U.S. NUCLEAR REGULATORY COMMISSION

DESIGN-SPECIFIC REVIEW STANDARD FOR NuScale DESIGN

15.9.A THERMAL HYDRAULIC STABILITY REVIEW

RESPONSIBILITIES

Primary - Organization responsible for review of transient and accident analyses for the NuScale Small Modular Reactor (SMR)

Secondary - Organization responsible for review of instrumentation and controls for the NuScale SMR

I. AREAS OF REVIEW

The specific areas of review are as follows:

1. Coupled neutronic-thermal-hydraulic instabilities, also known as density-wave instabilities, are safety concerns for nuclear reactors with potential boiling under anticipated operational occurrences (AOOs). For reactors using natural circulation as a means for heat removal, one of the causes of potential instability is the relatively low reactor coolant fluid velocities and the large coolant temperature rise across the reactor core. Specifically, there may be AOOs of the NuScale reactor plant design under which a density wave oscillation (Type I) flow instability would be conceivable under two-phase (subcooled boiling) natural circulation conditions. Bubble formation and collapse may also result in local excessive coolant density changes and a pressure drop that will cause core instability (Type II). In addition, natural circulation may cause stratification in horizontal pipes, which may cause the flow in the core region to oscillate under normal operation.

   Three recognized modes of density-wave instability are core-wide (when the power and flow of all the core channels oscillate in phase), regional (when the power and flow of half the core channels oscillate out-of-phase with the other half), and local flow instability (resulting from localized pressure, temperature, or power differences).

2. Instability modes other than the density-wave type are possible in reactors and their systems. The most common sources of unstable power oscillations are poorly-tuned control systems because of the nonlinear nature of the natural circulation phenomenon. For example, passive natural-circulation reactors may be susceptible to oscillations or loop instabilities during the startup phase or decay heat removal. The reviewer should verify and determine if the applicant includes discussions on any potential issues in this regard and has provided acceptable solutions.

   Certain instability events can lead to unacceptable consequences to the fuel if the reactor is not shut down on time. As such, the reactor design must include means to mitigate any events that may cause unacceptable reactor instability or the reactor protection system must be able to shut down the reactor in a timely manner if an event that caused an unacceptable instability is detected.

   For the NuScale core, if boiling is present in some hot regions, the flow and power distribution will be affected because of the change in local thermal neutron flux, fission density, and hence, the power density, due to void formation. Oscillations can develop, especially out-of-phase oscillations between regions of the core. The possibility of these oscillations and their impact on specified acceptable fuel design limits (SAFDLs) must be evaluated by analysis.

   If the NuScale reactor design has potential instability issues that are not similar to that of boiling water reactors (BWRs), the applicant should provide information on the technical bases of its assessment of the frequency, magnitude, and consequences of any plausible power oscillations. The applicant should provide solutions to control and mitigate any significant oscillations if they were to occur during reactor operations. The reviewer should examine the applicant's analyses of core instability to determine if the applicant has correctly and accurately identified all factors that could potentially cause instabilities and their consequences. The analyses should demonstrate that design features that are implemented prevent unacceptable consequences to the fuel. To this effect, use of NRC-approved

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solutions for BWR instability issues may still be acceptable provided that there is a sufficient justification for the applicability of the solutions to systems using natural circulation for core heat removal under both normal operating conditions and AOOs.

3. Combined License (COL) Action Items and Certification Requirements and Restrictions. For a design certification (DC) application, the review will also address COL action items and requirements and restrictions (e.g., interface requirements and site parameters).

   For a COL application referencing a DC, a COL applicant must address COL action items (referred to as COL license information in certain DCs) included in the referenced DC. Additionally, a COL applicant must address requirements and restrictions (e.g., interface requirements and site parameters) included in the referenced DC.

Review Interfaces

Other design specific review standards (DSRS) and standard review plan (SRP) sections interface with this section as follows:

1. General information on transient and accident analyses is provided in DSRS Section 15.0.

2. Design basis radiological consequence analyses associated with design basis accidents are reviewed under DSRS Section 15.0.3.

