acceptance criterion of a 95-percent probability at a 95-percent confidence level (95/95) is used for the Monte Carlo pressure calculation. However, since conservative values are used for other inputs to the NPSHa calculation, the tolerance limit on NPSHa is greater than the 95/95 value.

For the special events, realistic input values may be used. Licensees should attempt to quantify uncertainty in the calculation of NPSH margin. Where this is not possible, the NRC staff recommends using bounding values of inputs.

B-4 Use of Containment Accident Pressure in Determining the Net Positive Suction Head Margin of Emergency Core Cooling System and Containment Heat Removal Pumps

"NPSH Required" and "NPSH Required Effective"

NPSHr is a property of the pump. In addition to the pump design, NPSHr varies with the pump flow rate and the temperature of the pumped water.

NPSHr corresponds to an acceptable level of pump cavitation: that is, a level that allows the pump to perform its safety function for the necessary period of time. This period includes not only the duration of the accident, when the NPSH margin may be limited, but also any time after recovery from the accident during which pump operation is needed to maintain the reactor or containment in a stable, cool condition; during this time, the NPSH margin may be much greater. The additional time after recovery is usually taken to be 30 days. It should be applied to both the DBA and special events.

The staff proposes that the NPSH margin be calculated as NPSHa − $NPSHr_{eff}$, where $NPSHr_{eff}$ is the $NPSHr_{3\%}$ value with uncertainties included. This calculated NPSH margin should be greater than or equal to zero.

NPSHr as a function of flow rate is typically obtained by testing the pump in question or a similar pump at the pump vendor's facility in accordance with ANSI/HI 14.6-2016. Operating experience shows that the NPSHr of a pump installed in the field is greater than the NPSHr obtained by testing at the pump vendor's facility. This is because the following factors may differ between the field and the vendor's tests, introducing additional uncertainty:

a. pump speed (because of motor slip)
b. water temperature
c. suction piping configuration
d. air content of water (which may be lower in the vendor's test than in pumped water in the field)

These sources of uncertainty are discussed in greater detail below.

a. Pump speed

The NPSHr varies as the square of the pump speed, which changes with change in the motor slip. Operation at less than full rated motor power or with high-efficiency motors tends to reduce motor slip. Motor slip can cause the pump to operate at slightly higher speeds in the field compared to a factory test speed with the factory-calibrated motor.

b. Water temperature

The NPSHr decreases as water temperature increases. Pump vendor tests are mostly run with water at lower temperatures than in the field. At higher water temperatures, the saturated vapor pressure and vapor density increase, which reduces the NPSHr, resulting in higher apparent NPSH margin. However, this could be offset by the effect of an increase in the vapor pressure on the NPSHa, which would reduce the apparent margin. Therefore, the effect of water temperature should not be included when determining the NPSHr in the field.

c. Suction piping configuration

For acceptable pump operation, it is important that the flow entering the pump inlet be as uniform as possible and free of swirl (prerotation, before entering the impeller) and vortices. For improved pump performance, the suction piping should be short and straight. This is not always possible in piping configurations in the field. The pressure drop in the piping should be minimized to obtain the maximum NPSHa.

d. Air content of pumped water

The NPSH margin is affected by the release of noncondensable gases (such as air or nitrogen) dissolved in the water as the minimum pressure in the pump approaches the saturation pressure. The air has several effects: (1) it dampens the effect of cavitation by lessening the shock due to implosion of the condensing vapor bubbles, which causes cavitation erosion damage, (2) it increases the NPSHr, and (3) it may interfere with the water cooling of pump seals.

Figure B-2 (taken from Budris, "Technical Report on Task #4 Findings," dated November 14, 2009 (Ref. B-7)) shows an example of the effect of air on the NPSHr. The "knee" of the curve with high air occurs at a higher value of NPSHr.

The solubility of air and nitrogen in water decreases with increasing temperature. This tends to decrease the gas entrained in the pump flow. Figure B-3 (taken from Ref. B-7) shows the effect of air coming out of solution on the erosion rate. The figure is a plot of cavitation noise (due to bubble collapse and measured with acoustic instrumentation) as a function of the NPSH margin ratio. Cavitation noise is a measure of the intensity of cavitation occurring in the pump; it is correlated with the extent of cavitation erosion. The cavitation noise reaches a maximum value at an NPSH margin ratio greater than 1.0 (NPSHa = NPSHr), then decreases. The decrease occurs because air comes out of solution with the vapor formation, cushioning the effect of the vapor bubble collapse. The cavitation noise (an indication of the cavitation erosion rate) is greatly reduced as more air comes out of solution. The amount of dissolved air varies with the water temperature (Budris and Mayleben, "Effects of Entrained Air, NPSH Margin, and Suction Piping on Cavitation in Centrifugal Pumps," 1998 (Ref. B-8)).

