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GE-Hitachi Nuclear Energy

Proprietary Notice

This letter transmits proprietary information in accordance with 10 CFR 2.390. Upon the removal of Enclosure 1, the balance of the letter may be considered non-proprietary.

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M240080
April 18, 2024

Canadian Nuclear Safety Commission
280 Slater Street
P.O. Box 1046, Station B
Ottawa, Ontario, K1P 5S9, Canada

Subject: NEDC-33926P/NEDO-33926, Revision 2, BWRX-300 Steel-Plate Composite Containment Vessel (SCCV) and Reactor Building (RB) Structural Design

References:

1. Email from Jordan Glisan (US NRC) to Suzanne Karkour (GEH), “RE: GE Hitachi Request for Additional Information (RAI-10121-R1) for Topical Report NEDC 33926P,” January 26, 2024.
2. GEH Letter M230114, “NEDC 33926P/NEDO 33926, Revision 1, BWRX 300 Steel-Plate Composite Containment Vessel (SCCV) and Reactor Building (RB) Structural Design,” August 18, 2023.

Enclosed is Revision 2 of the referenced GE-Hitachi Nuclear Energy Americas, LLC (GEH) Licensing Topical Report (LTR) describing the approach and methodology for structural design Steel-Plate Composite (SC) modules with diaphragm plates for the integrated Reactor Building (RB) housing the Steel-Plate Composite Containment Vessel (SCCV) and Reactor Building (RB) and containment internal structures. This revision includes technical and licensing updates in response to Reference 1 Nuclear Regulatory Commission (NRC) Request for Additional Information No. 018 (RAI-10121-R1) and audit observations related to the NRC and CNSC review of the GE-Hitachi Nuclear Energy Americas, LLC (GEH) Licensing Topical Report (LTR) NEDC-33926P/NEDO-33926, Revision 1, submitted in Reference 2.

A similar correspondence has been transmitted to the U.S. Nuclear Regulatory Commission (USNRC) in support of the Memorandum of Collaboration between CNSC and USNRC on performance of joint reviews of the BWRX-300 Small Modular Reactor (SMR) design.

Enclosure 1 contains proprietary information of the type that GEH maintains in confidence and withholds from public disclosure. The affidavit contained within Enclosure 3 identifies that the information contained in Enclosure 1 has been handled and classified as proprietary to GEH. GEH hereby requests that the information in Enclosure 1 be withheld from public disclosure in accordance with the provisions of Access to Information Act (R.S.C., 1985, C. A-1). Enclosure 2 is a non-proprietary version of Enclosure 1.

If you have any questions, please contact me at 289-385-1935.

Sincerely,

S. Karke

Suzanne Karkour
Manager, Canadian Product Regulatory Affairs
GEH SMR Canada

Enclosures:

1. NEDC-33926P, Revision 2, BWRX-300 Steel-Plate Composite Containment Vessel (SCCV) and Reactor Building (RB) Structural Design – Proprietary Information
2. NEDO-33926, Revision 2 BWRX-300 Steel-Plate Composite Containment Vessel (SCCV) and Reactor Building (RB) Structural Design – Non-Proprietary Information
3. Affidavit

cc: Sarah Eaton, CNSC
Bartek Rzentkowski, CNSC
Monica Hornof, CNSC
George Stoyanov, CNSC
Cedric Androuet, CNSC
Matthew Naraine, CNSC
Doug Miller, CNSC
PLM Specification 008N5378 Revision 0

Document Components:
001 M240080 Cover Letter.pdf
002 M240080 Enclosure 1 Proprietary.pdf
003 M240080 Enclosure 2 Non-Proprietary.pdf
004 M240080 Enclosure 3 Affidavit.pdf

ENCLOSURE 1

M240080

NEDC-33926P, Revision 2, BWRX-300 Steel-Plate Composite Containment Vessel (SCCV) and Reactor Building (RB) Structural Design – Proprietary Information

GEH Proprietary Information – Non-Public

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GE Hitachi Nuclear Energy

NEDC-33926P
Revision 2
April 2024

GEH Proprietary Information – Non-Public

Licensing Topical Report

BWRX-300 Steel-Plate Composite (SC) Containment Vessel (SCCV) and Reactor Building Structural Design

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This document contains confidential and proprietary information of GE-Hitachi Nuclear Energy Americas, LLC (GEH), customers, and other third parties, and is furnished in confidence solely for the purpose of obtaining Nuclear Regulatory Commission (NRC) review and determination of acceptability for use for the BWRX-300 design and licensing basis information contained herein, and for facilitating collaborative review by the NRC and Canadian Nuclear Safety Commission (CNSC). No other use, direct or indirect, of the document or the information it contains is authorized. Disclosure of this information may: violate export control laws and regulations of the United States or Canada; disclose scientific, technical or other information (including advice or recommendation for a government institution) provided in confidence by GEH, customers, or other third parties; facilitate the commission of an offence in relation to the security of critical structures or systems; threaten the safety of individuals; and/or result in material financial loss or contractual interference for a third party.

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IMPORTANT NOTICE REGARDING CONTENTS OF THIS REPORT

Please Read Carefully

The design, engineering, and other information contained in this document is furnished for the purpose of obtaining NRC review and determination of acceptability for use for the BWRX-300 design and licensing basis information contained herein, and for facilitating collaborative review by the NRC and CNSC. The only undertakings of GEH with respect to information in this document are contained in the contracts between GEH and its customers or participating utilities, and nothing contained in this document shall be construed as changing those contracts. The use of this information by anyone for any purpose other than that for which it is intended is not authorized; and with respect to any unauthorized use, no representation or warranty is provided, nor any assumption of liability is to be inferred as to the completeness, accuracy, or usefulness of the information contained in this document. Furnishing this document does not convey any license, express or implied, to use any patented invention or, except as specified above, any proprietary information of GEH, its customers or other third parties disclosed herein or any right to publish the document without prior written permission of GEH, its customers or other third parties.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

REVISION SUMMARY

Revision Number	Description of Change
0	Initial Issue
1	Updated to reclassify selected content as non-proprietary including Figures 3-1, 3-2, and 3-4; Sections 5.18 and 6.22; and Table 6-1.
2	• Revised to incorporate the following response to NRC Requests for Additional Information No. 018 (RAI-10121-R1):NRC RAI 2.1.2-1 (Question 1) deleted Subsection 2.1.2 since the 10 CFR 100.21 requirements are outside the scope of this report and added Subsection 2.2.7 to address conformance to the regulatory guidance of NUREG-0800, SRP 19.0. • NRC RAI 5.3-1 (Question 2) revised Section 5.3 to clarify that steel headed studs contribute to the composite action of Diaphragm Plate Steel-Plate Composite (DP-SC) modules, to provide the methodology used to quantify the contribution of diaphragm plates and steel headed studs to the DP-SC composite actions, and to provide the design and detailing requirements for the steel headed studs. Subsection 5.3.1 is added to provide methodology used to determine shear connectors capacity. Section 5.4 and Subsection 5.7.5.2 are revised to capture the changes in Section 5.3. Subsection 5.7.6 is revised to provide the methodology for evaluating the interaction of the idealized diaphragm plates under out-of-plane and interfacial shear stresses. • NRC RAI 5.4-1 (Question 3) revised Section 5.4 by deleting the statement “Tie plates or bars may be added for additional stiffness and strength.” • NRC RAI 5.5.1-1 (Question 4) revised Subsections 5.5.1 and 6.5.1 to provide clarity on the BWRX-300 methodology and modeling approach for heat transfer analysis. • NRC RAI 5.7.2-1 (Question 5) revised Subsection 5.7.2 to clarify the applicability of Equation [5-19] (previously Equation [5-16]) to temperature limits and temperature-dependent properties listed on Subsections 5.2.1 and 5.2.2. • NRC RAI 5.8-1 (Question 6) revised Table 5-1 and Table 5-3, footnote 1 included, to remove non-Steel-plate Composite (non-SC) or DP-SC materials that are outside the scope of this report. • NRC RAI 5.8-1 (Question 6) revised Subsection 5.8.1.3 and Table 5-2, footnotes included, to provide clarity on levels of damage and deformation limits for normal and severe environmental load combinations, and for abnormal and extreme environmental load combinations; and to provide acceptance criteria for SC slabs and SC walls, including DP-SC.

	• NRC RAI 5.8-1 (Question 6) revised Subsection 5.8.3 by adding bullet #4 to address conformance to Regulatory Position C11.1.8.3 of U.S. NRC RG 1.243. • NRC RAI 5.18-1 (Question 7) revised Section 5.18 to describe the plan for identifying and developing measured baseline data to facilitate the evaluation, monitoring and trending of applicable aging effects for DP-SC modules. Proposed changes to Section 5.18 in response to audit observations #16, 68 and 69 are superseded by the response to RAI 5.18-1 (Question 7). • NRC RAI 6.2-1 (Question 8) revised Section 6.2 to clarify that materials used in the SCCV DP-SC modules meet the general requirements of ASME BPVC, Section III, Division 2, Subarticle CC-2000 as applicable to DP-SC modules without reinforcing steel or prestressing tendons. • NRC RAI 6.2-1 (Question 8) revised Subsection 6.2.4 to clarify the specific SCCV load bearing steel materials this section applies to. • NRC RAI 6.13-1 (Question 9) revised Subsection 2.1.1.14 to point to Sections 6.2 and 6.15 for the SCCV quality control and quality assurance requirements, and Sections 6.13, 6.14, 6.15 and 6.16 to provide a figure equivalent to Figure CC-3831-1 of ASME Section III, Division 2 that is representative of SCCV DP-SC welded joints to clarify the DP-SC permitted welded joint types and welding examination requirements. • NRC RAI 6.22-1 (Question 10) revised Section 6.22 to provide the characterization of the SCCV components for the purposes of inservice inspection in accordance with 10 CFR 50.55a(g)(4). • NRC RAI 7.2-1 (Question 11) revised Subsections 7.2.1.1, 7.2.2.2, 7.2.2.5, 7.2.3.5, 7.2.4.5, 7.2.5.1, 7.2.5.2, 7.2.5.5, 7.3, 7.3.1.1, 7.3.1.2, 7.3.2.1, 7.3.2.2, 7.3.2.3, 7.3.3.1, 7.3.3.2, 7.3.4.1, 7.3.4.2 and the last paragraph of Section 8.0 to refer to the revised acceptance criterion and nominal strength consistent with code terminology and added Table 7-2 to provide a summary of the NRIC Prototype test results. Revised to incorporate the following responses to NRC audit observations: • Audit observation #3 revised Sections 5.1, 5.3, 5.7.1, 5.7.2, 5.11, 5.13, 5.13.1.2, 5.13.2.1, 5.18, 6.11, 6.14, 7.2.4.5 and 7.2.5.5 to specify the edition of the ANSI/AISC 360 referenced, deleted the reference to ANSI/AISC 360 related to Equation [5-19] (previously Equation [5-16]) and deleted the first paragraph of Section 5.4. • Audit observation #3 revised Sections 5.18 and 9.0 to replace NUREG-1801 with NUREG-2191.

	• Audit observation #3 revised Section 9.0 to update the revisions of U.S. NRC RG 1 136, U.S. NRC RG 1.26 and NUREG-0800, SRP 3.8.3 to the latest and to list the 2016 edition of ANSI/AISC 360. • Audit observation #4 revised Subsection 2.1.1.5 to clarify how the design will meet the requirements of 10 CFR 50.150. • Audit observation #5 revised Subsection 2.1.1 to specify that the design will meet the requirements of the regulations and guidance discussed in the section. • Audit observation #6 revised Subsection 2.1.1.15 (previously Subsection 2.1.1.14) to demonstrate compliance with regulations for Type B and Type C local leak rate tests. • Audit observation #7 revised Subsection 2.1.1.16 (previously Subsection 2.1.1.15) to demonstrate how the Operational Basis Earthquake (OBE) requirements in "10 CFR Part 50, Appendix S" for plant shutdown and load combinations are met. • Audit observation #8 revised Subsections 2.2.2, 2.2.3 and Section 6.1 to clarify that the SCCV is designed, fabricated, constructed, inspected, examined and tested to applicable portions of ASME BPVC, Section III, Division 2 requirements along with the modified requirements outlined in Section 6.0 of this report. • Audit observation #9 revised Subsection 2.3.6 and Section 9.0 to clarify that the DP-SC damping values are based on values provided for SC walls in Tables 1 and 2 of U.S. NRC RG 1.61, Revision 2. • Audit observation #10 revised Section 5.5 to specify that analysis for load combinations involving accident thermal conditions will include heat transfer analysis, deleted the last paragraph in Section 5.5 and added Subsection 5.5.1 to discuss methodology used for performing the heat transfer analysis. Section 5.5.1 was later updated per RAI 5.5.1-1 (Question 4). • Audit observation #11 revised Section 4.0 to clarify the code jurisdictional boundary for the Reactor Building (RB) walls and floors connections. • Audit observation #13 revised Subsection 7.2.1.1 to add a paragraph on GEH's Quality Assurance (QA) program that was implemented during the NRIC testing program and used to review and accept test results. • Audit observation #14 revised Section 3.4 to describe the curved assemblies of DP-SC modules, and Section 6.18 to specify the requirements for faceplates rolling and bending. • Audit observation #16 revised Section 5.18 to add a discussion on the failure mode effect analysis that will be performed to identify

	aging and degradation mechanisms, inspection processes and proposed repair methods for DP-SC modules. • Audit observation #20 revised Section 5.18 to add a discussion on the failure mode effect analysis that will be performed to identify aging and degradation mechanisms, inspection processes and proposed repair methods for DP-SC modules. • Audit observation #21 revised Section 5.18 to provide acceptable techniques for inservice inspection and testing of DP-SC modules. • Audit observation #22 revised the first two bullets of Section 1.1 to clarify that the purpose of this report is to seek regulatory approval for the use of DP-SC structural elements for the construction of the integrated RB. • Audit observation #23 revised Subsection 2.1.1 to provide a statement of compliance to 10 CFR 50 Appendix A, General Design Criterion (GDC) 52 in Subsection 2.1.1.12, revised Subsection 2.1.1.15 (previously Subsection 2.1.1.14) to specify the applicable GDCs, including GDC 52, met by the containment provisions for periodic integrated leakage rate testing and listed U.S. NRC RG 1.163 as a reference in Section 9.0. • Audit observation #24 revised Subsections 2.1.1.5, 2.1.1.8 and 2.2.8 (previously Subsection 2.2.7) to remove all references to site-specific aircraft impact assessments. • Audit observation #25 revised Subsection 2.1.1.3 by deleting the statements of compliance to 10 CFR 50.55a(f) and 10 CFR 50.55a(g) requirements not applicable to the scope of this report. • Audit observation #25 revised Subsection 2.1.1.15 (previously Subsection 2.1.1.14) by deleting the reference to Section 6.17. • Audit observation #25 revised Section 4.4 by specifying the edition of ASME BPVC Section XI to be followed for the containment pre-service and periodic inservice inspection and testing program. • Audit observation #25 revised Section 9.0 by updating Reference 9-1 to be specific to ASME Section III, Division 2, 2021 Edition and deleting the U.S. NRC RG 1.192 and RG 1.147 references not applicable to the scope of this report. • Audit observation #26 revised Section 4.3 to (1) clarify the design philosophy used for the RB DP-SC design provisions (2) to confirm that external pressure loads resulting from pressure variation inside or outside the containment (P_v) are considered under the normal operating pressure load (P_o) (3) to replace "MSLB" by "LOCA" (4) to update "Seismic Loads (E)" to "Seismic Loads (Es)" (5) to add a paragraph on OBE Seismic loads (E_o) (6) to clarify local load effects considered for the containment (7) to clarify why loads resulting from relief valve or other high

	energy device actuation and prestress loads are not applicable for the containment. • Audit observation #26 revised Section 9.0 by listing ANSI/ANS-2.23 as a reference. • Audit observation #28 revised Section 6.22 to provide clarity on the SCCV components that will be examined in accordance with Subsection IWE. The audit observation revision of Section 6.22 is superseded by the response to RAI 6.22-1 (Question 10). • Audit observation #29 revised Sections 3.4 and 5.1 to specify that DP-SC faceplates and diaphragm plates can have different thicknesses, clarified the parameters listed in Section 3.4 and updated Figure 5-1. • Audit observation #30 revised Section 5.1 to clarify the basis for the BWRX-300 DP-SC thickness limitations. • Audit observation #31 revised Section 5.1 to specify that the minimum reinforcement ratio for DP-SC modules is per ANSI/AISC N690, Section N9.1.1.(c). • Audit observation #31 revised Section 5.2.1 to (1) delete the concrete compressive strength statement from the first paragraph, (2) to specify that self-consolidating concrete is used in the integrated RB DP-SC modules and (3) that the self-consolidating concrete compressive strength is a function of reinforcement ratio per draft ANSI/AISC N690-XX added as Reference 9-59 in Section 9.0 in the absence of the published version. • Audit observation #32 revised Section 5.3 to indicate that steel headed stud anchors will not be used in accessible tight locations and to provide clarity on how the stud anchors diameter, height and spacing are determined, and Section 6.1 to indicate that stud anchors may not always be needed. These changes were overridden by the response to RAI 5.3-1 (Question 2). • Audit observation #33 revised Subsections 5.2.1 and 6.2.1 to indicate that self-consolidated concrete is used in the integrated RB DPSC modules, and Subsection 7.2.1.1 to clarify that self-consolidating concrete was used as concrete infill in the NRIC Phase I testing specimens. • Audit observation #34 revised Subsection 5.7.2 to correct the compressive strength resistance factor from 0.9 to 0.75. • Audit observation #38 revised Section 5.6 by deleting the last paragraph, and Section 9.0 by deleting the Revision 1 Reference 9-57 related to Sarraj's alternative component model. • Audit observation #39 revised Subsection 5.7.5.1 to correct the equation in the first bullet to "Equation (a) in Table 22.5.5.1," and to add "W_{sc} in Figure 5-1" in the (a) statement.

	• Audit observation #40 revised Subsection 5.7.5.2 to clarify that V_{conc} is calculated using Equations [5-26] and [5-27] (previously Equations [5-23] and [5-24]). • Audit observation #42 revised Subsection 5.7.5.1 to clarify how the nominal tensile strength of diaphragm segments between diaphragm openings are determined. • Audit observation #43 revised Table 5-2 to clarify the damage level or ductility criteria that will be used to determine design adequacy for the stated load cases where the structures are allowed to have permanent, plastic deformations. Changes to Table 5-2 and associated footnotes were superseded by the response to RAI 5.8-1 (Question 6). • Audit observation #44 revised the first bullet in Subsection 5.8.1.3 to clarify how the reference to ACI 349.4R will be replaced with U.S. NRC RG 1.243, CNSC REGDOC-2.5.2, Version 1, and International Atomic Energy Agency (IAEA) Safety Reports Series No 87. First bullet was later updated per response to RAI 5.8-1 (Question 6). • Audit observation #45 revised the second paragraph in Subsection 5.8.2.2 to identify the basis for the definition of local areas for missile impact and to clarify the units for 5√(tsc). • Audit observation #46 revised Subsection 5.8.2.2.1 to add Section 7.4.4 in the first paragraph, to define the parameters t_c and V_r , to correct Equations [5-43] and [5-48] (previously Equations [5-41] and [5-46]), to clarify the unit for $x_{c.sc}$, ρ_c , $V_{p.conc}$ and F_y, to add Equation [5-47] and to provide the basis for the parameters "K", m_t , σ_s and Equations [5-35] to [5-48] (previously Equations [5-33] to [5-46]). • Audit observation #49 revised Section 5.11 to clarify the definition of A_v in Equation [5-49] (previously Equation [5-47]), to provide an illustrative figure (Figure 5-10) of SC connections to which Equation [5-49] is intended to be applied and to clarify the applicability of Equation [5-49] to compressive axial loads. • Audit observation #50 revised Section 5.13 and Subsections 5.13.1.1 and 5.13.2 to remove all references to ANSI/UL 263 and to add the criteria for identifying the fire rating of DP-SC components. • Audit observation #51 revised Section 5.13 to address the modifications stated in Appendix N4 of ANSI/AISC N690 and to define the parameter "L" in Equations [5-51] and [5-52] (previously Equations [5-48] and [5-49]). • Audit observation #52 removed the proprietary designation from Sections 5.16 and 6.4.

	• Audit observation #53 revised Section 5.16 by adding a paragraph at the end of the section to clarify how potential locked-in stresses in the faceplates and diaphragm plates from initial imperfections and hydrostatic pressure exerted by the concrete pour during construction are accounted for in the design. • Audit observation #54 revised Section 5.1 to clarify the maximum allowable plate thickness for DP-SC modules and Subsection 5.2.1 to include the requirements from second public review draft of ANSI/AISC N690 (dated October 9, 2023), Section N9.1.1(e) related to compressive strength of concrete. • Audit observation #55 revised Subsection 5.2.1 to clarify the concrete temperature limitations for normal operational and accidental conditions, Subsection 5.2.2 to clarify how the effect of elevated temperatures on mechanical properties of steel materials of DP-SC modules is determined, Subsection 5.13.1.1 to point to Section 5.2 of the report in the third paragraph, and to Section 4.2 for how material properties are defined. • Audit observation #58 revised the last bullet in Section 6.2.1 to indicate that the word “concrete” in Table CC-2231.7.1-1 is to be replaced by “DP-SC concrete infill”. • Audit observation #59 revised Subsection 6.2.2 to remove the word “hollow”. • Audit observation #60 revised Section 6.5 to clarify that the loading criteria provisions are supplemented by U.S. NRC RG 1.136 and to remove the proprietary designation. • Audit observation #61 revised Tables 6-1(a) and 6-1(b) to include footnote (1) against the “Primary + Secondary” force classification for Steel Plates, Table 6-1(a) footnotes (1)-(4) and the first paragraph of Subsection 6.7.3 to clarify that the DP-SC concrete tensile strength is not relied upon to resist flexural and membrane tension. • Audit observation #62 revised the T_{sc} parameter in Subsection 6.7.1 to t_{sc} for consistency with other sections. • Audit observation #63 revised Subsection 6.7.2 to replace steel plates with steel faceplates and to point to the allowable stresses for service loads summarized in Table 6-2. • Audit observation #64 revised Subsection 6.7.3 to provide the equation for σ_{c2} for case (c). • Audit observation #65 revised Subsection 6.7.1 to define the DP-SC notional halves, to clarify that positive principal stresses are tensile and negative principal stresses are compressive and to update Equation [6-1] membrane force and bending moment parameters.

	• Audit observation #65 revised Subsections 6.7.2 and 6.7.3 to point to the allowable stresses for service loads summarized in Table 6-2. • Audit observation #66 revised Section 6.7 to clarify how the in-plane membrane forces and out-of-plane moments interaction and the out-of-plane shear of containment DP-SC members are calculated. • Audit observation #66 deleted Subsections 6.8.1 to 6.8.3and 6.8.5 related to the uniaxial tensile, compressive, flexural and tangential shear strength and revised Section 6.8 to specify that these parameters are evaluated using the procedure in Section 6.7 and the allowables provided in Section 6.6. • Audit observation #66 revised the number of Subsection 6.8.4 to 6.8.1 and added Subsections 6.8.1.1 and 6.8.1.2 to define the allowable stresses for factored loads and service loads, respectively, for one-way out-of-plane shear strength. • Audit observation #66 revised the number of Subsection 6.8.6 to 6.8.2 and added Subsections 6.8.2.1 and 6.8.2.2 to define the allowable stresses for factored loads and service loads, respectively, for punching shear. • Audit observation #66 revised the number of Section 6.9 to Subsection 6.8.3 and added Subsections 6.8.3.1 and 6.8.3.2 to discuss the out-of-plane shear interaction for factored loads and service loads, respectively. • Audit observation #66 added a new Section 6.9 to discuss the allowable bearing stress of containment steel-plate composite elements. • Audit observation #67 revised the first paragraph in Section 6.15 to replace “with the exception reported” with “in addition to the Regulatory Guidance of Position 10 reported” and to correct U.S. NRC RG 1.36 to RG 1.136. • Audit observation #68 revised the last but one paragraph of Section 6.17 to add a reference to ASME Section III, Paragraphs CC-6160 and CC-6510 and to clarify that the BWRX-300’s first unit will be treated as a prototype containment as per Paragraph CC-6150 definition. • Audit observation #69 changes to Section 6.22 are superseded by the response to RAI 6.22-1 (Question 10). • Audit observation #70 removed the proprietary designation of Section 6.23 and revised the section to specify GDC 50. • Audit observation #71 revised the last paragraph of Subsection 5.7.5.1, and Subsections 7.2.1.1, 7.2.2.2, 7.2.2.5, 7.2.3.5, 7.2.4.5, 7.2.5.5, 7.3.1.1, 7.3.1.2, 7.3.2.1, 7.3.2.2, 7.3.2.3, 7.3.3.1, 7.3.3.2,

	7.3.4.1, 7.3.4.2, and Section 8.0 to clarify that experimental strength are compared to the calculated nominal strength. • Audit observation #75 revised the second bullet of Section 1.1 to add a reference to Section 5.0. • Audit observation #76 revised Section 4.3 to define "Seismic Loads (Es)" as "SSE or DBE Seismic Loads (Es)." • Audit observation #77 revised the publication date of U.S. NRC RG 1.136 to February 2021, the referencing of ANSI/AISC N690-XX and the title of the M230099 Enclosure 2 in Section 9.0. • Audit observation #78 removed the proprietary designation of the following Sections and Subsections: 5.6, 5.7.3.1, 5.7.4, 5.7.5.3, 5.7.6, 5.10, 5.12, 6.3, 6.8, 6.8.1.1, 6.8.1.2, 6.8.2.1, 6.8.2.2, 6.8.3.1, 6.8.3.2, 6.9.1.1, 6.9.1.2, 6.15, 6.16, 6.17, 6.18 and 6.23.3. Revised to incorporate the following responses to NRC requests for additional information to support NRC acceptance review of the report, M230099, Enclosure 1: • Item #1 added the NRIC Prototype Test Report as a reference in Sections 7.3 and 9.0. • Item #3 revised Bullet (A) in Section 3.4, added the last two paragraphs in Section 3.4 and revised Figures 3-5 and 3-6 (previously Figures 3-6 and 3-7) to provide clarity on the different configurations and composite action of DP-SC modules. • Item #3 added a paragraph in Section 4.0 to discuss connections and attachment welds of DP-SC modules. • Item 4 removed the reference to ACI 349.4R and added a reference to U.S. NRC RG 1.243, REGDOC-2.5.2 and IAEA Safety Reports Series No, 87 in Subsection 5.8.1.3 and Section 9.0, and specified a design strain acceptance criterion of 0.35% for concrete compression in footnote (4) of Table 5-2. Revised to incorporate the following licensing and technical updates: • Acronyms and Acronym Table are updated. • Sections 1.1 and 1.2 are revised to clarify the intent of this report. • The statements of compliance in Subsections 2.1.1.1, 2.1.1.3, 2.1.1.4, 2.1.1.6, 2.1.1.9, 2.1.1.11, 2.1.1.14 and 2.1.1.16 are updated to provide more clarity. • The statements of conformance in Subsections 2.2.4, 2.2.5, 2.3.2, 2.3.3, 2.3.5, 2.3.7, 2.3.8, 2.3.9, 2.3.10, 2.3.11 and 2.3.12 are updated to provide more clarity. • Conformance to U.S. NRC RG 1.54 is discussed in newly added Subsection 2.3.4.

