UNITED STATES NUCLEAR REGULATORY COMMISSION

FINAL SAFETY EVALUATION FOR NUSCALE POWER, LLC,

LICENSING TOPICAL REPORT, TR-0920-71621, REVISION 1,

"BUILDING DESIGN AND ANALYSIS METHODOLOGY

FOR SAFETY-RELATED STRUCTURES"

1.0 INTRODUCTION

By letter dated December 18, 2020 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML20353A404), NuScale Power, LLC (NuScale or the applicant), submitted Licensing Topical Report (TR)-0920-71621, Revision 0, "Building Design and Analysis Methodology for Safety-Related Structures," (Reference 7.1) to the U.S. Nuclear Regulatory Commission (NRC) for staff review and approval. By email dated February 12, 2021 (ADAMS Accession No. ML21041A392), NRC accepted the TR for review because the report provided sufficient technical information for the NRC staff to conduct a detailed technical review. Revision 1 of the TR submitted October 6, 2021 (ADAMS Accession No. ML21279A336) incorporates information provided in NuScale responses to NRC staff requests for additional information (Reference 7.2).

The TR describes advanced building design and analysis methodologies to be used in the evaluation of seismic Category I and II structures, systems, and components (SSCs) for applicability to the new generation of small modular reactor (SMR) designs. It is intended but not required to be used in conjunction with NRC-approved NuScale TR-0118-58005, "Improvements in Frequency Domain Soil-Structure-Fluid Interaction Analysis," Revision 2, dated September 2, 2020, for the evaluation of complex seismic Category I and II structures (Reference 7.3).

The TR describes methodologies for the application of steel-plate composite (SC) walls designed in accordance with the 2018 edition of American National Standards Institute (ANSI)/American Institute of Steel Construction (AISC) N690-18, "Specification for Safety-Related Steel Structures for Nuclear Facilities" (Reference 7.4), hereinafter referred to as Specification N690-18, and the referenced ANSI/AISC 360-16, "Specification for Structural Steel Buildings," hereinafter referred to as Specification 360-16 (Reference 7.5), and relevant guidance in NRC Regulatory Guide (RG) 1.243, "Safety-Related Steel Structures and Steel-Plate Composite Walls for Other Than Reactor Vessels and Containments," issued September 2021 (Reference 7.6), that endorses with exceptions and clarifications the procedures and standards of Specification N690-16. Both specifications contain substantial upgrades with respect to the design of structural steel and SC wall sections and represent a significant enhancement from previous versions.

The TR offers, in order of presentation, a discussion of computer software used for design and analysis of seismic Category I and II SSCs (Section 3.0), an advanced in-structure response spectra (ISRS) and design methodology for seismic Category I and II SSC (Section 4.0), determination of effective stiffness for seismic Category I and II structures analysis (Section 5.0), a design methodology for SC walls (Section 6.0), a design methodology for SC

wall connections (Section 7.0), and design methodology for seismic Category I and II concrete structures (Section 8.0). The report provides an improved methodology for the use of a nuclear power plant licensee or applicant in performing seismic analysis of SSCs important to safety in compliance with the applicable requirements of 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 Criteria (GDC), and 10 CFR Part 50, Appendix S, "Earthquake Engineering Criteria for Nuclear Power Plants."

The staff's safety evaluation (SE) is divided into seven sections. Section 1.0, the current section, is the introduction; Section 2.0 presents the applicable regulatory requirements and guidance; Section 3.0 contains a summary of the technical information presented in the TR; Section 4.0 contains the staff's evaluation of the methodologies presented in the TR; Section 5.0 presents the staff conclusions of this review; Section 6.0 contains the limitations and conditions on the use of the TR; and Section 7.0 lists the references.

2.0 REGULATORY REQUIREMENTS AND GUIDANCE

Applicable Regulations:

Appendix A to 10 CFR Part 50, "General Design Criteria for Nuclear Power Plants," establishes necessary design, fabrication, construction, testing, and performance requirements for SSCs important to safety. GDC applicable to the review of the TR include the following:

- GDC 1, "Quality standards and records," requires, in part, that SSCs important to safety be designed, fabricated, erected, and tested to quality standards commensurate with the importance of their safety function. Where generally recognized codes and standards are used, they shall be identified and evaluated for applicability, adequacy, and sufficiency and shall be supplemented or modified as necessary to assure a quality product in keeping with the required safety function.

- GDC 2, "Design bases for protection against natural phenomena," requires, in part, that SSCs important to safety shall be designed to withstand the effects of natural phenomena such as earthquakes without loss of capability to perform their safety functions.

- GDC 4, "Environmental and dynamic effects design bases," requires, in part, that SSCs important to safety be designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation, maintenance, testing, and postulated accidents.

Additional requirements applicable to this review include:

- Appendix S to 10 CFR Part 50, "Earthquake Engineering Criteria for Nuclear Power Plants," provides criteria for the implementation of GDC 2 with respect to earthquakes. Appendix S requires, in part, that the safety functions of SSCs important to safety must be assured during and after the vibratory ground motion associated with the safe shutdown earthquake ground motion through design, testing, or qualification methods, and that the evaluation must consider soil-structure interaction effects.

- Appendix B, “Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants,” to 10 CFR Part 50 establishes overall quality assurance for SSCs important to safety.

Relevant Guidance:

The following regulatory guidance and associated acceptance criteria relevant to the staff review of the TR include applicable NRC RGs and NRC NuScale Design-Specific Review Standards (DSRSs) for SMR designs that provide review guidance pertaining to the seismic analysis of Category I SSCs and structural design including consideration of seismic events:

- RG 1.243, “Safety-Related Steel Structures and Steel-Plate Composite Walls for Other Than Reactor Vessels and Containments,” September 2021 (Reference 7.6), provides updated regulatory guidance for the design, fabrication, and erection of safety-related steel structures and SC walls. The guide endorses, with exceptions and clarifications, the procedures and standards of Specification N690-18 and the referenced Specification 360-16.

- RG 1.142, “Safety-Related Concrete Structures for Nuclear Power Plants (Other than Reactor Vessels and Containments),” Revision 3, issued May 2020, provides guidance for the design, evaluation, and quality assurance of safety-related nuclear concrete structures, excluding concrete reactor vessels and concrete containments (Reference 7.7).

- RG 1.199, “Anchoring Components and Structural Supports in Concrete,” Revision 1, issued April 2020, (Reference 7.8) endorses Appendix D to American Concrete Institute (ACI) 349-13, “Code Requirements for Nuclear Safety-Related Concrete Structures and Commentary,” (Reference 7.17) D, and provides guidance for design, testing, evaluation, and quality assurance, including installation and inspection of anchors (steel embedment) used for anchoring component and structural supports on concrete structures.

- NRC Design-Specific Review Standard (DSRS) for NuScale SMR Design, Section 3.7.2, “Seismic System Analysis,” issued June 2016 (Reference 7.9).

- NRC DSRS for NuScale SMR Design, Section 3.8.4, “Other Seismic Category I Structures,” issued June 2016 (Reference 7.10).

3.0 SUMMARY OF TECHNICAL INFORMATION

The TR discusses the advanced building design and analysis methodologies to be used in the evaluation of seismic Category I and II structures for applicability to the new generation of SMR designs.

Section 1.0 of the TR presents methodologies to be used in building design and analysis for seismic Category I and II reinforced concrete (RC) and SC structure designs. Although these methodologies are intended to be used in conjunction with the NuScale TR-0118-58005, such methodologies can be used with a commercially available analysis program that can perform seismic analyses of a complex safety-related structure. The results of this analytical procedure

provide design parameters for the seismic qualification of SSCs in nuclear facilities including SMR designs.

Section 2.0 of the TR provides background into industry advancements in advanced design and analysis methodologies, which have improved the design and evaluation of complex seismic Category I and II structures for applicability to the new generation of SMR designs.

Section 3.0 presents computer software used in the development of the TR.

Section 4.0 of the TR presents an advanced design methodology for generation of in-structure response spectra and member forces for design of Seismic Category I and II SSCs. It updates the methodology traditionally used for the evaluation of seismic Category I and II structures by employing analytical models with damping values and stiffness properties in Specification N690-18 based on the actual stress state of the members under seismic load.

Section 5.0 of the TR describes a methodology for determining the effective stiffness of RC members and SC walls for use in seismic analysis, including modeling approaches to represent effective stiffness for RC wall and slab members and for SC walls.

Section 6.0 of the TR presents a design methodology for the application of SC walls in lieu of RC walls designed in accordance with Specifications N690-18 and 360-16.

Section 7.0 of the TR addresses the methodology for SC wall connections in accordance with Specifications N690-18 and 360-16, and illustrations provided in AISC Steel Design Guide 32 used in conjunction with Specification N690-18.

Lastly, Section 8.0 of the TR presents an analysis and design methodology for RC structures.

4.0 TECHNICAL EVALUATION

Background

The TR states that industry advancements have improved the design and evaluation of complex seismic Category I and II structures while facilitating constructability, increasing cost efficiencies, and shortening schedules for assembly. As such, the TR presents advanced design and analysis methodologies implementing these new developments in the design and evaluation of complex seismic Category I and II structures for applicability to the new generation of SMR designs.