3. Determination of the adequacy of the hardware implementation of the Detect-and-Suppress (D&S) system is reviewed under DSRS Sections 7.0-A and 7.2.

4. Determination of stability during anticipated transients without scram events is reviewed under SRP 15.8.

II. ACCEPTANCE CRITERIA

Requirements

Acceptance criteria are based on meeting the relevant requirements of the following Commission regulations:

1. 10 CFR Part 50, Appendix A, General Design Criterion (GDC) 10, “Reactor design”, as it relates to the reactor coolant system being designed with appropriate margin to assure that specified acceptable fuel design limits are not exceeded during normal operations, including AOOs.

2. 10 CFR Part 50, Appendix A, GDC 12, “Suppression of reactor power oscillations,” which requires that power oscillations which can result in conditions exceeding specified acceptable fuel design limits be either not possible or reliably and readily detected and suppressed.

3. 10 CFR Part 50, Appendix A, GDC 13, “Instrumentation and control,” as it relates to instrumentation provided to monitor variables and systems over their anticipated ranges for normal operation, for anticipated operational occurrences, and for accident conditions, and to maintain these variables and systems within prescribed operating ranges.

4. 10 CFR Part 50, Appendix A, GDC 20, “Protection system functions,” which requires the reactor protection system to initiate automatic action to assure that SAFDLs are not exceeded as a result of AOOs. Conditions that result in unstable power oscillations are AOOs.

5. 10 CFR Part 50, Appendix A, GDC 29, “Protection against anticipated operational occurrences,” which requires that D&S Systems be designed to assure an extremely high probability of accomplishing their safety functions in the event of AOOs.

DSRS Acceptance Criteria

Specific DSRS acceptance criteria acceptable to meet the relevant requirements of the NRC’s regulations identified above are set forth below. The DSRS is not a substitute for the NRC’s regulations, and compliance with it is not required. As an alternative, and as described in more

detail below, an applicant may identify the differences between a DSRS section and the design features (DC and COL applications only), analytical techniques, and procedural measures proposed in an application and discuss how the proposed alternative provides an acceptable method of complying with the NRC regulations that underlie the DSRS acceptance criteria.

1. Specific DSRS acceptance criteria acceptable to meet the relevant requirements of the NRC's regulations identified above are as follows for review described in this DSRS section. The DSRS is not a substitute for the NRC's regulations, and compliance with it is not required. Identifying the differences between a DSRS section and the design features, analytical techniques, and procedural measures proposed (for the DC design, COL facility, or ESP site), and discussing how the proposed alternative provides an acceptable method of complying with the regulations that underlie the DSRS acceptance criteria, is sufficient to meet the intent of the regulations (in 10 CFR 52.47(a)(9), 10 CFR 52.79(a)(41), or 10 CFR 52.17(a)(1)(xii), as applicable).

2. To meet the requirements of GDC 12, either (1) the reactor core and its systems should be designed with sufficient margin to be free of undamped oscillations and other thermal-hydraulic instabilities for all conditions of steady-state operation and for AOOs, or (2) if potential oscillations cannot be eliminated, design proposals should detect and suppress them reliably and readily. As it relates to the review under this DSRS Section, compliance with GDC 12 ensures compliance with GDC 10.

3. For the D&S System, it should be demonstrated by analysis that either (i) the probability of instabilities in the allowed operating region is sufficiently small or (ii) unstable power oscillations can be detected and suppressed readily without SAFDL violations. The SPS may use a combination of both demonstrations for different instability modes. A reactor is considered stable if it satisfies one of the following criteria:

    A. The calculated decay ratio (DR) for all three common stability modes (core-wide, regional, and local) satisfies the relationship DR < (1 -σ), where σ is the uncertainty of the calculation. The staff reviews and approves both the calculation methodology and its uncertainty.