	• The statement of compliance in Subsection 2.4.2 and the statements of compliance to REGDOC-2.5.2, Sections 7.12.1 and 8.6, in Subsection 2.4.3 are updated to provide more clarity. • The statement of compliance to REGDOC-2.6.3, Section 4.3, in Subsection 2.4.4 is updated to provide more clarity. • Subsections 2.5.1 to 2.5.3 are updated to provide more clarity on how CSA N291, CSA N287 and CSA N289 requirements are met. • Subsections 2.5.4 to 2.5.6 are added to discuss compliance with CSA N293, CSA N286 and CSA N299. • Figure 3-1 and Figure 3-2 are updated to reflect latest Power Block layout and structures. • The integrated RB structures overview in Section 3.3 is updated. • Figure 3-3 and Figure 3-4 are updated to identify the DP-SC components of the integrated RB. • Figure 3-5 is deleted. • Fourth paragraph in Section 3.4 is revised to align with updated Section 5.4. • Sections 4.0 and 4.2 are updated to provide more clarity on the BWRX-300 overall analysis, design and modeling approach. • The last but one paragraph of Section 4.4 is updated to clarify the ASME code edition considered. • The last paragraph of Section 4.4 is moved to Subsections 2.1.1.14 and 2.5.5. • Equation [5-14] (previously Equation [5-11]) is updated. • Figure 5-4 and Figure 5-5 are updated. • Equation [5-15] (previously Equation [5-12]) and associated parameters are updated. • Parameters of Equation [5-23] (previously Equation [5-20]) are updated. • The concrete compressive strength units in Subsection 5.7.5.1 are updated. • The first paragraph of Sections 5.9, 5.17 and 5.18 are updated. • Section 5.12 is updated to indicate that curved walls research findings are applicable to the integrated RB SC, including DP-SC, curved walls. • The concrete and water density parameters in Subsection 5.14.1 are updated. • Section 5.15 is updated to address RG 1.54. • Section 6.2 is revised to provide a technical update on the local use of reinforcing steel bars in SCCV connections regions.

	• Section 6.3 is revised to remove the ANSI/AISC N690 reference. • First bullet in Section 6.15 is deleted. • Equation numbers in Section 5.0 are updated due to the addition of two new equations per response to RAI 5.3-1 (Question 2). • Reference numbers are updated. • "Steel Bricks^{TM}" is replaced with "DP-SC" in the first paragraph of Section 7.0. Revised to incorporate the following editorial changes: • "Intent" is replaced with "Safety and performance objectives" in Section 1.2, in Subsections 2.2.3, 2.2.4, 2.2.5, 2.2.6, 2.3.7 and in Section 8.0. • "Meeting" is replaced with "in conformance with" or "conforms to" in Subsections 2.2.1, 2.3.1, 2.3.2 and 2.3.10. • "In-service" is replaced with "Inservice" throughout the report. • Typographical errors in the sixth and seventh bullets of Subsection 2.2.6 and in Sections 2.4, 2.4.1, 2.4.2, 2.4.3, 2.4.4, 4.2 and 6.15 are corrected. • "Is in compliance with" is replaced with "conforms to the guidance of" in Subsection 2.3.6. • "Requirements" is replaced with "guidance" in Subsection 2.3.7. • "Surfaces" is deleted and "RB SC modules" is replaced with "RB DP-SC modules" in Section 2.6. • "Safety-related" is replaced with "systems and components required for accidents mitigation and safe shutdown" and "referred to as DP-SC" is added in Section 3.1. • "Safety-related" is removed from Section 2.5, the second paragraph of Section 3.3 and from the second bullet of Section 7.1. • "SC pedestal" is replaced with "DP-SC pedestal" in the fourth paragraph of Section 3.3. • "Delay" is replaced with "control" in the third paragraph of Section 3.4. • The missing "0" is added to the caption of Figure 4-1. • The first paragraph of Section 5.0 is deleted since conformance to U.S. NRC RG 1.243 is addressed in Subsection 2.3.12 and the second paragraph is split in two. • "Spanning" is added to Figure captions 5-4 and 5-5 (previously Figure 5-2 and Figure 5-3). • "SC modules/walls" are replaced by "DP-SC modules/walls" in Subsection 5.8.2.1 and 5.8.4.

	• The reference to CSA N291 and CSA N287 is removed from Section 5.8 since the conformance of the impactive and impulsive design to the CSA requirements is now addressed in Subsection 2.4.3. • The conformance to REGDOC-2.6.3 is removed from Section 5.18 since it is stated in Section 2.4.4. • A pointer is added to Section 5.1 in Section 6.1. • “DP-SC” is added in the first sentence of Section 6.2.2. • The reference to REGDOC-2.5.2 is removed from Section 6.10 since the conformance of the impactive and impulsive design to the CSA requirements is now addressed in Subsection 2.4.3. • Title of Section 6.16 is revised. • Second paragraph in Section 6.17 is revised and reformatted. • The reference to REGDOC-2.5.2 is removed from Section 6.22 and Subsections 6.23.3 and 6.23.3.2 since the conformance is now addressed in Section 2.4.3. • “Subsubarticle” is replaced with Paragraph, Subparagraph or Subsubparagraph in Sections 4.3, 5.8.2.2, 6.6 and 6.7.3. • “Design” is removed from the fourth line, third column of Table 7-1.

Acronyms and Abbreviations

Term	Definition
3D	Three-Dimensional
ACI	American Concrete Institute
ACT	Advanced Construction Technology
ANSI	American National Standard Institute
AISC	American Institute of Steel Construction
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BDBA	Beyond Design Basis Accident
BPVC	Boiler and Pressure Vessel Code
BWR	Boiling Water Reactor
CEPSS	Containment Equipment and Piping Support Structure
CJP	Complete Joint Penetration
CNSC	Canadian Nuclear Safety Commission
CP	Construction Permit
CSA	CSA Group
DBA	Design Basis Accident
DBE	Design Basis Earthquake
DBT	Design Basis Threat
DEC	Design Extension Condition
DEE	Design Extension Event
DP-SC	Diaphragm Plate Steel-Plate Composite
EPRI	Electric Power Research Institute
ESBWR	Economic Simplified Boiling Water Reactor
FE	Finite Element
FMEA	Failure Mode Effect Analysis
GDC	General Design Criterion
GEH	GE Hitachi Nuclear Energy
HGNE	Hitachi-GE Nuclear Energy, Ltd.

Term	Definition
IAEA	International Atomic Energy Agency
ILRT	Integrated Leak Rate Test
IN	Information Notice
IPV	In-Plane Shear
ISO	International Organization for Standardization
LOCA	Loss-Of-Coolant-Accident
LRFD	Load and Resistance Factor Design
NDRC	National Defense Research Council
NEI	Nuclear Energy Institute
NRC	Nuclear Regulatory Commission
NRIC	National Reactor Innovation Center
OBE	Operating Basis Earthquake
OOPV	Out-Of-Plane Shear
PCCS	Passive Containment Cooling System
QA	Quality Assurance
QC	Quality Control
RB	Reactor Building
RG	Regulatory Guide
RPV	Reactor Pressure Vessel
SASSI	System for Analysis of Soil-Structure Interaction
SC	Steel-Plate Composite
SCCV	Steel-Plate Composite Containment Vessel
SEI	Structural Engineering Institute
SIT	Structural Integrity Test
SMR	Small Modular Reactor
SR	Safety Reports
SRP	Standard Review Plan
SRV	Safety Relief Valve
SSCs	Structures, Systems, and Components
SSE	Safe Shutdown Earthquake

Term	Definition
SSI	Soil-Structure Interaction
SSPC	The Society for Protective Coatings

1.0 INTRODUCTION

1.1 Purpose

This licensing topical report is being furnished to the U.S. Nuclear Regulatory Commission (U.S. NRC) and the Canadian Nuclear Safety Commission (CNSC) for their collaborative reviews to support licensing activities for the deployment of the GE Hitachi Nuclear Energy (GEH) BWRX-300 structural design using Steel-Plate Composite (SC) modules with diaphragm plates for the integrated Reactor Building (RB) housing the Steel-Plate Composite Containment Vessel (SCCV) and containment internal structures.

The purpose of this licensing topical report includes the following:

- U.S. NRC approval and CNSC acceptance is requested for the design approach and methodology of Diaphragm Plate Steel-Plate Composite (DP-SC) structural elements for the GEH BWRX-300 Seismic Category I (Canadian Seismic Category A) SCCV and RB structures that demonstrates compliance with the safety and performance objectives of established regulatory requirements.
- U.S. NRC approval is requested for the requirements for the material, fabrication, construction, inspection, examination and testing of DP-SC modules for the GEH BWRX-300 SCCV and RB structures presented in Sections 5.0 and 6.0 that demonstrate compliance with the safety and performance objectives of established U.S. regulatory requirements.
- CNSC acceptance is requested for the requirements for the material, fabrication, construction, inspection, examination and testing of DP-SC modules for the GEH BWRX-300 SCCV and RB structures described in Sections 5.0 and 6.0, and the alternative requirements discussed in Section 2.5 specific to Canadian sites, that demonstrate compliance with the safety and performance objectives of established Canadian regulatory requirements
- U.S. NRC design-specific approval is requested for the use of:
  - Proposed criteria and requirements for materials, design, fabrication, construction, inspection, examination, and testing for the BWRX-300 SCCV adapted from the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) 2021 Edition, Section III, “Rules for Construction of Nuclear Facility Components,” Division 2, “Code for Concrete Containments,” Subsection CC, “Concrete Containments,” Articles CC-1000 through CC-6000, including Division 2 Appendices (Reference 9-1).
  - Modified criteria and requirements to American National Standard Institute (ANSI)/American Institute of Steel Construction (AISC) N690-18 (Reference 9-2), Chapters NM, NN, and Appendix N9 for material, design, analysis, fabrication, construction, inspection, examination, and testing of BWRX-300 non-containment Seismic Category I structural members, including slabs and curved walls, built using DP-SC modules.
- CNSC acceptance is requested for the use of:

  - Proposed design criteria and requirements for the BWRX-300 SCCV adapted from the ASME BPVC, 2021 Edition, Section III, Division 2, Subsection CC, Articles CC-1000 through CC-6000, including Division 2 Appendices, and the alternative material, fabrication, construction, inspection, examination, testing and quality assurance requirements specific to Canadian sites discussed in Section 2.5.2.
  - Modified criteria and requirements to ANSI/AISC N690-18, Chapters NM, NN, and Appendix N9 for material, design, analysis, fabrication, construction, inpection, examination and testing of BWRX-300 non-containment Seismic Category A structural members, including slabs and curved walls, built using DP-SC modules, and the alternative material, fabrication, construction, inspection, examination, testing and quality assurance requirements specific to Canadian sites discussed in Section 2.5.1.

1.2 Scope

The scope of this document includes the following:

- Regulatory evaluation of compliance of the proposed design rules to applicable U.S. regulations, regulatory guidance of NUREG-0800, and Regulatory Guides (RGs), presented in Sections 2.1, 2.2 and 2.3, respectively
- Regulatory evaluation of compliance of the proposed design rules to applicable Canadian requirements, codes, and standards, and proposed alternative requirements specific to Canadian sites, presented in Sections 2.4 and 2.5
- Description of generic issues relevant to the scope of this report, presented in Section 2.6
- General description of the BWRX-300 integrated RB structures and a general overview of SC structural elements and technical justification for the proposed use of DP-SC modules for the integrated RB structures, presented in Section 3.0
- Overall structural analysis and design approach for the BWRX-300 integrated RB, including analysis method, structural modeling, loads and load combinations, and design code jurisdictions, presented in Section 4.0
- Technical evaluation of the proposed design parameters and requirements applicable to the proposed use of DP-SC modules for the BWRX-300 non-containment SC structures and a demonstration of how the proposed design approach meets the safety and performance objectives of applicable codes, presented in Section 5.0
- Technical evaluation of the proposed design parameters and requirements applicable to the proposed use of DP-SC modules for the BWRX-300 SCCV and a demonstration of how the proposed design approach meets the safety and performance objectives of applicable codes, presented in Section 6.0
- Summary of the National Reactor Innovation Center (NRIC) Demonstration Program Prototype test conclusions, presented in Section 7.0 confirming the proposed design approaches discussed in Sections 5.0 and 6.0
- Radiation shielding function requirements are not under the purview of this report.

2.0 REGULATORY EVALUATION

2.1 U.S. NRC Regulatory Requirements and Guidance

U.S. NRC regulatory requirements and guidance are evaluated to determine compliance or to justify the BWRX-300 specific approaches to compliance, where applicable.

2.1.1 10 CFR 50 Regulations

2.1.1.1 10 CFR 50.34(f)

10 CFR 50.34(f), "Additional TMI-related requirements," requires license applications to provide sufficient information to describe the nature of the studies required, how they are conducted, and a program to ensure that the results of these studies are factored into the final design of the facility, and the studies must be submitted as part of the final safety analysis report. This includes the capability of the containment to resist: (1) those loads that are generated by pressure and dead loads during an accident that releases hydrogen generated from 100-percent fuel clad metal-water reaction and accompanied by either hydrogen burning or added pressure from post-accident inerting; and (2) those loads that are generated as a result of an inadvertent full actuation of a post-accident inerting hydrogen control system, excluding seismic or Design Basis Accident (DBA) loadings. The following requirements are evaluated as they are related to containment structural integrity:

Regulatory Requirement:10 CFR 50.34(f)(3)(v)(A)(1) requires that containment integrity be maintained for steel containments by meeting the requirements of ASME BPVC, Section III, Division 1, Subarticle NE 3220, Service Level C Limits and for concrete containments by meeting the requirements of the ASME BPVC, Section III, Division 2. The specific code requirements for each type of containment will be met for a combination of dead load and an internal pressure of 45 psig. Modest deviations from these criteria will be considered by the NRC Staff, if good cause is shown by an applicant. Systems necessary to ensure containment integrity shall also be demonstrated to perform their function under these conditions.

> Statement of Compliance: The ASME BPVC, Section III, Division 1 requirements are met in the design of the BWRX-300 containment metal closure head and other Class MC components. The proposed containment material, design, fabrication, construction, inspection, examination and testing requirements presented in Section 6.0 of the report are adapted from the ASME BPVC, Section III, Division 2 requirements and ensure the containment structural integrity in compliance with the requirements of 10 CFR 50.34(f)(3)(v)(A)(1).

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50.34(f).

2.1.1.2 10 CFR 50.44

10 CFR 50.44, "Combustible gas control for nuclear power reactors," 10 CFR 50.44(c), Requirements for future water-cooled reactor applicants and licensees, apply to all water-cooled reactor Construction Permits (CPs) or operating licenses under this part, and to all water-cooled reactor design approvals, design certifications, combined licenses, or manufacturing licenses under Part 52 of this chapter, any of which are issued after October 16, 2003.

Regulatory Requirement: 10 CFR 50.44(c)(5), Structural analysis, requires that an applicant must perform an analysis that demonstrates containment structural integrity. This demonstration must use an analytical technique that is accepted by the NRC and include sufficient supporting justification to show that the technique describes the containment response to the structural loads involved. The analysis must address an accident that releases hydrogen generated from 100 percent fuel clad coolant reaction accompanied by hydrogen burning. Systems necessary to ensure containment integrity must also be demonstrated to perform their function under these conditions.

> Statement of Compliance: 10 CFR 50.44 (c)(1) through (c)(4) compliance is addressed in NEDC-33911P-A, "BWRX-300 Containment Performance," (Reference 9-3). The design requirements for the BWRX-300 containment structural integrity analysis performed to demonstrate the survivability of the containment to the structural loads generated from an accident where a 100 percent fuel clad coolant reaction accompanied by hydrogen burning occurs are provided in Section 6.0.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50.44(c)(5).

2.1.1.3 10 CFR 50.55a

10 CFR 50.55a(b), "Use and conditions on the use of standards," requires that systems and components of boiling water-cooled nuclear power reactors must meet the requirements of the ASME BPVC and the ASME OM Code (Reference 9-4) as specified in this paragraph (b).

Regulatory Requirement: 10 CFR 50.55a(b) includes applicability to the BWRX-300 SCCV as a pressure-retaining component.

> Statement of Compliance: Based on the justification provided in Section 6.22 of this report, the proposed inspection and testing approach provides an acceptable level of quality and safety when applied to the materials, design, fabrication, construction, inspection, examination, and testing of the BWRX-300 SCCV.

10 CFR 50.55a(g)(4), "Pre-service and inservice inspection requirements" requires that inservice inspection of Class CC concrete containments and metallic shell and penetration liners of concrete containments shall be performed in accordance with the applicable edition of the ASME BPVC, Section XI, Division 1, "Rules for Inspection and Testing of Components of Light-Water-Cooled Plants," (Reference 9-5), Subsections IWE and IWL, as incorporated by reference and subject to conditions stated in this regulation.

Regulatory Requirement: The most recent standard applicable to the BWRX-300 SCCV approved by the NRC in 10 CFR 50.55a(a)(1)(ii), ASME BPVC, Section XI, Division 1.

> Statement of Compliance: As discussed in Section 6.22 of this report, the pre-service and inservice inspection requirements of the SCCV meet the requirements of ASME Section XI, Division 1, complying with the requirements of 10 CFR 50.55a(g)(4).

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50.55a.

2.1.1.4 10 CFR 50.65

10 CFR 50.65, "Requirements for monitoring the effectiveness of maintenance at nuclear power plants," requires monitoring of the performance or condition of Structures, Systems, and Components (SSCs) against licensee-established goals, in a manner sufficient to provide reasonable assurance that these SSCs, as defined in Paragraph (b) of this section, are capable of fulfilling their intended functions. These goals shall be established commensurate with safety and,

where practical, take into account industrywide operating experience. When the performance or condition of an SSC does not meet established goals, appropriate corrective action shall be taken. This includes structures monitoring and maintenance requirements for Seismic Category I structures.

Regulatory Requirement: 10 CFR 50.65 requires safety-related SSCs that are relied upon to remain functional during and following design-basis events to ensure the integrity of the reactor coolant pressure boundary, the capability to shut down the reactor and maintain it in a safe shutdown condition, or the capability to prevent or mitigate the consequences of accidents that could result in potential off-site exposure.

> Statement of Compliance: An inservice inspection and maintenance program is established for the BWRX-300 Seismic Category I integrated RB structures to ensure the structures can fulfill their intended functions throughout their design service life in compliance with 10 CFR 50.65. Inspection methodology for the DP-SC non-containment structures and the SCCV are discussed in Sections 5.18 and 6.22 of this report.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50.65.

2.1.1.5 10 CFR 50.150

10 CFR 50.150, “Aircraft impact assessment,” each applicant listed shall perform a design-specific assessment of the effects on the facility of the impact of a large, commercial aircraft. Using realistic analyses, the applicant shall identify and incorporate into the design those design features and functional capabilities to show that, with reduced use of operator actions, the reactor core remains cooled, or the containment remains intact and spent fuel cooling or spent fuel pool integrity is maintained. The assessment must be based on the beyond design basis impact of a large, commercial aircraft used for long distance flights in the U.S., with aviation fuel loading typically used in such flights, and an impact speed and angle of impact considering the ability of both experienced and inexperienced pilots to control large, commercial aircraft at the low altitude representative of a nuclear power plant’s low profile.

Regulatory Requirement: A design-specific aircraft impact of a large, commercial aircraft assessment on the facility is required to ensure that (i) The reactor core remains cooled, or the containment remains intact; and (ii) Spent fuel cooling or spent fuel pool integrity is maintained.

> Statement of Compliance: The BWRX-300 design applies the Nuclear Energy Institute’s (NEI’s) methodology in NEI 07-13 (Reference 9-6) for aircraft crash evaluations and explicit dynamic analysis methods, where appropriate, to evaluate the consequences of regulatory defined threats on a BWRX-300 reactor site as discussed in Subsection 5.8.4 of this report. Specific requirements and approaches for aircraft impact explicit dynamic analyses are not in the scope of this report. The beyond design basis evaluation will demonstrate that the BWRX-300 design includes adequate design features that allow the containment to remain intact, and the fuel pool to maintain structural integrity for safe operations.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50.150.

2.1.1.6 10 CFR 50 Appendix A, GDC 1

Regulatory Requirement: 10 CFR 50 Appendix A, General Design Criterion (GDC) 1, “Quality standards and records,” requires that SSCs important to safety shall be designed, fabricated, erected, and tested to quality standards commensurate with the importance of the safety functions to be performed. Where generally recognized codes and standards are used, they shall be identified and evaluated to determine their applicability, adequacy, and sufficiency, and shall be supplemented or modified as necessary to assure a quality product in keeping with the required safety function. A Quality Assurance (QA) program shall be established and implemented in order to provide adequate assurance that these SSCs will satisfactorily perform their safety functions. Appropriate records of the design, fabrication, erection, and testing of SSCs important to safety shall be maintained by or under the control of the nuclear power unit licensee throughout the life of the unit.

> Statement of Compliance: As described in this report, the BWRX-300 Seismic Category I SSCs are designed, fabricated, erected, and tested to quality standards commensurate with the importance of their safety functions in accordance with generally recognized codes and standards, and under an approved QA program with approved control of records. The use of the proposed modifications to ANSI/AISC N690 and ASME BPVC addressing the materials, design, fabrication, construction, inspection, examination, and testing for the BWRX-300 Seismic Category I integrated RB are evaluated in Sections 5.0, 6.0 and 7.0 of this report to demonstrate their applicability, adequacy, and sufficiency.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix A, GDC 1.

2.1.1.7 10 CFR 50 Appendix A, GDC 2

10 CFR 50 Appendix A, GDC 2, “Design bases for protection against natural phenomena,” requires that SSCs important to safety shall be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions. The design bases for these SSCs shall reflect: (1) Appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated; (2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena; and (3) the importance of the safety functions to be performed.

> Statement of Compliance: The BWRX-300 Seismic Category I integrated RB, including containment, is designed to withstand the effects of natural phenomena such as earthquakes, tornadoes and tornado missiles without loss of capability to perform its safety functions. Loads and load combinations considered in the design are discussed in Section 4.3 of this report.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix A, GDC 2.

2.1.1.8 10 CFR 50 Appendix A, GDC 4

10 CFR 50 Appendix A, GDC 4, “Environmental and dynamic effects design bases,” requires that SSCs important to safety shall be designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation, maintenance, testing, and postulated accidents, including Loss-Of-Coolant Accidents (LOCAs). These SSCs shall be appropriately protected against dynamic effects, including the effects of missiles, pipe whipping, and discharging fluids, that may result from equipment failures and from events and conditions outside the nuclear power unit. However, dynamic effects associated with postulated pipe ruptures in nuclear power units may be excluded from the design basis when analyses reviewed and

approved by the Commission demonstrate that the probability of fluid system piping rupture is extremely low under conditions consistent with the design basis for the piping.

> Statement of Compliance: Loads and load combinations considered in the design BWRX-300 Seismic Category I integrated RB include normal operating, testing, accident pressure and reaction loads that may result from equipment or piping failures as discussed in Section 4.3 of this report. For sites where nonterrorism-related aircraft crashes cannot be screened out, site-specific loading will be developed consistent with Regulatory Position C.8.a(4) of U.S. NRC RG 1.136 (Reference 9-7) for the SCCV and Regulatory Position C.2.2.6 of U.S. NRC RG 1.243 (Reference 9-8) for the RB.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix A, GDC 4.

2.1.1.9 10 CFR 50 Appendix A, GDC 16

10 CFR 50 Appendix A, GDC 16, "Containment design," requires that reactor containment and associated systems shall be provided to establish an essentially leak-tight barrier against the uncontrolled release of radioactivity to the environment and to assure that the containment design conditions important to safety are not exceeded for as long as postulated accident conditions require.

> Statement of Compliance: The BWRX-300 SCCV enclosing the Reactor Pressure Vessel (RPV) and the containment internal structures is leak-tight, with the inner steel faceplate of the DP-SC modules serving as the leak barrier. The design of the containment penetrations that follows the requirements in Section 6.12 of this report also includes leak-tight isolation design features, including containment isolation valve, blind flanges, hatches, and electrical penetrations. The design and detailing of the SCCV penetrations and openings are coordinated with the fabricator to meet the code requirements.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix A, GDC 16.

2.1.1.10 10 CFR 50 Appendix A, GDC 50

10 CFR 50 Appendix A, GDC 50, "Containment design basis," requires that the reactor containment structure, including access openings, penetrations, and the containment heat removal system shall be designed so that the containment structure and its internal compartments can accommodate, without exceeding the design leakage rate and with sufficient margin, the calculated pressure and temperature conditions resulting from any LOCA. This margin shall reflect consideration of: (1) the effects of potential energy sources which have not been included in the determination of the peak conditions, such as energy in steam generators and as required by 10 CFR 50.44 energy from metal-water and other chemical reactions that may result from degradation but not total failure of emergency core cooling functioning; (2) the limited experience and experimental data available for defining accident phenomena and containment responses; and (3) the conservatism of the calculational model and input parameters.

> Statement of Compliance: The containment design is based upon consideration of a full spectrum of postulated accidents that would result in the release of reactor coolant to the containment. The BWRX-300 containment structural design includes sufficient margin to account for uncertainties from a full spectrum of postulated accidents that would result in the release of reactor coolant to the containment. The containment ultimate pressure capacity

> discussed in Subsection 6.23.1 will demonstrate compliance to 10 CFR 50, Appendix A, GDC 50.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix A, GDC 50.

2.1.1.11 10 CFR 50 Appendix A, GDC 51

10 CFR 50 Appendix A, GDC 51, "Fracture prevention of containment pressure boundary," requires that the reactor containment boundary shall be designed with sufficient margin to assure that under operating, maintenance, testing, and postulated accident conditions: (1) its ferritic materials behave in a nonbrittle manner; and (2) the probability of rapidly propagating fracture is minimized. The design shall reflect consideration of service temperatures and other conditions of the containment boundary material during operation, maintenance, testing, and postulated accident conditions, and the uncertainties in determining: (1) material properties; (2) residual, steady-state, and transient stresses; and (3) size of flaws.

> Statement of Compliance: The BWRX-300 containment possesses ductility and energy absorbing capacity which permits inelastic deformation without failure under design basis transients and accidents. The design material selection reflects consideration of service temperatures and other conditions of the pressure boundary during operation, maintenance, testing, and design basis accident conditions, and the uncertainties in determining: (a) material properties; (b) residual, steady-state, and transient stresses; and (c) the size of flaws. The containment seismic design is qualified to meet the ductility detailing and design requirements for steel and SC structures of ANSI/AISC N690, with the supplementary guidance of U.S. NRC RG 1.243. Additionally, the ductility is confirmed by the ultimate capacity analysis of the BWRX-300 containment described in Section 6.23.1 and results of the NRIC tests discussed in Section 7.0.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix A, GDC 51.

2.1.1.12 10 CFR 50 Appendix A, GDC 52

10 CFR 50 Appendix A, GDC 52, "Capability for Containment Leakage Rate Testing," requires that the reactor containment and other equipment which may be subjected to containment test conditions shall be designed so that period integrated leakage rate testing can be conducted at containment design pressure.

> Statement of Compliance: As stated in NEDC-33911P-A and in Section 6.22 of this report, the BWRX-300 containment is designed with provisions to conduct periodic integrated leakage rate testing at containment design pressure to comply with 10 CFR 50, Appendix J and the guidance of U.S. NRC RG 1.163 (Reference 9-9).

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix A, GDC 52.