Applicable Codes, Standards, and Specifications

The TR references industry consensus codes, standards, and specifications applicable to seismic Category I structures. The staff reviewed the references to confirm that the methodologies presented in the TR are consistent with established criteria acceptable to the staff, as presented in NRC NuScale DSRS Sections 3.7.2 and 3.8.4. In addition, the staff's review relied upon Specifications N690-18 and 360-16, as endorsed with exceptions and clarifications by RG 1.243 (September 2021). The specifications supersede all previous versions and differs significantly from them. For concrete structures, the procedures are in accordance with ACI 349, as supplemented by RG 1.142. The design and analysis of anchors

(steel embedment) used for component and structural supports on concrete structures are acceptable if found to be in accordance with Appendix D to ACI 349, as endorsed by RG 1.199.

Use of NRC NuScale Design-Specific Review Standards

The DSRSs provide guidance and acceptance criteria to the staff related to NuScale SMR applications. DSRS Sections 3.7.2 and 3.8.4 refer to applicable codes and standards, loads and load combinations, design and analysis procedures, structural acceptance criteria, and materials and special construction techniques. DSRS Section 3.7.2-II, "Acceptance Criteria," and DSRS Section 3.8.4-II, "Structural Acceptance Criteria for Steel Structures," states that the structural acceptance criteria appear in AISC N690-1994, ACI 349, and RG 1.142 for concrete structures with additional criteria provided in RG 1.142, Revision 3, and RG 1.199, Revision 1. DSRS 3.8.4, Section II.4.J, provides reference to guidance contained in NUREG/CR 6486, "Assessment of Modular Construction for Safety-Related Structures at Advanced Nuclear Power Plants," issued March 1997 and other applicable industry documents related to the use of modular construction methods. Use of these guides and specifications provides additional assurance and imposes specific restrictions to ensure that SSCs will perform their intended safety function.

Computer Software

In TR Section 3.0, the applicant presented ANSYS Version 18.2.2 computer software used in the development of the TR methodology for the analysis and design of seismic Category I and II SSCs. ANSYS is a general purpose commercially available finite element program that has been widely scrutinized and accepted by the engineering community and used in a variety of structural applications including both linear and nonlinear static and dynamic analyses. In particular, the nuclear industry has employed ANSYS in applications similar to that for which the TR is intended. Moreover, the engineering community has accepted ANSYS and used it in nuclear applications to obtain results that are acceptable in the staff's experience. The TR also discusses the use of general purpose, utility, or software tools used to prepare plots contained in the TR for calculations that are verified by alternate calculations or inspection; these include Mathcad (version 15.1), Microsoft Excel and Python (Windows version 2.7.13 and Linux version 2.7.5) for alternative calculations and plotting figures.

The staff concluded that the programs discussed can be accepted for design and analysis of seismic Category I and II SSCs without further validation since DSRS Section 3.8.4 II.4.D(i) states that computer programs are acceptable if the computer program is recognized in the public domain and has had sufficient history of use to justify its applicability and validity without further demonstration. It should be noted that the staff did not review, nor did the applicant demonstrate their acceptability through verification and validation relative to the methodologies presented in the TR.

4.1 In-Structure Response Spectra and Design Methodology of Member Forces for Seismic Category I and Seismic Category II Structures, Systems, and Components

In Section 4.0 of the TR, the applicant presented a methodology to obtain ISRS for subsystem design and member forces for design of seismic Category I and II SSCs. The goal of this methodology is to provide analytical models with damping values and stiffness properties based on the actual stress state of the members under the most critical seismic load combination. The

process includes the development of two ANSYS finite element computer models for seismic and static evaluation comprising a representative SMR Reactor Building (RXB), Control Building (CRB), and Radioactive Waste Building (RWB), surrounded by engineered backfill. These models are referred to as triple building (TRB) models. The TRB seismic model is used in conjunction with the “soil library” methodology presented in NRC-approved NuScale TR-0118-58005 with appropriate dynamic impedance and load vectors is used to conduct the seismic analysis of the structure to determine the member forces and the ISRS from the safe shutdown earthquake (SSE). The TRB static model is used to calculate the forces in the structural members from nonseismic loads.

This proposed methodology uses three different material models from the soil library to represent widely different surrounding media: soil type 11 representing a soft soil profile, soil type 7 representing a rock profile, and soil type 9 representing a hard rock profile. These representative soil types are identical to those given in NuScale Final Safety Analysis Report (FSAR) Section 3.7.1.3.1 “Seismic Design Parameters,” Revision 5, issued 2020 (Reference 7.11).

Five certified seismic design response spectra (CSDRS)-compatible seismic motions have been used with soil types 7 and 11. They are identified by the station name at which the strong ground motion has been recorded: Capitola (CAP), Chi-Chi (CHI), El Centro (ELC), Izmit (IZM), and Yermo (YER), as given in NuScale FSAR Section 3.7.1.1.2.1. Soil type 9 (hard rock) has been evaluated with a certified seismic design response spectra-high frequency (CSDRS-HF) compatible excitation from Lucerne recording station (NuScale FSAR Section 3.7.1.1.2.1). A 50 percent reduction in the soil stiffness is taken as appropriate for potential settlement effects in soil type 11 (soft soil) using the TRB static model. The rationale for using this soil profile with an additional 50 percent reduction in stiffness than the soft soil profile (soil type 11) is to amplify the differential settlement and its effects on the TRB structures. If the structures can withstand the amplified differential settlement, then the settlement effects have been accounted for. NuScale FSAR Section 3.8.5.6.4 “Settlement,” Revision 5, issued 2020 (Reference 7.12) shows that even with the amplified differential settlement, the design limits for both total and differential settlements are not exceeded. Based on the preceding discussion, the staff finds that the effects of differential settlement on the structures have been appropriately considered in the TRB static model, and the approach is acceptable.

Methodology

The applicant described the approach to determine the ISRS and design of structural members in Sections 4.0 through 4.3 of the TR. The process starts with the TRB seismic model with structural members having uncracked material properties subjected to a CSDRS motion. This harmonic analysis is repeated for the three soil types considered, namely soil types 7, 9 and 11. In accordance with American Society of Civil Engineers (ASCE)/Structural Engineering Institute (SEI) 4-16 “Seismic Analysis of Safety-Related Nuclear Structures and Commentary” (Reference 7.13), a national consensus code and standard, the in-plane cracking of the structural members (walls and slabs) is evaluated considering the most critical seismic load combination. The maximum force calculated in a structural member during the entire time-history is used to determine the state of cracking of that member.

The seismic load-resisting RC members and SC wall sections are checked for potential cracking from the CSDRS motion; structural members experiencing out-of-plane shear are considered

uncracked, as described in Section 4.1 of the TR. Following ASCE/SEI 4-16 and Specification N690-18, walls and slabs subjected to out-of-plane flexure are considered cracked. All structural members experiencing out-of-plane shear are considered uncracked. All cracked RC members are assigned the effective stiffness values and corresponding damping, expressed as fraction of critical damping, in accordance with Tables 3-1 and 3-2 of ASCE/SEI 4-16 and Table 3-1 of ASCE/SEI 43-19 “Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities” (Reference 7.14). This approach is consistent with DSRS Section 3.7.2, which is applicable for Category I seismic and structural analysis reviews of SSCs, including the modeling of soil-structure interaction (SSI) effects. All SC members are assigned the effective stiffness values consistent with the Specification N690-18 and the damping values provided in ASCE/SEI 43-19. Both ASCE/SEI 4-16 and ASCE/SEI 43-19 provide the level of cracking in terms of the Response Level (RL) of the seismic load-resisting members defined in Table 3-2 of ASCE/SEI 43-19, and the damping values used are consistent with the recommended values in RG 1.61 “Damping Values for Seismic Design of Nuclear Power Plants,” Revision 1, issued March 2007 (Reference 7.15).

For load combinations without the seismic loads, the member forces from the full load combinations as provided in ACI 349-13 (Reference 7.17) for the concrete members or Specification N690-18 for the SC walls are calculated using the TRB static model with the uncracked in-plane stiffness assigned to the members. Member forces from non-seismic and seismic loads are combined in each time step for load combinations involving the seismic loads. In addition, the in-plane stiffness values of the load resisting members in the TRB static model are matched with those in the TRB seismic model. The Demand-to-Capacity Ratio (DCR) for each structural member is determined, as discussed in TR Section 4.2.3. The maximum DCR over the time history is determined for the load combinations with seismic loads. Reinforcement is added to a structural member, if needed. The average DCR is determined for the CSDRS-compatible input ground motions. The controlling DCR is determined for each member enveloping the reinforcement from the load combinations.

A new harmonic analysis is conducted with the updated stiffness and damping values of the structural members for the five CSDRS motions or the one CSDRS-HF motion, as appropriate for the selected soil type, to determine the force in a structural member from the seismic loads. The ISRS at a given location of a structural member is generated from the harmonic analysis, as discussed in TR Section 4.3, for each of the five CSDRS motions or the one CSDRS-HF motion in the three mutually orthogonal X, Y, and Z directions at 2 percent, 3 percent, 4 percent, 5 percent, 7 percent and 10 percent of the critical damping. The average ISRS is calculated from the results obtained for each CSDRS or CSRDS-HF ground motion used. The ISRS calculated at all the nodes of the model is enveloped in each floor region. The peak is broadened by ±15 percent following RG 1.122 “Development of Floor Design Response Spectra for Seismic Design of Floor-Supported Equipment or Components” (Reference 7.16) to account for uncertainties in the structural frequencies. The final ISRS envelops the ISRS determined for each soil type.