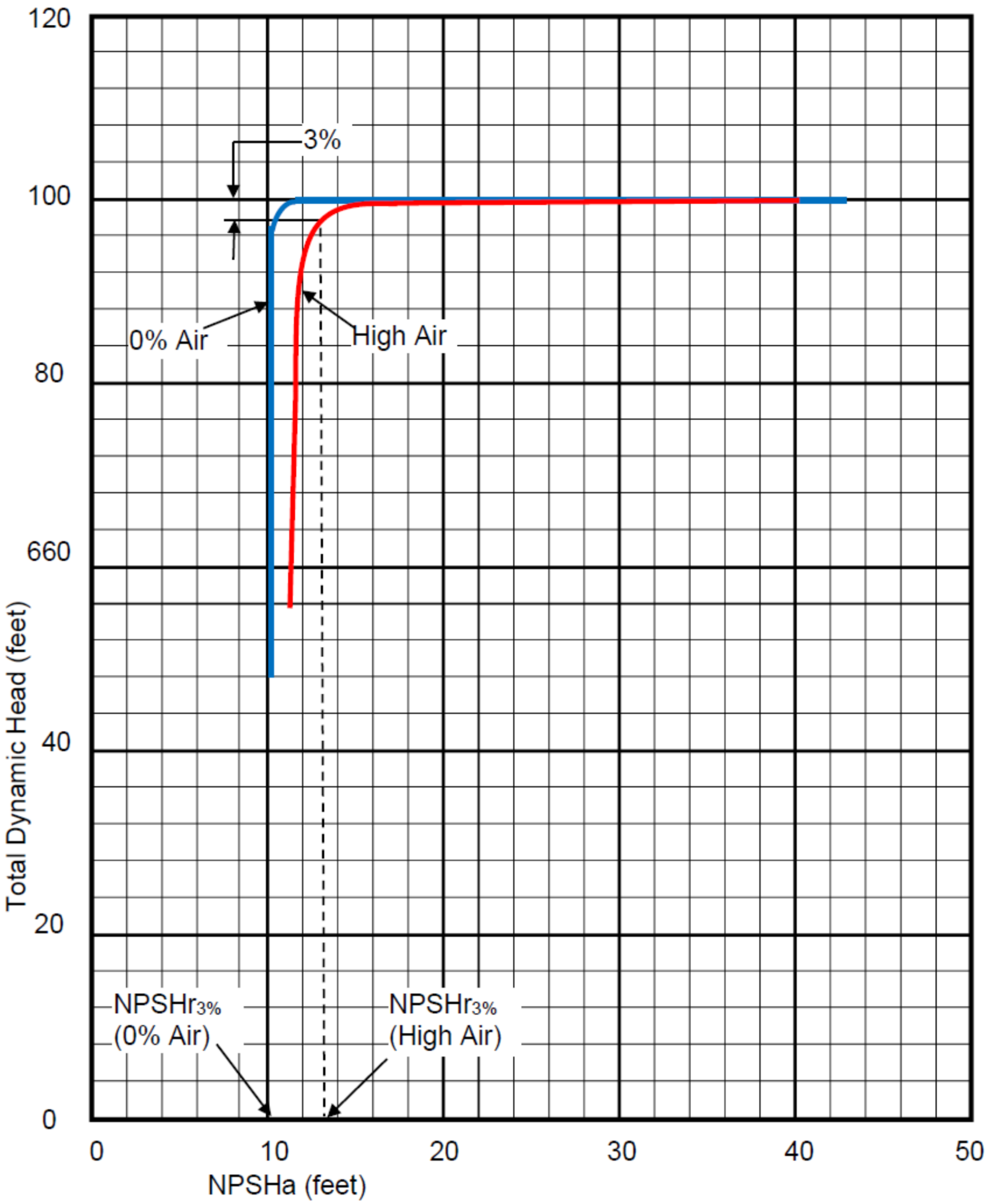


Figure B-2: Impact of dissolved and entrained air on NPSHr

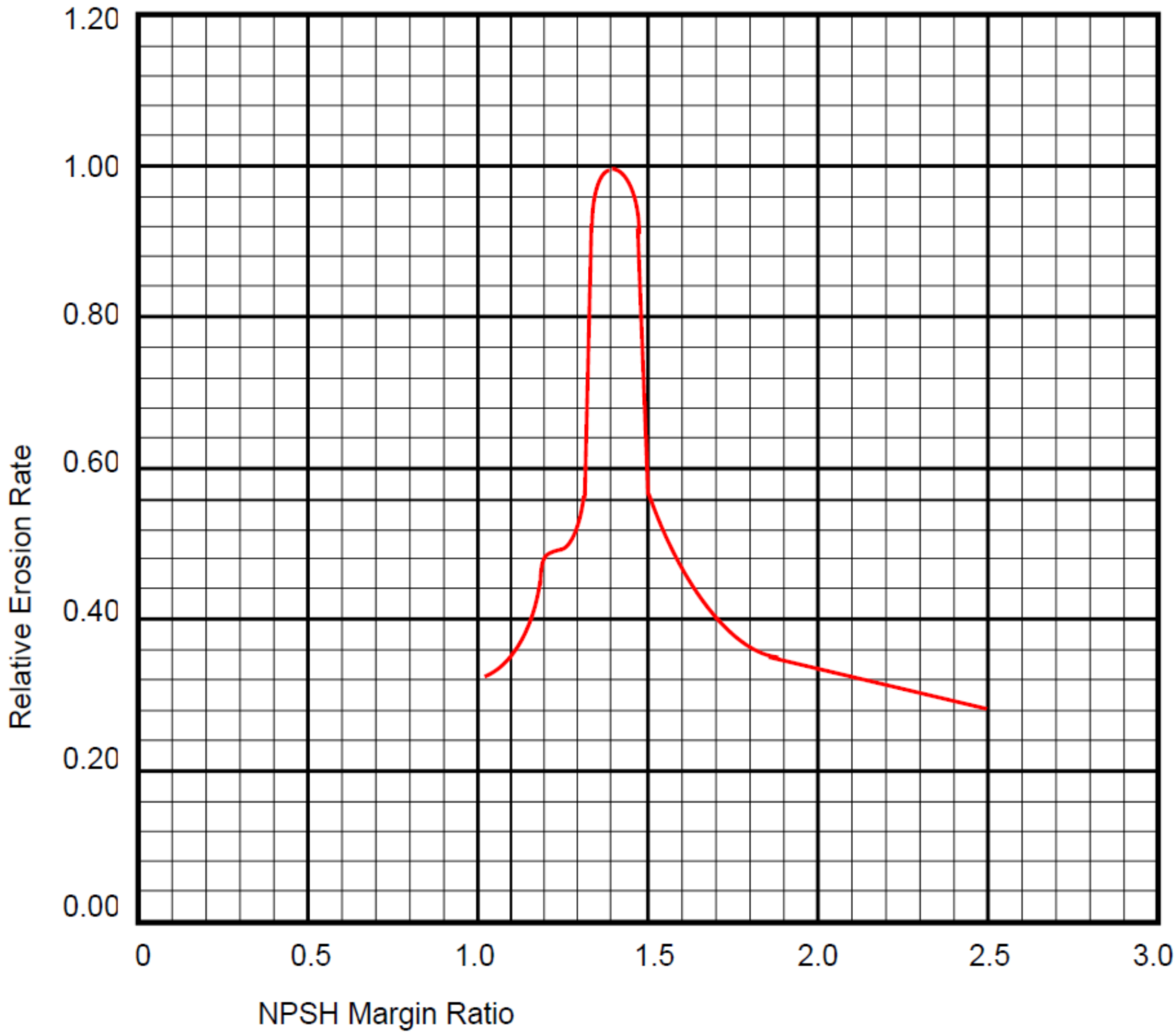


Figure B-3: Typical relative cavitation erosion rate versus NPSH margin ratio near best efficiency point flow rate

The second effect of non-condensable gas coming out of solution at the low-pressure region within the pump is to increase the NPSHr by increasing blockage. Sufficient gas can interrupt pumping altogether through “gas locking” or “gas binding.” Both entrained and dissolved air/gas will increase the NPSHr of a pump by increasing the blockage of entrained and dissolved air at the low local internal pressures within the pump. (See Figure 4-2 of NUREG/CR-2792, “An Assessment of Residual Heat Removal and Containment Spray Pump Performance under Air and Debris Ingesting Conditions,” issued September 1982 (Ref. B-9).)

NUREG/CR-2792, Section 4.2, discusses the effects of air and proposes an “arbitrary” relationship between NPSHr and the fraction of air at the pump suction:

$$NPSHr_{air/water} = NPSHr_{water} (1 + 0.5\ AF),$$

where AF is the air volume fraction in percent. As noted in NUREG/CR-2792, Section 4.2, this guideline is intended for use only for air volume fractions less than 2 percent.

The effect of air on required NPSH is included as an uncertainty component of $NPSHr_{eff}$.

Licensees should determine a value of $NPSHr_{eff}$ applicable to their pumps, considering the effects of pump speed, suction piping configuration, and air contents of pumped water, as described above in (a), (c), and (d), respectively. The $NPSHr_{eff}$ should be used to determine the NPSH margin for the DBA NPSH analysis.

For special events in BWRs that raise the temperature of the suppression pool (e.g., shutdown after an Appendix R fire, an ATWS, or an SBO), no uncertainty on $NPSHr_{3\%}$ is required. NPSHa may also be calculated using realistic (rather than conservative) assumptions.

It is possible that the NPSHa may be less than $NPSHr_{eff}$. In this case, it is acceptable to allow operation in this mode if tests are performed in which the pump is run in cavitation, and posttest inspection shows acceptable wear and no damage. As stated in a report by Budris, "Technical Report on Task #3 Findings," dated October 14, 2009 (Ref. B-10), the following conditions should apply:

- Predicted operation during the postulated accident below $NPSHr_{eff}$ (LOCA) or $NPSHr_{3\%}$ (special events) is of limited duration (less than 100 hours).

- The tests are conducted on the actual pump, with the same mechanical shaft seal (including flush system), or at least on a pump of the same model, size, impeller diameter, materials of construction, and pump seal/flush system.

- The test is conducted at the same speed as at the plant site.

- The test is conducted at the actual predicted NPSHa, since testing at a lower NPSHa can actually reduce, rather than increase, the cavitation erosion rate in some cases.

- The test duration is for the time during which NPSHa is predicted to be less than $NPSHr_{eff}$ (LOCA) or $NPSHr_{3\%}$ (special event).

- The flow rate and discharge head remain above the values necessary to provide adequate core and containment cooling.

B-5 Cavitation Erosion and the Use of Containment Accident Pressure

One of the adverse effects of insufficient NPSH margin whether CAP is used or not used in the determination of NPSHa, is cavitation that results in erosion (pitting) of impeller blade surfaces and possibly of other parts of the pump, due to the implosion caused by condensation of vapor bubbles near a solid surface.

Visual studies, acoustical measurements, and field experience show that the maximum cavitation erosion rate occurs at an NPSHa value between the $NPSHr_{3\%}$ value (NPSH margin ratio = 1.0) and the point of cavitation inception (NPSH margin ratio of 4.0 or higher). The exact value will depend on the pump, the amount of air dissolved in the water, and the point of operation on the pump curve with respect to the best efficiency point.

Figure B-4, a plot of NPSH versus pump flow rate, is a qualitative representation of the various operating regions with respect to cavitation erosion. The figure shows three curves. The top curve is the

NPSH corresponding to incipient cavitation ($NPSH_i$). The middle curve is the NPSH at which the maximum erosion rate occurs ($NPSH_d$). The bottom curve is $NPSHr_{3\%}$. It is noted that the maximum erosion curve lies above the $NPSH_{3\%}$ curve. The NPSHa at which the maximum erosion rate occurs can be two to four times $NPSHr_{3\%}$.

The NPSH curve of incipient cavitation and the NPSH curve of maximum cavitation erosion have similar shapes. At the bottom point on these curves, the impeller pressure distribution is most favorable, and incipient cavitation and cavitation erosion are minimum. As the flow rate decreases from the bottom point, the incipient pump cavitation occurs at higher values of NPSH, and the NPSH corresponding to the maximum erosion rate also increases. Hydraulic instabilities may occur in this region.

Since the NPSHa depends on the containment pressure, which the operator cannot control (except to limit it using containment sprays and/or fan coolers), the NPSHa will vary during a postulated accident and could fall in the region of the maximum erosion rate for a certain duration.