2.1.1.13 10 CFR 50 Appendix A, GDC 53

10 CFR 50 Appendix A, GDC 53, "Provisions for containment testing and inspection," requires that the reactor containment shall be designed to permit: (1) appropriate periodic inspection of all important areas, such as penetrations; (2) an appropriate surveillance program; and (3) periodic testing at containment design pressure of the leak tightness of penetrations which have resilient seals and expansion bellows.

> Statement of Compliance: The BWRX-300 containment and associated penetrations have provisions for conducting individual leakage rate tests on applicable penetrations. Penetrations and other important areas are visually inspected, and pressure tested for leak tightness at periodic intervals in accordance with 10 CFR 50, Appendix J as stated in NEDC-33911P-A, Section 2.2.7 and in Section 6.22 of this report.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix A, GDC 53.

2.1.1.14 10 CFR 50 Appendix B

10 CFR 50 Appendix B, "Quality assurance criteria for nuclear power plants and fuel reprocessing plants," requires, by the provisions of § 50.34, to include in its preliminary safety analysis report a description of the QA program to be applied to the design, fabrication, construction, and testing of the SSCs of the facility. Every applicant for an operating license is required to include, in its final safety analysis report, information pertaining to the managerial and administrative controls to be used to assure safe operation. Nuclear power plants and fuel reprocessing plants include SSCs that prevent or mitigate the consequences of postulated accidents that could cause undue risk to the health and safety of the public. This appendix establishes QA requirements for the design, manufacture, construction, and operation of those SSCs. The pertinent requirements of this appendix apply to all activities affecting the safety-related functions of those SSCs; these activities include designing, purchasing, fabricating, handling, shipping, storing, cleaning, erecting, installing, inspecting, testing, operating, maintaining, repairing, refueling, and modifying.

> Statement of Compliance: NEDO-11209-A, "GE Hitachi Nuclear Energy Quality Assurance Program Description," (Reference 9-10) complies with ASME NQA-1, "Quality Assurance Requirements for Nuclear Facility Applications," (Reference 9-11). The NRC Staff reviewed the QA measures implemented by GEH in Section 1.0 of Reference 9-10 and concluded that the organizational changes in Reference 9-10 continue to meet the guidance in 10 CFR Part 50, Appendix B. Computer programs used in the structural analyses of the BWRX-300 integrated RB are verified in accordance with NEDO-11209-A. NRIC test plans and results are also reviewed and accepted in accordance with NEDO-11209-A as discussed in Subsection 7.2.1.1. The SCCV quality control and quality assurance requirements are discussed in Sections 6.2 and 6.15 of this report consistent with the requirements of 10 CFR 50 Appendix B.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix B.

2.1.1.15 10 CFR 50 Appendix J

10 CFR 50 Appendix J, "Primary reactor containment leakage testing for water-cooled power reactors," requires that primary reactor containments shall meet the containment leakage test requirements set forth in this appendix. These test requirements provide for pre-operational and periodic verification by tests of the leak-tight integrity of the primary reactor containment, and systems and components which penetrate containment of water-cooled power reactors and establish the acceptance criteria for these tests. The purposes of the tests are to assure that: (a) leakage through the primary reactor containment and systems and components penetrating primary containment shall not exceed allowable leakage rate values as specified in the technical specifications or associated bases; and (b) periodic surveillance of reactor containment penetrations and isolation valves is performed so that proper maintenance and repairs are made during the service life of the containment and systems and components penetrating primary

containment. These test requirements may also be used for guidance in establishing appropriate containment leakage test requirements in technical specifications or associated bases for other types of nuclear power reactors.

> Statement of Compliance: The BWRX-300 design includes provisions for periodic integrated leakage rate testing, and local leak rate test for the SCCV (type A testing) and containment penetrations (type B testing), in compliance with the requirements of 10 CFR 50 Appendix A, GDC 52, GDC 53 and 10 CFR 50, Appendix J as discussed in NEDC-33911P-A and in Sections 4.3 and 6.22 of this report.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix J.

2.1.1.16 10 CFR 50 Appendix S

10 CFR Part 50, Appendix S, "Earthquake engineering criteria for nuclear power plants," requires that for Safe Shutdown Earthquake (SSE) ground motions, SSCs will remain functional and within applicable stress, strain, and deformation limits. The required safety functions of SSCs must be assured during and after the vibratory ground motion through design, testing, or qualification methods. The evaluation must take into account Soil-Structure Interaction (SSI) effects and the expected duration of the vibratory motion.

> Statement of Compliance: The compliance of the BWRX-300 seismic design to the requirements of 10 CFR 50, Appendix S is evaluated in NEDO-33914-A, "BWRX-300 Advanced Civil Construction and Design Approach," (Reference 9-12), Section 2.3. The SSE ground motion used in the analysis of the integrated RB structures is site-specific and is developed per the methodology discussed in NEDO-33914-A. NEDO-33914-A provides additional requirements for the development of the SSE ground motion and seismic SSI analysis to address the deeply embedded design of the RB. Section 4.0 of this report provides an overview of the BWRX-300 SSI analyses, including seismic analysis, performed to evaluate demands on the structures, and of the integrated RB Finite Element (FE) model used in the analyses. Floor response spectra or acceleration time histories obtained from the seismic SSI analysis are used to qualify systems and components required to remain functional during and following an SSE. Complying with the requirements of 10 CFR 50, Appendix S, Operating Basis Earthquake (OBE) loads and load combinations are considered in the BWRX-300 design when the OBE is set larger than 1/3 of the site-specific SSE. For U.S. sites, the OBE is selected by the applicant based on the site conditions to serve as reference for shutdown of the plant per criteria in ANSI/ANS-2.23 (Reference 9-13).

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix S.

2.2 NUREG-0800 Standard Review Plan (SRP) Guidance

2.2.1 NUREG-0800, SRP 3.5.3

NUREG-0800, SRP 3.5.3, "Barrier Design Procedures," (Reference 9-14), provides review guidance to the NRC Staff responsible for the review of procedures utilized in the design of Seismic Category I structures to withstand the effects of missile impact to ensure conformance with 10 CFR 50, GDC 2 and 4. This includes the following specific areas of review:

- Procedures utilized for the prediction of local damage in the impacted area
    - This includes the estimation of the depth of penetration.

- Procedures utilized for the prediction of the overall response of the barrier or structures due to the missile impact
  - This includes the assumptions on acceptable ductility ratios where elasto-plastic behavior is relied upon, and procedures for estimation of forces, moments, and shear induced in the barrier by the impact force of the missile.
- Adequacy of missiles' parameters considered

Statement of Conformance: The BWRX-300 design considers local and global effects of impactive loads as discussed in Sections 5.8 and 6.10 of this report in conformance with the regulatory guidance of SRP 3.5.3.

2.2.2 NUREG-0800, SRP 3.8.1

NUREG-0800, SRP 3.8.1, "Concrete Containment," (Reference 9-15), provides review guidance to the NRC Staff responsible for structural analysis reviews for concrete containments. Although this SRP section is not directly applicable to the design of the SCCV, the guidance is reviewed to determine what remains relevant for the NRC Staff to consider in their review. This includes the following specific areas of review:

- Descriptive information, including plans and sections of the containment structure, to establish that sufficient information is provided to define the primary structural aspects and elements relied upon to perform the containment function, including structural and functional characteristics
- Design codes, standards, specifications, regulations, RGs, and other industry standards that are applied in the design fabrication, construction, testing, and inservice surveillance of the containment
- Information pertaining to the applicable design loads and various combinations thereof, with emphasis on the extent of compliance with ASME BPVC requirements
- Design and analysis procedures used for the containment with emphasis on the extent of compliance with ASME BPVC requirements
- Design limits imposed on the various parameters that quantify the structural behavior of the containment, with emphasis on the extent of compliance with ASME BPVC requirements
- Materials that are used in construction of the containment with emphasis on the extent of compliance with ASME BPVC requirements
- Quality Control (QC) program that is proposed for the fabrication and construction of the containment, with emphasis on the extent of compliance with ASME BPVC requirements
- Any special design provisions (e.g., providing sufficient physical access, providing alternative means for identification of conditions in inaccessible areas that can lead to degradation, or providing remote visual monitoring of high-radiation areas) to accommodate inservice inspection
- Pre-operational structural testing program for the completed containment and for individual components, such as personnel and equipment locks and hatches, which includes

the objectives of the test program and acceptance criteria, with emphasis on the extent of compliance with ASME BPVC requirements, including inservice surveillance programs

Statement of Conformance: For code applicability, the BWRX-300 SCCV is designed, fabricated, constructed, inspected, examined and tested to applicable portions of ASME BPVC, Section III, Division 2 requirements along with the modified requirements outlined in Section 6.0 of this report. The code jurisdictional boundary for application of the proposed design approach presented in Section 6.0 to the SCCV is shown in Figure 4-1. The proposed design approach for the BWRX-300 SCCV meets the safety and performance objectives of the regulatory guidance of SRP 3.8.1.

2.2.3 NUREG-0800, SRP 3.8.2

NUREG-0800, SRP 3.8.2, "Steel Containment," (Reference 9-16), provides review guidance to the NRC Staff responsible for structural analysis reviews for steel containments. Although this SRP section is not directly applicable to the design of the SCCV, the guidance is reviewed to determine what remains relevant for the NRC Staff to consider in their review. This includes the following specific areas of review:

- Descriptive information, including plans and sections of the containment structure, to establish that sufficient information is provided to define the primary structural aspects and elements relied upon to perform the containment function, including structural and functional characteristics, including steel components of concrete containments that resist pressure and are not backed by structural concrete (e.g., the containment head in a Boiling Water Reactor (BWR))
- Design codes, standards, specifications, regulations, RGs, and other industry standards that are applied in the design fabrication, construction, testing, and inservice surveillance of the containment
- Information pertaining to the applicable design loads and various combinations thereof, with emphasis on the extent of compliance with ASME BPVC requirements
- Design and analysis procedures used for the containment, with emphasis on the extent of compliance with ASME BPVC requirements
- Design limits imposed on the various parameters that quantify the structural behavior of the containment, with emphasis on the extent of compliance with ASME BPVC requirements
- Materials that are used in construction of the containment, with emphasis on the extent of compliance with ASME BPVC requirements
- QC program that is proposed for the fabrication and construction of the containment, with emphasis on the extent of compliance with ASME BPVC requirements, including nondestructive examination of the materials, including tests to determine their physical properties, welding procedures, and erection tolerances
- Any special construction techniques, if proposed, to determine their effects on the structural integrity of the completed containment
- Pre-operational structural testing program for the completed containment and for individual components, such as personnel and equipment locks and hatches, which includes

the objectives of the test program and acceptance criteria, with emphasis on the extent of compliance with ASME BPVC requirements, including inservice surveillance programs

- Special testing and inservice surveillance requirements proposed for new or previously untried design approaches, and for new reactors, it is important to accommodate inservice inspection of critical areas.

Statement of Conformance: For code applicability, the BWRX-300 SCCV is designed, fabricated, constructed, inspected, examined and tested to applicable portions of ASME BPVC, Section III, Division 2 requirements, along with the modified requirements outlined in Section 6.0 of this report. The code jurisdictional boundary for application of the proposed design approach presented in Section 6.0 to the SCCV is shown in Figure 4-1. The proposed design approach for the BWRX-300 SCCV meets the safety and performance objectives of the regulatory guidance of SRP 3.8.2. Design of Class MC components of the containment is not in the scope of this report as discussed in Section 4.0 of the report.

2.2.4 NUREG-0800, SRP 3.8.3

NUREG-0800, SRP 3.8.3, "Concrete and Steel Internal Structures of Steel or Concrete Containments" (Reference 9-17), provides review guidance to the NRC Staff responsible for structural analysis reviews. This includes the following specific areas of review:

- Descriptive information, including plans and sections of the various internal structures, to establish that sufficient information is provided to define the primary structural aspects and elements relied upon to perform the safety-related functions of these structures
- Capability of the internal structures to resisting loads and load combinations to which they may be subjected and should not become the initiator of an LOCA, with the structures able to mitigate its consequences by protecting the containment and other engineered safety features from the accident's effects such as jet forces and whipping pipes
- Plant designs may also use modular construction methods for the major containment internal structures:
  - With wall modules typically constructed from large, prefabricated sections of steel plates spaced apart with intermittent steel members, joined with other modules at the site, and then filled with concrete
  - With the concrete fill used in wall modules either structural concrete with reinforcement (composite construction) or fill concrete of low strength without reinforcement, or heavy concrete for radiation shielding
  - With floor modules consisting of prefabricated steel members and plates combined with poured concrete to create a composite section, and the structural module design, fabrication, configuration, layout, and connections may be reviewed on a case-by-case basis
- Design codes, standards, specifications, and RGs, as well as industry standards that are applied in the design, fabrication, construction, testing, and surveillance of the containment structures
- Applicable design loads and associated load combinations

- Design and analysis procedures used for the containment internal structures, with an emphasis on the extent of compliance with the applicable codes as indicated in Subsection II.2 of SRP 3.8.3
- Design limits imposed on the various parameters that quantify the structural behavior of the various interior structures of the containment, particularly with respect to stresses, strains, deformations, and factors of safety against structural failure, with emphasis on the extent of compliance with the applicable codes indicated in Subsection II.5 of SRP 3.8.3
- Materials used in the construction of the containment internal structures, including concrete ingredients, reinforcing bars and splices, structural steel, and various supports and anchors
- QC program proposed for the fabrication and construction of the containment internal structures, including nondestructive examination of the materials to determine physical properties, placement of concrete, and erection tolerances
- Special, new, or unique construction techniques, such as the use of modular construction methods, if used
- For Seismic Category I structures inside containment, information on structures monitoring and maintenance requirements, including inservice inspection of critical areas, special design provisions (e.g., sufficient physical access, alternative means for identification of conditions in inaccessible areas that can lead to degradation, remote visual monitoring of high-radiation areas) to accommodate inservice inspection of containment internal structures, and post-construction testing and inservice surveillance programs for containment internal structures such as periodic examination of inaccessible areas

Statement of Conformance: Following the guidance of NUREG-0800, SRP 3.8.3, Subsection II.2, the analysis and design, fabrication, construction and testing of the containment internal structures is in accordance with ANSI/AISC N690 with the supplementary guidance of U.S. NRC RG 1.243. The proposed modified ANSI/AISC N690 design rules for the BWRX-300 SC (including DP-SC) containment internal structures presented in Section 5.0 of this report meet the safety and performance objectives of the regulatory guidance of SRP 3.8.3.

2.2.5 NUREG-0800, SRP 3.8.4

NUREG-0800, SRP 3.8.4, “Other Seismic Category I Structures” (Reference 9-18), provides review guidance to the NRC Staff responsible for structural analysis reviews. This includes specific areas of review that are applicable to the RB Seismic Category I structure surrounding the containment, including the following:

- Descriptive information, including plans and sections of each structure, to establish that there is sufficient information to define the primary structural aspects and elements relied upon for the structure to perform the intended safety function, and the relationship between adjacent structures, including the separation provided or structural ties, if any
- Design codes, standards, specifications, RGs, and other industry standards that are applied in the design, fabrication, construction, testing, and surveillance of Seismic Category I structures
- Applicable design loads and various load combinations

- Design and analysis procedures used for Seismic Category I structures focusing on the extent of compliance with American Concrete Institute (ACI) 349 (Reference 9-19), with supplemental guidance by U.S. NRC RG 1.142 (Reference 9-20) for concrete structures and ANSI/AISC N690 supplemented by U.S. NRC RG 1.243 for steel structures
- Design limits imposed on the various parameters that serve to quantify the structural behavior of each structure and its components, with specific attention to stresses, strains, gross deformations, and factors of safety against structural failure, and for each load combination specified, the allowable limits compared with the acceptable limits delineated in Subsection II.5 of SRP 3.8.4
- Materials used in the construction of Seismic Category I structures, including concrete ingredients, reinforcing bars and splices, and structural steel and anchors
- QC parameters that are proposed for the fabrication and construction of Seismic Category I structures, including nondestructive examination of the materials to determine physical properties, placement of concrete, and erection tolerances
- Special construction techniques, such as modular construction methods, if used
- Information on structures monitoring and maintenance requirements, including accommodation for inservice inspection of critical areas, any special design provisions (e.g., providing sufficient physical access, providing alternative means for identification of conditions in inaccessible areas that can lead to degradation, remote visual monitoring of high-radiation areas). Post-construction testing and inservice surveillance programs, such as periodic examination of inaccessible areas, monitoring of ground water chemistry, and monitoring of settlements and differential displacements

Statement of Conformance: Following the guidance of NUREG-0800, SRP 3.8.4, the analysis and design, fabrication, construction, inspection, examination and testing of the RB structure is in accordance with the ANSI/AISC N690 with the supplementary guidance of U.S. NRC RG 1.243. The proposed ANSI/AISC N690 modified design rules for the BWRX-300 RB presented in Section 5.0 of this report meet the safety and performance objectives of the regulatory guidance of SRP 3.8.4.

2.2.6 NUREG-0800, SRP 3.8.5

NUREG-0800, SRP 3.8.5, “Foundations,” (Reference 9-21), provides review guidance to the NRC Staff relating to the foundations of all Seismic Category I structures. This includes the following specific areas of review:

- Descriptive information, including plans and sections of each foundation, to establish that sufficient information is provided to define the primary structural aspects and elements relied on to perform the foundation function
    - Major plant Seismic Category I foundations that are reviewed, together with associated descriptive information, includes concrete structure foundation, containment enclosure building foundation, auxiallry building foundation and other Seismic Category I foundations.

- Codes, standards and specifications, RGs, and other industry standards that are applied in the design, fabrication, construction, testing, and surveillance of Seismic Category I foundations
- Applicable design loads and various load combinations
- Design procedures used for Seismic Category I foundations other than containment, focusing on the extent of compliance with ACI 349, with supplemental guidance by U.S. NRC RG 1.142 for concrete structures and ANSI/AISC N690 supplemented by U.S. NRC RG 1.243 for steel structures
- Structural acceptance criteria limits imposed on the various parameters that serve to quantify the structural behavior of each foundation, emphasizing the extent the allowable limits and the factors of safety against overturning and sliding to ensure adequate safety margins
- Materials, QC, and special construction used in the construction of Seismic Category I foundations, including concrete ingredients, reinforcing bars, structural steel, and rock anchors
- Testing and inservice surveillance programs focusing on any special design provisions (e.g., providing sufficient physical access, furnishing alternative means for identification of conditions in inaccessible areas that can lead to degradation, conducting remote visual monitoring of high-radiation areas) to accommodate inservice inspection of Seismic Category I foundations

Statement of Conformance: The proposed design approach for the portion of the common mat foundation supporting the BWRX-300 integrated RB is discussed in Section 5.0 of this report. Similarly, the proposed design approach for the portion of the common mat foundation supporting the BWRX-300 SCCV is discussed in Section 6.0. The proposed approaches in Sections 5.0 and 6.0 meet the safety and performance objectives of the regulatory guidance of SRP 3.8.5.

2.2.7 NUREG-0800, SRP 19.0

NUREG-0800, SRP 19.0, "Probabilistic Risk Assessment and Severe Accident Evaluation for Reactors," (Reference 9-22), provides review guidance to the NRC staff of the applicant's design-specific probabilistic risk assessment and deterministic evaluation of design features for the prevention or mitigation of severe accidents. The structural performance of the containment under severe accident loads encompasses: (1) the applicant's assessment of the Level C (or factored load) pressure capability of the containment in accordance with 10 CFR 50.44(c)(5); (2) the applicant's demonstration of the containment capability to withstand the pressure and temperature loads induced by the more likely severe accident scenarios as stipulated in SECY-93-087, "Policy, Technical, and Licensing Issues Pertaining to Evolutionary and Advanced Light-Water Reactor Designs," Section I.J (Reference 9-23); (3) the applicant's containment structural fragility assessment for overpressurization; and (4) the applicant's assessment of the seismic capacity of the containment structure in meeting the expectation documented in SECY-93-087, Section II.N.

Statement of Conformance: The BWRX-300 containment structural performance under beyond design basis and severe accident loads related to the containment ultimate pressure capacity combustible gases, and containment ability to maintain leak-tight barrier following the onset of core damage is evaluated following the regulatory guidance of SRP 19.0 as described in Section 6.23. As stated in Subsection 6.23.3, the BWRX-300 containment is designed to maintain its structural integrity under severe accidents complying with SRP 19.0 and meeting the containment structural performance goals stipulated in SECY-93-087. The plant-specific probabilistic risk assessment and severe accident evaluations that will demonstrate the survivability of the containment and its robustness against the four conditions specified in SRP 19.0 will be presented in Chapter 19 and Section 15.6, respectively, of each plant-specific final safety analysis report in conformance with the regulatory guidance of SRP 19.0.

2.2.8 NUREG-0800, SRP 19.5

NUREG-0800, SRP 19.5, "Adequacy of Design Features and Functional Capabilities Identified and Described for Withstanding Aircraft Impacts," (Reference 9-24), provides review guidance to the NRC Staff to perform a design-specific assessment of the effects on the facility of the impact of a large commercial aircraft. Using realistic analysis, the applicant shall identify and incorporate into the design those design features and functional capabilities to show that, with reduced use of operator actions: (1) the reactor core remains cooled, or the containment remains intact; and (2) spent fuel cooling or spent fuel pool integrity is maintained.

Statement of Conformance: The BWRX-300 design applies the methodology in NEI 07-13 for aircraft crash evaluations and explicit dynamic analysis methods, where appropriate, to evaluate the consequences of regulatory defined threats on a BWRX-300 reactor site as discussed in Subsection 5.8.4 of this report. Specific requirements and approaches for aircraft impact explicit dynamic analyses are not in the scope of this report. The beyond design basis evaluation will demonstrate that the BWRX-300 design includes adequate design features that allow the containment to remain intact, and the fuel pool to maintain structural integrity for safe operations in conformance with SRP 19.5.

2.3 Regulatory Guides

2.3.1 Regulatory Guide 1.7

RG 1.7, "Control of Combustible Gas Concentrations in Containment Following a Loss of Coolant Accident" (Reference 9-25), describes methods acceptable to the NRC Staff for implementing the regulatory requirements of 10 CFR 50.44 for reactors subject to the provisions of Sections 50.44(b) or 50.44(c) with regard to control of combustible gases generated by Beyond Design Basis Accident (BDBA) that could be a risk significant threat to containment integrity. For applicants and holders of a water-cooled reactor CP or operating license under 10 CFR 50 that are docketed after October 16, 2003, containments must have an inerted atmosphere or limit combustible gas concentrations in containment during and following an accident that releases an equivalent of combustible gas as would be generated from a 100% fuel clad coolant reaction, uniformly distributed, to less than 10% (by volume) and must maintain containment structural integrity.

Statement of Conformance: The criteria and approach presented in Subsection 6.23.2 for demonstrating the containment structural integrity under loads resulting from combustible gases generated by metal-water reactions of the fuel cladding conform to the guidance of Regulatory Position 5 of U.S. NRC RG 1.7.

2.3.2 Regulatory Guide 1.26

RG 1.26, "Quality Group Classifications and Standards for Water , Steam , and Radioactive Waste Containing Components of Nuclear Power Plants" (Reference 9-26), describes methods acceptable to the NRC Staff for use in implementing the regulatory requirements of 10 CFR 50 Appendix A, GDC 1, "Quality Standards and Records," with regard to a quality classification system related to specified national standards that may be used to determine quality standards acceptable to the NRC Staff for components containing water, steam, or radioactive material in light water cooled nuclear power plants.

> Statement of Conformance: The BWRX-300 containment is classified as Quality Group B and its design complies with the requirements of 10 CFR 50 Appendix A, GDC 1. The BWRX-300 containment design discussed in Section 6.0 of the report conforms to the guidance of U.S. NRC RG 1.26.

2.3.3 Regulatory Guide 1.28

RG 1.28, "Quality Assurance Program Criteria (Design and Construction)," for addressing 10 CFR 50 Appendix B QA requirements, as it applies to the RB and SCCV, describes methods that the staff of the U.S. NRC considers acceptable for complying with the provisions of 10 CFR Part 50, Appendix B, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants," for establishing and implementing a QA program for the design and construction of nuclear power plants and fuel reprocessing plants. 10 CFR Part 50, Appendix A, GDC 1 and 10 CFR 50.34(a)(7) provide a description of the QA program to be applied to the design, fabrication, construction, and testing of the SSCs of the facility, and a discussion of how the applicable requirements of Appendix B to 10 CFR Part 50 Appendix B will be satisfied.

> Statement of Conformance: The BWRX-300 SSCs are designed, fabricated, erected, and tested to quality standards commensurate with the importance of the safety functions to be performed in accordance with NEDO-11209-A, which complies with NRC approved ASME NQA-1 and conforms to the guidance of U.S. NRC RG 1.28.

2.3.4 Regulatory Guide 1.54

RG 1.54, "Service Level I, II, III and In-Scope License Renewal Protective Coatings Applied to Nuclear Power Plants" (Reference 9-27), describes a method that the staff of the U.S. NRC considers acceptable for complying with NRC requirements for the selection, application, qualification, inspection, and maintenance of protective coatings applied to nuclear power plants.

> Statement of Conformance: As stated in Sections 5.15 and 6.19 of the report, the selection, application, qualification, inspection, and maintenance of coatings used for corrosion protection of the containment and non-containment DP-SC modules will conform to the guidance of U.S. NRC RG 1.54.

2.3.5 Regulatory Guide 1.57

RG 1.57, "Design Limits and Loading Combinations for Metal Primary Reactor Containment System Components" (Reference 9-28), describes an approach to the NRC Staff to consider an acceptable for use in satisfying the requirements of General Design Criteria 1, 2, 4, and 16, as specified in 10 CFR Part 50 Appendix A, "General Design Criteria for Nuclear Power Plants." The leak tightness of the containment structure must be tested at regular intervals during the life of the plant, in accordance with the provisions of 10 CFR Part 50, Appendix J, "Primary Reactor Containment Leakage Testing for Water-Cooled Power Reactors." In addition, for certain reactors specified in 10 CFR 50.34(f), 10 CFR 50.34(f)(3)(v)(A) and (B) require steel containments to meet specific provisions of the ASME BPVC when subjected to loads resulting from fuel damage, metal-water reactions, hydrogen burning, and inerting system actuations.

> Statement of Conformance: The design limits, load combinations, and leak tightness of the containment closure head, and other Class MC components conform to the guidance of U.S. NRC RG 1.57. Design limits, load combinations, and leak tightness of Class MC components of the containment backed by concrete are discussed in Sections 4.0 and 6.0 of this report.

2.3.6 Regulatory Guide 1.61

RG 1.61, "Damping Values for Seismic Design of Nuclear Power Plants" (Reference 9-29), describes an acceptable damping value that the NRC Staff can use in reviewing the seismic response analysis of Seismic Category I nuclear power plant SSCs in accordance with 10 CFR Part 50, GDC 2, and requires that SSCs important to safety be designed to withstand the effects of natural phenomena such as earthquakes without losing the ability to perform their safety functions. Such SSCs must also be designed to accommodate the effects of and be compatible with the environmental conditions associated with normal operation and postulated accidents. Appendix S specifies the requirements for the implementation of GDC 2 with respect to earthquakes.

> Statement of Conformance: OBE and SSE damping values for the SCCV and the non-containment Seismic Category I DP-SC elements are based on the values provided for SC walls in Tables 1 and 2 of U.S. NRC RG 1.61. The response level considered for the generation of in-structure response spectra conforms to the guidance U.S. NRC RG 1.61.