The staff review shows the process to determine the ISRS of a structural member and its forces is similar to that given in DSRS 3.7.2. Whether a particular member would crack in the SSE is determined using ASCE/SEI 4-16 and AISC N690-18 for in-plane bending and shear of the walls and slabs. Corresponding damping values appropriate for the level of cracking, determined by the DCR at limit state D (essentially elastic behavior) is considered in this methodology and the RL of the member is directly determined from this ratio. Both ASCE/SEI

standards use the effective stress and RL based on the in-plane cracking state of the members used for resisting the seismic loads laterally. The staff found the methodology presented is acceptable.

4.2 Effective Stiffness for Seismic Category I and Category II Structures Analysis

In TR Section 5.0, the applicant presented a methodology for the inclusion of effective stiffness in building models comprised of either RC members or SC walls and describes modeling approaches to represent effective stiffness. This methodology applies to modeling seismic Category I and II structures (e.g., RXB, CRB and RWB) of a representative SMR that is primarily comprised of thick structural components such as RC basemats, walls, slabs, and SC walls.

The methodology implements the code-specific stiffness values for both uncracked and cracked RC members and SC walls using ANSYS finite element models. Two ANSYS element types, SOLSH190 and SHELL181, are used to implement the methodology. Two alternative methods have also been presented to implement the effective stiffness values using the SOLSH190 element. For SC walls, the section stiffnesses of the structural members are equal to the effective section stiffnesses defined in Section N9.2.2 of Specification N690-18.

For RC walls and slabs, Section 3.3.2(c) of ASCE/SEI 4-16 allows use of the effective stiffness approach in safety-related buildings in lieu of detailed stiffness calculations. The TR states that the basemat of each building is considered uncracked following guidance provided in National Institute of Standards and Technology (NIST) GCR 12-917-22 “Seismic Design of Reinforced Concrete Mat Foundations: A Guide for Practicing Engineers,” issued August 2012 (Reference 7.18). An RC wall or slab in a building is considered cracked in bending if the bending stress exceeds the critical strength, $\mathrm{f_{cr}}$, given by Equation 19.2.3.1 of ACI 318-14, “Building Code Requirements for Structural Concrete and Commentary” (Reference 7.19). RG 1.243, Section C.5, recommends that the reference made to ACI 318-14 in the TR should be ACI 349-13, the nuclear specification, since Equation 9-12 of ACI-349-13 (Section 9.5.2.3) is the same equation. Similarly, the critical shear stress or the normal concrete shear capacity, $\mathrm{V_c}$, above which a wall or a slab is considered cracked is provided in ASCE/SEI 4-16. The out-of-plane flexural moments in a design-basis earthquake typically produce flexural stresses exceeding the cracking strength of the RC wall or slab. Consequently, the TR recommends using 50 percent reduction of the out-of-plane flexural stiffness without reducing the shear rigidity as typically the shear stresses are relatively low. Both flexural and shear stiffnesses are reduced by 50 percent for in-plane bending and shear without reducing the axial stiffness. The stiffness reduction is in accordance with ASCE/SEI 4-16 and is considered acceptable.

<u>Determination of Effective Stiffnesses</u>

As presented in the TR, the effective stiffness of an SC wall for both operational and thermal conditions is specified in Section N9.2.2 of Specification N690-18, and the out-of-plane flexural stiffness is calculated based on the stiffnesses of the cracked concrete infill and the faceplates using Equation A-N9-8 from Section N9.2.2 of Specification N690-18. The effective in-plane shear stiffness per unit width of the SC wall for operating conditions depends on the ratio of the average in-plane required shear strength, $\mathrm{S_{rxy}}$, and the concrete cracking threshold, $\mathrm{S_{cr}}$, and is calculated by the trilinear relationship given by Equations A-N9-9 through A-N9-14 of Section N9.2.2. The effective in-plane shear stiffness per unit width of the SC wall for

accidental thermal conditions is determined using Equation A-N9-12 assuming cracked concrete. The threshold for crack developing in concrete, S_{cr}, is given by Equation A-N9-10. The method used to determine the effective stiffness is recommended by Specification N690-18 and is considered acceptable.

In accordance with Specification N690-18, an elastic finite element model can simulate the composite SC section using a single material provided the conditions prescribed in Section N9.2.3 of Specification N690-18 are satisfied. As the specification does not have a recommended approach to estimate the effective in-plane flexural stiffness and the effective in-plane axial stiffness, the TR proposes a methodology to calculate them using the analytical approach. The staff has reviewed the methodology and found that the equations for effective in-plane flexural and axial stiffnesses have been derived following common engineering mechanics principles and are considered acceptable.

The TR presents two alternative methods, namely Method 1 and Method 2, to implement the code-specified stiffness values of uncracked and cracked RC members and SC walls in the ANSYS finite element code using the SOLSH190 solid-shell and SHELL181 shell elements. The SOLSH190 element is useful for simulating a wide range of thicknesses (from thin to moderately -thick) and has eight nodes, each node with three degrees-of-freedom (DOF) (translations in the X, Y, and Z directions). As presented in the TR, SHELL181 elements are suitable for analyzing thin to moderately thick shell structures and have 24 DOFs, i.e., four nodes with six DOFs at each node, translations in the X, Y, and Z directions, and rotations about the X, Y, and Z axes. Both elements are acceptable for the analysis of SC walls and RC members.

Implementation in the ANSYS Finite Element Code

Traditionally, the seismic analysis of nuclear power plant facilities has been performed using finite element models with isotropic material properties. However, the methodology presented herein in the TR makes use of the ANSYS orthotropic material model. An orthotropic material has nine independent elastic constants: three Young's moduli, three shear moduli, and three Poisson's ratios. The TR describes the methodologies to estimate the values of these nine parameters. The model thickness t_m and in-plane Young's modulus E_m are derived by equating the out-of-plane flexural stiffness and in-plane axial stiffness to the corresponding values of effective stiffnesses per unit width of a wall or a slab. The staff has reviewed the methodologies to determine the unit weight, model section thickness, and stiffness values, and found that they follow common engineering mechanics principles and are considered acceptable.

To implement the effective stiffness values using Method 1, a single orthotropic material is used with the outer layers used as dummy materials (having zero density and insignificant Young's and shear moduli). Poisson's ratio is assumed to be same as that of the concrete with the thickness of the middle layer equal to the equivalent thickness calculated. The middle layer has the effective elastic properties defined by ASCE/SEI 4-16 and Specification N690-18. Both RC and SC walls can be modeled using Method 1.

Method 2 presents an alternative approach for implementing the effective stiffness values of SC walls to use in SOLSH190 element in ANSYS. The thicknesses of the outer layers are equal to or greater than the actual thickness of the faceplates and the elastic properties of the middle and outer layers as defined in ASCE/SEI 4-16 and Specification N690-18. The model uses

different material properties for the middle and outer layers to match the effective stiffness defined in Section N9.2.2 of Specification N690-18. Material properties for uncracked and cracked cases to be used in the SOLSH190 elements are derived from known quantities using Equations A-N9-8, A-N9-9, and A-N9-12, and the guidelines provided in Specification N690-18. The staff reviewed the methodologies to derive the specific values of orthotropic material properties of the SOLSH190 elements from the stiffness values for both uncracked and cracked RC members and SC walls as provided in ASCE/SEI 4-16 and Specification N690-18 and determined them to be acceptable because the methodologies follow accepted engineering mechanics principles. The TR also described implementation of the effective stiffness of the SC walls or slabs to the SHELL181 element of ANSYS with both Method 1 and Method 2. No dummy layers are needed using Method 1 with SHELL181 elements as only the mid-plane nodes are used in the implementation. This implementation to SHELL181 elements using both Method 1 and Method 2 follows the practice used in traditional finite element formulation and is considered acceptable.

Implementation Examples

The TR presented five examples to show the implementation of the proposed methodologies for both RC and SC walls or slabs with both uncracked and cracked members. A test model with a box type structure has been developed using SOLSH190 elements and Method 1. This prototype structure has aspect ratios similar to that of an RXB in a representative SMR and has either RC walls and slabs or SC walls with RC slabs. The RC members are modeled with (1) gross or uncracked stiffness for members in X, Y, Z directions (uncracked Gross Model); (2) uncracked stiffness for members in X, Y, Z directions without-of-plane effective flexural stiffness as given in ASCE/SEI 4-16 (50 percent reduced) (uncracked $\mathrm{EI_{cr}}$ model); and (3) cracked members in X, Y, Z directions with cracked effective stiffness values (cracked model). The SC members with 0.75 -inch-thick steel faceplates (outer plates) are modeled with either uncracked stiffness for members in X, Y, Z directions with the out-of-plane effective flexural stiffness using Equation A-N9-8 of Specification N690-18 (uncracked-SC model) or effective stiffness values of cracked-SC walls in X, Y, Z directions (cracked-SC model). In both cases, the analysis was performed under normal thermal conditions.