    B. Use of an approved correlation to estimate the regional stability based on calculated core-wide and local DRs is permitted. Because of NuScale's special characteristics, a design specific analysis tool should be provided, which includes the algorithm and software that implements the algorithm, that can demonstrate that the core-wide and channel DRs is acceptable. The algorithm and software should be reviewed as part of the safety review.

4. An acceptable D&S methodology to satisfy GDC 12 reduces the operating domain by defining an exclusion region where the reactor is not allowed to operate. The exclusion region, defined by the area in the operating map where stability criteria are not met, should be enforced automatically with an approved D&S System. In addition to the exclusion region, the D&S System defines a larger buffer region enforced with administrative controls. The buffer region minimizes challenges to the reactor protection system.

5. An alternative acceptable D&S methodology to satisfy GDC 12 will readily detect and suppress unstable power oscillations by scramming the reactor before SAFDLs are violated. An approved D&S should be implemented. SAFDL guidance is specified in DSRS Section 4.2, "Fuel System Design," and DSRS Section 4.4, "Thermal and Hydraulic Design."

6. To meet GDC 12 and 29, D&S Systems rely on calculations of the reduction in margin to the critical heat flux for oscillations of a given amplitude. The response to these D&S hardware oscillations should be modeled by a series of likely oscillation-amplitude contours and randomly failed power instruments.

7. To meet GDC 12 and 29 all D&S implementations should have backup options in case the licensing solution is declared inoperable. Technical specifications should require that the primary licensing solution be restored in a relatively short period (no longer than 120 days). Backup options in effect for short periods may rely on administrative controls and manual operator actions only if operator actions required to prevent SAFDL exceedances can be accomplished within the two minutes allowed for operator action in the demonstration calculations. Backup solution exclusion regions should be confirmed for specific cycles and specified in the core operating limits report (COLR).

8. The following criteria are used to determine the acceptability of the D&S System and its

compliance with the requirements of GDC 20:

A. The D&S System should protect against SAFDL violations automatically.

B.

C. The D&S option should include generic technical specifications that address:

i. The methodology for setpoint and region calculation and documentation of the setpoint on a cycle-specific basis (e.g., COLR).

ii. Operability and surveillance requirements for the licensing basis option.

iii. A time limit (120 days maximum) for operation under the backup option.

9. To meet the requirements of GDC 13, a D&S system should be provided to monitor process variables and systems and to maintain these variables and systems within prescribed operating ranges, or justification should be provided that thermal hydraulic stability can be maintained without the need for a D&S system.

10. Stability-related instrumentation functionality should be demonstrated by analysis. Hardware implementation should follow DSRS Section 7.2.

11. In addition to the density-wave instability modes, the applicant should ensure, in accordance with GDC 12, that the plant is free from other instability modes that could violate SAFDLs (e.g., startup or control system instabilities) or that oscillations can be detected and suppressed readily. Note: Some instability modes may be acceptable with no potential for SAFDL violation, (e.g., bi-stable flow or small-flow oscillations during low-pressure startup).

12. To meet GDC 29, the D&S System must be designed to assure an extremely high probability of accomplishing its functions in the event of an AOO.

Technical Rationale

The technical rationale for application of these acceptance criteria to the areas of review addressed by this DSRS section is discussed in the following paragraphs:

1. GDC 12 states, "The reactor core and associated coolant, control, and protection systems shall be designed to assure that power oscillations which can result in conditions exceeding specified acceptable fuel design limits are not possible or can be reliably and readily detected and suppressed." GDC 12, therefore, sets two types of generic requirements that can be satisfied by the following two types of solutions:

A. Exclusion region solutions that reduce the operating domain by defining an exclusion region where the reactor is not allowed to operate, and

B. D&S solutions that scram the reactor if oscillations develop that can result in conditions exceeding specified acceptable fuel design limits.