2.3.7 Regulatory Guide 1.136

RG 1.136, "Materials, Construction, and Testing of Concrete Containments", describes an approach that is acceptable to the NRC Staff to meet regulatory requirements for materials, design, construction, fabrication, examination, and testing of concrete (reinforced or prestressed) containments in nuclear power plants.

10 CFR Part 50 Appendix A provides minimum requirements for the principal design criteria that establish the necessary design, fabrication, construction, testing, and performance requirements for SSCs important to safety to provide reasonable assurance that the facility can be operated without undue risk to the health and safety of the public. GDC 1, 2, 4, 16, and 50 are applicable to U.S. NRC RG 1.136.

> Statement of Conformance: The BWRX-300 SCCV is designed, fabricated, erected, inspected, examined and tested to quality standards commensurate with the importance of the safety functions to be performed in accordance with generally recognized codes and standards, and under an approved QA program with approved control of records. The safety and performance objectives of the regulatory guidance of U.S. NRC RG 1.136 for materials, design, construction, fabrication, examination, and testing of concrete containments are met by following the SCCV design approach provided in Section 6.0.

2.3.8 Regulatory Guide 1.160

RG 1.160, “Monitoring the Effectiveness of Maintenance at Nuclear Power Plants” (Reference 9-30), describes methods that are acceptable to NRC Staff for demonstrating compliance with the provisions of Section 50.65, “Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants,” of 10 CFR Part 50. 10 CFR 50.34(b)(6)(iv) requires an operating license to include a final safety analysis report that includes plans for conduct of normal operations, including maintenance, surveillance, and periodic testing of SSCs.

> Statement of Conformance: As stated in Sections 5.18 and 6.22, an inservice inspection and testing program is established to satisfy the general requirements for examination of the integrated RB to ensure the structure can fulfill its intended functions throughout the design service life of the BWRX-300, in compliance with 10 CFR 50.65 and conforming to the guidance of U.S. NRC RG. 1.160.

2.3.9 Regulatory Guide 1.199

RG 1.199, “Anchoring Components and Structural Supports in Concrete” (Reference 9-31), describes a method acceptable to the NRC Staff for compliance with regulations for the design, installation, testing, evaluation, and QA of anchors (steel embedment’s) used for component and structural supports in concrete. 10 CFR Part 50, Appendix A, GDC 1, 2, and 4; 10 CFR Part 50 Appendix B; and 10 CFR 50 Appendix S are applicable.

> Statement of Conformance: Load bearing steel materials may be used in the connections and for some attachments that require embedment anchors/stiffeners. If used, design of load bearing steel materials embedded in DP-SC structures will meet the requirements of ASME BPVC, 2021 Edition, Section III, Division 2, Subsection CC and conform to the regulatory guidance of U.S. NRC RG 1.199.

2.3.10 Regulatory Guide 1.216

RG 1.216, “Containment Structural Integrity Evaluation for Internal Pressure Loadings Above Design-Basis Pressure” (Reference 9-32), describes the methods that the NRC Staff considers acceptable for: (1) predicting the internal pressure capacity for containment structures above the DBA pressure; (2) demonstrating containment structural integrity related to combustible gas control; and (3) demonstrating containment structural integrity through an analysis that specifically addresses the Commission’s performance goals related to the prevention and mitigation of severe accidents. 10 CFR 50, Appendix A, GDC 50, “Containment Design Basis,” requires that the reactor containment structure and its internal compartments can accommodate, without exceeding the design leakage rate and with sufficient margin, the calculated pressure and temperature conditions caused by an LOCA.

> Statement of Conformance: The leak tightness evaluation of the containment structure, including the SCCV, containment closure head, and other Class MC components, under beyond design basis internal pressure loads conforms to the guidance of U.S. NRC RG 1.216 as discussed in Section 6.23.

2.3.11 Regulatory Guide 1.217

RG 1.217, “Guidance for the Assessment of Beyond-Design-Basis Aircraft Impacts for Aircraft Impact Assessment” (Reference 9-33), describes a method that the NRC Staff considers acceptable regarding the consideration of aircraft impacts for new nuclear power reactors. In particular, this RG endorses the methodologies described in the industry guidance document, NEI 07-13, “Methodology for Performing Aircraft Impact Assessments for New Plant Designs,” Revision 8, dated April 2011. The objective of the aircraft impact rule is to require nuclear power plant designers to rigorously assess their designs to identify design features and functional capabilities that could provide additional inherent protection to withstand the effects of an aircraft impact. The NRC expects this rule to result in new nuclear power reactor facilities that are inherently more robust with regards to an aircraft impact than if they were designed in the absence of the aircraft impact rule. The rule provides an enhanced level of protection beyond that which is provided by the existing adequate protection requirements applicable to currently operating power reactors.

> Statement of Conformance: The BWRX-300 design applies the methodology in NEI 07-13 for the beyond design basis aircraft crash evaluations as discussed in Subsection 5.8.4 of this report. Specific requirements and approaches for aircraft impact explicit dynamic analyses are not in the scope of this report. The beyond design basis evaluation will demonstrate that the containment remains intact, and the fuel pool structural integrity is maintained for safe operations in conformance with the guidance of U.S. NRC RG 1.217.

2.3.12 Regulatory Guide 1.243

RG 1.243, “Safety-Related Steel Structures and Steel-Plate Composite Walls for Other Than Reactor Vessels and Containments,” describes a method acceptable to the NRC Staff for compliance with regulations for the design, fabrication, and erection of safety-related steel structures and SC walls for other than reactor vessels and containments. 10 CFR Part 50, Appendix A, GDC 1, 2, and 4; 10 CFR 50 Appendix B; and 10 CFR Appendix S are applicable. This guide endorses, with exceptions and clarifications, the procedures and standards of the ANSI/AISC N690 code.

> Statement of Conformance: The analysis, design, fabrication, construction, inspection, examination and testing of the non-containment Seismic Category I DP-SC structures discussed in Section 5.0 of the report follow the regulatory guidance of U.S. NRC RG 1.243.

2.4 CNSC Regulatory Requirements and Guidance

CNSC regulatory requirements and guidance are evaluated to determine compliance, to establish the use of the graded approach, or justify an alternative approach, where applicable. The information below is provided to assist the CNSC in their review with the purpose of soliciting feedback in support of licensing activities for the deployment of the BWRX-300 in Canada, and for the purpose of facilitating collaborative review by the NRC and CNSC regarding the proposed use of SC materials for the BWRX-300 Seismic Category A integrated RB. This information is complementary to details provided in the Licence to Construct Application. As outlined in the application, design principles for the BWRX-300 structures are provided in a graded manner commensurate to their importance to safety. Use of the graded approach is considered for the GEH BWRX-300 SC materials, in accordance with REGDOC-1.1.5, “Supplemental Information for Small Modular Reactor Proponents” (Reference 9-34) used in conjunction with REGDOC-1.1.2, “Licence Application Guide: Licence to Construct a Reactor Facility” (Reference 9-35).

2.4.1 CNSC Regulatory Document REGDOC-1.1.2

REGDOC-1.1.2, “Licence Application Guide: Licence to Construct a Reactor Facility”

Regulatory Requirement: REGDOC-1.1.2, Section 4.3.2 includes requirements for presenting information on procedures that will be implemented for the construction and commissioning of the reactor facility in accordance with REGDOC-2.3.1, "Conduct of Licensed Activities: Construction and Commissioning Programs" (Reference 9-36). The requirement includes the overall process to be followed to satisfactorily complete the concrete work during the construction phase, including fabrication and placing requirements for reinforcing systems of concrete containments and confinements to comply with the relevant design and construction drawings.

> Statement of Compliance: Requirements in Sections 5.16 and 6.15 of this report contribute to the compliance of REGDOC-1.1.2, Section 4.3.2 for the fabrication and construction of the integrated RB structures, including the SCCV. Information in Sections 5.16 and 6.15 is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-1.1.2, Section 4.3.2 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-1.1.2, Section 4.5.5 describes the requirements for presenting relevant information on the design of the site layout and on civil engineering works and structures associated with the nuclear facility, with sufficient detail for CNSC staff to verify that the design is in accordance with Sections 7.15 and 8.6.2 of REGDOC-2.5.2, "Design of Reactor Facilities: Nuclear Power Plants" (Reference 9-37).

> Statement of Compliance: This report contributes to the compliance of REGDOC-1.1.2, Section 4.5.5, by providing the design approaches for the integrated RB structures, including the SCCV. Information in Sections 5.0 and 6.0 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-1.1.2, Section 4.5.5 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-1.1.2, Section 4.5.6 includes requirements for relevant information on pressure- or fluid-retaining SSCs in accordance with REGDOC-2.5.2, including pressure boundary standards and codes.

> Statement of Compliance: This report contributes to the compliance of REGDOC-1.1.2, Section 4.5.6 for pressure- or fluid-retaining SSCs by providing the material, design, construction and inspection requirements for the SCCV in Section 6.0. Information in Section 6.0 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-1.1.2, Section 4.5.6 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-1.1.2, Section 4.5.9 describes the requirements for presenting information on safety systems as defined in REGDOC-2.5.2, which includes SSCs supporting containment and means of confinement to limit the consequences of anticipated operational occurrences or DBAs.

> Statement of Compliance: The proposed design approach for the SCCV structure, which acts as a leak-tight pressure boundary and provides radiation shielding, presented in Section 6.0 of

this report contributes to the compliance of REGDOC-1.1.2, Section 4.5.9. Information in Section 6.0 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-1.1.2, Section 4.5.9 as described in this report and in conjunction with information presented in the Licence to Construct Application.

2.4.2 CNSC Regulatory Document REGDOC-1.1.5

REGDOC-1.1.5, *Supplementary Information for Small Modular Reactor Proponents*

Regulatory Requirement: REGDOC-2.5.2, Section 3.1 details the use of the graded approach, which an applicant may use to address CNSC requirements in a manner that is commensurate with the novelty, complexity and potential for harm that the activity represents. The graded approach is a method or process by which elements such as the level of analysis, the depth of documentation and the scope of actions necessary to comply with the requriements are commensurate with the following:

- Relative risks to health, safety, security, the environment, and the implementation of international obligations to which Canada has agreed
- Characteristics of a facility or activity

Statement of Compliance: This report contributes to the compliance of REGDOC-1.1.5, Section 3.1 for the acceptability of use of DP-SC modules for the construction of the integrated RB structures. Information in Sections 5.0 and 6.0 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-1.1.5, Section 3.1 as described in this report and in conjunction with information presented in the Licence to Construct Application.

2.4.3 CNSC Regulatory Document REGDOC-2.5.2

REGDOC-2.5.2, “Design of Reactor Facilities: Nuclear Power Plants”

Regulatory Requirement: REGDOC-2.5.2, Section 5.4 requires identification of the codes and standards that are used for the plant design, and an evaluation of those codes and standards for applicability, adequacy, and sufficiency to the design of required SSCs.

Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 5.4 for the identification of codes and standards used for the BWRX-300 integrated RB structural design. Information in Sections 5.0 and 6.0 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 5.4 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 6.1.1 requires that the design provides multiple physical barriers to the uncontrolled release of radioactive materials to the environment, which include the containment.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 6.1.1 for integrity of physical barriers to ensure defense-in-depth is maintained. The integrated RB proposed design requirements presented in Sections 5.0 and 6.0 of this report ensure the safety functions of the structure under design basis and beyond design basis conditions. Information in Sections 5.0 and 6.0 is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 6.6.1 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 6.6 requires development of a facility layout that considers postulated initiating events to enhance protection of required SSCs with the final design reflecting an assessment of options, demonstrating that an optimized configuration has been sought for the facility layout.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 6.6 for the BWRX-300 facility layout. Information on the facility layout is presented in Section 3.0. BWRX-300 overall design approach, design loads and load combinations are presented in Section 4.0. Design requirements for protection against external and internal impactive hazards are addressed in Sections 5.8, 5.13, 6.10, 6.20, and 6.23. Information in this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2 Section 6.6 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Sections 7.4.1 and 7.4.2 require that SSCs important to safety be designed and located in a manner that minimizes the probability and effects of hazards (e.g., fires and explosions) caused by external or internal events, and that all natural and human-induced external hazards that may be linked with significant radiological risk be identified. External hazards which the plant is designed to withstand are to be selected and classified as DBAs or Design Extension Conditions (DECs) as subset of BDBAs.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Sections 7.4.1 and 7.4.2 for internal and external hazards assessed for the BWRX-300 integrated RB. Information in Sections 3.0, 4.0, 5.8, 5.13, 6.10, 6.20, and 6.23 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Sections 7.4.1 and 7.4.2 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 7.7 requires that all pressure-retaining SSC be protected against overpressure conditions, and be classified, designed, fabricated, erected, inspected, and tested in accordance with established standards. Section 7.7 also requires that, for DECs, relief capacity be sufficient to provide reasonable confidence that pressure boundaries credited in severe accident management will not fail.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 7.7 for pressure-retaining SSCs. The loads and load combinations discussed in Section

> 4.3 and the proposed design requirements for the SCCV presented in Section 6.0 ensure the SCCV can perform its safety functions under design basis and beyond design basis conditions. Information in Sections 4.3 and 6.0 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 7.7 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 7.12.1 requires that provisions for fire safety be included in design of buildings and structures.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 7.12.1 for DP-SC modules fire protection. Information in Sections 5.13 and 6.20 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2 Section 7.12.1 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirements: REGDOC-2.5.2, Section 7.13.1 requires that the seismically qualified SSCs important to safety be qualified to a Design Basis Earthquake (DBE), that the design of these SSCs meets the DBE criteria to maintain all essential attributes, such as pressure boundary integrity, leak tightness and operability in the event of a DBE and that SSCs credited to function during and after a BDBA be capable of performing their intended function under the expected condition.

> Statement of Compliance: The proposed design rules presented in Sections 5.0 and 6.0 of this report ensure that the pressure boundary integrity, leak tightness and structural integrity of the integrated RB, and the safety functions of SSCs, are maintained during and following DBE and BDBAs. Information in this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 7.13.1 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 7.15.1 requires that the environmental effects be considered in the design of civil structures and the selection of construction materials, and that the choice of construction material be commensurate with the design service life and potential life extension of the plant.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 7.15.1 for design of the integrated RB structures. Environmental effects are considered in the design of the structures as demonstrated by the loads discussed in Section 4.3 and the alternative design requirements presented in Sections 5.0 and 6.0. Information in Sections 5.0 and 6.0 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 7.15.1 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 7.15.2 requires that the design enables implementation of periodic inspection programs for structures important to safety in order to verify that the as-constructed structures meet their functional and performance requirements.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 7.15.2 for inservice inspection and testing of the integrated RB structures, including the SCCV. Information in Sections 5.18 and 6.22 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 7.15.2 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 7.15.3 requires that the lifting and handling of large and heavy loads, particularly those containing radioactive material be considered in the design.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 7.15.3 for the design of the integrated RB structures. Information in Sections 5.8 and 6.10 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 7.15.3 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 7.17 requires that the design takes due account of the effects of aging and wear on SSCs, including additional requirements provided in REGDOC-2.6.3, "Aging Management" (Reference 9-38).

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 7.17, including the additional requirements provided in REGDOC-2.6.3 (addressed in Subsection 2.4.4), for aging and wear. Information in Sections 5.18 and 6.22 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 7.17 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 7.22 requires that the design provides physical features such as protection against Design Basis Threats (DBTs), in accordance with the requirements of the Nuclear Security Regulations.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 7.22 for robustness against malevolent acts. Information in Sections 5.0 and 6.0 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 7.22 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 8.6 requires that each nuclear power reactor be installed within a containment structure, to minimize the release of radioactive materials to the environment during operational states and DBAs. Containment is to also assist in mitigating the consequences of DECs. In particular, the containment and its safety features are to be able to perform their credited functions during DBAs and DECs, including melting of the reactor core. To the extent practicable, these functions shall be available for events more severe than DECs.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 8.6 for the BWRX-300 containment. As described in Section 3.0, the BWRX-300 containment is completely enclosed within the RB to protect it from external hazards and to minimize the release of radioactive materials to the environment during operational states and DBAs. Design requirements presented in Sections 5.0 and 6.0 of the report ensure the safety functions of the RB and SCCV during DBAs and DECs and meet the requirements of Section 8.6.12 for containment leak-tightness and control of fission products release following the onset of core damage. Information in Sections 5.0 and 6.0 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 8.6 as described in this report and in conjunction with information presented in the Licence to Construct Application.

2.4.4 CNSC Regulatory Document REGDOC-2.6.3

REGDOC-2.6.3, “Aging Management”

Regulatory Requirement: REGDOC-2.6.3, Section 2 requires that the design considers aging and obsolescence of SSCs, including systematic and integrated approaches to aging management.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.6.3, Section 2 for aging and obsolescence management of SSCs. Information in Sections 5.18 and 6.22 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.6.3, Section 2 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.6.3, Section 3 requires that appropriate measures be taken in design to facilitate proactive and effective aging management throughout the lifetime of the reactor facility.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.6.3, Section 3 for proactive strategy for aging management. Information in Sections 5.18 and 6.22 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.6.3, Section 3 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.6.3, Section 4.3 requires that a document screening process be used to establish a list of SSCs to be included in the scope of the overall integrated aging management program framework.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.6.3, Section 4.3 for screening and selection of SSCs for inclusion in the scope of the overall integrated aging management program. Information in Sections 5.18 and 6.22 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.6.3, Section 4.3 as described in this report and in conjunction with information presented in the Licence to Construct Application.

2.5 Canadian Codes and Standards

The following CSA Group (CSA) standards govern the design, construction, inspection and testing of the BWRX-300 nuclear structures categorized in accordance with the Canadian regulatory guidance as Seismic Category A.

2.5.1 CSA N291 Standard

The design and construction of the BWRX-300 non-containment Seismic Category A structures, including the RB structures surrounding the containment and the containment internal structures, meet the safety and performance objectives of CSA N291 (Reference 9-39) standard following the regulatory guidance of REGDOC-2.5.2, Sections 7.15.1 and 8.6.8.

The design of the BWRX-300 non-containment Seismic Category A structures is in accordance with Clause 6.1.2 of CSA N291 that permits the use of alternate design methods not covered by the CSA standards that do not provide guidance for the design of SC structures. By following the provisions of ANSI/AISC N690, Appendix N9, supplemented by the regulatory guidance of U.S. NRC RG 1.243 and the proposed design rules provided in Section 5.0 of this report, the design, construction, testing and inspection of the BWRX-300 non-containment DP-SC structures ensure a level of safety and performance commensurate with the requirements of CSA N291, CSA S16 (Reference 9-40) (for steel) and CSA A23.1/A23.2 (Reference 9-41) and CSA A23.3 (Reference 9-42) (for concrete) design standards. The BWRX-300 design for impactive and impulsive loads discussed in Section 5.8 of the report satisfies the requirements of CSA N291, Clauses 6.1.3, A.2.2 and A.2.3 in addition to the local and global response criteria of Clause A.5.

For BWRX-300 Small Modular Reactors (SMRs) built in Canada, specifically for non-containment Seismic Category A structures, applicable CSA N291 material, fabrication, construction, inspection, examination, testing and quality assurance requirements may be followed as an alternative to the requirements presented in Section 5.0 of the report, as shall be specified in a project specific implementation specification.

Per the guidance of REGDOC-2.6.3, Section 2.2, the approach implemented for the aging management of non-containment Seismic Category A structures in Canada follow the requirements of CSA N291, Clause 10.

2.5.2 CSA N287 Standard Series

Per the guidance of Section 7.15.1 and Appendix A of REGDOC-2.5.2, the design and construction of the BWRX-300 SCCV meet the applicable safety and performance objectives of the CSA N287 series of standards for concrete containment structures for nuclear power plants, including:

- General requirements of CSA N287.1 (Reference 9-43)
- Material requirements of CSA N287.2 (Reference 9-44)
- Design requirements of CSA N287.3 (Reference 9-45)
- Construction, fabrication and installation requirements of CSA N287.4 (Reference 9-46)
- Construction examination and testing requirements of CSA N287.5 (Reference 9-47)

The CSA N287 series of standards does not include provisions for SC containments. Clause 4.3 of CSA N287.3 permits the use of alternate design methods for design of concrete containments in Canada. The SCCV material, design, construction, fabrication, inspection and examination requirements discussed in Section 6.0 of this report ensure a level of safety and performance commensurate with CSA N287 standard series. As noted in Subsection 6.23.1 of this report, the internal pressure capacity of the BWRX-300 containment is at least twice the DBA internal pressure in accordance with CSA N287.3. The BWRX-300 design for impactive and impulsive loads discussed in Section 5.8 of the report satisfies the local and global response criteria of CSA N287.3, Clause B.4.

In accordance with the regulatory guidance of REGDOC-2.5.2, Section 7.15.2, the BWRX-300 containment requirements for:

- Pre-operational pressure and leakage rate testing in Section 6.17 meet the applicable provisions of CSA N287.6 (Reference 9-48)
- Inservice examination and testing in Section 6.22 meet the applicable provisions of CSA N287.7 (Reference 9-49)

The aging management and maintenance programs implemented for the BWRX-300 containment follow the requirements of CSA N287.8 (Reference 9-50).

For BWRX-300 SMRs built in Canada, applicable CSA N287 material, fabrication, construction, inspection, examination, testing and quality assurance requirements may be followed as an alternative to the requirements presented in Section 6.0 of the report, as shall be specified in a project specific implementation specification. Additional Canadian site-specifc requirements related to the containment examination and testing, aging management and maintenance programs, beyond those discussed in Section 6.22, will also be addressed in the project specific implementation specification.

2.5.3 CSA N289 Standard Series

Per Section 7.13 of REGDOC-2.5.2, the seismic qualification of the BWRX-300 structures meets the applicable requirements of the CSA N289 standard series. The specific requirements for seismic analysis of the deeply embedded BWRX-300 integrated RB structures provided in Section 5.0 of NEDO-33914-A meet the safety objectives of CSA N289.3 (Reference 9-51). The seismic design of the BWRX-300 structures meets the safety objectives of CSA N289.3, Clause 7 and the applicable requirements of CSA N291, Clause 6.10 for the seismic design of non-containment Seismic Category A structures and CSA N287.3, Clause 11 for the seismic design of concrete containments. The beyond design basis seismic robustness of the integrated RB is evaluated following the guidance of CSA N289.1, Annex F.

2.5.4 CSA N293

Per Section 7.12.1 of REGDOC-2.5.2, the BWRX-300 DP-SC containment and non-containment Seismic Category A structures are designed to be fire resistant as discussed in Sections 5.13 and 6.20 of the report. The fire resistance rating of the BWRX-300 containment and non-containment Seismic Category A structures is evaluated per the methodology presented in Section 5.13 of the report and will comply with the fire resistance rating requirements of CSA N293 (Reference 9-52).

2.5.5 CSA N286 Standard Series

The requirements of the CSA N286 series for the life cycle activities management of the BWRX-300 DP-SC containment and non-containment structures in Canada are applicable and shall be followed.

Computer programs used in the analyses of the BWRX-300 integrated RB structures are verified in accordance with NEDO-11209-A which complies with CSA N286.7 (Reference 9-53).

2.5.6 CSA N299 Standard Series

The CSA N299 (Reference 9-54) quality assurance program requirements for the supply of items and services of BWRX-300 DP-SC non-containment structures in Canada may be followed as an alternative to the requirements presented in Section 5.0, as shall be specified in a project specific implementation specification.

2.6 Generic Issues

The following generic issues are provided based on their relevance to the scope of this report, and an up-to-date evaluation of generic issues is to be provided during future licensing activities by GEH in support of a 10 CFR 50 CP application or by a license applicant for requesting an operating license under 10 CFR 50.

NUREG/CR-7193, "Evaluations of NRC Seismic Structural Regulations and Regulatory Guidance, and Simulation Evaluation Tools for Applicability to Small Modular Reactors (SMRs)," (Reference 9-55) for the design of deeply embedded SMRs identified specific areas of concerns related to the subgrade characterization, development of proper input parameters for the SSI analysis, and stability of deeply embedded SMRs.

The innovative approaches presented in NEDO-33914-A, Sections, 3, 4, and 5 address these concerns ensuring a proper design of the deeply embedded BWRX-300 integrated RB.

U.S. NRC Information Notice (IN) 86-99 (Reference 9-56) issued on December 8, 1986, Supplement 1: Degradation of Steel Containments in response to the discovery of significant corrosion on the external surface of the carbon steel drywell in the sand bed region of the Oyster Creek plant. Corrosion protection of the SCCV surfaces is discussed in Section 6.19 of this report.

U.S. NRC IN 89-79 (Reference 9-57) issued on December 1, 1989, degraded coatings, and the corrosion of steel containment vessel. Duke Power Company reported significant coating damage and base metal corrosion on the outer surface of the steel shell of the McGuire Unit 2 containment which was discovered during a pre-integrated leak rate test inspection. Subsequently, Duke Power identified similar degradation of the McGuire Unit 1 containment, which is essentially identical to the Unit 2 structure. The NRC regulations (Appendix J to 10 CFR Part 50) require that a general visual inspection of the accessible surfaces in the containment be performed before each integrated leak rate test. The purpose of this inspection is to identify any evidence of structural deterioration or other problems that may affect containment integrity or leak tightness. As a result of these and other inspections, several instances of containment wall thinning due to corrosion have been discovered during the past 3 years at operating power reactors. However, the visual inspections done in connection with the integrated leak rate tests are only required to be performed three times in each 10-year period. In addition, because of the physical arrangement of plant systems, the steel in the annular spaces of some containments may not be easily accessible to the visual inspections associated with leak tests. Considering the frequency and severity of recent instances of containment degradation due to corrosion, additional efforts to inspect steel containment surfaces potentially susceptible to corrosion may be prudent.

The corrosion protection of the integrated RB DP-SC modules is addressed in Sections 5.15 and 6.19 of this report. The inservice inspection of the integrated RB structures is addressed in Sections 5.18 and 6.22.

3.0 DESCRIPTION OF THE BWRX-300 INTEGRATED REACTOR BUILDING

3.1 Background

The BWRX-300 integrated RB consists of the RB structure enclosing the containment, the containment structure comprised of the SCCV, containment closure head and other Class MC components, and the containment internal structures. The integrated RB is the only BWRX-300 Seismic Category I structure.

The BWRX-300 integrated RB is constructed using SC modules to maximize its safety performance during the operational and decommissioning life of the plant and to optimize the construction cost and schedule. The BWRX-300 integrated RB is deeply embedded so that the majority of the RPV, SCCV structure, and other important systems and components required for accidents mitigation and safe shutdown are located below grade to mitigate the effects of possible external events, including aircraft impact and adverse weather.

Current design codes do not address the use of SC systems as a containment pressure boundary. Therefore, design rules for the SCCV are proposed in Section 6.0 that are based on the ASME BPVC, Section III, Rules for Construction of Nuclear Facility Components, Division 2, Code for Concrete Containments, Subsection CC, Concrete Containments, Articles CC-1000 through CC-6000, for materials, design, fabrication, construction, examination and testing for the BWRX-300 SCCV, including Division 2 Appendices to the extent they apply to an SC containment without reinforcing steel or tendons. Design rules for the RB and containment internal structures that are not part of the containment pressure boundary follow existing codes and standards for design of SC structures with proposed modifications provided in Section 5.0 to cover design elements beyond the scope of current codes and standards.