Results from the analyses show that the 50 percent reduction of the out-of-plane flexural stiffness of the RC walls and slabs (uncracked $\mathrm{EI_{cr}}$ model) when compared to the uncracked model in effect makes the structure softer as evident in lower main structural frequencies, especially in X and Z (vertical) directions. Results of the cracked model show significantly further reduction of the main structural frequencies. Modal analysis results using SC walls and an RC roof are similar to the models with all RC members; however, the SC walls make the members stiffer resulting in higher modal frequencies. Implementation of Method 2 for modeling the effective stiffness of SC walls was tested with a box type structure modeled using the SOLSH190 elements. Additionally, another test model with SHELL181 elements has been developed with model thickness calculated by Method 1. Both models have been analyzed with two different variations of the material properties: (1) one model with uncracked stiffness for members with the out-of-plane effective flexural stiffness given by Equation A-N9-8 of Specification N690-18, and (2) one model with effective stiffness values for the members for the cracked cases. Both scenarios have been analyzed assuming operational thermal conditions. Results of the analyses show that the model with the SOLSH190 elements using both Method 1 and Method 2 produces a similar response. Although the results from the model with SHELL181 elements are generally in agreement with those from the models with SOLSH190

elements, the calculated frequencies are slightly lower. The staff reviewed the results from the implementation examples and found them consistent with what is expected given the parameter values.

The TR also provides recommendations where Method 1 would be better compared to Method 2 and vice versa. The TR concludes that SOLSH190 elements better represent the connection region of a structure and therefore are preferred as the element thickness represents the actual wall thickness. The TR also concludes that SOLSH190 elements facilitate connections with other continuum elements such as contact and fluid elements. However, SHELL181 elements can accurately represent some open spans using a single layer, while SOLSH190 elements need multiple layers complicating post-processing operations.

The staff found the methodology acceptable to model the effective stiffness values for RC and SC walls and slabs subjected to seismic events because the seismic analysis approach and methods presented represent generally recognized and accepted methods consistent with the established analytical procedures used in industry-wide consensus codes and standards acceptable to the staff. The methodology also conforms to the general guidance and acceptance criteria in DSRS Sections 3.7.2 and 3.8.4, and RG 1.243, which endorses, with exceptions and clarifications, the procedures and standards of Specification N690-18. The appropriateness of the methodology is further demonstrated through the staff review of the five examples presented in TR Section 5.6 that verify satisfactory implementation for both RC and SC walls or slabs with both uncracked and cracked members in the ANSYS finite element code.

4.3 Design Methodology for Steel-Plate Composite Walls

In Section 6.0 of the TR, the applicant presents a design methodology for SC walls based on the requirements of Specification N690-18 and the referenced Specification 360-16. Specification N690-18 is not a stand-alone document as it relies on Specification 360-16 as the baseline document that identifies any additions, deletions, modifications, or replacements to make it applicable to safety-related steel structures in nuclear facilities. Specification N690-18, recently endorsed by RG 1.243, supersedes all previous editions and represents a significant update to AISC Specification N690-1994, Supplement 2 (2004), referred to in NRC NuScale DSRS Section 3.8.4 and other corresponding NUREG–0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition," the standard review plan (SRP) sections. AISC code requirements and Commentary related to the design of SC walls was first introduced in 2015 in Appendix N9 to ANSI/AISC N690-12, including Supplement No.1.

The methodology presented in this section of the TR applies to straight SC walls (refer to user note in Section N9.1 of Specification N690-18) that can be connected to each other and anchored to a traditionally constructed RC basemat, SC walls with steel-headed stud anchors, and structures designed using load and resistance factor design (LRFD). The methodology also includes requirements and rules for designing and detailing SC walls including response and sizing requirements under impactive and impulsive loading.

Requirements for the Design of Steel-Plate Composite Walls

The requirements for the design, fabrication, and erection of SC walls are provided in Appendix N9 to Specification N690-18 and Specification 360-16, as required by Specification N690-18, with endorsement provided by RG 1.243. According to AISC, extensive research has been conducted over the past decade to evaluate the behavior of SC walls and connections and to develop consensus design standards such as Specification N690-18. Research has included the behavior of SC walls to accident thermal and mechanical loading, in/out-of-pane shear, local buckling, axial tension and compression, missile impact, lateral load capacity, and connection design. The applicant described the methodology of the design of straight SC walls that can be connected to each other and anchored to an RC basemat using LRFD strength design by referring to Appendix N9 and the Commentary of Specification N690-18. TR Figure 6-1, "Typical steel-composite wall configuration," illustrates the composite construction of SC walls, which consist of two steel-plates (faceplates) with concrete infill where the composite action is provided by steel-headed stud anchors on both faceplates connected to each other with steel tie bars for integrity. The applicant stated that SC walls provide better resistance to blast and earthquake events and have higher ultimate strength and ductility, and optimize schedule and labor requirements.

In TR Figure 6-2, SC walls are divided into interior regions and connection regions in accordance with Section N9.2, "Analysis Requirements," of Specification N690-18. The applicant specified that since lightweight concrete will not be used for the construction of SC walls, the compressive strength (f_c') shall not be less than 4 kilopounds per square inch (ksi) nor more than 8 ksi in accordance with Section N9.1.1(e). The staff reviewed the parameters for the dimensional and material properties and found them consistent with Section N9.1, "Design Requirements," of Specification N690-18. The staff also noted that the applicant correctly referred to the appropriate TR sections for steel anchors and ties (Sections 6.3.3.1 and 6.3.3.2, respectively) in determining the steel anchor and tie spacings dimensions. The staff confirmed that the required equations are consistent with those specified in Section N9.1.4, "Requirements for Composite Action," including faceplate slenderness, which is consistent with Equation A-N9-2 of Section N9.1.3 of Specification N690-18.

In addition to Specifications N690-18 and 360-16, AISC Steel Design Guide 32, "Design of Modular Steel-Plate Composite Walls for Safety-Related Nuclear Facilities" (Reference 7.20), hereinafter referred to as "the Guide," supplements Specification N690-18. A regulatory review of the Guide was not performed by the staff as part of its development of RG 1.243 since it was not part of the N690 Specification. However, the Guide informed the staff's review as it is intended to facilitate the design of SC walls by providing guidance on the many aspects of analysis and design of SC structures. The determination and basis of individual design strength equations is presented as well as guidelines for modeling and analysis of SC walls. The implementation of the provisions of Specification N690-18, Appendix N9, is illustrated using a detailed design example. The design methodology for SC walls includes consideration of faceplate slenderness, and shear connector and tie detailing; the performance of an elastic, three-dimensional, finite element analysis (FEA) of the structure comprised of SC walls, using conventional finite element software and thick shell elements to determine the highest individual design demands; a comparison of required strength for each element versus available strength; and an evaluation of demand capacity ratios, impactive and impulsive loading, and connection design. In 2019, the Guide was reprinted with no changes made to the contents. The

requirements for the design of SC walls are consistent with the provisions of Specification N690-18, and are considered acceptable.

Finite Element Analysis Model Requirements

With respect to the analysis of SC walls, the applicant described in TR Section 6.4 the following FEA modeling parameters for the general and stiffness requirements:

- Use of elastic three-dimensional thick shell or solid elements.
- Using at least four elements along the short side and six to eight elements along the long side to capture local modes of vibration in accordance with the Guide.
- The viscous damping ratio is appropriate to determine the required strength for SC walls.
- Heat transfer analysis is conducted to estimate the accident thermal loads, and
- SC walls related to nuclear facilities satisfy the stability requirements.

Stability is checked to ensure that second-order analyses are not required per Section N9.1.2b of Specification N690-18 if Equation 10-7 of Section 10.10.1(b) of ACI 318-08, "Building Code Requirements for Structural Concrete and Commentary" (Reference 7.19) is satisfied, as shown in TR Equation 6-14. The applicant also provided TR Table 6-2, "Load Combinations," which is consistent with Chapter NB2.5 of Specification N680-18 for the LRFD method and provided equations for modeling requirements for effective flexural and in-plane shear stiffnesses. The staff compared the equations in Appendix N9.2.2.(a) and (b) of Specification N690-18 against TR Sections 6.4.2.1 and 6.4.2.2 and confirmed consistency with the equations in Appendix N9.2. For the elastic FEA, the applicant provided geometric and material properties such as Poisson's ratio, thermal expansion coefficient, and thermal conductivity of the concrete as required in Appendix N9.2.3(a) of Specification N690-18. The applicant described the need to perform the heat transfer analysis only for accident thermal condition but did not provide any discussion in the TR as how to determine the limit of out-of-plane flexural strengths, per unit width in the SC wall, using Equation A-N9-15 in Section N9.2.5 of Specification N690-18. Since the applicant is strictly following the requirements for the design of SC walls in Specification N690-18, the staff found that the applicant's discussion for the accident thermal condition in TR Section 6.4.4 is consistent with the methods discussed in DSRS Section 3.8.4 and is acceptable.