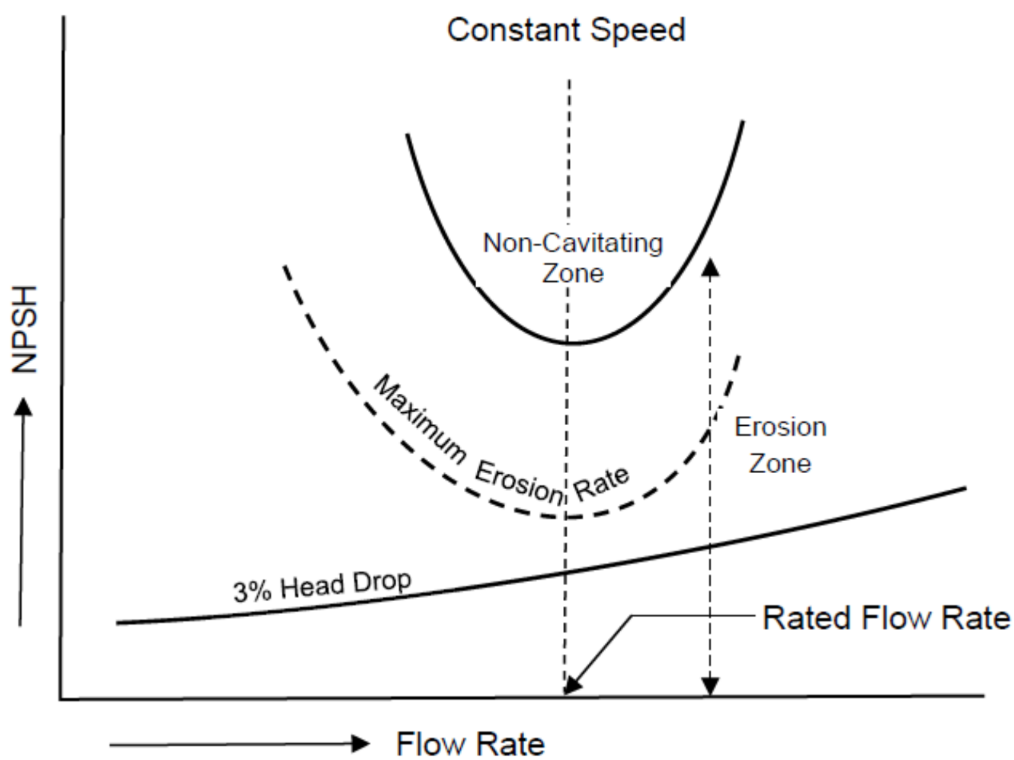


Figure B-4: Erosion zone boundary

Pump tests indicate that the zone of maximum erosion rate lies between NPSH margin ratios of 1.2 and 1.6 for pumps operating outside of the zone of suction recirculation (Refs. B-7 and B-8). While pumps with very high suction energy, such as BWR RHR and LPCS pumps, are subject to cavitation erosion, the time operating in the maximum erosion zone has not been correlated with the degree of damage. There are no technical data available on how long a pump may operate in the maximum erosion zone without failing and on how this cumulative time to failure relates to the pump mission time. A limit of 100 hours is selected for the time permitted in the maximum erosion zone unless the licensee provides a technical basis for an alternate time duration.

Figure B-5 shows a sample plot of the NPSH margin ratio (NPSHa/NPSHr) versus time for a BWR/4 with a Mark I containment. Four NPSHa values are calculated. These are based on a conservative analysis, which used conservative inputs, and a realistic analysis, which used nominal inputs, statistical mean values, and statistical minimum values based on Monte Carlo analysis. The value of $NPSHr_{eff}$ shown in Figure B-5 is based on engineering judgment of typical numbers and is not applicable to any specific pumping system. Figure B-5 merely illustrates the application of the maximum erosion criterion. Note that the statistical mean values and the “realistic” curve show reasonable agreement in this example. This figure shows the application of the 100-hour limit between the NPSH margin ratios of 1.2 and 1.6. The NPSH margin ratio is plotted versus time to 100 hours. At the end of this time, in this example, the NPSH margin ratio based on realistic calculations is above the zone of maximum cavitation erosion, while the conservative value is still within the zone.

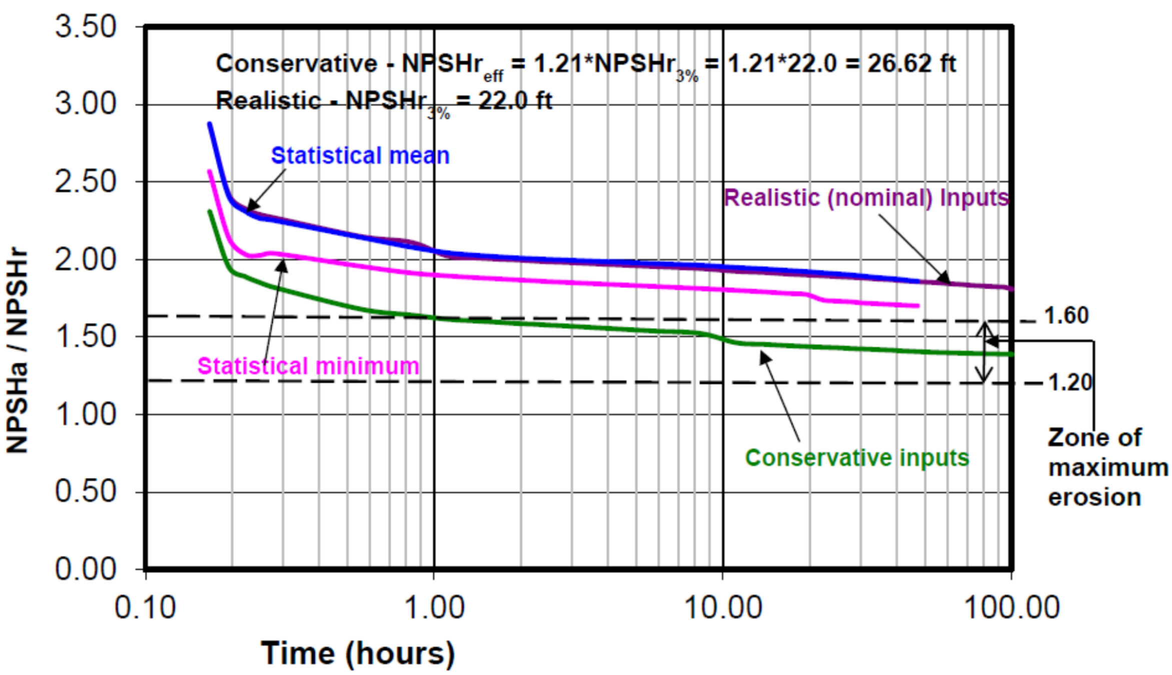


Figure B-5: NPSH margin ratio for RHR pump and zone of maximum erosion

B-6 Containment Accident Pressure and Net Positive Suction Head Available

To determine the pump NPSH margin, the NPSHa should be calculated from the following equation for the simple flowpath in Figure B-6, which shows a pump taking suction from a closed tank:

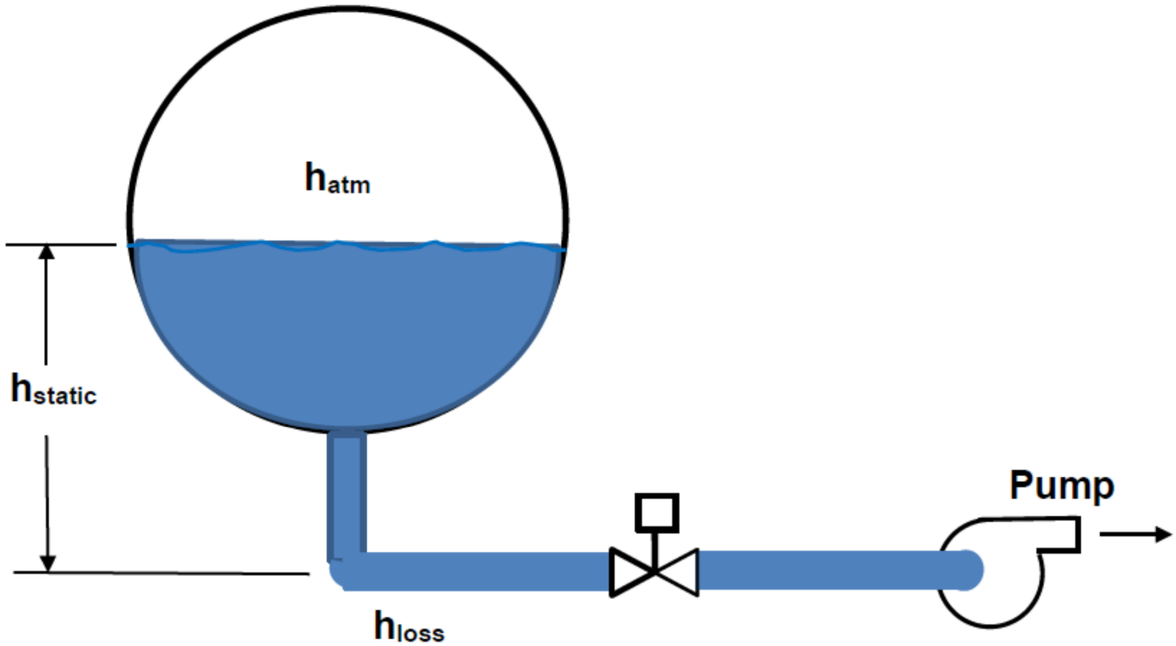


Figure B-6: Illustration of NPSHa

$NPSHa = h_{atm} + h_{static} - h_{loss} - h_{vp}$

where—

- h_{atm} = the head on the liquid surface resulting from the pressure in the atmosphere above
- h_{static} = the head resulting from the difference in elevation between the liquid surface and the centerline of the pump suction
- h_{loss} = the head loss resulting from fluid friction and fittings in the flowpath to the pump suction flange
- h_{vp} = the head equivalent to the vapor pressure at the water temperature