The SC modules used in the construction of the BWRX-300 integrated RB consist predominantly of SC modules with diaphragm plates referred to as DP-SC modules (see Section 3.4 for details). The proposed design approaches for the RB, containment internal structures and SCCV using these SC modules are supplemented by a test program that is being performed under the NRIC Advanced Construction Technology (ACT) project in the United States. This program is known as the NRIC Demonstration Project and is described in Section 7.0.

3.2 BWRX-300 General Description

The BWRX-300 is an approximately 300 MWe, water-cooled, natural circulation SMR utilizing simple safety systems driven by natural phenomena. It is being developed by GEH in the USA and Hitachi-GE Nuclear Energy Ltd. (HGNE) in Japan. It is the tenth generation of the BWR. The BWRX-300 is an evolution of the U.S. NRC-licensed, 1,520 MWe Economic Simplified Boiling Water Reactor (ESBWR). Target applications include base load electricity generation and load following electrical generation.

The BWRX-300 containment design is based upon GEH BWR experience and fleet performance, including the following features:

- Containment size comparable to a small BWR drywell
- Containment peak accident pressure and temperatures within existing BWR experience base

- Containment load simplified when compared to conventional BWRs with pressure suppression containments
- Nitrogen inerted containment same as BWR Mark I and Mark II containments
- Pressure and temperature during normal operation maintained by fan coolers, similar to existing BWRs
- Upon loss of active containment cooling, heat removal achieved by the Passive Containment Cooling System (PCCS)

The BWRX-300 Power Block consists of several structures as shown in Figure 3-1. Each structure houses components that perform the various functions which result in the generation of electricity in the Turbine Building. The integrated RB is the circular structure in Figure 3-1. The integrated RB houses the main function of steam generation and is separated from the rest of the Power Block structures by seismic gaps, limiting the physical interaction between its structure and the adjacent Power Block structures during a seismic event. Figure 3-2 provides a Three-Dimensional (3D) view of the Power Block Structures. The Power Block layout shown in Figures 3-1 and 3-2 is for information only and may be optimized and changed based on the site-specific conditions.

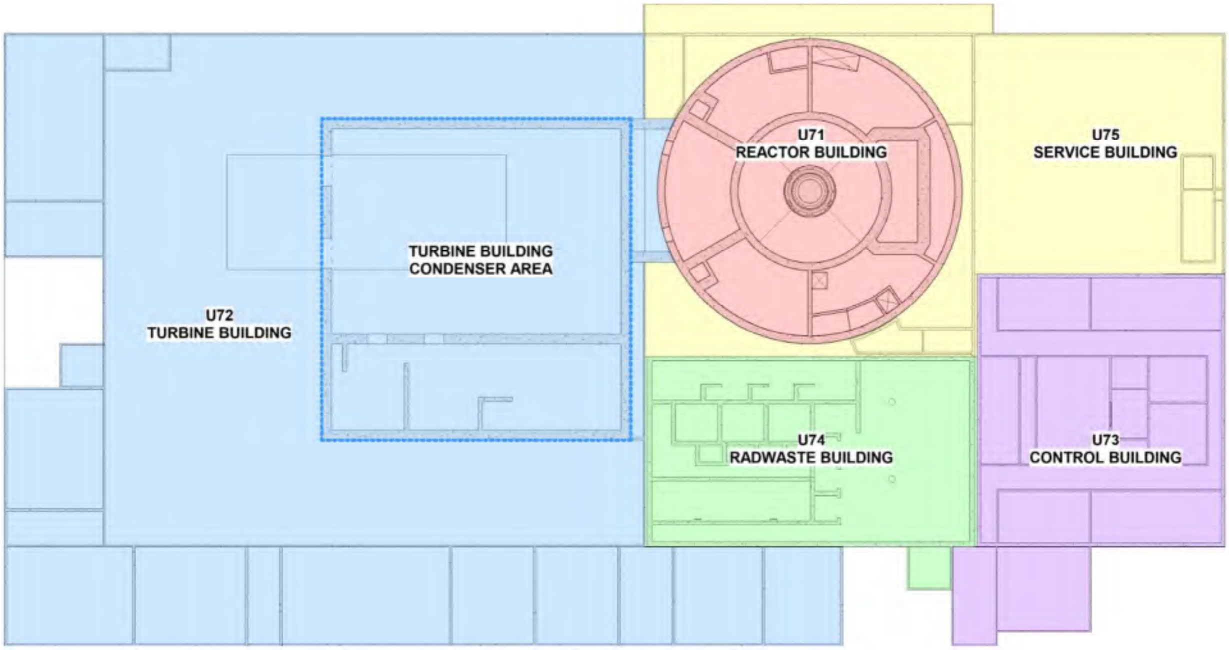


Figure 3-1: BWRX-300 Power Block Plan View

* For information only. Layout may be optimized and changed based on site-specific conditions.

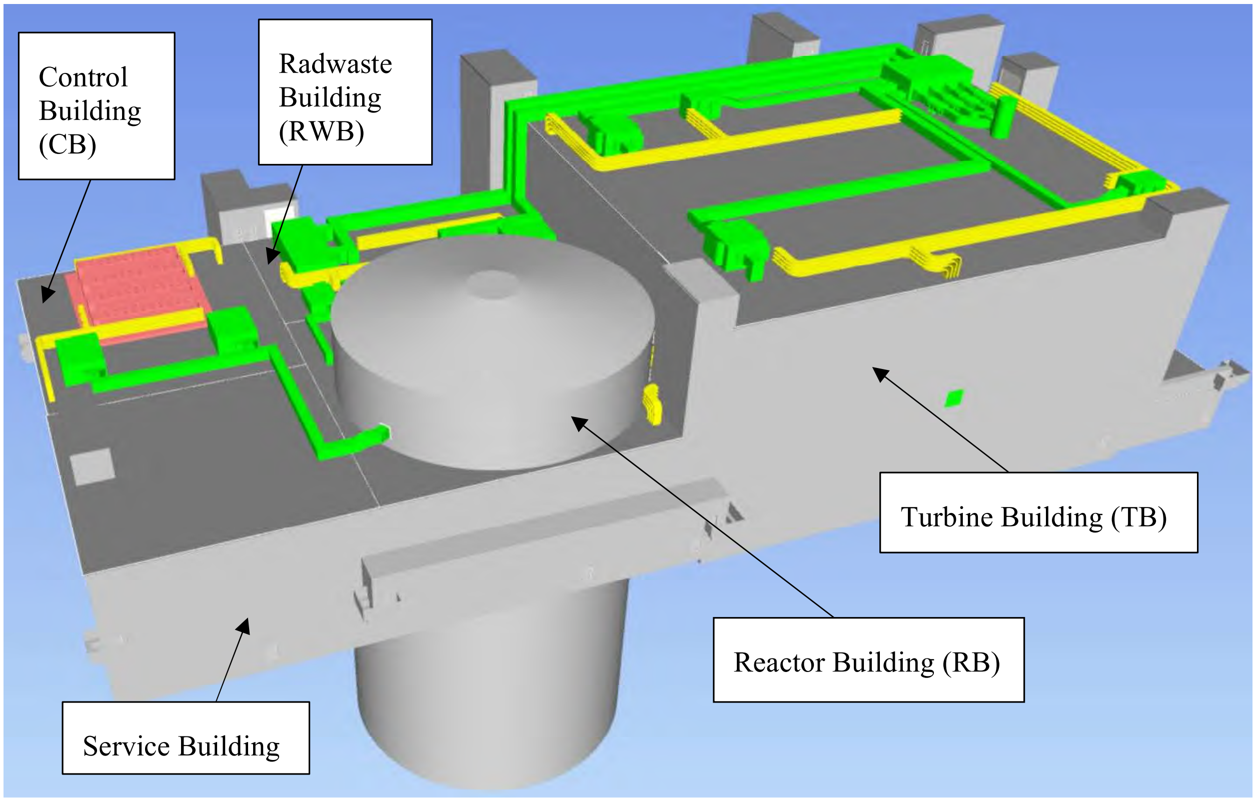


Figure 3-2: BWRX-300 Power Block Three-Dimensional View

* For information only. Layout may be optimized and changed based on site-specific conditions.

3.3 Integrated Reactor Building Structures Overview

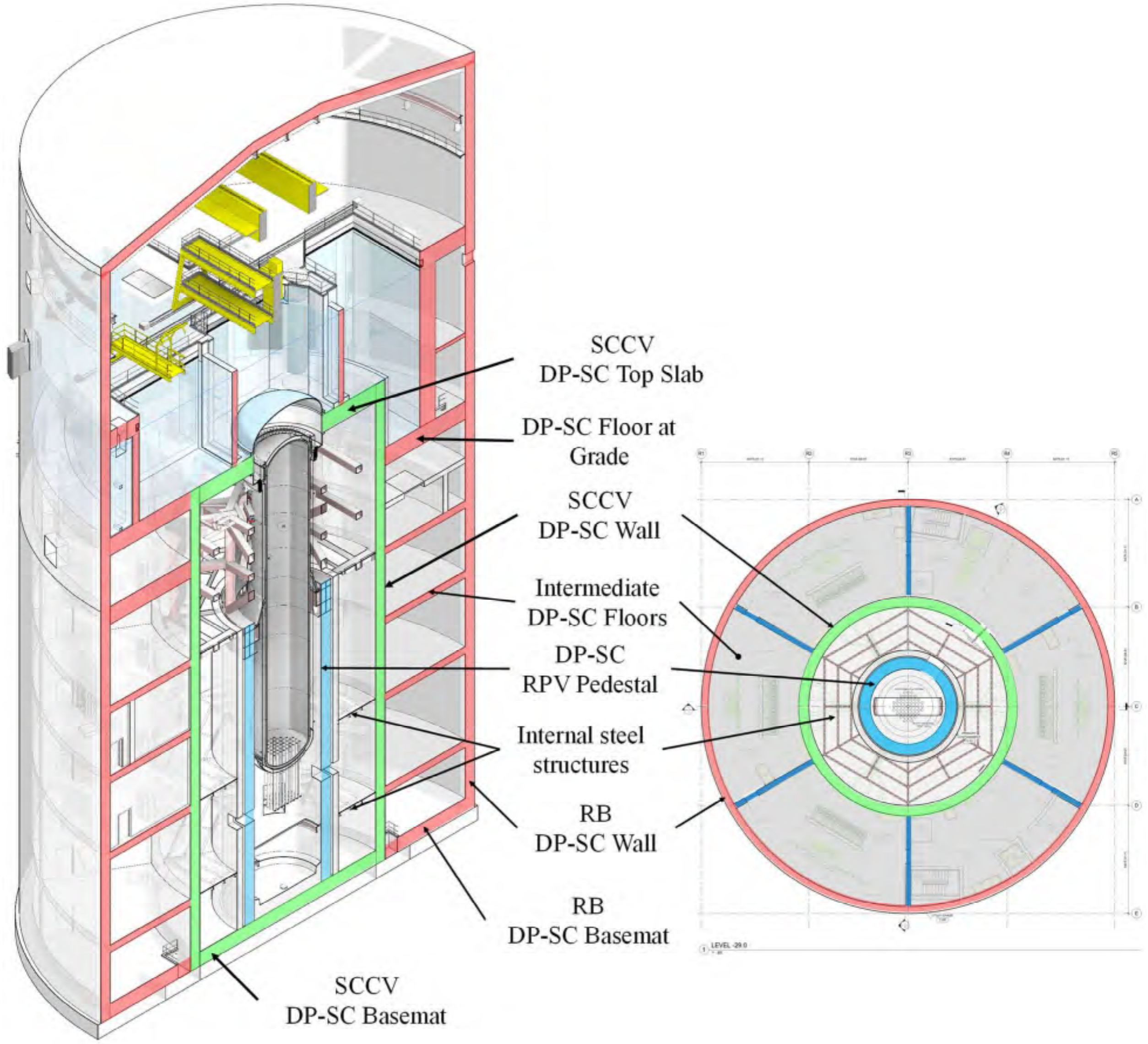
The BWRX-300 RB structure is a cylindrical-shaped, shear wall building that is deeply embedded to an approximate depth of 36 meters below grade. Figure 3-3 and Figure 3-4 show the 3D and orthogonal representation, respectively, of a typical integrated RB cross-section and depict the finished grade level. In these figures, the boundary of the RB structure is shown in red and the containment is shown in green.

The walls, floors, roof, and mat foundation of the RB structure are primarily constructed using DP-SC modules. The below-grade portion of the RB houses the containment and containment internal structures as well as the RPV and safety systems, and the majority of vital and non-vital power supplies and equipment. The above grade portion of the RB structure houses the refueling floor, refueling and fuel handling systems, fuel pool, water needed for the BWRX-300 passive cooling systems, and polar crane. The RB protects the containment structure from external hazards (i.e., wind loads, fires, floods, tornado loads, aircraft hazard, missiles) and external beyond design basis scenarios (i.e., aircraft impact, blast impact).

The SCCV portion of the containment consists of a cylindrical wall, mat foundation and top slab constructed using DP-SC modules. The metal containment closure head and other metal components (i.e., personnel/equipment hatches, mechanical and electrical penetrations) not backed by concrete at the containment boundary are ASME Class MC components.

The SCCV houses the containment internal structures which includes the DP-SC pedestal that supports the RPV, the Containment Equipment and Piping Support Structure (CEPSS), main steam pipes and other safety important equipment. The SCCV also houses the bioshield SC wall that together with the RPV pedestal provides shielding around the fuel core. The bioshield is a standalone structure separated from the RPV pedestal by a seismic gap. The bioshield is designed per the requirements of ANSI/AISC N690 as supplemented by U.S. NRC RG 1.243 in addition to Section 5.12 of this report. The bioshield and SCCV walls support the lower elevation containment steel platforms at Levels -21 m and -29 m as shown in Figure 3-4.

The RB, containment and containment internal structures are integrated at the DP-SC mat foundation. The RB and SCCV structures are also integrated at the wing walls and floor slabs, including the pool slab and walls. Floor slabs that integrate the RB exterior wall and SCCV wall are connected with either rigid, semi-rigid, pinned or released connections. Connections are designed per the requirements in Sections 5.11, 6.11, and 6.14 of this report. Failure of these connections has no impact on the pressure-retaining function of the containment. The BWRX-300 integrated RB including walls, floors, and RB roof act in an integrated manner to provide suitable load path for gravity and lateral loads.



(a) Three dimension section elevation

(b) Typical Plan below grade

[[{3}]]

Figure 3-3: Three-Dimensional Depiction of Integrated Reactor Building

*For information only. Integrated RB layout is based on current design. Layout may change as the design progresses.

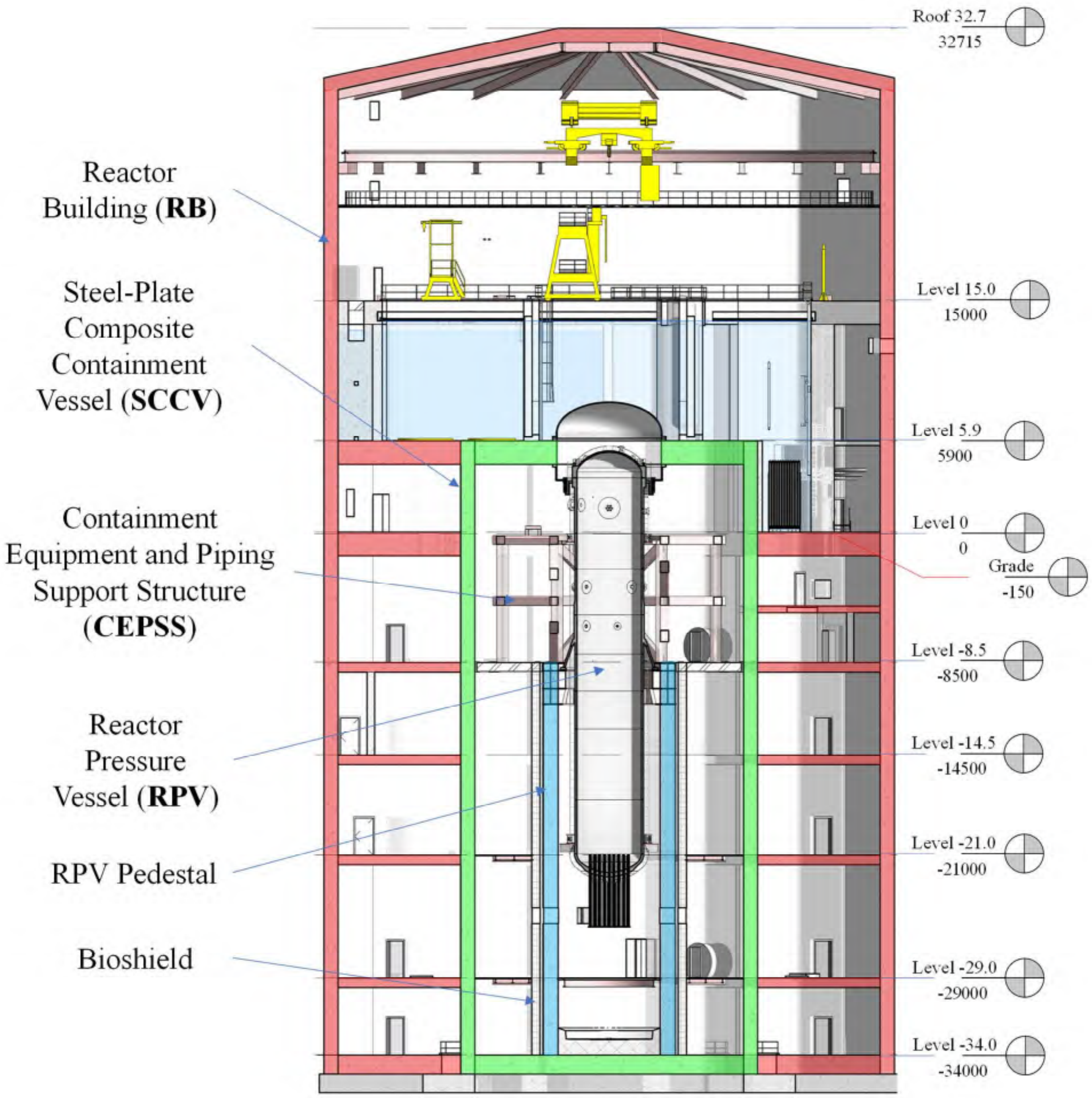


Figure 3-4: Section View of Integrated Reactor Building

*For information only. Integrated RB layout is based on current design. Layout may change as the design progresses. Elevations provided in m/mm.

3.4 Steel-Plate Composite Structures

SC structures are proven structural systems with demonstrated structural performance that enable ease of fabrication and construction and have been widely used in the commercial and nuclear industry.

SC structural modules are constructed by placing concrete between two steel faceplates that serve as the main reinforcement and permanent formwork. Steel ties and steel anchors, such as steel headed stud anchors, are used in the SC modules to develop the composite action between the concrete and the faceplates and to maintain the strain compatibility between the concrete and steel.

SC modules can be categorized into two groups based on the steel ties' configuration as illustrated in Figure 3-5. In the first group (Figure 3-5(a)), discrete tie bars, having round or rectangular cross-section, are used to connect the two faceplates and provide the composite action. This type of SC modules is referred to in this report as "conventional SC modules". Before concrete casting, the stiffness and strength of the empty modules are provided by the ties along with the steel faceplates. After concrete casting, the ties provide structural integrity to the composite section by preventing delamination of the plain concrete core and serving as out-of-plane shear reinforcement. Additional shear stud anchors may be used to anchor the steel faceplates to the concrete infill and control faceplates local buckling. SC walls may have sleeves for penetrations and embedded plates for attachments. Conventional SC modules have first been employed in Japan for construction of containment internal structures of a number of operating pressurized water reactors. In the U.S, the Westinghouse designed and U.S. NRC certified AP1000® pressurized water reactor uses conventional SC structural modules.

In the second group (Figure 3-5(b)), continuous diaphragm plates with holes to allow the flow of concrete are used to attach the two faceplates and provide the composite action between the steel faceplates and the concrete core. This type of SC modules is referred to in this report as Diaphragm Plate Steel-Plate Composite (DP-SC) modules. Before concrete casting, the diaphragm plates and steel faceplates provide stiffness and strength to the empty steel modules. When compared to conventional SC designs, DP-SC modules can have greater stiffness and stability in the empty module configuration due to the continuous support provided by the diaphragm plates to the steel faceplates. After concrete casting, the diaphragm plates provide structural integrity to the composite section by preventing delamination of the plain concrete core. Additionally, the diaphragm plates and headed studs steel anchors provide composite action between the steel faceplates and the concrete infill, and out-of-plane shear reinforcement for the composite section.

As shown in Figure 3-5(b), DP-SC modules can be built by welding a series of components:

(A) Multi-web components: straight or curved faceplates are connected by multi-diaphragm plates

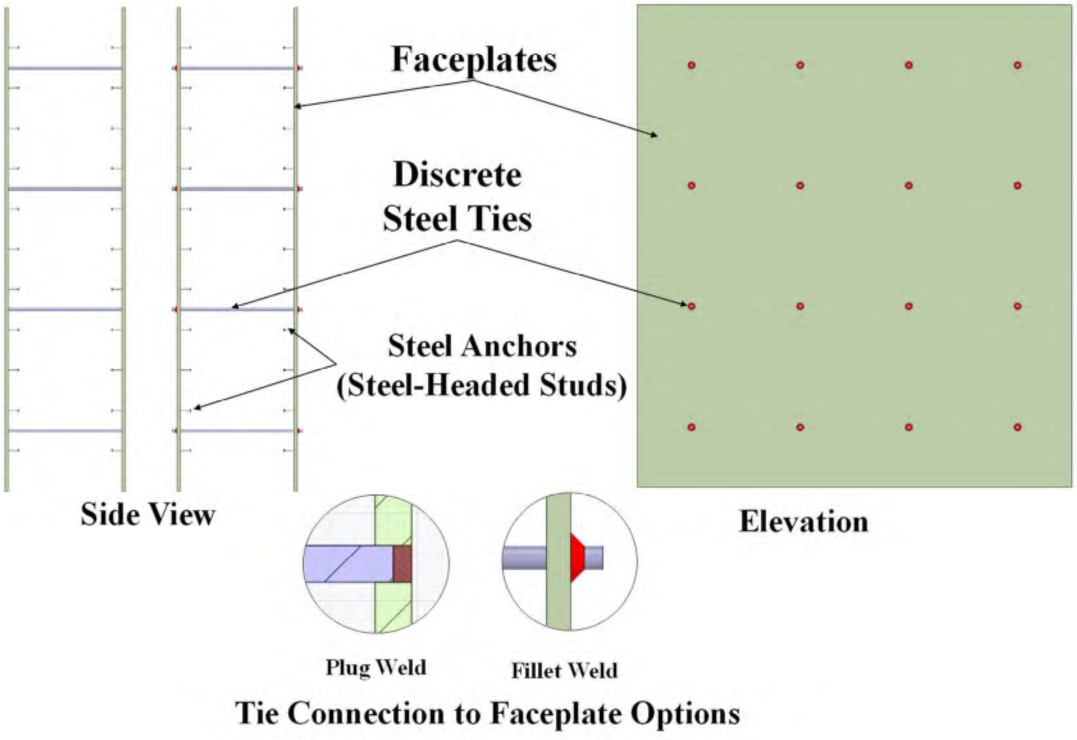
(B) Single web I-shape components: built-up or hot rolled I-beams having web holes, or castellated and cellular beams

(C) Single web U-shape components: steel channels having web holes, or Steel Bricks™ where a steel plate is first profiled and then bent into an L shape, after which the L-shaped elements are welded to each other to make U-shaped bricks

A DP-SC module system, including Steel Bricks™, consists of multiple components (or bricks) arranged and welded together to form a module. Each component consists of an individual steel element. The DP-SC modules are spliced together to form structural walls, floors, or mat foundation sections as shown in Figure 3-6. The DP-SC faceplates can be straight or curved in the multi-web DP-SC modules. For straight modules, the diaphragm plates are welded directly to the planar faceplates per the design configuration. For curved modules, faceplates are rolled first, then the diaphragm plates are welded to the curved faceplates to create a curved multi-web DP-SC subassembly. For multi-web DP-SC components, the DP-SC faceplate can have a different thickness and/or steel grade as compared to the diaphragm plate due to design demands or shielding requirements.

For all DP-SC configurations, the stiffness depends on the faceplates and the concrete infill as discussed in Section 5.5. The steel faceplates and diaphragm plates contribute to the out-of-plane flexural capacity, whereas the diaphragm plates develop the out-of-plane shear capacity. The in-plane shear capacity is developed by the steel faceplates.

The diaphragm plates are either welded to the steel faceplates to develop their capacity as in configuration (A), hot-rolled as in configuration (B), or made of the same plate and bent then welded with Complete-Joint-Penetration (CJP) welds as in configuration (C). In either configuration (A, B, or C), the structural performance of the components is equivalent, as each configuration consists of faceplates and fully developed diaphragm plates.