Required Strength Determination

The applicant described the required strength determination of in-plane membrane forces, out-of-plane moments, and out-of-plane shear forces (force demands) in Section 6.5 of the TR. The required strength for each demand type is determined by averaging the demand over the panel sections away from the opening, not larger than twice the SC wall thickness, and in the vicinity of openings and in connection regions, not larger than the SC wall thickness. The applicant described the required strengths for each demand type of SC walls with notations in the local coordinate system. The staff confirmed that the required strength determination presented in the TR is consistent with Section N9.2.5 of Specification N690-18 for the required panel section

dimensions and the required strength notations associated with the finite element model, and is considered acceptable.

Available Strength Calculation

In Sections 6.6.1–6.6.7 of the TR, the applicant described the available strength determinations with equations of tensile strength from Chapter D of Specification 360-16, compressive strength, out-of-plane flexure strength, in/out-plane shear strength, combined out-of-plane shear forces, in-plane-membrane, and out-of-plane moments using available strengths consistent with individual demand types associated with SC walls and equations consistent with the requirements in Section N9.3 of Specification N690-18. According to the Guide, the concrete contribution to the tensile strength of an SC wall section and the contribution of the steel ribs to available strength are neglected since the ribs are provided primarily to increase faceplate stiffness and strength to handle construction loads.

The available compressive strength per unit width of the SC wall section is calculated per Section I2.1b of Specification 360-16, as modified in Section N9.3.2 of Specification N690-18. The available flexural strength per unit width is determined using Equation C-AN9-11 of Section N9.3.3 of the Commentary to Specification N690-18, as shown in TR Equation 6-30. The available in-plane shear strength per unit width of the panel section is calculated per Section N9.3.4 of Specification N690-18 and shown in TR Equation 6-33, out-of-plane shear strength is calculated per Section N9.3.5 of Specification N690-18. The interaction of out-of-plane shear forces and in-plane membrane forces and out-of-plane moments is evaluated using Sections N9.3.6a/b of Specification N690-18. These requirements are consistent with the provisions of Specification N690-18 and are considered acceptable.

Design for Impactive and Impulsive Loads

The applicant described in TR Section 6.7 the design for impactive and impulsive loads for local and global effects such as tornado-borne missiles, pipe whip, and aircraft missiles and impulsive loads such as jet impingement, blast pressure, and compartment pressurization. These loads are considered in extreme environmental and abnormal load combinations acting concurrent with other loads as provided in TR Section 6.4.1, Table 6-2 (based on Chapter NB2.5 of Specification N690-18). For the evaluation of the global response of SC walls under impactive and impulsive loads, the TR provided Table 6-3, "Dynamic Increase Factors," that can be applied to the static material strength of steel and concrete to determine section strength, and Table 6-4, "Ductility Ratio Demand," providing ductility ratio demands (μ_{dd}) for flexure-control, shear-control and axial compassion. These tables are consistent with Specification N690-18, Table A-N9.1.1, and Table 12-1," Ductility Ratio Demand," in the Guide, respectively. The applicant considered using one of the following three methods for dynamic effects of impulsive loads as is consistent with Section N9.1.6c, "Response Determination," of Specification N690-18:

(1) The dynamic effects of the impulsive loads are considered by calculating a dynamic load factor (Reference 7.21).

(2) The dynamic effects of impulsive loads are considered by using impulse, momentum, and energy balance techniques.

(3) The dynamic effects of impulsive loads are considered by performing a time history dynamic analysis.

The applicant described the effects of impactive, and impulsive loads determined using inelastic analysis and considering the limitations of the ductility ratio demand and the principal strain of plate. In TR Section 6.7.1.3, “Ductility Ratios,” the applicant described that it is permissible to determine the effects for impactive or impulsive loads using inelastic analysis with limits provided in TR Table 6-4. The ductility ratio demand limit for "Flexure-controlled SC walls" is in accordance with Section N9.1.6b of Specification N690-18. In Item 2 of TR Section 6.7.1.4, “Response Determination,” the applicant stated that the plate principal strain is limited for SC walls subjected to impulsive loads consistent with Section N9.1.6c of the Commentary to Specification N690-18. However, the applicant did not consider in the TR the regulatory guidance position stated in Section C11.1.4 of RG 1.243 and the requirement in Section F.3.4 of ACI 349-13 regarding the rotational capacity of any yield hinge less than or equal to 0.07 radian (4 degrees), when flexure controls the design of SC walls. The staff requested the applicant provide an explanation for this omission.

In Revision 1 of the TR, the applicant provided a response that the rotational limit was not considered in the TR since the displacement ductility ratio controls the failure limit state due to the formation of flexural and shear cracks. The applicant also described that the principal strain limit on the plate at the tension side controls the failure limit state. Further, the staff noted that the yield hinge rotation capacity need not be checked if the deformation limit is kept under 10 for flexure-controlled sections, as stated in Section N9.1.6.b of the Commentary to Specification N690-18. Therefore, the applicant may not consider a rotational capacity of any yield hinge less than or equal to 0.07 radian as a limit for impactive and impulsive loads. The staff considered the applicant’s response in TR, Revision 1, to be acceptable.

The staff requested the applicant to describe how the maximum deformations would not result in the loss of intended function of the structural wall as well as not impair the safety-related function of other systems and components as required in provision F.3, "Deformation," of ACI 349-13. The applicant stated in TR, Revision 1, that the intended functions of the SC walls are not impaired because the critical impulsive and impactive load-wall analyses will be evaluated with the internal forces and maximum displacements due to the responses from the time history dynamic analyses using comprehensive mathematical models of the walls. The staff considered the applicant’s response acceptable.

For the evaluation of the local response of SC walls under impactive and impulsive loads, the staff requested the applicant to describe whether TR Equation 6-53 is applicable for SC walls. In TR, Revision 1, the applicant revised Step 1, Item 2, of the three-step approach to the design of an individual SC wall for a specific missile by adding clarification that the 70 percent is an initial assumption for determining the required wall thickness consistent with Section N9.6c of the Commentary to Specification N690-18. The applicant also illustrated the evaluation procedure in TR Figure 6-5, “Evaluation procedure against impact and conical plug geometry,” where the impacting missile striking the surface of the steel-plate is neglected in the analysis for conservatism; therefore, the impact of a missile on concrete dislodges a conical concrete plug, which in turn impacts the rear steel-plate. The approach is based on the method provided in Reference 7.22, which refers to Nuclear Energy Institute (NEI) 07-13, “Methodology for Performing Aircraft Impact Assessments for New Plant Designs,” Revision 8P, issued April 2011 (Reference 7.23) and DOE-STD-3014-2006, “Accident Analysis for Aircraft Crash into

Hazardous Facilities," reaffirmed May 29, 2006 (Reference 7.24) for determining SC wall thickness, and the residual velocity of the missile, respectively. The required faceplate thickness is determined using the formulas from RG 1.243 to satisfy the requirement of Section N9.1.6c of Specification N690-18. The staff considered the applicant's response acceptable.

The applicant stated that aircraft impacts are outside the scope of the TR and that such effects are covered in NEI 07-13. The staff confirmed that the local and global effects of impactive and impulsive loads with limitations are consistent with the requirements and equations provided in Appendix N9.1.6 of Specification N690-18, RG 1.243, and DSRS Section 3.8.4, and are therefore acceptable.

Design and Detailing Around Openings

The applicant described the design and detailing around openings in SC walls that create stress concentrations with the level of severity depending on factors such as the size of the openings and geometry, and types and magnitudes of loading. The applicant categorized the openings in SC walls as small if the largest dimension is not greater than half the wall thickness ($\leq t_{sc}/2$); and large if the largest dimension is as defined in the Glossary section of Specification N690-18. The applicant also described the modeling requirements for openings based on Section N9.1.7 of the Commentary to Specification N690-18. The staff compared the design and detailing requirements for openings in Sections 7a, 7b, and 7c of Appendix N9 against the applicant's description of the design and detailing requirements for openings in the TR and confirmed the description is consistent with Appendix N9.7 of the Commentary to Specification N690-18. The requirements for ductile failure of faceplates with holes, steel rib embedments, and connection strength of splices are discussed in TR Sections 6.9, 6.10, and 6.11 and comply with the requirements in Appendix N9.1.1 of Specification N690-18 and are therefore acceptable.

Corrosion Effects for Steel-Plate Composite Walls

During the review, the staff noted that the applicant did not address corrosion effects for SC walls. Therefore, the staff requested the applicant to provide a discussion in TR, Revision 1. The applicant stated in Section 6.0 of TR, Revision 1, that the implementation of mitigative defense-in-depth approaches is based on site-specific exposures due to environmental conditions and plant life extensions of up to 80 years. In addition, since performing inservice inspections and repairs of inaccessible below-grade external sections of the SC walls is not possible, the following graded approach for protecting below-grade exterior sections of SC walls may be considered:

- As a minimum, a coal tar epoxy system coating specifically suited for below-grade protection of carbon-steel.

- Additional protection such as controlled low strength material or shotcrete may be employed as a cementitious material only for environments with high chloride or hydrogen sulfide.

- Backfill with controlled pH and chloride limits governed by site-specific conditions is placed and thoroughly compacted to reduce impact from corrosive properties of the soil.