If the tank is open to the atmosphere, h_{atm} is the head resulting from atmospheric pressure. Pressurizing the tank increases h_{atm} and therefore increases the pump NPSHa. If the tank is assumed to be the suppression chamber (wetwell) of a BWR or the containment sump of a PWR, the pressure of the atmosphere above the liquid surface is the pressure of the containment atmosphere. During some postulated accidents, the pressure in the containment will increase because of the discharge of steam and flashing hot water into the containment. Because of conditions adverse to NPSH margin, such as increased water temperature in the sump pool (PWRs) or the suppression pool (BWRs), or increased head loss at the pump suction screens due to debris blocking the screens, sufficient NPSH margin may not be available in some cases if the CAP is not available.

The NPSHa for many PWRs at elevated sump water temperatures (e.g., over 212 degrees Fahrenheit) is determined under the assumption that the pressure at the liquid surface (h_{atm}) equals the vapor pressure (h_{vp}) at the sump water temperature; that is, the following equation applies:

$$NPSHa = h_{static} - h_{loss}.$$

This approach ensures that the determination of the NPSHa does not include the partial pressure resulting from the air (or nitrogen) in containment above the liquid surface; the NPSHa value is therefore conservative. However, when the temperature of the sump water is over 212 degrees Fahrenheit, the vapor pressure will be greater than the pressure in containment before the postulated accident, and containment integrity is assumed.

As described previously, $NPSHr_{3\%}$ is defined as the value of NPSH that results in a 3-percent drop in pump discharge head. The $NPSHr_{3\%}$ value is used for two reasons. First, it is relatively easy to determine by testing. Second, most standard low-suction-energy pumps can operate with little or no margin above $NPSHr_{3\%}$ without serious effects on their long-term operation. However, the full published pump head is not achieved when the NPSHa equals $NPSHr_{3\%}$. The head is 3 percent less than the fully developed head. It can take from 1.05 to 2.5 times the $NPSHr_{3\%}$ value to achieve the 100-percent discharge head.

Normal practice in pump operation requires that the NPSHa exceed the NPSHr by some margin. The amount of CAP needed is determined so that the NPSHa equals the NPSHr, with no margin specified. This practice is acceptable for the calculated containment pressure for a LOCA because the calculation is conservative and therefore contains margin. Also, following this guidance, the uncertainty in NPSHr is to be included in the calculation.

If the calculated NPSHa, under the assumption that the containment pressure is at its pre-accident value, is less than $NPSHr_{eff}$, then the containment pressure is increased so that NPSHa equals $NPSHr_{eff}$. The amount of containment pressure necessary for NPSHa to equal $NPSHr_{eff}$ is the amount of CAP used. The amount of CAP used must be less than the total CAP available at that instant.

To determine NPSHa, it is necessary to know the temperature of the pumped water, the pressure above the water free surface, and the head loss in the suction piping from the water source (suppression pool in a BWR or sump pool in a PWR).

The CAP, water temperature, and water elevation above the pump suction should be calculated with an NRC-approved method. Calculation of CAP and water temperature involves heat and mass transfer processes within the containment and the tracking of the water, gas, and vapor inventory in the containment. It is also necessary to model the plant equipment, such as heat sinks, and to determine the mass and energy released into the containment by the postulated accident or the special event according to NRC-approved or -accepted methodologies.

The containment calculations for NPSH analyses should typically be conservative. That is, all parameters that have a significant effect on the containment pressure and water temperature are assumed to be simultaneously at bounding values; these values are typically either TS limits, such as LCOs, or values known to bound the expected value of a parameter.

Boiling-Water Reactor Plants

In the NRC-approved topical report NEDC-33347P-A/NEDO-33347-A, Revision 2, the BWROG proposed a Monte Carlo method for calculating the lower tolerance limit (e.g., the 95/95 value) of a variable H_{ww}, which is defined as follows:

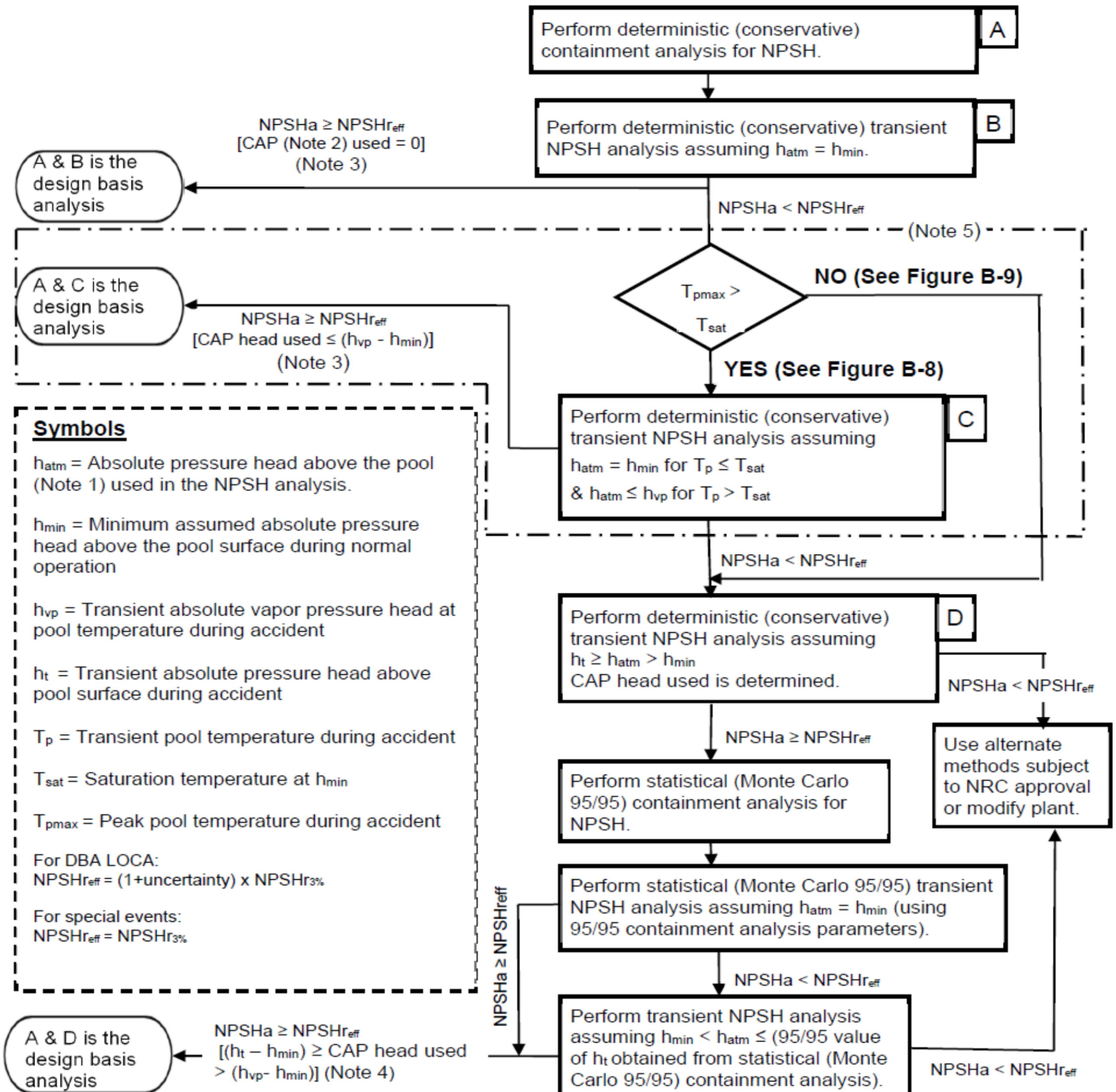
$$H_{ww} = \frac{P_{ww} - P_v}{\rho_w}$$

where—

- P_{ww} = the wetwell pressure above the pool surface
- P_v = the water vapor pressure
- ρ_w = density of water

The variable H_{ww} involves two of the terms in the equation for the NPSHa obtained from the containment analysis. The other two terms in the calculation of NPSHa are the height of the water surface above the pump suction centerline and the suction piping head loss. The height of the water level above the pump centerline can either be determined in the containment calculation or set to a conservatively low value. The head loss term in the NPSHa equation is calculated conservatively to bound the expected value. For a LOCA, the head loss term includes the flow resistance due to the accumulation of debris on the suction strainers or screens upstream of the pump suction.