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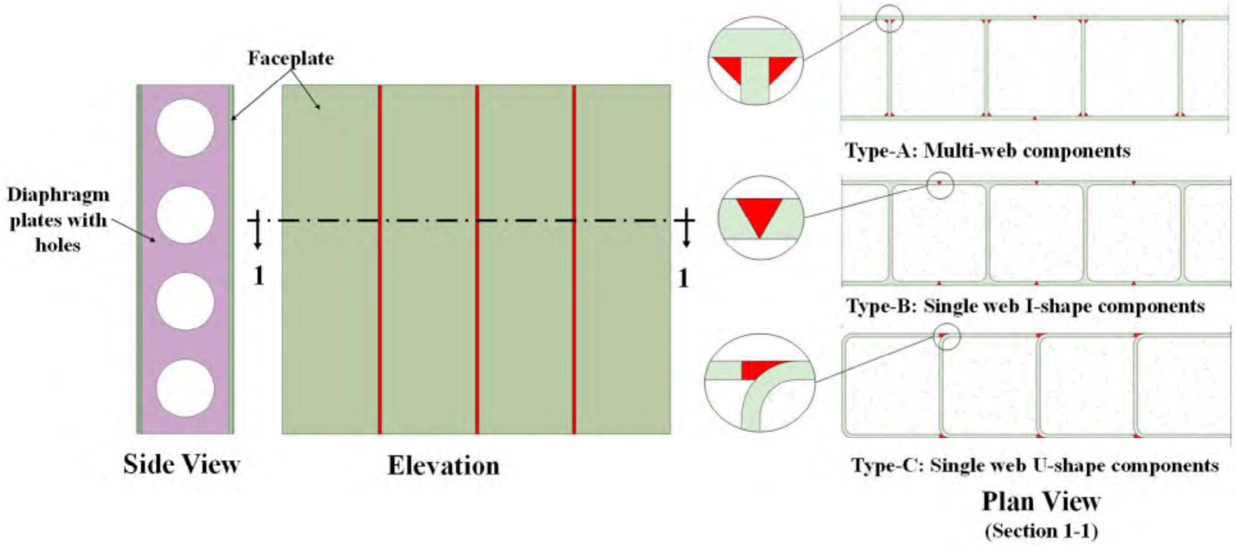
(a) [[Conventional Steel-Plate Composite Modules Using Discrete Round or Rectangular Steel Ties {3}]]



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(b) [[Diaphragm Plate Steel-Plate Composite Modules Using Diaphragm Plates with Holes for Concrete Flow {3}]]

Figure 3-5: Different Configurations of Steel-Plate Composite Structural Modules

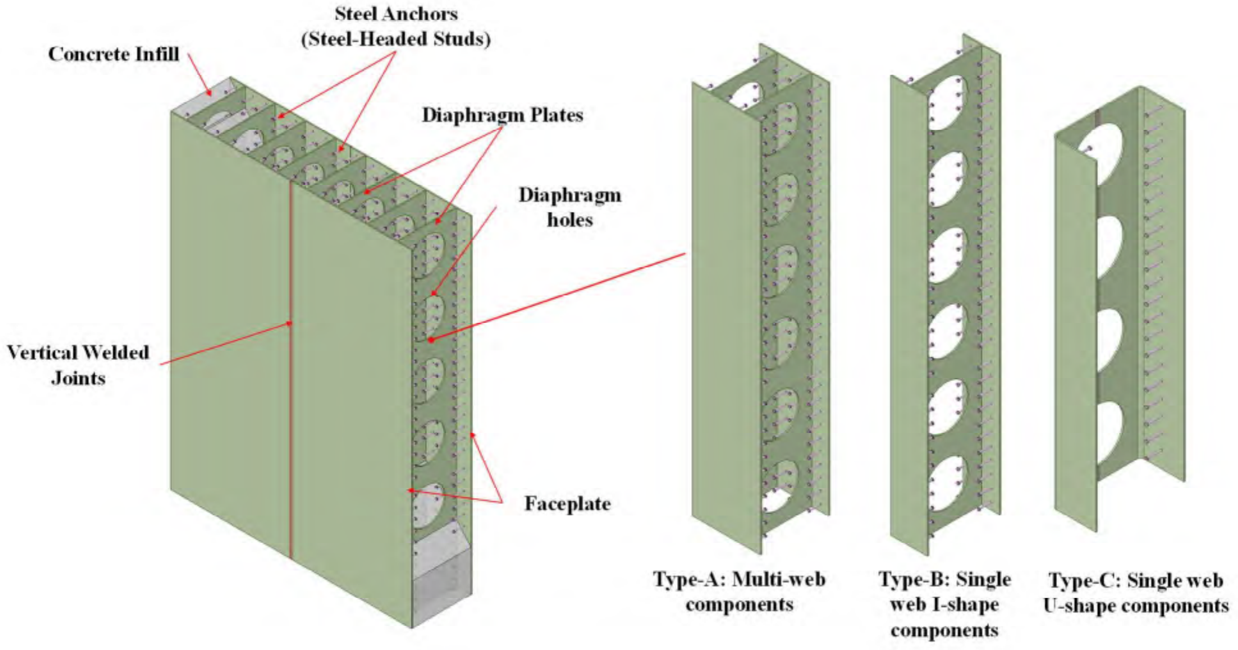

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Figure 3-6: Diaphragm Plate Steel-Plate Composite Module System

In conventional SC construction, welding of ties (i.e., rectangular, or round bars) is a manual process which can be time consuming. In the DP-SC module construction, the welding process can be automated. DP-SC modules can be used in floor construction where additional holes at the top faceplate can be provided to allow filling and flow of concrete in the plane of the floor. These holes can be sealed later if leak tightness is a design requirement.

4.0 BWRX-300 OVERALL ANALYSIS AND DESIGN APPROACH

The BWRX-300 Seismic Category I integrated RB is designed to meet the serviceability, strength, and stability requirements for all possible load combinations under the categories of normal operation and DBA in compliance with the requirements of 10 CFR 50 Appendix A, GDC 4 and CNSC REGDOC-2.5.2, Sections 7.15.1 and 7.7. The robustness of the design to prevent potential release of radioactivity to the public and environment under BDBAs and DECs is considered in compliance with the regulatory guidance of SRP 19.5 and the requirements of CNSC REGDOC-2.5.2, Sections 7.7, 7.15.1, 7.22, and 8.6.

Design codes jurisdictions are illustrated in Figure 4-1. The analysis, design, construction and maintenance of:

- The Seismic Category I DP-SC structures, excluding the SCCV pressure boundary, are governed by the provisions of ANSI/AISC N690, endorsed and modified per U.S. NRC RG 1.243, and the modified design rules discussed in Section 5.0 of this report.
- The SCCV containment boundary is governed by the provisions in Section 6.0.
- The RPV pedestal and internal steel structures are designed according to ANSI/AISC N690 including the modified design rules for the BWRX-300 non-containment DP-SC structures provided in Section 5.0.
- The containment metal closure head and Class MC components are governed by the provisions of ASME BPVC, 2021 Edition, Section III, Division 1, Subsection NE for Class MC and are beyond the scope of this report.

The connections of the RB walls and floors to the outer face of the SCCV wall are designed per Section 5.0 of this report, with the exception of attachment welds. Attachment welds to the SCCV outer face are designed per Section 6.11, and follow the quality assurance, welding procedures, and inspection requirements of Sections 6.13, 6.15 and 6.16.

This section presents the overall approach for the structural analysis and design of BWRX-300 Seismic Category I structures that include the BWRX-300 containment, containment internal structures, and the RB structure surrounding the containment. Demands from global design loads are obtained from analyses of a linear elastic FE model of the RB integrated structures presented in Section 4.2.

Different types of analyses performed on the FE model of the integrated RB structures to calculate design demands from different loads and load combinations.

Design demands from localized loads are obtained from separate analysis of refined models of the affected portions of the RB integrated structures.

4.1 One-Step Analysis Approach

Since the integrated RB is deeply embedded, the interaction of the structure with the surrounding subgrade is important for its structural integrity and its response under static and dynamic loads. The interaction with the surrounding subgrade determines the boundary conditions at the interfaces of the RB below-grade exterior wall and mat foundation thus affecting the response and stress distribution of the deeply embedded structure subjected to global design loads.

In accordance with the guidance of NEDO-33914-A, Section 5.1, the one-step approach, as defined in Section 3.1.2 of American Society of Civil Engineers (ASCE)/Structural Engineering Institute (SEI) 4-16 (Reference 9-58) is implemented for the design of the BWRX-300 integrated RB to adequately account for the effects of interaction of the deeply embedded structure with the surrounding subgrade.

A set of different linear elastic analysis cases are performed on FE models of the integrated RB, described in Section 4.2, that have the same node and FE type configurations and differ only in the assigned structural properties depending on the type of analysis and the considered load conditions. The use of linear elastic models with identical FE configuration enables the demands obtained from different analysis cases to be combined on an element-by-element basis for the applicable design load combinations per governing design codes.

Seismic demands for the design of the BWRX-300 Seismic Category I structure are obtained from seismic SSI analyses that consider the interaction of the integrated RB with the surrounding subgrade and adjacent Power Block structures. Quasi-dynamic SSI analyses provide design demands for the combination of gravity loads with static soil and rock pressure loads, including overburden pressures from the surrounding Power Block foundations, by applying a very low-frequency ground motion excitation on the SSI model to simulate (1-g) gravity load. Following the guidelines of NEDO-33914-A, Section 5.0, the seismic and static 1-g SSI analyses are performed using the System for Analysis of Soil-Structure Interaction (SASSI) method.

The interaction with the surrounding subgrade determines the boundary conditions at the interfaces of the integrated RB and the subgrade which affects, in turns, the structural response and stress distribution from other mechanical and temperature design loads. To account for the stiffness of the subgrade surrounding the RB, stiffness impedance sub-structuring methodology is used for:

- Static analyses of internal static and quasi-static design loads that affect the global response of the deeply embedded integrated RB
- Thermal stress analyses of normal operating and DBA temperature loads

In the SSI and subgrade stiffness impedance sub-structuring analyses, the subgrade is represented by layered half-space continuum. To account for the soil nonlinear behavior and the variation of subgrade conditions, the seismic SSI analyses are performed for a set of profiles of dynamic subgrade properties compatible with the strains generated by design earthquake ground motions developed following the guideline of NEDO-33914-A, Section 5.2.4. The static 1-g SSI and subgrade stiffness impedance analyses use equivalent linear subgrade static properties developed following the guidelines of NEDO-33914-A, Section 5.2.1.

Contact spring elements model the conditions at the interfaces of the RB below-grade exterior wall and mat foundation with the surrounding subgrade. Stiffness properties are assigned to these contact springs that provide conservative demands for the design of the integrated RB structures.

4.2 Integrated Reactor Building Finite Element Model

A 3D FE model of the integrated RB is developed for the one-step approach analyses following the modeling guidelines of NEDO-33914-A, Section 5.1.1. The model adequately represents the configuration of all main load carrying structural members of the integrated RB structures and meets the mesh refinement and quality attributes required for accurate calculation of structural stress demands.

Openings and penetrations smaller than half the DP-SC wall or slab thickness are not included in the integrated RB FE model in accordance with ANSI/AISC N690, Appendix N9. Openings and penetrations larger than the associated DP-SC wall or slab thickness are modeled explicitly, and other openings and penetrations are evaluated for modeling depending on the applicable loads and potential impact on the structural design at the opening/penetration location. Finer meshes are used around penetrations and openings in accordance with ANSI/AISC N690 and ASME BPVC, Section III to enable accurate computations of the stress demands for design of the opening/penetration locations.

Where semi-rigid connections are used, they are represented by six linear springs, with three translational and rotational stiffnesses each, at each pair of near coincident nodes of the connecting DP-SC members. Section 5.6 describes the method used to calculate the stiffness properties assigned to the springs representing the semi-rigid connections between the DP-SC members, if applicable. The stiffness properties of springs representing the semi-rigid connections between the SCCV wall, and the RB wing walls and slabs are calculated as discussed in Subsection 6.3.

The SCCV and RB walls, slabs and mat foundation are modeled using thick shell elements with an equivalent thickness, elastic modulus, Poisson’s ratio and material density calibrated to match the stiffness and mass properties of DP-SC modules. Effective stiffness properties are assigned to the DP-SC elements for the analyses of load combinations that exclude accidental thermal loads. For load conditions that include the high accidental temperatures, reduced stiffness is considered to account for the effects of concrete cracking on the redistribution of forces and moments.

Effective and reduced stiffnesses of non-containment DP-SC members are calculated as described in Section 5.5. Section 6.3 discusses the methodology for calculation of effective and reduced stiffness properties of the SCCV shell elements.

Damping values assigned to the RB and SCCV DP-SC structures and components in the integrated RB FE model are discussed in Sections 5.5 and 6.4, respectively.

4.3 Design Loads and Load Combinations

Loads and load combinations used in the design of the BWRX-300 integrated RB are in accordance with:

- ASME BPVC, 2021 Edition, Section III, Division 2, Subsection CC, Subsubarticle CC-3230, supplemented by U.S. NRC RG 1.136 for the SCCV
- ANSI/AISC N690, Section NB2.5 Load and Resistance Factor Design (LRFD) provisions for the RB steel and DP-SC structures supplemented with load combinations specified in U.S. NRC RG 1.243 that prescribes more conservative load factors

The following are the main design loads considered in the design of the BWRX-300 containment and other Seismic Category I structures:

- Dead Load (D)

  Dead load (D) includes the self-weight of the structural members and the weight of permanently attached equipment, tanks, machinery, cranes, and elevators, including fluid contained within the piping and equipment under normal operating conditions. It also includes the weight of distributed systems, including piping, conduits and cable trays. Demands due to dead loads are obtained from the results of 1-g SSI analyses.

- Hydrostatic Loads (F)

  The hydrostatic loads (F) include the vertical and lateral hydrostatic pressures of liquids contained in the RB pools acting on the surfaces of pool walls and slabs. Vertical hydrostatic loads on pool slabs are considered in the 1-g SSI analysis as gravity inertia loads by adding the liquid weight to the shell elements of the pool floors. Design demands from lateral hydrostatic pressures are obtained from separate static analyses by applying pressure loads with amplitude linearly increasing with the liquid depth on the pool wall shell elements.

- Live Load (L)

  Live loads (L) include floor area loads, laydown loads, equipment handling loads, rated capacity of cranes, and similar items. Demands due to live loads are calculated from results of separate subgrade impedance analyses.

- Static Earth and Groundwater Pressure Loads (H)

  Earth pressure loads (H) include loads due to the weight of soil (including groundwater in soil) on the RB outer cylinder wall and lateral soil pressures due to surcharge loads applied on the ground surface in the proximity of the RB. Design demands from static earth pressure loads associated with dry weight of the soil, including the overburden loads from the surrounding structures are obtained from results of SSI 1-g analyses.

  The design considers the groundwater loads as a static pressure loading on the RB mat foundation and below-grade exterior wall. Additional earth pressure loads (H) may be applied on the below-grade exterior wall of RB structural model to account for pressures from potentially unstable blocks of rock mass or in-situ rock pressures and pressures distributions that cannot be modeled by the 1-g SSI analysis. Design demands from groundwater loads and additional rock pressure loads are obtained from separate static analyses with prescribed boundary conditions.

- Normal Operating and Testing and Accident Pressure Loads (P_o, P_t and P_a)

  The normal operating pressure load (P_o) includes the internal containment pressures during normal operating conditions. External pressure loads resulting from pressure variation either inside or outside the containment (P_v), as defined in ASME BPVC Section III, Division 2, Subsection CC, Subparagraph CC-3221.1, are considered under the P_o load case. The test pressure load (P_t) includes the internal pressure load applied to the containment during Structural Integrity Test (SIT) or Integrated Leak Rate Test (ILRT).

  DBA internal pressure load (P_a) resulting from a LOCA is considered. Quasi-static pressures resulting from this event is applied on the containment structure. Although the DBA pressures (P_a) resulting from LOCA are dynamic in nature, the internal accident pressure loads are represented by quasi-static pressure loads. The quasi-static pressure loads include dynamic load factor amplifications to account for dynamic response effects.

  Demands from normal operating and testing and accident pressure loads are obtained from the results of subgrade impedance analyses of RB integrated FE model.

- Crane Load (C)

Crane loads (C) include the maximum wheel loads of the crane and the vertical, lateral and longitudinal forces induced by the moving crane. Static and quasi-static subgrade impedance analyses provide design demands from crane loads. The most critical position of the crane and the lifted load is considered for the design. The critical crane position is determined based on the results of sensitivity static analyses performed on a fixed base RB FE model.

- Normal Operating and Accident Reaction Loads (R_o and R_a)

  The design of the containment and RB structures considers nozzle, equipment and piping reaction loads due to the plant operation under normal operating and DBA conditions. These local loads are applied as point loads at nozzle, equipment support and pipe support locations to calculate demands for the design of the containment and RB structures.

- Severe Wind and Tornado Wind Loads (W and W_t)

  The severe wind load (W) and extreme tornado wind load (W_t) are considered by the design as static pressure loads applied on the exterior of the RB structure. Design demands due to wind and tornado wind pressure loads are obtained from static subgrade impedance analyses.

- Severe and Extreme Precipitation Event Loads (S, R, and S_x)

  Severe snow and rain loads (S and R) and extreme precipitation event design loads (S_x) are considered in the design and are applied, as applicable, as a pressure to the RB roof shell elements. Since the snow and rain have only local effect on the RB structural response, design load demands from these loads can be obtained from the results of fixed base static analyses.

- SSE or DBE Seismic Loads (E_s)

  The design of RB integrated structure considers the following seismic load (E_s) demands:

  - Seismic inertia load demands that are obtained directly from results of one-step seismic SSI analyses
  - Seismic lateral pressure load demands that include structure-soil-structure interaction effects with surrounding Power Block structures and foundations, that are also obtained directly from results of one-step seismic SSI analyses
  - Additional torsion load demands obtained from a separate quasi-static analysis
  - Hydrodynamic pressure load demands including impulsive hydrodynamic pressures associated with the rigid mass inertia response of the liquid, and convective or sloshing pressures associated with the low-frequency response at the pool water surface

  The one-step seismic SSI analyses provide earthquake load (E_s) demands from:

  - Hydrodynamic loads on the RB pool floors
  - Impulsive hydrodynamic pressures on the pool walls due to the horizontal components of the design ground motion

  Additional static analysis cases are performed to calculate demands from hydrodynamic pressure loads that are not captured by the one-step approach seismic SSI analyses of the

RB, including sloshing pressure loads and breathing mode hydrodynamic pressures due to the vertical earthquake component.

Additional quasi-static analysis cases may also be performed, where additional dynamic earth pressure loads are applied on the below-grade exterior walls of the integrated RB structural model as quasi-static pressures to account for loads from potentially unstable rock blocks.

- OBE Seismic Load (E_o)

  These loads are generated by the OBE. The OBE ground motion is only associated with plant shutdown and inspection. OBE loads and load combinations are considered only when the OBE is set larger than 1/3 of the site-specific SSE as stated in Subsection 2.1.1.16.

- Normal Operating and DBA Thermal Loads (T_o and T_a)

  Thermal stress analyses performed on subgrade impedance sub-structuring models provide structural design demands from:

  - Normal operating thermal loads (T_o) that consist of steady-state linear temperature profiles through the containment and RB slabs and walls
  - DBA thermal loads (T_a) resulting from accident conditions from LOCAs and heat-up of fuel pool

  The LOCA accident thermal loads (T_a) are accompanied by the corresponding accident pressure loads (P_a). The heat-up of the fuel pool is also considered as a separate DBA event from LOCA DBA events.

  Normal and accident temperature loads (T_o and T_a) consider ambient (outdoor) temperatures for both Winter and Summer conditions. Operating temperatures for interior rooms consider environmental requirements of operating equipment.

- Local Load Effects on Containment

  The design considers local load effects on the containment due to high-energy line breaks during a DBA, including jet impingement load generated by the postulated accident (R_{rj}/Y_j), missile impact load, such as pipe whip generated by or during the postulated accident (R_{rm}/Y_m), loads on the structure generated by the reaction of the broken high-energy pipe during the postulated accident (R_{rr}/Y_r), and blast loads (R_b) that may be postulated due to instantaneous break of a large pipe. These local loads are applied on the integrated RB model to calculate demands for the design of the containment and RB structures. Local refined models with appropriate boundary conditions based on the response of the global model are used, as needed.

- Internal Flooding Loads (H_a)

  The design of integrated RB structures considers the loads associated with the post-accident internal flooding of the containment following a DBA. The hydrostatic loads from the maximum possible water level are applied as pressures to the affected walls and mat foundation and applicable loads are also used for design of containment metal components.

- Loads Resulting from Relief Valve or Other High Energy Device Actuation (G)

The BWRX-300 does not have Safety Relief Valves (SRVs), therefore, SRV loads are not applicable to the BWRX-300 design.

- Loads Resulting from the Application of Prestress

  The BWRX-300 integrated RB structures do not include prestressed structural components. As a result, prestress loads are not applicable to the BWRX-300 design.

4.4 Overall Design Approach

Acceptance criteria for the design of the RB DP-SC structures, including welded and bolted connections, are in accordance with ANSI/AISC N690, Appendix N9, as endorsed by the regulatory guidance of US NRC RG1.243, and the modified design rules in Section 5.0. Acceptance criteria for the design of the SCCV are discussed in Section 6.6.

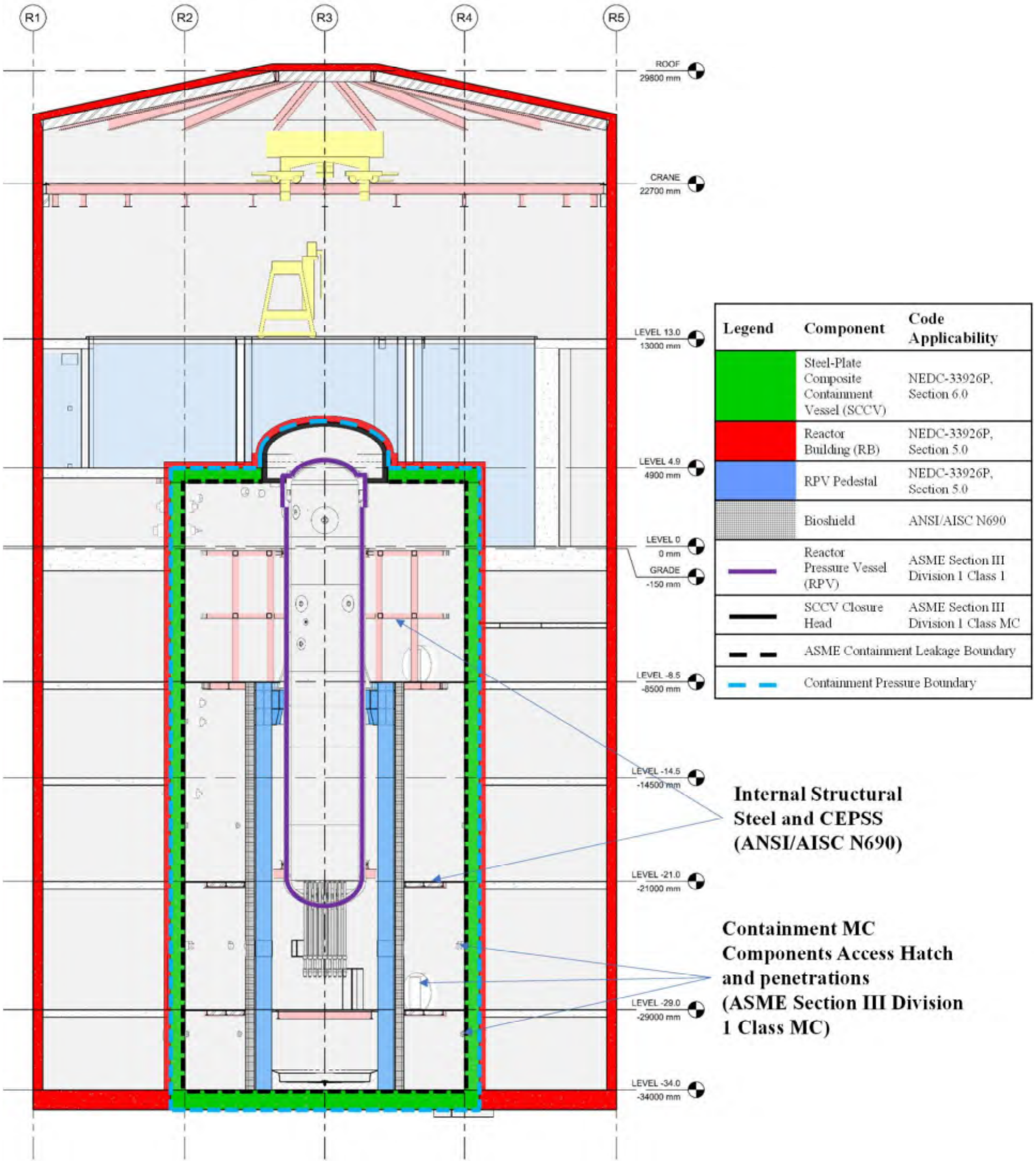
Design procedures and acceptance criteria for the containment internal structures are the same as those for the RB structure. Design procedures and acceptance criteria for the containment mat foundation are the same as those for the SCCV. The mat foundation portion outside of the containment boundary is designed to ANSI/AISC N690, supplemented by U.S. NRC RG 1.243.

Since design requirements in ANSI/AISC N690, Appendix N9 are limited to traditional SC walls, modified and compensatory detailing and design requirements were developed for the integrated RB DP-SC structures. Section 5.0 presents these proposed modified and compensatory measures and addresses the applicability of ANSI/AISC N690 to the design of the DP-SC floors and curved walls. These modified rules allow the use of the most current methods and technology while meeting the safety goals established by the NRC for ensuring the protection of public health and safety and the environment.

The proposed design approach and rules for the BWRX-300 SCCV are presented in Section 6.0. ASME BPVC, Section III, Division 2, Subsection CC establishes rules for material, design, fabrication, construction, examination, and testing for prestressed and reinforced concrete containments. ASME Subsection CC is not directly applicable to SC containments due to some fundamental differences between SC containments and prestressed and reinforced concrete containments. One of the fundamental differences being that SC containments do not require a separate liner plate on their inside surfaces to serve as leak barrier. In the case of SC containments, the inner steel faceplate of the containment serves as the leak barrier, with the composite SC section (i.e., outer and inner faceplates, diaphragm plate, and concrete infill working together) serving as the pressure-retaining boundary for the containment. The outer containment faceplate is not considered as part of the leak-tight barrier. Consequently, concrete cracking inside the SC containment, bounded by steel plates on the inside and outside surfaces, is less significant for the containment design or performance.

To address the particularities of DP-SC elements, ASME BPVC, 2021 Edition, Section III, Division 2 Articles CC-1000 through CC-6000 and the Division 2 Appendices were reviewed for changes or additions that need to be made to allow and provide appropriate requirements for the use of a DP-SC containment vessel. All Division 2 Appendices are followed to the extent they apply to a DP-SC containment without reinforcing steel or tendons.

The BWRX-300 containment is still considered a ASME BPVC, Section III, Division 2 containment. The applicable sections of the remaining ASME BPVC consistent with the Section III division 2 edition, such as Section II; Section III, Subsection NCA; Section V; and Section IX are followed to the extent they apply to a DP-SC containment without reinforcing steel or tendons. ASME BPVC, Section XI incorporated by reference in 10 CFR 50.55a(g)(4) 18 months before the date of issuance of the operating license for the initial 120-month ISI interval as described in 10 CFR 50.55a(g)(4)(i) is followed for the containment pre-service and periodic ISI and testing program.



Legend	Component	Code Applicability
🟩	Steel-Plate Composite Containment Vessel (SCCV)	NEDC-33926P, Section 6.0
🟥	Reactor Building (RB)	NEDC-33926P, Section 5.0
🟦	RPV Pedestal	NEDC-33926P, Section 5.0
▨	Bioshield	ANSI/AISC N690
—	Reactor Pressure Vessel (RPV)	ASME Section III Division 1 Class 1
—	SCCV Closure Head	ASME Section III Division 1 Class MC
– –	ASME Containment Leakage Boundary	
– –	Containment Pressure Boundary	

Internal Structural Steel and CEPSS (ANSI/AISC N690)

Containment MC Components Access Hatch and penetrations (ASME Section III Division 1 Class MC)

[[{3}]]

Figure 4-1: BWRX-300 Integrated Reactor Building Design Codes Jurisdictions

* Integrated RB layout is based on current design. Layout may change as the design progresses.

5.0 MODIFIED DESIGN RULES FOR NON-CONTAINMENT STEEL-PLATE COMPOSITE STRUCTURES

This section presents the modified design rules for the BWRX-300 non-containment DP-SC structures adapted from ANSI/AISC N690 and adjusted to address the particularities of DP-SC construction. They include the modified ANSI/AISC N690, Appendix N9 design equations used to compute the DP-SC sectional capacities that account for the contribution of diaphragm plates.

This section also addresses the effects of curvature on SC (including DP-SC) walls, and the applicability of the ANSI/AISC N690 modified rules to SC (including DP-SC) horizontal modules. Only those provisions that differ from ANSI/AISC N690 are discussed in this section.

The modified design rules presented in this section are supported by the NRIC prototype testing data discussed in Section 7.0, and current literature and design methods.