The applicant described that a coating suitable for above-grade protection of carbon-steel should also be applied. If additional protection is deemed necessary, a concrete coating or vinyl or aluminum siding may be employed. The staff found the applicant's discussion acceptable as required in Section B3.13 of Specification 360-16. The issue of corrosion effects for SC walls is not discussed in Specification N690-18 or RG 1.243, however Section B3.13 of Specification 360-16 has a general requirement that states that "structural components shall be designed to tolerate corrosion or shall be protected against corrosion."

The staff reviewed the strength design methodology of SC walls based on the requirements of Specifications N690-18 and 360-16 and found the methods consistent with the acceptance criteria in DSRS Section 3.8.4 and RG 1.243, which recently endorsed Specifications N690-18 and 360-16. The DSRS provides guidance and methods acceptable to the staff regarding basic specifications for concrete and steel structures in compliance with NRC regulations and cites certain RGs and industry consensus codes and standards, specifically ACI 349-13, endorsed by RG 1.142. These guides and specifications include specific provisions to ensure that SSCs will perform their intended safety function. Meeting these requirements and criteria provides added assurance that the SSCs described herein will perform their safety function.

4.4 Design Methodology for Steel-Plate Composite Wall Connections

In Section 7.0 of the TR, the applicant presented a design methodology for SC wall connections to be used in the design and construction of a representative RXB, CRB, and RWB in compliance with Specifications N690-18 and 360-16 and ACI 349. Previous editions of these specifications, namely ANSI/AISC N690-1994, have been acknowledged in several NUREG-0800 SRP guidance documents, including DSRS Section 3.8.4 used by the NRC staff for review guidance in this area. The staff reviewed the methodology for the development of the types of connections between SC wall structures and their adjoining structures in accordance with Section N9.4 of Specifications N690-18 and 360-16 and well-established industry consensus codes and standards such as ACI-349. Since Specification N690-18 has limited details for the design of SC wall connections, it focuses on developing available strength for each demand type using the applicable force transfer mechanism (FTM) and available strength of the contributing connectors, as discussed in Commentary Section N9.4.3 of Specification N690-18. Additional guidance is presented in the User Note in Section N9.4.1, which refers to the use of AISC Steel Design Guide (the Guide) (Reference 20).

In Chapter 11, the Guide provides additional details and illustrations of SC wall connections and discusses the behavior and design of SC walls subjected to various individual and combined seismic and nonseismic force demands resulting from an FEA, connection types and regions, demand types, FTMs, connection philosophy and required strength, connection detailing, and design of SC wall connections. Twenty-eight figures are presented, illustrating several typical connection configurations and FTMs for SC wall-to-basemat anchorage, SC wall-to-wall joint, and RC slab-to-SC wall joint connections. The implementation of the provisions of Specification N690-18, Appendix N9, is illustrated using a design example presented in Appendix A to the Guide.

The review of the TR covered the design methodology for SC wall connections including review of each connection detail with the types of loads it is expected to transfer, e.g., FTM, anchorage design (concrete capacity design) for steel studs and other connectors, SC connection details, and welding design. SC walls used in safety-related nuclear facilities are typically connected to

each other and anchored to the concrete basemat. Specification N690-18, Section N9.4, addresses design requirements for the following types of SC connections: splices between SC wall sections; splices between SC and RC wall sections; connections at the intersection of SC walls; connections at the intersection of SC walls with RC walls; anchorage of SC walls to RC basemats; and connections between SC walls to RC slabs.

A connection may be defined as the assembly of steel connectors consisting of steel-headed stud anchors, anchor rods, tie bars, reinforcing bars, dowels, post-tensioning bars, shear lugs, embedded steel shapes, and welds and bolts that participate in the FTMs mechanisms for multiple demand types between connected parts including tension, compression, in-plane shear, out-of-plane shear, and out-of-plane flexure. Since SC connections involve plate/shell type SC elements, the design becomes more complicated than connections for linear composite members. The staff considers these types of steel connectors acceptable to transfer SC wall demands to the connections.

In Section 7.1 of the TR (illustrated in Section 11.2 of the Guide), the applicant presented a discussion of FTM, which needs to be identified for each of the required strengths, namely required membrane axial force, membrane in/out-of-plane shear force or out-of-plane moment. Each FTM involves connectors of the same type in the connection region. For design purposes, SC walls are divided into interior regions and connection regions in accordance with Section 9.2 of Specification N690-18. The connection region, similar to that of load transfer regions for composite columns in Specification 360-16, is specifically designed to undergo ductile yielding and energy dissipation during overloads whereas the interior region is available to dissipate energy for beyond design-basis events (DBEs), which can be stronger than a nuclear plant's current design. Force transfer from the composite SC wall to the supports or connected structures occurs within these connection regions. Connection regions consist of perimeter strips with a length not less than the SC wall thickness, t_{sc}, and not more than twice the SC wall thickness, $2t_{sc}$.

Connection Required Strength

In TR Section 7.2.1, as illustrated in Sections 11.3.1 and 11.3.2 of the Guide, the applicant presented the methodology for determining the required connection strength allowed by Appendix N9.4.2 of Specification N690-18 that permits the design of SC walls based the design philosophy of either a full-strength connection or an over-strength connection. A full-strength connection is designed to be stronger than the expected strength of the weaker of the two connected parts and remains elastic for beyond DBEs. For this case, the required strength of the connection is determined as 125 percent of the smaller of the corresponding nominal strengths of the connected parts, which is consistent with the concrete anchorage and design provisions of Chapter 21, and Commentary Section R21.5.4.1 of ACI 349-13, which uses a load factor of 1.25 to account for strain hardening. The required strengths are compared with available strengths determined in accordance with the provisions of Section N9.3 of Specification N690-18.

As discussed in the User Note in Section N9.4.2 of Specification N690-18, the full-strength design philosophy ensures ductile behavior with yielding and inelasticity occurring away from the connection in one of the connected parts. It is generally preferred over the use of an over-strength connection. The required strength of an over-strength connection is determined as 200 percent of the required strength due to seismic plus loads 100 percent of the required strength

due to nonseismic loads, including thermal loads. The connectors utilized in over-strength connection FTMs are designed to exhibit ductile failure modes involving steel yielding. Connections available strength for steel-headed anchors and studs is discussed later in this SE section.

In Section 7.2.2 of the TR (illustrated in Section 11.1 of the Guide), the applicant stated that the required connection demands per unit length of the connection are obtained from an FEA conducted in accordance with Section A-N9.2, “Analysis Requirements,” of Specification N690-18, where the results are used to determine the design demands per unit length of the connection depending on the connection design philosophy. The demands are membrane axial force, membrane in-plane shear force, in/out-of-plane shear force, and out-of-plane bending moment. Based on the connection design philosophy, each connection design demand can be differentiated into demands due to seismic and nonseismic loading conditions.

Design Methodology for Typical Steel-Plate Composite Wall Connections

In Sections 7.4 - 7.6 of the TR (illustrated in Sections 11.5 - 11.7 of the Guide), the applicant presented a discussion of typical connection configurations for SC wall-to-basemat anchorage, SC wall-to-SC wall connection, and RC slab-to SC wall connection, and discusses the detailing and possible FTMs for each connection configuration based on Specification N690-18 Commentary. The Commentary is nonmandatory and furnishes background information and references related to the derivation and limits of nuclear Specification N690-18 and 360-16. Commentary Section N9.4, “Design of SC Wall Connections,” presents three connection design flowcharts in Section N9.4.3. Figure C-A-N9.4.1 shows the procedure to be followed in calculating the required strength of the connection. Figure C-A-N9.4.2 shows the procedure to be followed in calculating the available strength of the connection. Figure C-A-N9.4.3 shows the procedure for connection qualification. Both Figures C-A-N9.4.1 and C-A-N9.4.2 are also presented in the Guide as Figures 11-2 and 11-3, respectively. It should be noted that the connection available strength for each demand type should be calculated using the applicable FTM and the available strength of its contributing connectors.

In TR Section 7.4, the applicant presented the design methodology for a typical SC wall-to-basemat anchorage connection that can be designed as either full-strength or over-strength. Considering a full-strength connection, the adequacy of the connection is evaluated for individual demand types corresponding to 1.25 times the available strength of the SC wall and also checked for a combination of demands obtained from an FEA for different SC wall load combinations. The single base plate type connection, illustrated in Figure 11-4 of the Guide, consists of a base plate welded to the faceplates of the SC wall connected to the concrete infill by steel anchors and to the basemat by welded coupled bars. Figure 11-4 of the Guide illustrates the connection layout and typical connection detailing.

In Section 7.4.1 of the TR, the applicant presented a discussion of the FTM for individual demand types for the single base plate connection and stated along with Section 11.5.1 of the Guide that more than one FTM is possible for some demand types in which case the one with the largest connector design strength is the governing mechanism. For tensile force demand, the base plate weld is designed for 1.25 times the available tensile strength of the SC wall. The mechanism conservatively ignores force transfer through the steel anchors at the SC concrete infill base plate interface. The force in the base plate transfers to the concrete basemat by anchor rods welded to the base plate and embedded in the basemat concrete, as illustrated in

Figure 11-5 of the Guide. Compression force demand is transferred through bearing to the base plate and then transferred to the basemat and the limit states of bearing for the concrete and yielding for the base plate are checked for this FTM. Cantilever bending in the base plate due to the reaction from the basemat is also considered, as illustrated in Figure 11-6 of the Guide.