2. For plants with D&S solutions, unstable power oscillations are AOOs. GDC 20 requires effective reactor protection system protection against SAFDLs for AOOs. Thus, the success criteria for protection system actuation during unstable power oscillations are avoidance of boiling transition and other criteria specified in DSRS Sections 4.2 and 4.4 even though during short events fuel damage may not occur.

3. The D&S System protection should be automatic. Manual and administrative actions are acceptable as backup systems when the primary licensed D&S is declared inoperable for a period of up to 120 days. Manual actions are acceptable for a short time if only a small probability of an instability that would challenge SAFDLs can be shown in reasonable operator action times. If this small probability cannot be demonstrated, there should be an automatic backup.

4. There is a third acceptance option for instability modes other than density-wave stability. In accordance with GDC 12, the reactor may be designed to operate with any such oscillations if they cannot violate SAFDLs.

III. REVIEW PROCEDURES

These review procedures are based on the identified DSRS acceptance criteria. For deviations from these acceptance criteria, the staff should review the applicant's evaluation of how the

proposed alternatives provide an acceptable method of complying with the relevant NRC requirements identified in Subsection II.

1. Selected Programs and Guidance - In accordance with the guidance in NUREG-0800, "Introduction - Part 2: Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: Integral Pressurized Water Reactor Edition" (NUREG-0800 Intro Part 2) as applied to this DSRS Section, the staff will review the information proposed by the applicant to evaluate whether it meets the acceptance criteria described in Subsection II of this DSRS. As noted in NUREG-0800 Intro Part 2, the NRC requirements that must be met by an SSC do not change under the SMR framework. Using the graded approach described in NUREG-0800 Intro Part 2, the NRC staff may determine that, for certain structures, systems, and components (SSCs), the applicant's basis for compliance with other selected NRC requirements may help demonstrate satisfaction of the applicable acceptance criteria for that SSC in lieu of detailed independent analyses. The design-basis capabilities of specific SSCs would be verified where applicable as part of completion of the applicable ITAAC. The use of the selected programs to augment or replace traditional review procedures is described in Figure 1 of NUREG-0800, Introduction - Part 2. Examples of such programs that may be relevant to the graded approach for these SSCs include:

    - 10 CFR Part 50, Appendix A, General Design Criteria (GDC), Overall Requirements, Criteria 1 through 5
    - 10 CFR Part 50, Appendix B, Quality Assurance (QA) Program
    - 10 CFR 50.49, Environmental Qualification of Electrical Equipment (EQ) Program
    - 10 CFR 50.55a, Code Design, Inservice Inspection and Inservice Testing (ISI/IST) Programs
    - 10 CFR 50.65, Maintenance Rule requirements
    - Reliability Assurance Program (RAP)
    - 10 CFR 50.36, Technical Specifications
    - Availability Controls for SSCs Subject to Regulatory Treatment of Non-Safety Systems (RTNSS)
    - Initial Test Program (ITP)
    - Inspections, Tests, Analyses, and Acceptance Criteria (ITAAC)

    This list of examples is not intended to be all-inclusive. It is the responsibility of the technical reviewers to determine whether the information in the application, including the degree to which the applicant seeks to rely on such selected programs and guidance, demonstrates that all acceptance criteria have been met to support the safety finding for a particular SSC.

2. In accordance with 10 CFR 52.47(a)(8),(21), and (22), and 10 CFR 52.79(a)(17), (20) and (37), for design certification or combined license applications submitted under Part 52, the applicant is required to (1) address the proposed technical resolution of unresolved safety issues and medium- and high-priority generic safety issues which are identified in the version of NUREG-0933 current on the date up to 6 months before the docket date of the application and which are technically relevant to the design; (2) demonstrate how the operating experience insights have been incorporated into the plant design; and, (3) provide information necessary to demonstrate compliance with any technically relevant portions of the Three Mile Island requirements set forth in 10 CFR 50.34(f), except paragraphs (f)(1)(xii), (f)(2)(ix), and (f)(3)(v) for a DC application, and except paragraphs (f)(1)(xii), (f)(2)(ix), (f)(2)(xxv), and (f)(3)(v) for a COL application. These cross-cutting review areas should be addressed by the reviewer for each technical subsection and relevant conclusions documented in the corresponding safety evaluation report (SER) section.