BWR licensees proposing to calculate NPSHa using CAP greater than the containment pressure before the postulated accident should follow the procedure in NEDC-33347P-A/NEDO-33347-A. Essentially, this procedure is applied when CAP is needed to ensure NPSHa ≥ NPSHr using conservative assumptions. The flowchart in Figure B-7 illustrates this process.



Notes

1. Pool refers to suppression pool for BWRs and sump pool for PWRs..
2. CAP is the transient absolute pressure developed above the pool surface during the accident minus the minimum assumed absolute pressure above the pool surface during normal operation; CAP head available = ($h_t - h_{min}$).
3. Containment leakage monitoring for a pre-existing leak during normal operation is not required.
4. Containment leakage monitoring for a pre-existing leak during normal operation is required. Note: All parameters in [($h_t - h_{min}$) ≥ CAP head used > (h_{vp} - h_{min})] are from deterministic (conservative) analyses in Box A and/or D.
5. The process in the enclosed is not included in NEDC-33347P-A/NEDO-33347-A. In case this process is applied for BWR containment NPSH analysis, it shall be subject to NRC review and approval.
6. Table B-1 lists the process flowchart symbols and terms which are related to but are not the same as the symbols and terms defined in NEDC-33347P-A/NEDO-33347-A. In addition, "transient NPSH analysis" in this flowchart is the same as time-dependent NPSH analysis in NEDC-33347P-A, i.e., analysis for NPSH as a function of time, as illustrated in Appendices A and B of the NEDC-33347P-A/NEDO-33347-A.

Figure B-7: Flowchart for containment and NPSH analyses

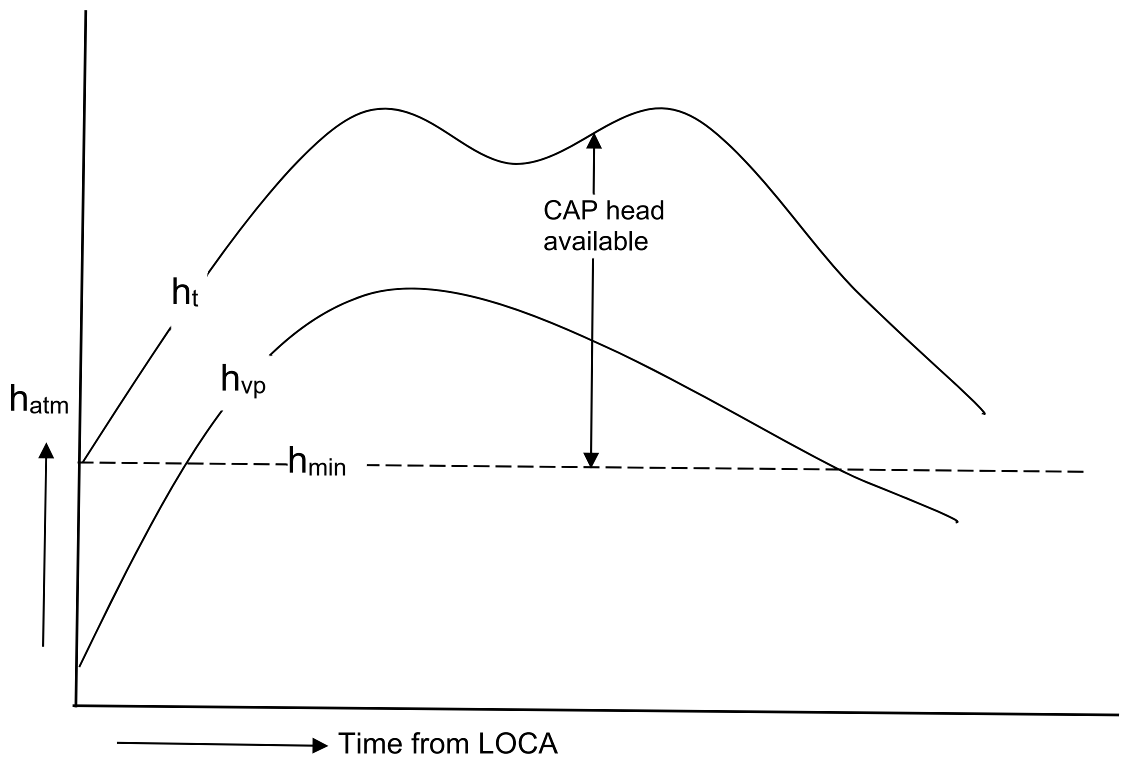


Figure B-8: Illustration of "h_{atm}" and "CAP head available" for $T_{pmax} > T_{sat}$

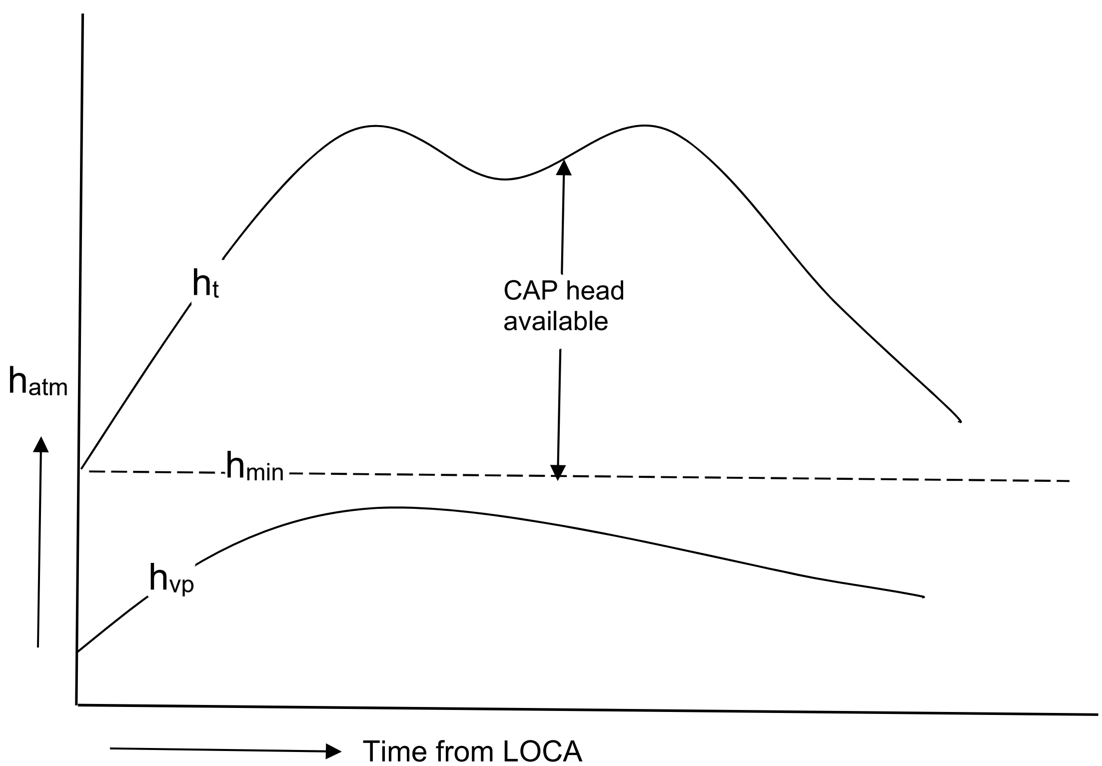


Figure B-9: Illustration of "h_{atm}" and "CAP head available" for $T_{pmax} < T_{sat}$

Table B-1: Comparison of Symbols and Definitions in NEDC-33347P-A/NEDO-33347-A, Revision 2, and Figure B-7

Variable	NEDC-33347P-A/NEDO-33347-A, Revision 2, Symbol or Definition	Symbol or Definition from Figure B-7
NPSH versus time	NPSH as a function of time (Note 1)	Transient NPSH
Wetwell (for BWRs) and sump pool (for PWRs) airspace pressure (psia)	P_{ww} is called "available wetwell pressure" in Appendices A and B, in psig.	h_t (Note 2)
Saturation vapor pressure at pool temperature (psia)	P_v	h_{vp} (Note 2)
Density of pool water (lbm/ft^3)	ρ_w	Not defined; assumed to be included in the pressure head values.
Absolute pressure head available above pool surface for NPSH analysis to determine CAP	Included in P_{ww} term; called "available WW pressure" in Appendices A and B, in psig	h_{atm} (Note 2)
Assumed minimum absolute pressure head above pool surface during normal operation	The containment (drywell/wetwell) initial pressure is at its minimum value (NEDC-33347P-A/ NEDO-33347-A, Revision 2, Section 3.1).	h_{min} (Note 2)
Transient pool temperature during accident	Suppression pool temperature; included in the P_v and ρ_w terms (Note 3)	T_p
Saturation temperature at h_{min}	Not used	T_{sat}
Peak pool temperature during accident	Maximum suppression pool temperature, included in the P_v and ρ_w terms (Note 3)	T_{pmax}
Elevation of pool surface above the pump suction (ft)	H_{pool}	Included in the NPSHa term
Elevation of pump suction (ft)	H_{pump}	Included in the NPSHa term
Suction strainer and suction line losses from pool to pump (ft)	H_{loss}	Included in the NPSHa term
CAP available in NPSH analysis	Available wetwell pressure (assumed absolute initial wetwell pressure above pool surface)	($h_{atm} - h_{min}$) (Note 2)

Notes for Table B-1

1. NEDC-33347P-A/NEDO-33347-A, Sections 3.1 and 3.1.2 for DBA LOCA, has short-term and long-term groups in which representative state points were selected as shown in Appendices A and B to NEDC-33347P-A/NEDO-33347-A.