5.1 Design Parameters

As shown in Figure 5-1, the fundamental aspects of DP-SC modules are:

(i) spacing between diaphragm plates W_{sc}, in (mm)

(ii) depth t_{sc}, in (mm)

(iii) concrete infill depth t_c, in (mm)

(iv) DP-SC faceplate and diaphragm plate thickness t_p, in (mm) (1)

(v) steel faceplate and diaphragm plate yielding strength F_y, ksi (MPa) (1)

(vi) diaphragm hole diameter D, in (mm)

(vii) diaphragm hole spacing S, in (mm)

(viii) studs anchor tensile strength F_{uta}, ksi (MPa)

(ix) stud anchor diameter d_{st}, in (mm)

(x) stud length l_{st}, in (mm)

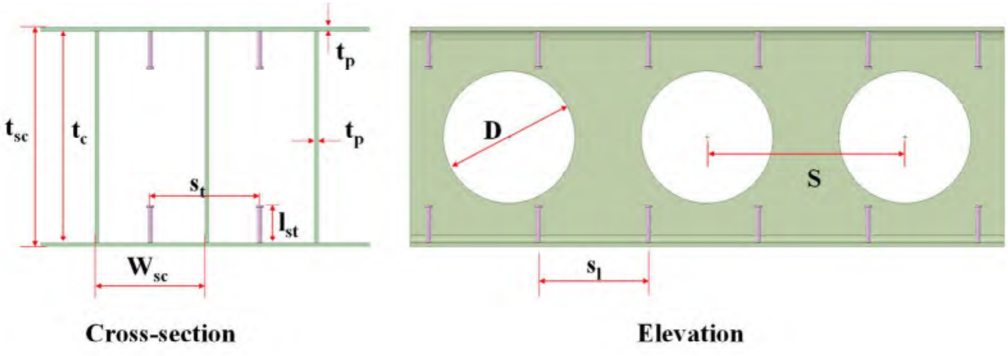
(xi) studs anchor transversal spacing (perpendicular to diaphragm plate direction) s_t, in (mm)

(xii) studs anchor longitudinal spacing (parallel to diaphragm plate direction), s_l, in (mm)

(xiii) concrete compressive strength f_c', ksi (MPa)

Note:

(1) DP-SC faceplate and diaphragm plates can have different thicknesses and use different steel grades in the range allowed by the applicable design code/standard. Design equations presented in this report use the same t_p and F_y for DP-SC faceplate and diaphragm plates. These equations can be modified as required to reflect the design parameters for each DP-SC component.



Cross-section

Elevation

[[{3}]]

Figure 5-1: Dimensions of Diaphragm Plate Steel-Plate Composite modules

The minimum and maximum depths, t_{sc}, of DP-SC modules are in accordance with ANSI/AISC N690, Appendix N9, Section N9.1.1a provisions. The minimum steel plate thickness, t_p, is 0.25 in (6.4 mm). Maximum allowable plate thickness is 1.5 in (38.1 mm) per ANSI/AISC N690, Section N91.1.1(b). In accordance with Section N9.1.1a of ANSI/AISC N690, any DP-SC section thickness greater than 60 in (1500 mm) is to be justified by experimental or numerical results to demonstrate the applicability and conservatism of Appendix N9 provisions to sections with greater section thicknesses.

The minimum reinforcement ratio is 0.015 per ANSI/AISC N690, Appendix N9, Section N9.1.1.(c). The maximum reinforcement ratio for the DP-SC walls is taken as 0.10 following the requirements of draft ANSI/AISC N690-XX (Reference 9-59), Section N9.1.1.(c) and ANSI/AISC 360-22 (Reference 9-60), Section I1.6.

The hole diameter of DP-SC panels is limited to a maximum of 0.6 times the panel thickness, t_{sc}. The spacing between the diaphragm plate holes centerlines is limited to a minimum of 0.9 times t_{sc}.

5.2 Materials

5.2.1 Concrete Infill

Self-consolidating concrete is used for the integrated RB DP-SC modules.

Per draft ANSI/AISC N690-XX (Reference 9-59), Section N9.1.1(e), the self-consolidating concrete compressive strength, f'_c, is a function of reinforcement ratio, ρ, and specified minimum yield stress of faceplates, F_y. as follows:

$$max\begin{pmatrix} 4ksi \\ [0.04+0.80\rho]F_y \end{pmatrix} \le f'_c \le 10ksi$$

[5-1]

$$max\begin{pmatrix} 28MPa \\ [0.04+0.80\rho]F_y \end{pmatrix} \le f'_c \le 70MPa$$

Where,

ρ = reinforcement ratio $= \frac{2t_p}{t_{sc}}$

Aggregates used in high-density concrete for radiation shielding purposes conform to American Society for Testing and Materials (ASTM) C637 (Reference 9-61), per ACI 349.

The concrete temperature limitations for normal operational and accidental conditions meet those specified in ACI 349, Appendix E, Section E.4. Reduction in concrete mechanical properties at elevated temperature is per ANSI/AISC N690, Appendix N4.

5.2.2 Steel Plates

The yield strength, F_y, of the steel plates of DP-SC modules ranges from 50 ksi (350 MPa) to 65 ksi (450 MPa) per the requirements of ANSI/AISC N690, Section N9.1.1.

The effect of elevated temperatures on the mechanical properties of steel materials of DP-SC modules is determined in accordance with ANSI/AISC N690, Section NB3.3.

5.3 Composite Action

The faceplates of DP-SC modules are anchored using shear connectors. Draft ANSI/AISC N690-XX (Reference 9-59), Appendix N9.1.4 defines shear connectors as ties and steel headed stud anchors that may serve as shear connectors to achieve composite action (i.e., diaphragm plates and steel headed stud anchors for the BWRX-300). The diaphragm plates of DP-SC modules act as ties preventing splitting of sections and serving as out-of-plane shear reinforcement. Requirements for composite action in this section are per draft ANSI/AISC N690-XX (Reference 9-59), Appendix N9, Section N9.1.4.

The BWRX-300 construction uses yielding steel headed stud anchors in all composite construction. As per ANSI/AISC N690, Appendix N9, Section N9.1.4a user note, the requirements for steel headed stud anchors are provided in ANSI/AISC 360-16 (Reference 9-62), Sections I8.1 and I8.3, including any modifications of ANSI/AISC N690, Chapter NI. Both diaphragm plates and steel headed stud anchors serve as shear connectors that achieve the composite action as shown in Section 5.3.1 below. The diaphragm plates and steel headed stud anchors are designed and detailed to meet the requirements of draft ANSI/AISC N690-XX (Reference 9-59), Appendix N9, Section N9.1.4b for the directions perpendicular and parallel to the diaphragm plates span. Furthermore, the steel headed stud anchors of DP-SC panels are designed to meet ANSI/AISC N690, Appendix N9, Section N9.1.3 for faceplate slenderness requirements.

In localized areas, where the faceplate slenderness requirements and the composite action requirements of ANSI/AISC N690, Appendix N9, Section N9.1.3 and draft ANSI/AISC N690-XX (Reference 9-59), Appendix N9, Section N9.1.4b respectively are met by the idealized diaphragm plates alone, steel headed stud anchors may not be used in order to facilitate the construction of DP-SC modules.

5.3.1 Shear Connectors Capacity

[[The shear strength of idealized as ties diaphragm plates (i.e., diaphragm plates portion between diaphragm plates holes spaced along their span) and steel headed stud anchors shall meet the requirements of draft ANSI/AISC N690-XX (Reference 9-59), Appendix N9, Section N9.1.4b. The weighted average of the available interfacial shear strength (Q_{cv}^{avg}) is not practical as the contribution from the diaphragm plate is greater than that from steel headed stud anchors. Hence, the summation of the available interfacial shear strengths of a group of headed stud anchors and diaphragm plate that accounts for tributary areas of diaphragm plate, Q_{cv}^{sum} , is considered over such tributary areas as shown in Figure 5-2 and Figure 5-3.

i. Yield strength development criterion

The spacing required to develop the yield strength of the faceplate (and the tensile rib) along the diaphragm direction over the development length, L_d, is per Equation [5-2]:

$$W_{sc} \times S \leq \frac{Q_{cv}^{sum} L_d}{T_p} \tag{5-2}$$

Where,

$Q_{cv}^{sum} = Q_{cv}^{dp} + Q_{cv}^{sa}$

$Q_{cv}^{sa} = \sum Q_{cv}$, the sum of steel headed stud anchors shear capacities contribution is taken for headed stud anchors in a panel having dimensions of S by W_{sc}, kip (N). Where studs are not used in localized areas, $Q_{cv}^{sa} = \text{zero}$

Q_{cv}= Headed stud anchor shear capacity computed per ANSI/AISC N690, Appendix N9, Section N9.1.4a, kip (N)

$Q_{cv}^{dp} = \phi * 0.6 * Fy * t_p * (S - D)$, kip (N), where ϕ =0.9

L_d = development length, in. (mm), and $L_d = 3t_{sc}$

S = diaphragm hole spacing, in. (mm)

D = diaphragm hole diameter, in. (mm)

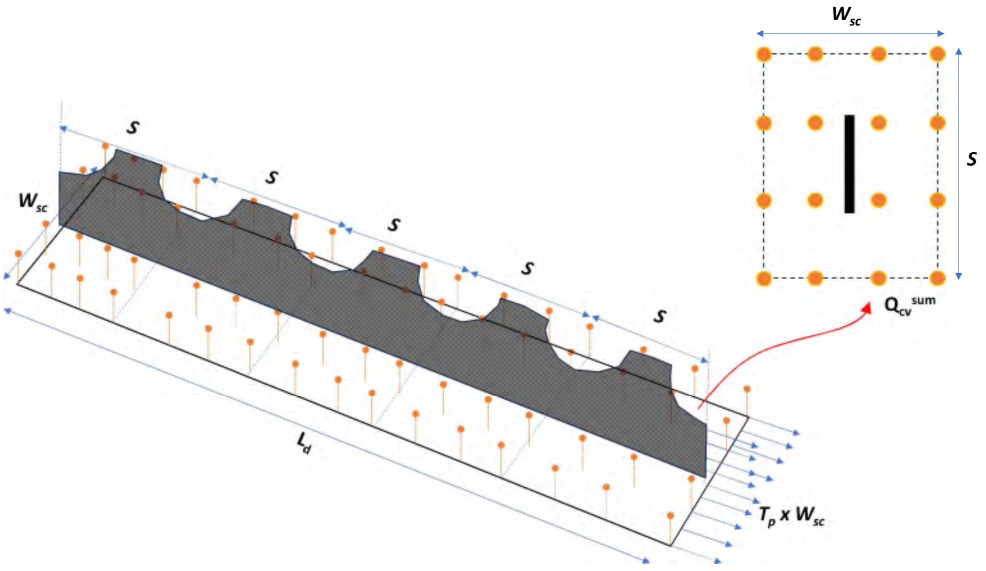
W_{sc}= spacing between diaphragm plates, in. (mm)

T_p = yield strength of the faceplate, kip/in (N/mm)

$= F_y(t_p + \frac{t_c - D}{2} \times \frac{t_p}{Wsc})$ in the direction parallel to the diaphragms (see Figure 5-2), including and the tensile rib portion of the diaphragm plate, and

$= F_y t_p$, in the direction perpendicular to the diaphragms

t_c = concrete infill thickness, in (mm) {3}]]



[[$^{\{3\}}$]]

Figure 5-2: Faceplate and tensile rib yielding strength development.

ii. [[Prevention of interfacial Shear failure before out-of-plane shear failure criterion:

The spacings required to prevent interfacial shear failure before out-of-plane shear failure of the DP-SC section:

$$W_{sc} \times S \le \frac{Q_{cv}^{sum} l(0.9t_{sc})}{\frac{M_n}{2.5t_{sc}}} \qquad [5\text{-}3]$$

Where,

M_n= nominal flexural strength per unit width of DP-SC structural element, as defined in Section 5.7.3.1 and Section 5.7.3.2, kip-in./ft (N-mm/m)

$Q_{cv}^{sum} = Q_{cv}^{dp} + Q_{cv}^{sa}$

$Q_{cv}^{sa} = \sum Q_{cv}$, the sum of steel headed stud anchors shear capacities contribution is taken for headed stud anchors in a panel having dimensions of S by W_{sc}, kip (N). Where studs are not used in localized areas, Q_{cv}^{sa} = zero

Q_{cv}= Headed stud anchor shear capacity computed per ANSI/AISC N690, Appendix N9, Section N9.1.4a, kip (N)

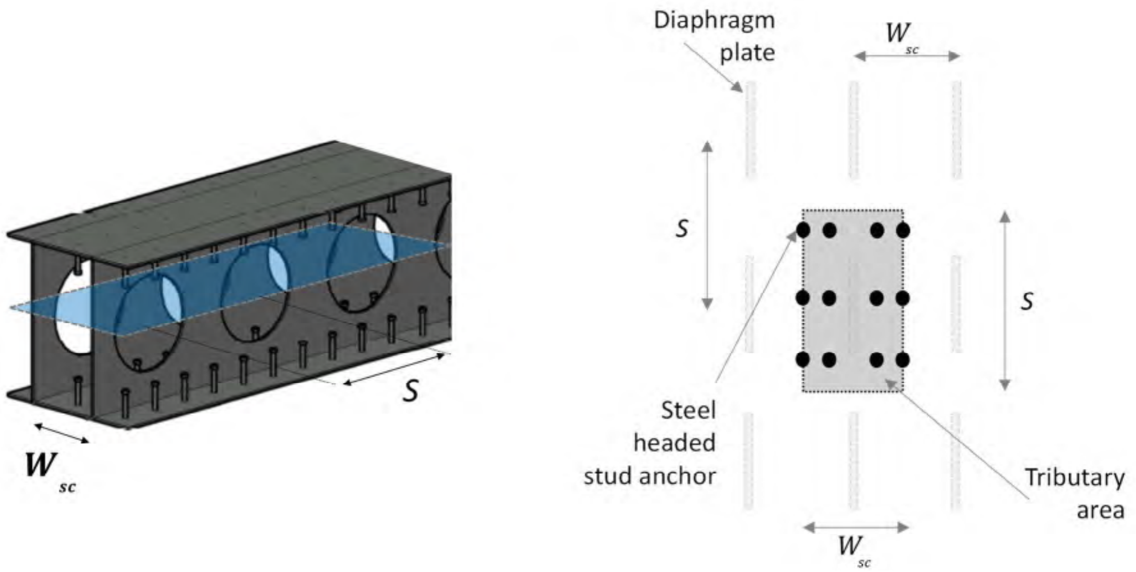
$Q_{cv}^{dp} = \phi * 0.6 * Fy * t_p * (S - D)$, kip (N), where ϕ =0.9

S = diaphragm hole spacing, in. (mm)

D = diaphragm hole diameter, in. (mm)

W_{sc}= spacing between diaphragm plates, in. (mm)

l = unit width of module, 12 in/ft (1000 mm/m)$^{\{3\}}$]]



[[{3}]]

Figure 5-3: Tributary area equivalent to Q_{cv}^{sum}

5.4 Diaphragm Requirements

The spacing of the modules diaphragm plates is limited to 1.0 times the panel thickness, t_{sc}, similar to maximum tie spacing in ANSI/AISC N690 and ACI 349 for reinforced concrete. Diaphragm plates shall meet draft ANSI/AISC N690-XX (Reference 9-59), Appendix. N9, Section N9.5.1, tie requirements.

5.5 Determination of Effective Stiffness of Steel-Plate Composite Elements

[[The DP-SC elements are modeled using elastic shell elements with an equivalent thickness, elastic modulus, and material density calibrated to match the module effective stiffness and mass properties developed using the procedure described below.

For operating conditions, the effective flexural stiffness of composite section combines both the steel and concrete stiffnesses using ANSI/AISC N690, Equation A-N9-8 given by Equation [5-4] below. The average of the maximum surface temperature increases for the faceplates due to normal operating conditions is taken as zero per ANSI/AISC N690 since the thermal gradients are small and develop over significant time.

The fully cracked condition is simulated by not considering the contribution of concrete infill flexural stiffness in Equation [5-4], as shown below in Equation [5-5].

The effective axial stiffness in operating condition is estimated using Equation I1-2 of ANSI/AISC 360-22 shown in Equation [5-6].

Shear stiffness of the fully cracked state is computed using ANSI/AISC N690, Equation A-N9-12 approximation, given by Equation [5-7].

The steel contribution to stiffness is based on the steel faceplates only per ANSI/AISC N690, i.e., the contribution of the diaphragm plates is not included. This is supported by the results from

NRIC OOPV-1 and OOPV-2 test specimens, showing that the stiffness is in the range of ANSI/AISC N690 equations.

For DP-SC sections, the Poisson's ratio, ν_m, thermal expansion coefficient, α_m, and thermal conductivity, k_m, are same as those of the concrete. Analysis for load combinations involving accident thermal conditions will include heat transfer analyses in accordance with ANSI/AISC N690, Section N9.2.4.

For load combinations involving operating conditions, which can include seismic loading, but no accidental pressure or thermal loading, the composite panels are considered to be partially cracked. The concrete contribution to the out-of-plane flexural, in-plane shear and axial stiffnesses assigned to the integrated RB elastic FE model is based on the extent of concrete cracking. Since only two of the three stiffness values are calibrated to obtain the effective thickness, t_m, and material modulus, E_m, for the elastic model, the stiffness values that are calibrated are the axial and out-of-plane flexural stiffnesses. The resulting in-plane shear stiffness value is noted and compared with the calculated value, per ANSI/AISC N690, Section N9.2.2b provisions, to confirm.

For load combinations involving accident conditions, which include pressure and thermal loading, the composite panels are considered to be fully cracked, with no concrete contribution to out-of-plane flexural stiffness. The concrete contribution to in-plane shear stiffness is included as a post-crack contribution. Since only two of three stiffness are calibrated to obtain the effective thickness, t_m, and material modulus, E_m, for the elastic model, the stiffness values that are calibrated in this case are the out-of-plane flexural and in-plane shear stiffnesses. The resulting axial stiffness value is noted and compared with the calculated cracked value, i.e., $E_s\,A_s$, to confirm.

The equivalent section properties of DP-SC elements are computed using Equations [5-8] to [5-10] for the operating conditions and Equations [5-11] to [5-13] for the fully cracked condition.

The equivalent specific heat of the calibrated material in both operational and accidental thermal conditions, c_m, is calibrated per Equation [5-14].

Effective flexural stiffness (operating condition)	$EI_{eff\_OC} = [\,E_s\,I_s + c_2\,E_c\,I_c\,]$ $c_2 = 0.48\left[\frac{2t_p}{t_{sc}}\cdot\frac{E_s}{E_c}\right] + 0.1$	[5-4]
Effective flexural stiffness (fully cracked condition)	$EI_{eff\_FCC} = [\,E_s \cdot I_s\,]$	[5-5]
Effective axial stiffness (operating condition)	$EA_{eff\_OC} = [\,E_s\,A_s + 0.45\,E_c\,A_c\,]$	[5-6]
Effective shear stiffness (fully cracked condition)	$GA_{eff\_FCC} = 0.5 \cdot \left[\frac{A_s \cdot F_y}{31.6 \cdot A_c \cdot \sqrt{f_c}}\right]^{-0.42} \cdot G_s \cdot A_s$ $GA_{eff\_FCC} = 0.5 \cdot \left[\frac{A_s \cdot F_y}{83 \cdot A_c \cdot \sqrt{f_c}}\right]^{-0.42} \cdot G_s \cdot A_s$(SI-Units) $G_s = \frac{E_s}{2 \cdot (1 + \nu_s)}$	[5-7]

$$A_s = 2 \cdot l \cdot t_p$$

$$A_c = l \cdot (\,t_{sc} - 2 \cdot t_p)$$

- **Operating conditions equivalent section properties:**

$$t_{m\_OC} = \sqrt{\frac{12\,EI_{eff\_OC}}{EA_{eff\_OC}}} \qquad [5\text{-}8]$$

$$E_{m\_OC} = \frac{E\,A_{eff\_OC}}{t_{m\_OC}} \qquad [5\text{-}9]$$

$$\gamma_{m\_OC} = \frac{\gamma_c \cdot t_c + 2\,\gamma_s \cdot t_p}{t_{m\_OC}} \qquad [5\text{-}10]$$

- **Fully cracked condition equivalent section properties:**

$$t_{m\_FCC} = \sqrt{\left(\frac{EI_{eff\_FCC}}{GA_{eff\_FCC}}\right) \cdot \left[\frac{12}{2 \cdot (1 + \nu_m)}\right]} \qquad [5\text{-}11]$$

$$E_{m\_FCC} = \frac{GA_{eff\_FCC} \cdot 2 \cdot (1 + \nu_m)}{t_{m\_FCC}} \qquad [5\text{-}12]$$

$$\gamma_{m\_FCC} = \frac{\gamma_c \cdot t_c + 2 \cdot \gamma_s \cdot t_p}{t_{m\_FCC}} \qquad [5\text{-}13]$$

- **Calibrated specific heat in operational and accidental conditions:**

$$C_m = \frac{C_c \cdot \gamma_c \cdot t_c}{\gamma_c \cdot t_c + 2\,\gamma_s \cdot t_p} \qquad [5\text{-}14]$$

Where,

E_c = modulus of elasticity of concrete = $\gamma_c^{1.5}\sqrt{f_c'}$, ksi ($0.043\gamma_c^{1.5}\sqrt{f_c'}$, MPa)

I_c = moment of inertia of concrete infill per unit width = $l\left(t_c^3/12\right)$, in^4/ft (mm^4/m)

I_s = moment of inertia of faceplates (corresponding to the condition when the concrete is fully cracked) = $l t_p \left(t_{sc} - t_p\right)^2/2$, in^4/ft (mm^4/m)

f_c' = specified compressive strength of concrete, ksi (MPa)

l = unit width, 12 in/ft (1000 mm/m)

t_c = concrete infill thickness, in (mm)

t_{sc} = DP-SC section thickness, in (mm)

A_c = area of concrete infill per unit width = $l t_c$, in^2/ft (mm^2/m)

A_s = gross area of faceplates per unit width = $l(2t_p)$, in^2/ft (mm^2/m)

G_s = shear modulus of elasticity of steel

G_c = shear modulus of concrete = $772\sqrt{f_c'}$, ksi ($2000\sqrt{f_c'}$, MPa)

ν_s= Poisson's ratio of steel

γ_c = concrete unit weight, lb/ft^3 (N/mm^3)

γ_s = steel unit weight, lb/ft^3 (N/mm^3)

C_c = concrete specific heat.{3}]]

5.5.1 Heat Transfer Analysis

Heat transfer analyses can be conducted using the geometric and material properties calculated in Section 5.5 to estimate the temperature histories and through-section temperature profiles produced by the thermal accident conditions in accordance with ANSI/AISC N690, Appendix N9, Section N9.2.4, as endorsed by regulatory guidance of U.S. NRC RG 1.243.

Alternatively, using an approach similar to that of ANSI/AISC 360-22, Appendix 4, Section 4.2.4c, an explicit model, representing the different components of steel plates, discretized studs, concrete infill, and contact between different components, simulating both thermal and mechanical responses of temperature-dependent properties of the steel plates and concrete infill can be used to estimate the temperature time histories and through-section temperature profiles produced by the thermal accident conditions for the different thermal gradient scenarios to calculate maximum corresponding structural demands (e.g. axial and/or flexure), both globally and locally. Material properties assigned to this model are developed per the provisions of ANSI/AISC 360-22, Appendix 4, Section 4.2.3, as modified per N690-18, Appendix N4. Following this approach, the BWRX-300 heat transfer analysis is conducted using explicit models for estimating the through thickness temperature time histories accounting for time lag effects between the different materials.

5.5.2 Damping Values

Damping values specified for SC walls in Tables 1 and 2 of U.S. NRC RG 1.61 are used to account for the dissipation of energy in the non-containment DP-SC elements. These values are consistent with the stiffness properties assigned to the non-containment DP-SC elements developed as described in Section 5.5.

5.6 Effective Stiffness of Semi-Rigid Connections

To model the behavior of the semi-rigid connections, an approach is adopted using a component-based model explained in Article 6.3 of Eurocode 3, Part 8 (Reference 9-63). The component-based model uses the behavior of the individual components within a connection (e.g., bolts, welds, endplate, column flange) to build a realistic representation of a connection's load-deformation characteristic and thus the equivalent connection translational and rotational stiffnesses can be computed.

5.7 Section Capacities of Steel-Plate Composite Elements

[[The capacities of DP-SC members do not consider contribution of the diaphragm plates except in the direction parallel to them, see Figure 5-4, as discussed in the following subsections. Figure 5-5 shows a unit width design strip perpendicular to the diaphragm plate span direction. {3}]]

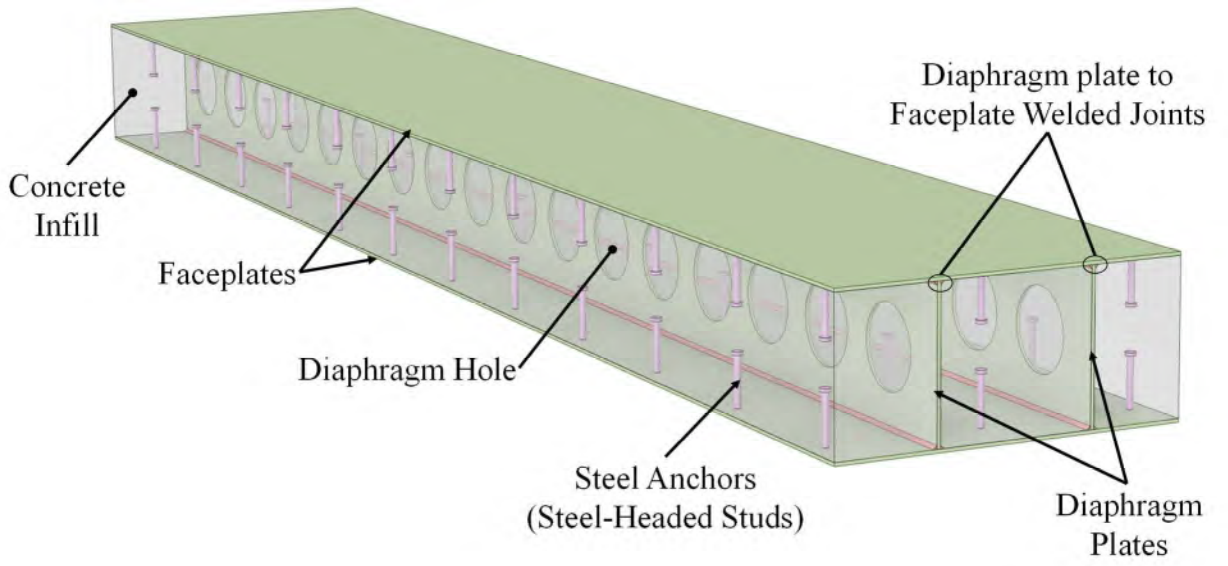


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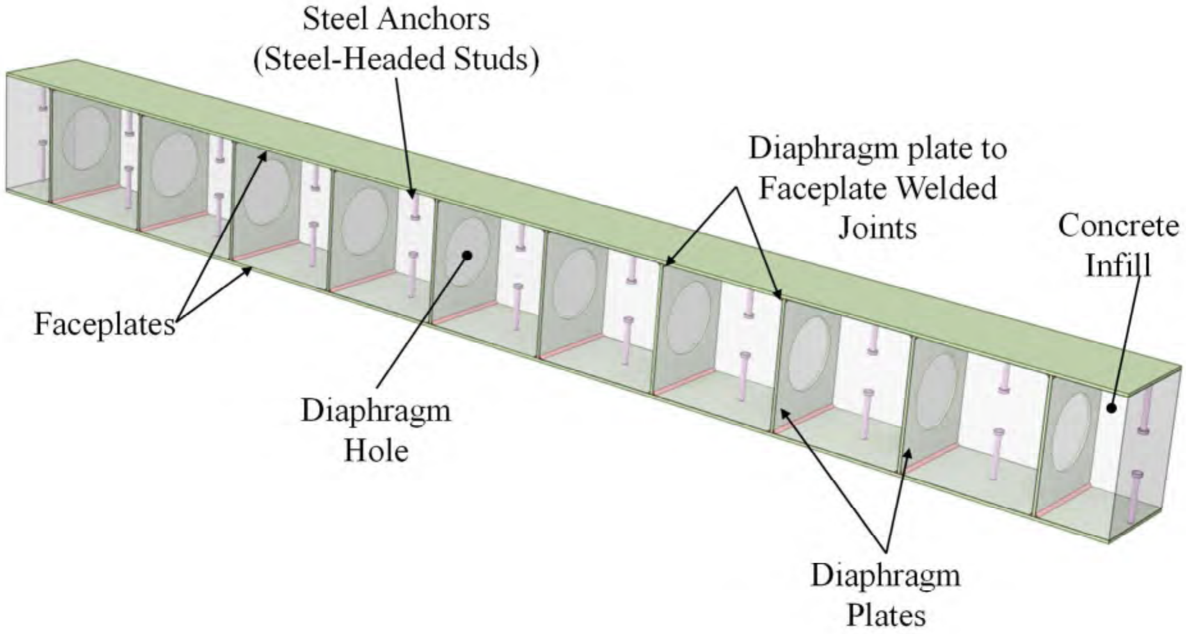
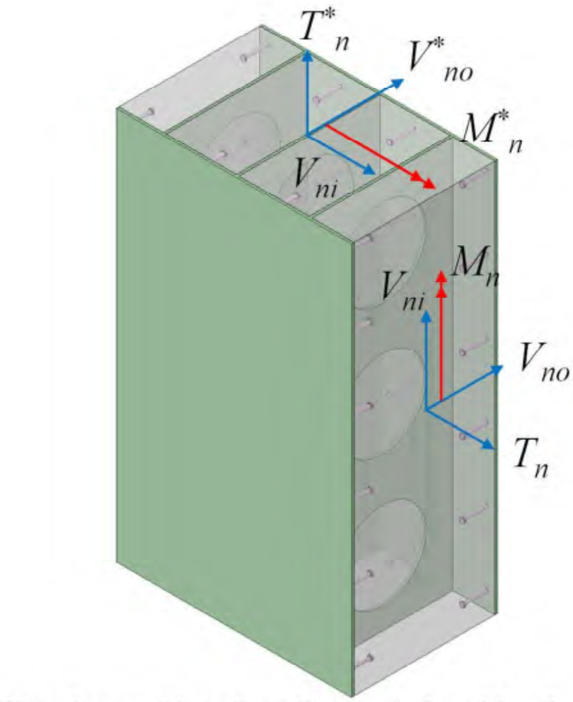
Figure 5-4: Unit Width Design Strip Spanning Along the Direction of Diaphragm Plates



[[{3}]]

Figure 5-5: Unit Width Design Strip Spanning Perpendicular to the Direction of Diaphragm Plates

[[Figure 5-6 below demonstrates the different capacities for axial tension, out-of-plane flexure, and out-of-plane shear for the different directions as explained in Subsections 5.7.1, 5.7.3, and 5.7.5. {3}]]



*Diaphragm Plate Contribution is Considered

[[{3}]]

Figure 5-6: Sectional Capacity of Different Directions

5.7.1 Uniaxial Tensile Strength

[[The uniaxial tensile strength per unit width of DP-SC sections is calculated in accordance with Chapter D of ANSI/AISC 360-16 which is based on the minimum of gross yielding and net section rupture limit states. The gross yielding limit state governs for DP-SC sections.