The reviewer evaluates the applicant's SAR information on thermal-hydraulic stability concerns during normal operations and AOOs for compliance with the specific acceptance criteria listed in subsection II of this DSRS section. Specifically:

1. The reviewer verifies whether the reactor and its systems facilitate automatic protective action either to prevent thermal-hydraulic instabilities or to make certain that specified acceptable fuel design limits are not exceeded in thermal hydraulic instabilities in accordance with an approved D&S methodology.

2. The reviewer verifies whether the reactor and its subsystems are free from instabilities other than density-wave instability (e.g., startup or control system instabilities) or

whether those instability modes have insignificant effects on SAFDLs.

3. The reviewer verifies whether technical specifications satisfy acceptance criteria listed in subsection II of this DSRS section.

4. The reviewer verifies that all analysis methodologies, including treatment of uncertainties, are acceptable.

5. The reviewer evaluates the need for staff-confirming calculations if design changes deviate significantly from established practice.

6. For review of a DC application, the reviewer should follow the above procedures to verify that the design, including requirements and restrictions (e.g., interface requirements and site parameters), set forth in the final safety analysis report (FSAR) meets the acceptance criteria. DCs have referred to the FSAR as the design control document (DCD). The reviewer should also consider the appropriateness of identified COL action items. The reviewer may identify additional COL action items; however, to ensure these COL action items are addressed during a COL application, they should be added to the DC FSAR.

For review of a COL application, the scope of the review is dependent on whether the COL applicant references a DC, an early site permit or other NRC approvals (e.g., site suitability report or topical report).

IV. EVALUATION FINDINGS

The reviewer verifies that the applicant has provided sufficient information and that the staff's technical review and analysis, as augmented by the application of programmatic requirements in accordance with the staff's technical review approach in the NUREG-0800 Introduction Part 2, support conclusions of the following type to be included in the staff's safety evaluation report. The reviewer also states the bases for those conclusions.

The staff concludes that the plant design adequately addresses thermal hydraulic stability issues and satisfies 10 CFR Part 50, Appendix A, GDCs 10, 12, 13, 20, and 29. This conclusion is based on the following findings:

1. The applicant's plant design includes a stability D&S implementation that either prevents density-wave instabilities or can readily detect and suppress power oscillations that can result in conditions exceeding specified acceptable fuel design limits.

2. The applicant has provided or referred to information and/or analyses that demonstrate that the plant design is free of other instability modes or that those instability modes cannot violate SAFDLs.

3. All calculation methodologies and referenced information have been reviewed and approved by the staff.

4. The applicant has provided technical specifications that address the stability D&S implementation, including setpoint generation, surveillance, and operability requirements. Setpoints and exclusion regions, if applicable, are defined in the COLR.

5. Hardware implementation of the SPS has been reviewed and satisfies DSRS Section 7.2.6. For DC and COL reviews, the findings will also summarize the staff's evaluation regarding requirements and restrictions (e.g., interface requirements and site parameters) and COL action items relevant to this DSRS section.

V. IMPLEMENTATION

The regulations in 10 CFR 52.17(a)(1)(xii), 10 CFR 52.47(a)(9), and 10 CFR 52.79(a)(41) establish requirements for applications for ESPs, DCs, and COLs, respectively. These regulations require the application to include an evaluation of the site (ESP), standard plant design (DC), or facility (COL) against the Standard Review Plan (SRP) revision in effect six months before the docket date of the application. While the SRP provides generic guidance, the staff developed the SRP guidance based on the staff's experience in reviewing applications for construction permits and operating licenses for large light-water nuclear power reactors. The proposed small modular reactor (SMR) designs, however, differ significantly from large light-water nuclear reactor power plant designs.