2. The head is converted to pressure using the liquid density.

3. Suppression pool temperature as a function of time can be calculated from a deterministic (conservative) analysis, or from a statistical analysis resulting in a minimum value of H_{ww} (combination of the suppression pool temperature and P_{ww}) for LOCA, or a mean H_{ww} value for special events. NEDC-33347P-A/NEDO-33347-A, Section 2.2, defines H_{ww} as $(P_{ww} - P_v) \times 144/\rho_w$.

Pressurized-Water Reactor Plants

For PWRs, the following options are acceptable when calculating NPSHa using CAP greater than the containment pressure before the postulated accident: (1) use the vapor pressure corresponding to the sump water temperature, or (2) use a Monte Carlo procedure.

It is possible that the NPSHa may be less than $NPSHr_{eff}$ (LOCA) or $NPSHr_{3\%}$ (special event). In this case, operation in this mode is acceptable if appropriate tests are done to demonstrate that the pump will continue to perform its safety function(s). The following conditions should apply:

- Predicted operation during the postulated accident below $NPSHr_{eff}$ (LOCA) or $NPSHr_{3\%}$ (special event) is of limited duration (less than 100 hours).

- The tests are conducted on the actual pump, with the same mechanical shaft seal (including flush system), or at least on a pump of the same model, size, impeller diameter, materials of construction, and pump seal/flush system.

- The test is conducted at the same speed as at the plant site.

- The test is conducted at the actual predicted NPSHa, since testing at a lower NPSHa can reduce, rather than increase, the cavitation erosion rate in some cases.

- The test duration is for the time during which NPSHa is predicted to be less than $NPSHr_{eff}$ (LOCA) or $NPSHr_{3\%}$ (special event).

- The flow rate and discharge head remain above the values necessary to provide adequate core and containment cooling.

B-7 Effect of Non-condensable Gas on Pump Mechanical Performance

As shown in Figure B-10 (taken from Ref. B-7), the amount of entrained air in a pump increases as the NPSH margin ratio is reduced toward 1.0 and below. The additional entrained air results from the dissolved air coming out of solution as local static pressure drops below the vapor pressure. Centrifugal pumps not specifically designed to transport gas-liquid mixtures can generally accommodate (at inlet pressures near 1 atmosphere) up to approximately 2-percent air volume in the inlet nozzle without appreciable effect (see NUREG/CR-2792). Operation in an airbound condition can cause overheating and failure (seizing of the impeller in the casing of the pump). This damage can occur in 10 minutes or less. Figure B-11 (taken from Ref. B-7) illustrates the impact of air in the pump suction on the pump performance. The figure shows an example of the drop in total pump head as a percentage of the best efficiency point flow rate. There is a large loss in performance when the air fraction is over 2 percent by volume.

Larger quantities of entrained air can affect pump mechanical performance, possibly causing complete loss of prime or air binding and mechanical damage. The entrained air may have come from the suction water source or been transported by vortices, or it may be previously dissolved air that has come out of solution. The configuration of the sump pool (PWRs) or suppression pool (BWRs) should eliminate consideration of entrained air (for instance, due to air entrained by containment sprays) and vortices, since any air bubbles will rise to the free surface of the pool, and steps are taken in sump design to eliminate vortices. In addition, the data developed for NUREG-0897, Revision 1, “Containment Emergency Sump Performance: Technical Findings Related to Unresolved Safety Issue A-43,” issued October 1985 (Ref. B-11), show that vortices decay to negligible levels within 14 pipe diameters; thus, vortices created in a pool would not reach the pump suction through the pump upstream piping.