The in-plane shear strength demand in the SC wall is transferred to the base plate by the steel anchors. The demand is then transferred to the basemat by means of shear friction force between the base plate and the basemat as illustrated in Figure 11-7 of the Guide. Other FTMs can also be considered for transferring force from the base plate to the basemat for example, shear lugs or concrete bearing on rebar couplers. Out-of-plane shear demand is governed by the available shear strength of the steel anchors, and the friction force between the base plate and the basemat concrete as illustrated in Figure 11-8 of the Guide. Out-of-plane flexural demand can be considered as an equivalent force couple acting on the faceplates with the resulting tension and compression forces in the faceplates transferred to the basemat as illustrated in Figure 11-9 of the Guide. The split base plate SC wall-to-basemat connection and the rebar SC wall-to-basemat connection types are also illustrated in Figures 11-10 and 11-11 of the Guide. Other typical connection types such as the SC wall-to-wall joint connection and RC slab-to-SC wall joint connection are presented in TR Sections 7.5 and 7.6, respectively, and illustrated in Section 11.6 (Figure 11-14) and Section 11.7 (Figure 11.23) of the Guide.

In TR Section 7.5, the applicant presented a discussion of the SC wall-to-wall joint connection. The joint shears produced by the FTM for this connection type are presented in Figure 11-17 of the Guide for tensile demand, Figure 11-20 for out-of-plane shear demand, and Figure 11-22 for out-of-plane flexural demand that contributes to the joint shear strength for an SC wall-to-wall joint based on ACI 349-13. In TR Section 7.6, the applicant presented a discussion of the RC slab-to-wall joint connection. For a full-strength connection, the individual force demands are transferred from the RC slab-to the SC wall through the joint region by considering axial tensile (Figure 11-25), in-plane and out-of-plane shear (Figures 11-26 and 11-27), and out-of-plane flexure FTMs, as illustrated in Figures 11-25 - 11-28 of the Guide. As shown in Figure 11-28, the out-of-plane flexural demand leads to a joint shear demand for the connection, which is resisted by the concrete joint shear capacity determined using Section 21.7.4 of ACI 349-13.

The staff reviewed the design example presented in Appendix A to the Guide for a full-strength SC wall-to-basemat connection similar to that discussed in TR Section 7.4 that incorporates the use of a single base plate and designed in accordance with the provisions of Specification N690, Appendix N9.4 (2015), the previous version of Specification N690-18. According to the Guide, the example is taken from a typical safety-related nuclear facility and discusses all aspects of SC wall connection design including design philosophies for determining the required connection strength, use of permissible connectors, and FTMs. Representative design demands are considered for design of the SC wall, which does not include any attachments or openings, nor was impactive and impulsive loading considered. The example was based on a full-strength connection option and equations from Specification 360 and ACI 349 were used to calculate various conditions associated with the individual demands. The staff concluded that the connection design methodology presented in Section 7.0 of the TR, as illustrated in the Guide, embodies many of the concepts and methods discussed in Specifications N690-18 and 360-16, ACI 349, and consistent with current guidance in DSRS Section 3.8.4 and is acceptable.

Connection Available Strength

In TR Section 7.7 (Section 11.4 of the Guide), the applicant discussed connector available strength and the applicable FTM of the contributing connectors based on the requirements of Section N9.4.3 of Specification N690-18. Available shear strength of steel-headed anchors, tension strength of steel-headed stud anchors, and steel studs subjected to both shear and tension are discussed, along with shear friction load transfer mechanism, embedded shear lugs and shapes, and anchor rods discussed in ACI 349. In TR Sections 7.6 and 7.7, over 30 equations conforming primarily to the provisions of Appendix D to ACI 318-08 are presented to calculate connector available strength to adequately transfer the factored load demand.

In TR Section 7.8, the available strength for welded connectors is calculated using the applicable FTM and the available strength of the connectors in accordance with Chapter J, "Design of Connections," of Specification 360-16, specifically Chapter J2, "Welds," while TR Section 7.9 discusses bolts and threaded parts designed in accordance with Chapters J3.6 and J3.10 of Specification 360-16. In TR Sections 7.10 - 7.13, the applicant presented various equations for available strength for compression transfer via direct bearing on concrete in accordance with Specification 360-16; shear friction load transfer mechanism determined in accordance with ACI 349-13; embedded shear lugs and shapes determined in accordance with Sections D.10 and D.11 of ACI 349-13, Appendix D; available bearing strength for concrete against shear lugs; and cast-in anchor rods for combined tension and shear calculated in accordance with Sections D.4 – D.6 of ACI 349-13, Appendix D.

The staff review confirmed that the methodology presented in TR Section 7.0 is consistent with the provisions of ACI 349-13 and its appendices, as modified by the exceptions specified in RG 1.142, and the structural acceptance criteria in DSRS Section 3.8.4 for steel and concrete components for seismic Category I and II structures. The methodology is also consistent with the provisions of Specifications N690-18 and 360-16, endorsed by RG 1.243, and various SC wall connection illustrations presented in Chapter 11 of the Guide.

Based on the applicant's use of applicable regulatory guidance documents, codes, standards, and specifications consistent with DSRS Section 3.8.4, and the implementation of Specifications N690-18 and 360-16, and ACI-349, the staff concludes that the SC wall connection methodology presented for use in seismic Category I and II structures is acceptable.

4.5 Design Methodology for Seismic Category I and Category II Reinforced Concrete Structures

In Section 8.0 of the TR, the applicant presented a methodology for the design of seismic Category I and II concrete structures in accordance with the requirements of ACI 349-13 and guidance from RG 1.142. This methodology applies to the design of RC members of a representative SMR RXB, CRB, and RWB. The design methodology describes the building load path and design actions on the main structural members and the different required strengths for RC members including floor slabs, basemats, beams, and columns. The applicant presented a methodology for the design of seismic Category I and II RC structures according to the requirements of ACI 349-13 and certain requirements of RG 1.142. The format of ACI 349-13 is based on ACI 318-08 and primarily used in TR Sections 7.0 and 8.0 when referencing ACI 318-08 equations. The design methodology describes the building load path and design actions on the main structural members and describes the required strengths for RC members,

including guidelines to determine critical sections in structural components where section cuts are to be provided.

Section Cut-Based Methodology

The applicant summarized the methodologies of design and analysis of RC structures as either an element-based approach in which stress results are obtain per unit width, or a section cut-based approach in which stress results are obtained in a member cross section. The applicant referred to the 2008 paper, “Integrated Seismic Analysis and Design of Shear Wall Structures” (Reference 7.25), which summarizes both approaches in which the demand consists of forces and moments obtained at element cross sections, or section cuts at critical locations of structures. The paper concludes that RC walls and slabs designed as element grouping (section cuts) have significant savings in RC design compared to the element-based approach. The applicant concluded that the section cut-based approach is preferred over the use of the element-based approach because it yields more realistic design demands. The staff also confirmed the consistency of the section cut-based approach with that in Section 9.1.1 of ACI 349-13, which states, “Structures and structural members shall be designed to have design strengths at all sections at least equal to the required strengths…,” and is also consistent with the code-based equations for design capacities.

The staff requested the applicant to describe the implementation of the integrated design approach using soil structure interaction analysis and the ANSYS code. In Section 8.1 of TR, Revision 1, the applicant described the approach using ANSYS models and the process described in TR Section 4.0 to determine the section cut forces for both static and time history analyses of selected seismic events. The applicant simplified the process of the ANSYS models using the same finite element mesh for RC members as for seismic and static analyses. As described in TR Section 4.2.3, a harmonic analysis is conducted using the updated stiffness and damping values of the structural members to determine the section cut forces from the seismic loads and the DCR, as defined in TR Section 8.13, for each structural member to assess for the need for additional steel reinforcement. The static and seismic analyses design forces and moments are determined for the section cuts located along a row of nodes as described in TR Section 8.4.2. Then using the ANSYS postprocessor, the forces and moments are calculated by summing the nodal forces about a point at the center of gravity of the section cuts that can be in either horizontal or vertical directions. The final load combinations used for the design will be performed independent from ANSYS.

The TR describes the RC members as floor slabs, beams, columns, and basemats and provides guidelines for determining the critical locations of section cuts for design. The buildings are RC bearing wall-type with RC slabs at different elevations connected to RC walls. The main seismic load-resisting elements are SC shear walls and RC diaphragms consisting of floor and roof slabs with a gravity load-resisting system comprised of floor slabs, T-beams, SC walls, isolated RC columns, and foundation basemat.

Lateral and Gravity Load-Resisting Systems

The applicant described the lateral and gravity load-resisting structural systems using information presented in NIST References 7.18 and 7.26 that describe structural elements configured to support gravity and lateral loads as shown in TR Figure 8-1, “In-plane (diaphragm) and out-of-plane actions in floor slabs.” The structural elements essentially are configured to

resist the gravity and lateral loads comprised of vertical elements that extend between the foundation to the elevated floors (walls, columns) and horizontal elements (diaphragms, including chords and collectors) as defined in the TR.