In view of the differences between the designs of SMRs and the designs of large light-water

power reactors, the Commission issued SRM- COMGBJ-10-0004/COMGEA-10-0001, “Use of Risk Insights to Enhance the Safety Focus of Small Modular Reactor Reviews,” dated August 31, 2010 (ML102510405) (SRM). In the SRM, the Commission directed the staff to develop risk-informed licensing review plans for each of the SMR design reviews, including plans for the associated pre-application activities. Accordingly, the staff has developed the content of the DSRS as an alternative method for the evaluation of a NuScale-specific application submitted pursuant to 10 CFR Part 52, and the staff has determined that each application may address the DSRS in lieu of addressing the SRP, with specified exceptions. These exceptions include particular review areas in which the DSRS directs reviewers to consult the SRP and others in which the SRP is used for the review. If an applicant chooses to address the DSRS, the application should identify and describe all differences between the design features (DC and COL applications only), analytical techniques, and procedural measures proposed in an application and the guidance of the applicable DSRS section (or SRP section as specified in the DSRS), and discuss how the proposed alternative provides an acceptable method of complying with the regulations that underlie the DSRS acceptance criteria.

The staff has accepted the content of the DSRS as an alternative method for evaluating whether an application complies with NRC regulations for NuScale SMR applications, provided that the application does not deviate significantly from the design and siting assumptions made by the NRC staff while preparing the DSRS. If the design or siting assumptions in a NuScale application deviate significantly from the design and siting assumptions the staff used in preparing the DSRS, the staff will use the more general guidance in the SRP as specified in 10 CFR 52.17(a)(1)(xii), 10 CFR 52.47(a)(9), or 10 CFR 52.79(a)(41), depending on the type of application. Alternatively, the staff may supplement the DSRS section by adding appropriate criteria in order to address new design or siting assumptions.

VI. REFERENCES

1. A. C. Thadani, "Acceptance for Referencing of Topical Reports NEDO-31960 and NEDO-31960 Supplement 1, BWR Owners Group Long-Term Stability Solutions Licensing Methodology," U.S. Nuclear Regulatory Commission, July 12, 1993.

2. NEDO-31960, "BWR Owners Group Long-Term Stability Solutions Licensing Methodology," General Electric Company, May 1991.

3. NEDO-31960 Supplement 1, "BWR Owners Group Long-Term Stability Solutions Licensing Methodology," General Electric Company, March 1992.

4. NEDO-32465A, “BWR Owners Group Reactor Stability Detect and Suppress Solutions Licensing Basis Methodology for Reload Applications,” GE Nuclear Energy, August 1996.

5. NEDC-33075P, Revision 5, “General Electric Boiling Water Reactor Detect and Suppress Solution-Confirmation Density,” GE Nuclear Energy, November 2005.

6. IAEA TECDOC 1474, “Natural Circulation in Water Cooled Nuclear Power Plants Phenomena, Models and Methodology for System Reliability Assessments”, IAEA, May, 2005. http://www-pub.iaea.org/books/IAEABooks/7376/Natural-Circulation-in-Water-Cooled-Nuclear-Power-Plants-Phenomena-Models-and-Methodology-for-System-Reliability-Assessments.

7. J. March-Leuba et.al, “Coupled thermalhydraulic-neutronic instabilities in boiling water nuclear reactors: a review of the state of the art,” Nuclear Engineering and Design, vol. 145, pp 97-111, 1993.

8. A. K. Nayak and P. K. Vijayan, “Flow Instabilities in Boiling Two-Phase Natural Circulation Systems: A Review,” Science and Technologies of Nuclear Installations, Vol. 2008, 2008.

9. G. Su, et. al., “Theoretical and experimental study on density wave oscillation of two-phase natural circulation of low equilibrium quality,” Nuclear Engineering and Design, vol. 215, pp 187-198, 2002.