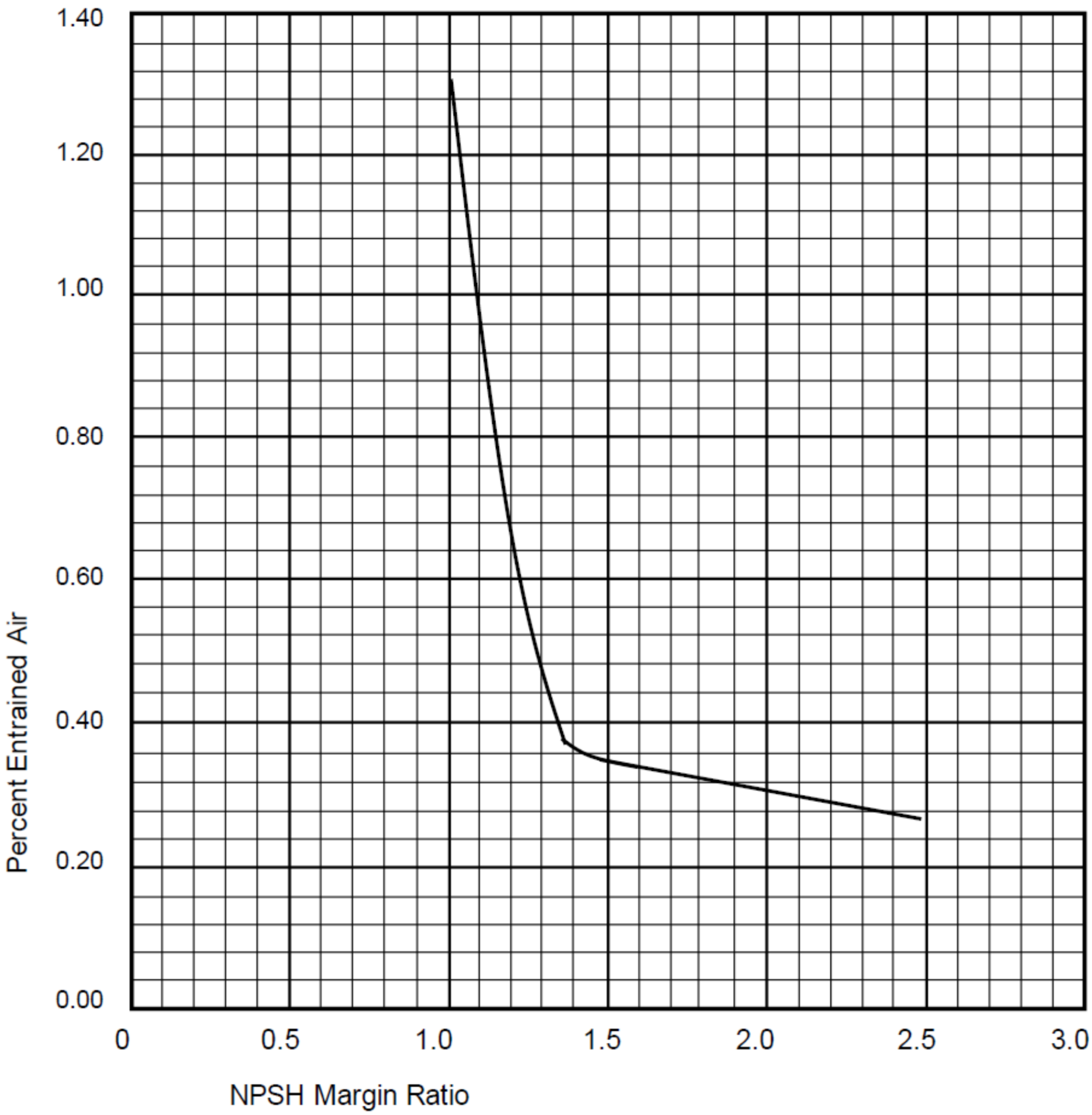


Figure B-10: Impact of cavitation on entrained air

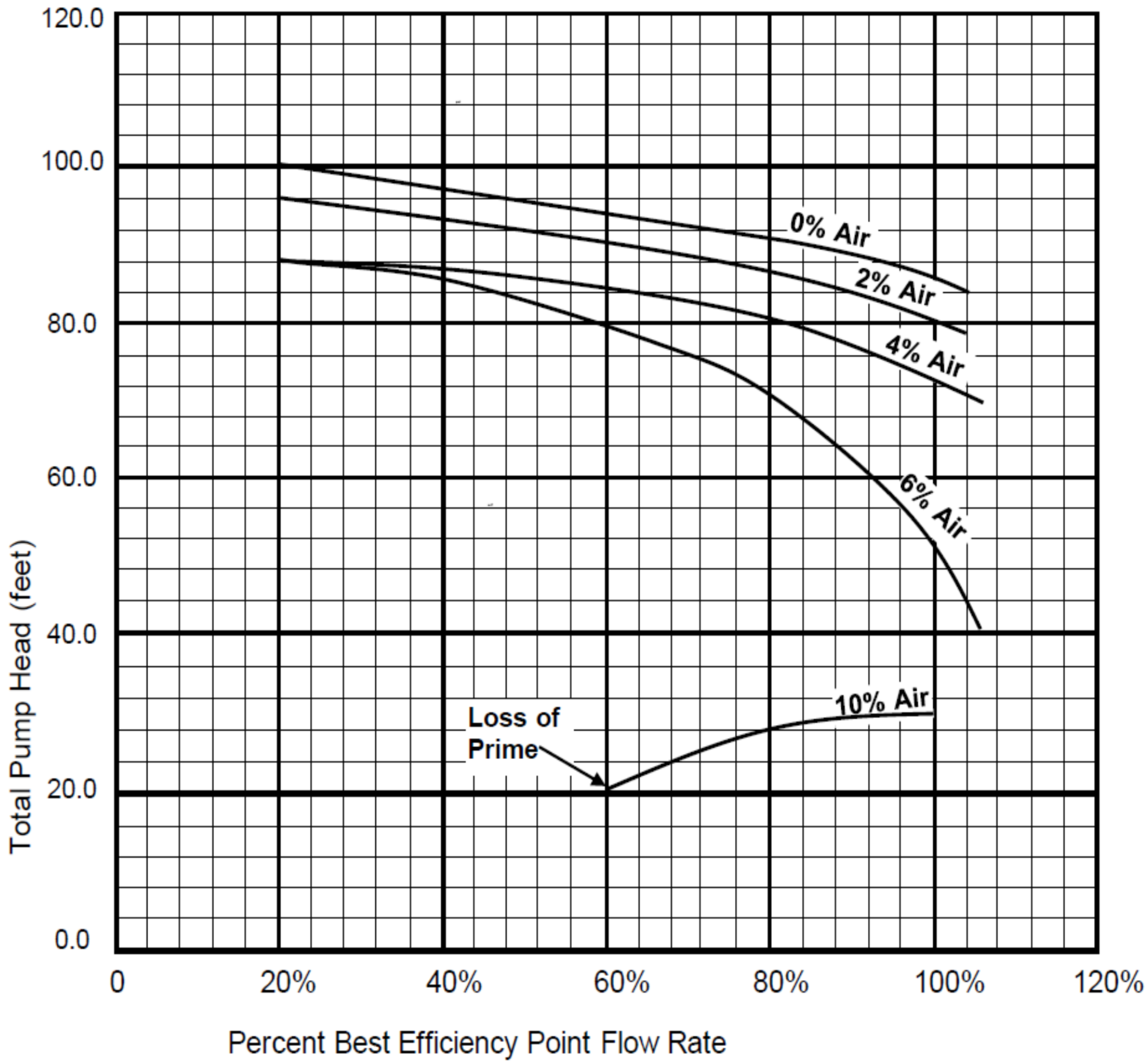


Figure B-11: Illustration of pump total head performance with entrained air

Another concern in operating a pump with NPSHa close to $NPSHr_{3\%}$ is the possibility that water vapor or entrained air could damage the mechanical shaft seal faces within the pump, which could fail very quickly if the seal faces run dry. Excessive entrained air tends to accumulate near the shaft, where the mechanical seal(s) is(are) housed. Therefore, to protect the mechanical seal faces from the excess entrained air expected when NPSHa is close to $NPSHr_{3\%}$, dual mechanical seals with an external cold water flush system (or equivalent) should be provided.

Pump Flow Rate

The flow rate chosen for the NPSHa analysis should be greater than or equal to the flow rate assumed in the safety analyses that demonstrate adequate core and containment cooling. This ensures that the safety analyses and the NPSH analysis are consistent.

If the CAP used is determined assuming that NPSHa equals $NPSHr_{eff}$, then the pump flow rate used in the core and containment cooling calculations should be equal to or less than the flow rate $Q_{3\%}$ (instead of Q_{normal}) resulting from a 3-percent decrease in pump TDH. Figure B-12 illustrates this.

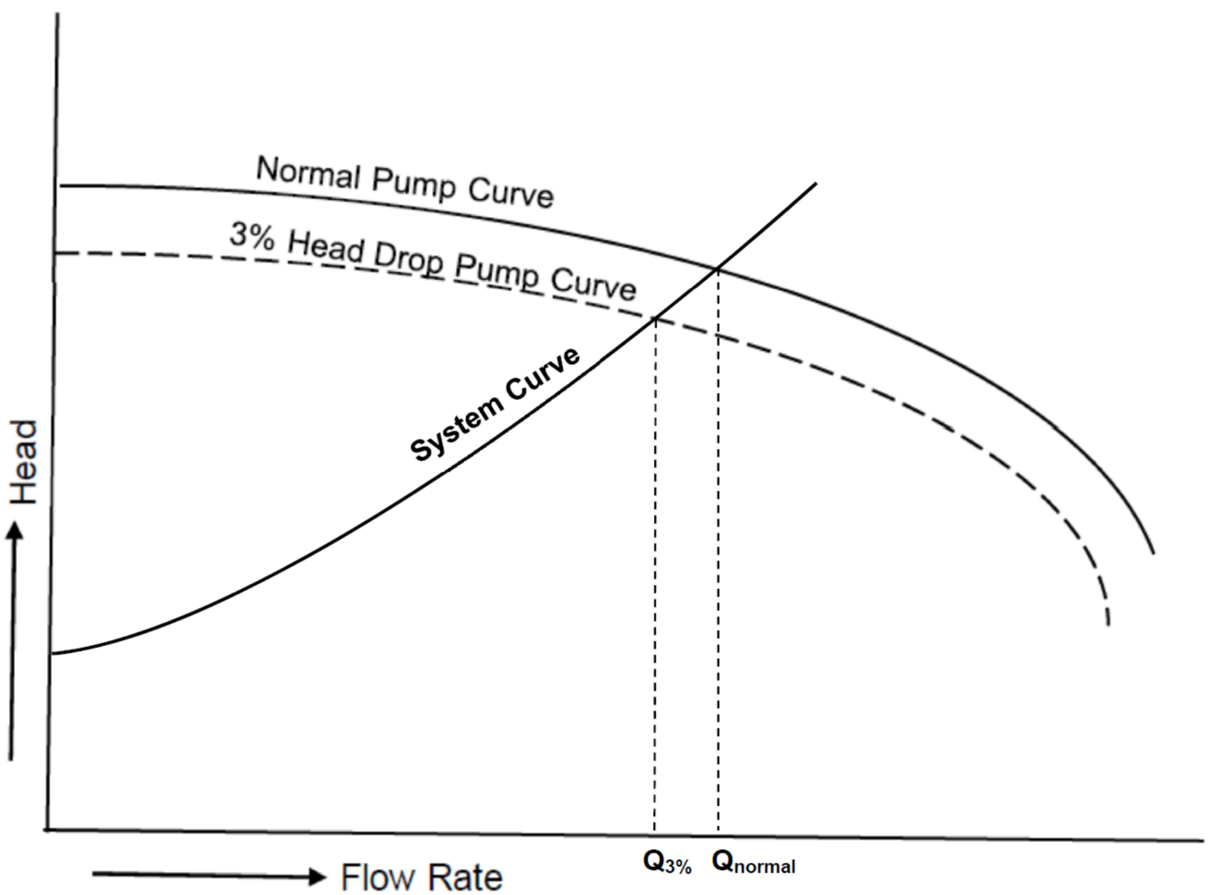


Figure B-12: Illustration of flow rate ($\leq Q_{3\%}$) to be used in safety analysis if NPSHa = $NPSHr_{eff}$

Duration of the Need for Containment Accident Pressure

As stated above, based on pump performance considerations, the time for operation in the region of maximum cavitation erosion should be limited.

In addition, in relation to containment integrity, the duration of the need for CAP to maintain acceptable NPSHa is, in general, not risk significant. Therefore, no time limit based on containment integrity is necessary, since such factors as preexisting leaks or failure to isolate the containment upon receipt of a containment isolation signal dominate risk and are independent of the time interval during which CAP is used.

Loss of Containment Isolation and Containment Leakage

A loss of containment isolation that could compromise containment integrity should be considered. Possible losses of containment integrity include containment venting required by procedures and loss of containment isolation due to a postulated Appendix R fire. Licensees should conservatively demonstrate that, for the plant examined, loss of containment integrity from these causes cannot occur or will occur only after use of CAP is no longer needed.