The functions of the lateral and gravity load-resisting elements of the RC floor slabs and basemat are discussed in TR Section 8.3.1, T-beams in TR Section 8.3.2, and columns in TR Section 3.8.3 subjected to static, dynamic soil pressure and hydrostatic/hydrodynamic water pressures. The applicant considered the critical section locations as the minimum set. However, additional section locations could be evaluated to investigate the possibility of larger demands outside these critical locations. Reference is made to the requirements of ACI 349-13, Chapters 1-19, for conventional RC member design and Chapter 21 for earthquake resistant design. Figures are provided in the TR showing the critical section locations separately for horizontal (horizontal seismic) and vertical (gravity) demand types resulting from in/out-of-plane actions of rectangular structures of slabs, frames, and slabs with openings.

<u>Required Strengths for the Design of Slabs, Columns, and T-Beams</u>

The applicant described the design methodology to obtain the required strengths from the section cuts of FEA models in TR Section 8.4 and TR Figures 8-2 through 8-4 for slabs, columns, and T-beams modeled using selected beam and shell elements (for T-beams the required effective slab width is determined by the requirements in Section 8.12 of ACI 318-08). The methodology also meets the requirements of Section 9.1.1 of ACI 349-13 The staff concluded that the design methodology is acceptable since it follows conventional engineering principles for selecting beam and shell elements from the FEA models and consistent with the acceptance criteria in Section II.4.A of DSRS Section 3.8.4. In TR Section 8.5, the applicant described how to determine the required strengths from the six types of demand components (axial force, in-plane and out-of-plane shear forces and bending moments, and torsional moment) with their interactions for the designs of slabs and basemats. In TR Sections 8.5.1 through 8.5.3, guidelines are provided to determine critical section cut locations where the largest demand is expected to account for axial force-moment (P-M) and axial force-shear (P-V) interactions in slabs and basemats subjected to vertical and lateral loading for a simple, four-edge, fixed rectangular structure. Information from the NIST references was used to describe integral components of chords and collectors and their ability to transfer gravity and seismic forces. The in-plane axial forces and out-of-plane moments are calculated to evaluate these section cuts considering P-M and/or P-V interactions. The following are examples of selected section cut locations:

- For out-of-plane forces (gravity) in TR Section 8.5.1, Figures 8-6 and 8-7 show out-of-plane moment at the center of the slab and at each slab-wall interface, and out-of-plane shear at the center at each slab-wall interface.

- For in-plane (diaphragm) forces (seismic forces), in TR Section 8.5.2, Figures 8-12 and 8-13 show chord forces at the mid-span and at the diaphragm edges in the seismic force direction, and at the mid-span and in-plane shear at the diaphragm edges in the seismic force direction.

- Section cut locations for openings at the middle of slabs, subject to gravity load and seismic forces, are shown in TR Figures 8-17 and 8-18. The applicant identified two types of chord forces, primary and secondary, as shown in TR Figure 8-16. Primary

chord forces result from in-plane bending of the slab as a whole while secondary chord forces result from in-plane bending of the diaphragm segments above and below the opening.

- Critical section locations at the ends of walls imposed by out-of-plane forces in basemats due to wall rocking (equilibrated by out-of-plane moment and out-of-plane shear) to the basemats are presented that describe the critical sections for one and two-way punching shear. The applicant considered this configuration as a general case of a T-shaped wall as shown in TR Figure 8-9 at the wall end subjected to two-way shear, and one-way shear at either side of the wall consistent with Sections 11.1.3.1 and 11.11.1.2 of ACI 318-08. Based on NIST recommendations in Reference 7.26, the applicant described the section cut locations for out-of-plane bending due to wall overturning shown in TR Figure 8-10. The critical section locations and their lengths can be determined based on the FEA stress resultants, which for this case are not limited to three times the member thickness.

The staff requested the applicant to describe the basis for how to determine the most appropriate section cut length. In Section 8.1 of TR Revision, the applicant described that the section cut lengths are determined through FEA stress resultants but generally need not be less than three times the member thickness unless the stress resultant changes sign along the section cut or it is limited by wall openings. The applicant did not consider three times the thickness as a fixed value but instead, it is used to average design loads to avoid unrealistic excessive conservatism. In all cases the design engineer needs to justify the use of this value or other averaging lengths. The FEA stress results are also used as described in TR Section 8.5.4 to determine the minimum set of critical locations as required. However, additional section locations could be evaluated to investigate the possibility of larger demands outside these critical locations. The section cuts determined from the FEA stress results are additional cuts as defined in TR Sections 8.5.1 through 8.5.3 and used for the evaluation of out-of-plane moments/shear demands. Basically, section cuts are determined from stress contour plots from each demand type (in-plane shear, chord force/collector forces, out-of-plane moment, and out-of-plane shear) for corresponding combined FEA stress results in the local coordinate system as shown in TR Figure 8-19.

The required strengths for T-beam and column designs are discussed in TR Sections 8.7 and 8.8. The T-beam design force resultants are bending and shear (M3 and V2 in the strong-axis) and axial load (P) and their interaction with moment and shear forces (P-M and P-V) in the designs for T-beams and columns be considered. The column force resultants are bending moments (M2 and M3), axial force (P), shear forces (V2 and V3), and the (P-M) interaction in orthogonal directions. The staff considered the applicant's description of force resultants and their interactions for the required strength for T-beam and column designs acceptable based on conventional engineering design principles. In TR Section 8.8, the applicant described an approach for determining the DCRs for P-M demand for the load combinations involving seismic loads for the full duration of time history and added nonseismic loads for the members, which the staff considered acceptable.

<u>Design Requirements for Reinforced Concrete Structures</u>

The applicant followed the general requirements and equations of ACI 349-13 and the applicable sections in ACI 318-08 associated with load combinations, basic design

requirements, member capacities, reinforcement requirements of the RC section cut of the members from slabs, T-beams, columns, basemats, and collector capacities presented in TR Sections 8.9 - 8.11 and 8.14. The calculation of DCR, described in TR Section 8.12, is performed to determine the acceptable design levels of members by assuring the ratio is less than 1.0. For the axial-bending (P-M) interaction capacity, the applicant described the process of calculating, by scaling, the total (P-M) demand to the capacity curve, as shown in TR Figure 8-24. The DCR for each structural member for load combinations involving seismic loads is determined as discussed in TR Section 4.2.3 and reinforcement may be added to a structural member based on implementation of the iterative design process until the member capacities exceed the demand. The staff reviewed the information in the TR related to load combinations, design requirements, member capacities, and total reinforcement requirements for RC section cuts and determined that the information was consistent with ACI 349-13, ACI 318-08 and the acceptance criteria in DSRS Section 3.8.4.

The design methodology presented by the applicant in TR Section 8.0 conformed to conventional engineering principles for identifying section cuts and lengths from geometric configurations, as described in several recognized NIST publications, considered load combinations and design requirements for steel reinforcement for RC members in accordance with the applicable sections of the ACI codes, and demonstrated consistency with the acceptance criteria in DSRS Section 3.8.4. The staff considered the applicant's approach acceptable.

5.0 STAFF CONCLUSIONS

The staff has completed its review of the methodologies in TR Revision 1 and conclude that subject to the limitations and conditions specified in Section 6.0 of this SE, the design and analysis methodologies presented are acceptable to perform building design and analysis for seismic Category I and II nuclear safety-related RC and SC structures other than containment. The methodologies presented were in compliance with the conservative implementation of the requirements of Specifications N690-18, Appendix N9, and 360-16, recently endorsed by RG 1.243, and consistent with the structural acceptance criteria in NRC NuScale DSRS Sections 3.8.4 and 3.7.2, and the applicable regulatory requirements in Section 2.0 of this SE. DSRS Section 3.8.4 provides guidance regarding basic specifications for concrete and steel structures in compliance with NRC regulations and cites certain RGs and industry consensus codes and standards, specifically ACI 349-13, endorsed by RG 1.142, that are acceptable to the staff.

These guides, specifications, and industry consensus codes and standards impose specific restrictions to ensure that SSCs will perform their intended safety function. Meeting these requirements and criteria provides added assurance that the SSCs described herein will perform their safety function. Additionally, the implementation examples provided in TR Section 4.2 further demonstrate the appropriateness of the methodology related to modeling the effective stiffness for RC and SC walls and slabs subjected to seismic events. The staff's conclusions for specific topics are found within the respective technical evaluations in Section 4.0 of this SE.

6.0 LIMITATIONS AND CONDITIONS

The staff's approval of this TR is limited to the proposed analysis methodology applied to problems that satisfy the assumptions implicitly taken in the subject TR, specifically that: (1) all material properties are considered linear elastic, and (2) all materials perform linear elastically during seismic events. Nonlinear response such as liquefaction of the subgrade or significant cracking of the structural components is outside the scope of the TR approval. A licensee or applicant who applies the methodologies approved in this SE to a site-specific application must consider the applicability of these limitations and conditions to the specific site conditions. The NRC staff will verify that each of these limitations and conditions has been satisfied in its review of a site-specific application.

7.0 REFERENCES

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