The following discussion is not considered a primary concern for plants in which containment pressure equals the vapor pressure corresponding to the temperature of the suppression pool (for BWRs) or sump pool (for PWRs). To reduce the likelihood of a preexisting leak in containment, licensees proposing to use any portion of the CAP that is above the normal operating pressure (h_{min}) in Figure B-9 or above the accident pressure (h_{vp}) in Figure B-8 should do the following:

a. Determine the minimum containment leakage rate sufficient to lose the CAP needed for adequate NPSH margin.

b. Propose a method to determine whether the actual containment leakage rate exceeds the leakage rate found in (a) above. For inerted containments, this method could consist of a periodic quantitative measurement of the nitrogen makeup, performed frequently enough to ensure that no unusually large nitrogen makeup occurs. Another method would be to monitor oxygen content. For sub-atmospheric containments, a similar procedure could be used.

c. Propose a limit on the time the plant can operate while the actual containment leakage rate exceeds the leakage rate determined in (a) above.

Containment Cooling during an Event in Which CAP Is Used

It should be demonstrated that operation of containment sprays and fan coolers will not cause the CAP to be less than that needed to maintain adequate NPSHa. Operator action to control the containment pressure by means of containment sprays or fan coolers is acceptable, if justified. Adequate guidance should be included in the appropriate procedures (emergency, abnormal, and other procedures).

B-8 Quantifying Net Positive Suction Head Margin

There are several ways to quantify the margin between the expected (realistic, best estimate, nominal) value of NPSH margin and the NPSH margin obtained from licensing calculations.

For BWR special events, realistic containment calculations are acceptable. This is consistent with NRC staff guidance in Section B-4 for these events. Realistic calculations imply that no conservative bias is built into the calculations. Conservative assumptions such as the single-failure assumption are not necessary. Input values may be those associated with normal operation, rather than values based on TS LCOs or bounding assumptions (e.g., 100-percent drywell relative humidity). Where a realistic value is not available or cannot be easily defined, a conservative value should be used. For example, the service water temperature may vary over a wide range (depending on the season), so the service water temperature giving the more limiting NPSH margin should be used.

For special events, the NPSHr may be used without considering its uncertainty.

For DBAs, a conservative (bounding) NPSH margin analysis should be used. Input values should be based on bounding values for significant parameters, and TS LCOs should be used where applicable. NRC staff calculations for the BWR/3 Mark I containment have shown that conservative calculations of NPSH margin fall close to the 95/95 lower tolerance limit of a Monte Carlo calculation of the same problem. This serves to quantify the margin in the conservative calculation. In addition, a realistic calculation should be performed to compare with the conservative calculation. This will also provide a measure of the margin in the conservative calculation.

It is also acceptable to perform a Monte Carlo calculation, using the 95/95 lower tolerance limit of available NPSH for the conservative case.

For DBA calculations that credit CAP, the NPSHr used should include its uncertainty.

B-9 Guidance Summary

The NRC guidance for the use of CAP in determining the NPSHa of safety-related pumps, as discussed in Section B-3, is summarized below.

B-9.1 For DBAs, analyses involving CAP should use a value of $NPSHr_{eff}$ that includes the uncertainty in the value of $NPSHr_{3\%}$ based on vendor testing and installed operation. The effects of motor slip, suction piping configuration, and air content should be included. $NPSHr_{eff}$ should be calculated from $NPSHr_{3\%}$ as follows:

$$NPSHr_{eff} = (1 + \text{uncertainty})\ NPSHr_{3\%}$$

For non-DBAs, $NPSHr_{3\%}$ may be used.

B-9.2 The maximum flow rate chosen for the NPSHa analysis should be greater than or equal to the flow rate assumed in the safety analyses that demonstrate adequate core and containment cooling. This ensures that the safety analyses and the NPSHa analysis are consistent. If the NPSHa is assumed to equal $NPSHr_{3\%}$ (the usual assumption for determining the amount of CAP used), then the flow rate used in the core and containment cooling analyses should also be greater than or equal to the flow rate resulting from a 3-percent decrease in pump TDH.

B-9.3 It should be demonstrated conservatively that, for the plant examined, loss of containment integrity from containment venting, Appendix R fire, or other causes cannot occur, or it will occur only after use of CAP is no longer needed.

B-9.4 Operator action to control CAP is acceptable. Any operator actions must be approved by the NRC staff as a part of human factors engineering according to 10 CFR 50.34(f)(2)(iii) (Reference B-12) and included in the appropriate procedures (emergency, abnormal, or other procedures).

B-9.5 It is possible that the NPSHa may be less than $NPSHr_{eff}$ (LOCA) or $NPSHr_{3\%}$ (special event). In this case, operation in this mode is acceptable if appropriate tests are done to demonstrate that the pump will continue to perform its safety function(s). The following conditions should apply:

- Predicted operation during the postulated accident below $NPSHr_{eff}$ (LOCA) or $NPSHr_{3\%}$ (special event) is of limited duration (less than 100 hours).
- The tests are conducted on the actual pump, with the same mechanical shaft seal (including flush system), or at least on a pump of the same model, size, impeller diameter, materials of construction, and pump seal/flush system.
- The test is conducted at the same speed as at the plant site.
- The test is conducted at the actual predicted NPSHa, since testing at a lower NPSHa can actually reduce, rather than increase, the cavitation erosion rate in some cases.
- The test duration is for the time during which NPSHa is predicted to be less than $NPSHr_{eff}$ (LOCA) or $NPSHr_{3\%}$ (special event).
- The flow rate and discharge head remain above the values necessary to provide adequate core and containment cooling.

B-9.6 To reduce the likelihood of a preexisting containment leak, licensees proposing to use CAP in determining NPSH margin as illustrated in the flowchart in Figure B-7 should do the following:

a. Determine the minimum containment leakage rate sufficient to lose the CAP needed for adequate NPSH margin.

b. Propose a method to determine whether the actual containment leakage rate exceeds the leakage rate found in (a) above. For inerted containments, this method could consist of a periodic, appropriately frequent quantitative measurement of the nitrogen makeup. For sub-atmospheric containments, a similar procedure could be used.

c. Propose a limit on the time the plant can operate while the actual containment leakage rate exceeds the leakage rate determined in (a) above.

B-9.7 The zone of maximum erosion rate should be between NPSH margin ratios of 1.2 and 1.6. For pumps of very high suction energy, the permissible time in this range should be limited unless operating experience, testing, or analysis justifies a longer time. Realistic calculations should be used to determine the time within this band of NPSH ratio values.

B-9.8 BWR licensees proposing to calculate NPSHa using CAP greater than the containment pressure before the postulated accident should follow the procedure in NEDC-33347P-A/NEDO-33347-A, which essentially determines whether a higher pressure is needed to ensure NPSHa ≥ NPSHr using conservative assumptions. If so, Monte Carlo calculations determine the 95/95 value of H_{ww}. This value is used to determine NPSHa, along with conservative values of h_{loss} and h_{static} (determined separately). The flowchart in Figure B-7 illustrates the process. For PWRs, the following are acceptable options for calculating NPSHa using CAP greater than the containment pressure before the postulated accident: (1) use the vapor pressure corresponding to the sump water temperature, or (2) use a procedure similar to the BWROG Monte Carlo procedure.

B-9.9 The necessary mission time for a pump using CAP should include not only the duration of the accident, when the NPSH margin may be limited, but also any time after recovery from the accident during which pump operation is needed to maintain the reactor or containment in a stable, cool condition; during this time, the NPSH margin may be much greater. This additional time is usually 30 days.

ACRONYM LIST

10 CFR	Title 10 of the *Code of Federal Regulations*
ACRS	Advisory Committee on Reactor Safeguards
ADAMS	Agencywide Documents Access and Management System
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ATWS	anticipated transient without scram
BWR	boiling-water reactor
BWROG	Boiling Water Reactor Owners' Group
CAP	containment accident pressure
CS	core spray
DBA	design-basis accident
ECCS	emergency core cooling system
GDC	general design criterion (criteria)
HI	Hydraulic Institute
LCO	limiting condition for operation
LOCA	loss-of-coolant accident
NPSH	net positive suction head
NPSHa	net positive suction head available
NPSH margin	net positive suction head margin (NPSHa – NPSHr)
NPSH margin ratio	net positive suction head ratio (NPSHa/NPSHr)
NPSHr	net positive suction head required
NRC	U.S. Nuclear Regulatory Commission
PWR	pressurized-water reactor
RHR	residual heat removal
SBO	station blackout
TDH	total dynamic head
TS	technical specification(s)

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B-11 U.S. NRC, "Containment Emergency Sump Performance: Technical Findings Related to Unresolved Safety Issue A-43," NUREG-0897, Rev. 1, October 1985, ML112440046.

B-12 *U.S. Code of Federal Regulations*, 10 CFR 50.34, "Contents of applications; technical information."