Equation [5-15] is used to calculate the design uniaxial tensile strength of DP-SC modules. As indicated by this equation, the nominal yielding tensile strength of DP-SC modules is based on the cross-sectional area, A_s, per unit width of the steel faceplates except in the direction of the diaphragm plates span where the diaphragm plates contribution is considered. No contribution from the concrete infill is considered in the axial tensile strength of DP-SC modules.

$$\phi T_n = \phi_t F_y \left(A_s + A_{rib} \frac{l}{W_{sc}} \right) \qquad [5\text{-}15]$$

Where,

A_s = cross-sectional area of steel faceplates, in^2 (mm^2)

A_{rib} = cross-sectional area of the diaphragm plate reduced by the area of hole

$=t_p(t_c - D)$, in^2 (mm^2)

D = diaphragm plate hole diameter

F_y = specified minimum yield stress of faceplate, ksi (MPa)

ϕ_t = 0.9 is resistance factor for tensile strength

l = unit width of module, 12 in/ft (1000 mm/m)

W_{sc} = spacing between diaphragm plates, in (mm). {3}]]

5.7.2 Compressive Strength

[[The diaphragm contribution to the axial compressive strength of DP-SC members is conservatively not considered.

The available compressive strength per unit width of DP-SC sections is determined in accordance with ANSI/AISC 360-16, Section I2.1b using Equations [5-16] to [5-18], complemented by Equations [5-19] to [5-21]:

(a) When $P_{no}/P_e \le 2.25$:

$$P_n = P_{no} \cdot \left(0.658^{\frac{P_{no}}{P_e}}\right) \qquad [5\text{-}16]$$

(b) When $P_{no}/P_e > 2.25$:

$$P_n = 0.877 \cdot P_e \qquad [5\text{-}17]$$

and the design compressive strength, ϕP_n is:

$$\phi P_n = \phi_c \cdot P_n \qquad [5\text{-}18]$$

Where,

ϕ_c = 0.75 is resistance factor for compressive strength.

P_{no} = nominal compressive strength per unit width, kip/ft (N/m)

Per Regulatory Position C.11.3 of U.S. NRC RG 1.243, for surface temperatures up to 300 degrees Fahrenheit (150 degrees Celsius), P_{no} is computed using Equation [5-19]. Where the surface temperature exceeds 300 degrees Fahrenheit (150 degrees Celsius), temperature dependent properties per Sections 5.2.1 and 5.2.2 shall be used in Equation 5-19. The concrete compressive strength at elevated temperature is determined per ANSI/AISC N690, Appendix N4, Table NA-4.2.2 and the steel yield strength at elevated temperature is determined per ANSI/AISC N690, Section NB3.3.

$$P_{no} = F_y A_{sn} + 0.85 f'_c A_c \qquad [5\text{-}19]$$

Equation [5-19] is consistent with ANSI/AISC N690, Section N9.3.2.

P_e = elastic critical buckling load per unit width, kip/ft (N/m)

$$P_e = \frac{\pi^2 EI_{eff}}{L^2} \qquad [5\text{-}20]$$

A_{sn}= net area of faceplates per unit width, in^2/ft (mm^2/m)

A_c = area of the concrete infill per unit width, in^2/ft (mm^2/m)

$A_c = l\,t_c$

l = unit width, 12 in/ft (1000 mm/m)

t_c = concrete infill thickness, in (mm)

F_y = specified minimum yield stress of faceplate, ksi (MPa)

f_c' = specified compressive strength of concrete, ksi (MPa)

EI_{eff} = effective DP-SC stiffness per unit width for buckling evaluation, kip-in^2/ft (N-mm^2/m)

L = laterally unbraced length of the member, in (mm).

$$EI_{eff} = E_s I_s + 0.6 E_c I_c \qquad [5\text{-}21]$$

E_s = modulus of elasticity of steel

E_c = modulus of elasticity of concrete = $w_c^{1.5}\sqrt{f_c'}$, ksi ($0.043 w_c^{1.5}\sqrt{f_c'}$, MPa), where w_c is the weight of concrete per unit volume in lb/ft^3 (kg/m^3)

I_s = moment of inertia of the faceplates per unit width (corresponding to the condition when concrete is fully cracked)

$I_s = l\left[t_p\left(t_{sc} - t_p\right)^2/2\right]$

I_c = moment of inertia of concrete infill per unit width

$I_c = \dfrac{l t_c^3}{12}$ $^{\{3\}}$]]

5.7.3 Out-of-Plane Flexural Strength

5.7.3.1 Perpendicular to Diaphragm Span

For DP-SC sections in the direction perpendicular to the diaphragm plate span (see Figure 5-5), the design flexural strength, $\phi_b M_n$, per unit width is determined for the limit state of yielding using Equation [5-22] for the available flexural strength, a similar equation to ANSI/AISC N690, Equation A-N9-19:

$$\phi_b M_n = \phi_b F_y (A_s^F)(0.9 t_{sc}) \qquad [5\text{-}22]$$

Where,

A_s^F = gross cross-sectional area of faceplate in tension due to flexure per unit width, in^2/ft (mm^2/m)

F_y = specified minimum yield stress of faceplate, ksi (MPa)

t_{sc}= panel thickness, in (mm)

ϕ_b= resistance factor for flexure = 0.90

The results of the NRIC OOPV-1 specimen test, as summarized in Section 7.0, confirm that Equation [5-22] conservatively estimates the out-of-plane flexural capacity.

5.7.3.2 Parallel to Diaphragm Span

[[For DP-SC sections in the direction of the diaphragm plate span (see Figure 5-4), the available flexural strength, $M_{n.ACI}$, per unit width is determined per ACI 349 principles demonstrated previously in literature (Reference 9-64) using Equation [5-20] as shown in Figure 5-7. Equation [5-23] conservatively estimates the out-of-plane flexural capacity as confirmed by the results of the NRIC OOPV-2 specimen test, as summarized in Section 7.0.

$$M_{n.ACI} = A_s^F F_y(t_{sc} - t_p) - \frac{1}{2} f b_w c\left(\frac{c}{3} + \frac{t_p}{2}\right) + F_y A_{rib.flex}\left|\frac{b_w}{W_{sc}}\right|\left(\frac{t_{sc} + d_{rib} - t_p}{2}\right) \quad [5\text{-}23]$$

Where,

t_p = plate thickness, in (mm)

$f = min\,(f_c', \frac{F_y}{n})$

b_w = section width, in (mm), = 12 in/ft (1000 mm/m) for capacity per unit width estimation

W_{sc} = spacing between diaphragm plates, in (mm)

c = height of the triangular stress block in concrete above the neutral axis

$= 2\left(t_p(n' - n) + \frac{F_y A_{rib.flex}}{f W_{sc}}\right) \geq 0$ in (mm)

$n = \frac{E_s}{E_c}$

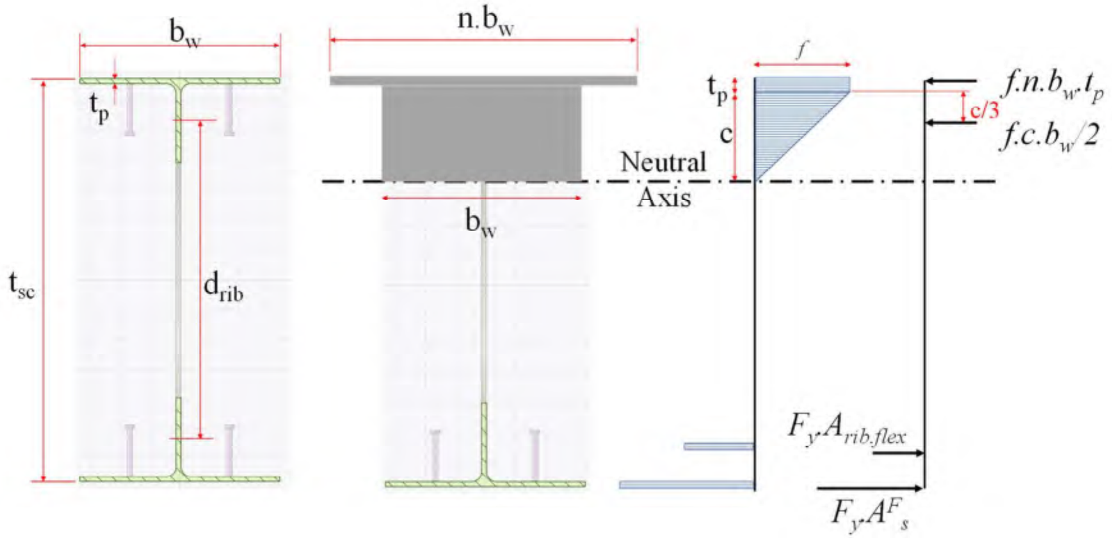
$n' = \frac{F_y}{f}$

$A_{rib.flex}$ = cross-sectional area of the steel diaphragm plate portion under flexural tension, in^2 (mm^2)

$= t_p(t_c - D)/2$

d_{rib} = distance between the centroidal axes of ribs on both faceplates, in (mm).

{3}]]



[[{3}]]

Figure 5-7: Stress and Force Distribution Across Diaphragm Plate Steel-Plate Composite Panel Section to Compute Out-of-Plane Flexural Capacity (Adopted from Reference 9-64)

5.7.4 In-Plane Shear Strength

The in-plane shear strength of DP-SC sections is calculated per ANSI/AISC N690, Section N9.3.4, based on the limit state of yielding of the faceplates.

5.7.5 Out-of-Plane Shear Strength

[[The following methodology is followed to estimate the out-of-plane shear capacity of DP-SC sections.

For calculation purposes, the modules diaphragm plates are classified as yielding shear reinforcement per ANSI/AISC N690, Section N9.1.5a provisions. {3}]]

5.7.5.1 Perpendicular to Diaphragm Span

[[For the calculation of out-of-plane shear strength in the direction perpendicular to the diaphragm span, the approach of ANSI/AISC N690, Section N9.3.5, is followed with the following exceptions:

- The shear strength of plain, unreinforced, concrete V_{conc}, can be obtained from ACI 318 (Reference 9-65), Equation (a) in Table 22.5.5.1, given as $0.063\sqrt{f_c'}$ (where f_c' is in ksi) for one-way shear in non-prestressed members with shear reinforcement. This matches the findings of Sener et al. (Reference 9-66), and the NRIC testing results for specimen OOPV-2 provided in Section 7.0.
- The upper limit imposed on the shear reinforcement contribution $V_s = 0.25\sqrt{f_c'}$ (where f_c' is in ksi) to the total nominal shear strength V_{no}, is not suitable for describing the shear resistance mechanism in DP-SC modules. As mentioned in ACI 318 Commentary

R22.5.1.2, the above limit is intended to minimize the likelihood of diagonal compression failure in the concrete and limit the extent of cracking. This is a necessary requirement in reinforced concrete design, where longitudinal bars and transverse shear reinforcement are typically wired together to form a cage. This requirement has little to no purpose in DP-SC modules, where longitudinal faceplates and transverse diaphragm plates are welded together to form a rectangular tube similar to filled composite members, shown in Section I4.2 of ANSI/AISC 360-22. Equations A-N9-23 and A-N9-23M of ANSI/AISC N690 are modified as shown in Equation [5-25]. This approach matches the findings of Sener et al. (Reference 9-66).

Two scenarios for the available out-of-plane shear strength as described in ANSI/AISC N690, Section N9.3.5 per the spacing of the diaphragm plates perpendicular to the diaphragm plates span, i.e., module width (see Figure 5-5), are presented below:

(a) When diaphragm spacing, i.e., W_{sc} in Figure 5-1 is not greater than half of the section thickness:

$$V_{no} = V_{conc} + V_s \quad [5\text{-}24]$$

$$\phi V_{no} = \phi_{vo} \cdot V_{no} \quad [5\text{-}25]$$

and,

$$V_{conc} = 0.063 \cdot (f'_c)^{0.5} \cdot t_c \cdot l \quad [5\text{-}26]$$

$$V_{conc} = 0.17 \cdot (f'_c)^{0.5} \cdot t_c \cdot l \quad \text{(SI Units)} \quad [5\text{-}27]$$

$$V_s = \xi \cdot p_s \cdot F_t \cdot \left(\frac{l}{s_{tt}}\right) \quad [5\text{-}28]$$

Where,

F_t = nominal tensile strength of diaphragm segments between diaphragms openings determined in accordance with ANSI/AISC N690, Chapter ND, kips (N) (See Figure 5-8)

f'_c = specified compressive strength of concrete, ksi (MPa)

l = unit width, 12 in./ft (1000 mm/m)

$p_s = t_c / s_{tl}$

s_{tl} = spacing of shear reinforcement along the direction of one-way shear, in. (mm)

= W_{sc}, spacing between diaphragm plates, in (mm)

s_{tt} = spacing of shear reinforcement transverse to the direction of one-way shear, in. (mm)

= S, diaphragm hole spacing, in. (mm)

t_c = concrete infill thickness, in. (mm),

ξ = 1.0 for DP-SC modules representing yielding shear reinforcement, and

ϕ_{vo} = resistance factor for out-of-plane shear = 0.75.

(b) When the shear reinforcements, i.e., diaphragm plates, are spaced more than half the section thickness perpendicular to the diaphragm plates span, i.e., module width:

The nominal out-of-plane shear strength is calculated per Equation [5-29]:

$$V_{no} = \max(V_{conc}, V_s) \qquad [5\text{-}29]$$

and,

$$V_s = F_t \cdot \left(\frac{l}{s_{tt}}\right) \qquad [5\text{-}30]$$

The nominal out-of-plane shear strength calculated per Equation [5-29] is compared with the NRIC OOPV-1 specimen experimental strength, as summarized in Section 7.0. {3}]]

5.7.5.2 Parallel to Diaphragm Span

[[The nominal out-of-plane shear strength capacity of DP-SC sections in the direction of the diaphragm plate span (see Figure 5-4) is calculated using Equation [5-31]. The design shear capacity is per Equation [5-25]. Equation [5-31] is based on a conservative reduced section (tie width) idealization of the diaphragm web plate and the superposition of the steel and concrete contributions. This approach yields more conservative capacities than those in Reference 9-66 by smearing the diaphragm plate area. The nominal out-of-plane shear strength, per unit width, calculated per Equation [5-31] is compared with the NRIC OOPV-2 specimen experimental strength, as summarized in Section 7.0..

$$V_{no} = V_{conc} + V_{s.diaph} \qquad [5\text{-}31]$$

$$V_{s.diaph} = F_t \left(\frac{l}{W_{sc}}\right)\left(\frac{t_c}{S}\right) \qquad [5\text{-}32]$$

$$F_t = F_y t_p (S - D) \qquad [5\text{-}33]$$

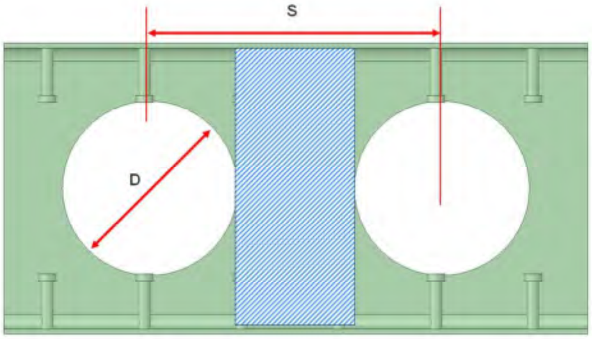
where,

V_{conc} is calculated using Equations [5-26] and [5-27]

S = diaphragm hole spacing, in. (mm)

D = diaphragm hole diameter, in. (mm)

W_{sc}= spacing between diaphragm plates, in. (mm)
t_c = concrete infill thickness, in (mm) {3}]]

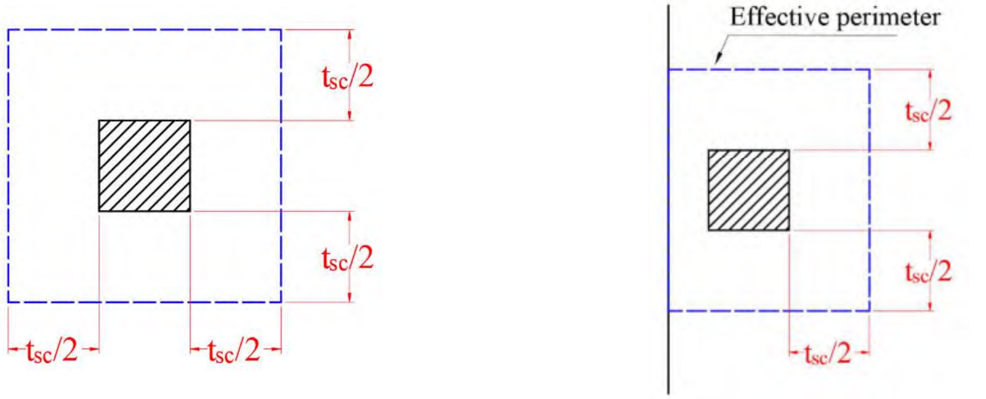


[[{3}]]

Figure 5-8: Idealized Reduced Section (Tie width)

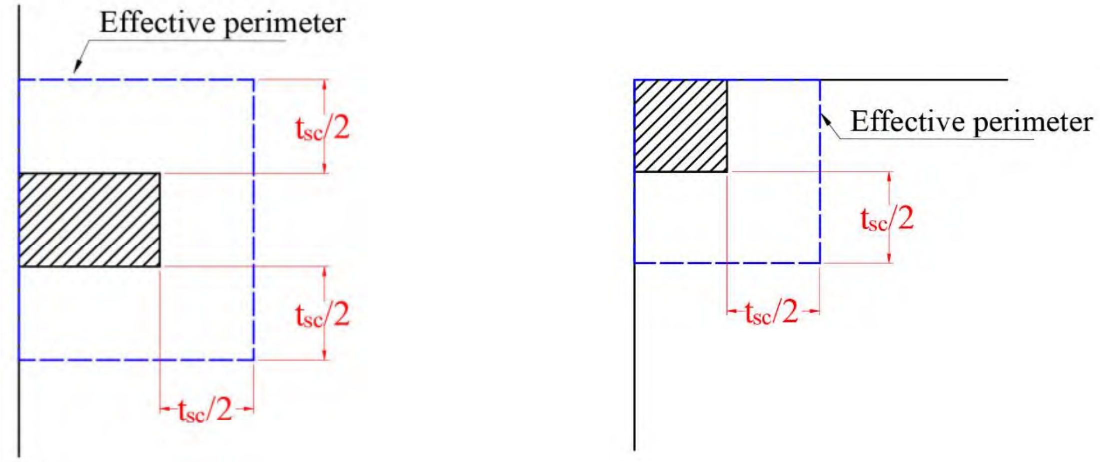
5.7.5.3 Two-Way (Punching) Shear

For punching shear, the shear strength is calculated as the minimum of the out-of-plane shear strength in both directions, if different (e.g., along and across the direction of the diaphragm plates in case of DP-SC modules), multiplied by the perimeter of the punching shear length at a distance $t_{sc}/2$ around the face of the concentrated load as shown in Figure 5-9.



(a) Center Concentrated load

(b) Concentrated load Near Edge



(c) Edge Concentrated Load

(d) Corner Concentrated Load

Figure 5-9: Punching Shear Effective Perimeter

5.7.6 Out-of-Plane Shear Force Interaction

The out-of-plane shear forces interaction is calculated per draft ANSI/AISC N690-XX (Reference 9-59), Section N9.3.6a conditions using the following Equation [5-34] for DP-SC sections.

$$\left(\left(\frac{V_r - V_{c\,conc}}{V_c - V_{c\,conc}}\right)_x + \left(\frac{V_r - V_{c\,conc}}{V_c - V_{c\,conc}}\right)_y\right)^2 + \left(\frac{\sqrt{(V_{rx})^2 + \left(V_{ry}\right)^2} \Big/ 0.9t_{sc}}{lQ_{cv}^{sum} \Big/ W_{sc} \times S}\right)^2 \le 1.0 \qquad [5\text{-}34]$$

Where,

V_r = Out-of-plane one-way shear demand per unit width of composite section in local x (V_{rx}) and y (V_{ry}) directions, kip/ft (kN/m)

$V_{c\,conc}$ = available out-of-plane shear strength contributed by concrete per unit width of section ($0.75\ V_{conc}$), kip/ft (kN/m)

V_c = Out-of-plane one-way shear strength per unit width of composite section in local x (V_{cx}) and y (V_{cy}) directions, ($0.75\ V_{no}$), kip/ft (kN/m)

$Q_{cv}^{sum} = Q_{cv}^{dp} + Q_{cv}^{sa}$

$Q_{cv}^{sa} = \sum Q_{cv}$, the sum of steel headed stud anchors shear capacities contribution is taken for headed stud anchors in a panel having dimensions of S by W_{sc}, kip (N). Where studs are not used in localized areas, Q_{cv}^{sa} = zero

Q_{cv}= Headed stud anchor shear capacity computed per ANSI/AISC N690, Appendix N9, Section N9.1.4a, kip (N)

$Q_{cv}^{dp} = \phi * 0.6 * Fy * t_p * (S - D)$, kip (N), where ϕ =0.9

S = diaphragm hole spacing, in. (mm)

D = diaphragm hole diameter, in. (mm)

W_{sc}= spacing between diaphragm plates, in. (mm)

l = unit width of module, 12 in/ft (1000 mm/m)

x = subscript relating symbol to the local x-axis

y = subscript relating symbol to the local y-axis

For the perpendicular to diaphragm span direction, where the spacing of the shear reinforcement is bigger than $0.5t_{sc}$, and V_c is governed by steel contribution only, $V_{c\,conc}$ is taken equal to zero.

5.7.7 In-Plane Membrane Forces and Out-of-Plane Moments Interaction

[[In-plane membrane forces and out-of-plane moments interaction of DP-SC members is calculated per ANSI/AISC N690, Section N9.3.6b. In this interaction check, the diaphragm plate contributions to the section axial tension strength and flexural strength are conservatively not considered. {3}]]

5.8 Design for Impactive and Impulsive Loads

DP-SC panels are designed to resist the effects of impulse loadings from pipe rupture and the impact of missiles resulting from pipe rupture, tornadoes, aircraft impact or any other missile.

In accordance with NUREG-0800, SRP 3.5.3, the design for impactive loads satisfies the criteria for both local effects and overall structural response as discussed in Subsections 5.8.2 and 5.8.3. For aircraft impact, see Subsection 5.8.4.

5.8.1 Design Allowable

5.8.1.1 General

- DP-SC panels are designed to resist loads in the normal and severe environmental load categories to stay essentially elastic.

- DP-SC panels designed to resist impulse loads and dynamic effects in the abnormal, extreme environmental, and abnormal and extreme environmental categories are allowed to have permanent, plastic deformations. Design adequacy is controlled by limiting the support rotation and ductility, as well as steel and concrete strains.

5.8.1.2 Allowable Stresses

Dynamic increase factors based on the strain rates involved are applied to static material strengths of steel and concrete for purposes of determining section strength but are not to exceed those specified in Table 5-1, adapted from NEI 07-13.

The dynamic increase factors are limited to 1.0 for all materials where the dynamic load factor associated with the impactive, or impulsive loading is less than 1.2.

Table 5-1: Dynamic Increase Factors for Diaphragm Plate Steel-Plate Composite Modules

Materials	**Dynamic Increase Factor**	
	Yield Strength	**Ultimate Strength**
Carbon steel plate	1.29	1.10
Stainless steel plate	1.18	1.00
Concrete compressive strength	—	1.25
Concrete shear strength	—	1.10

5.8.1.3 Allowable Limits

- Damage criteria for DP-SC structures subjected to impactive/impulsive loads, in addition to other simultaneously acting loads (e.g., gravity loads), are presented in Table 5-2, when separate material strains are not available, and Table 5-3. The damage criteria are based on U.S. NRC RG 1.243, ASME BPVC, Section III, Division 2, U.S. NRC RG 1.136, CNSC REGDOC-2.5.2, and International Atomic Energy Agency (IAEA) Safety Reports (SR) series No. 87 (Reference 9-67), and meet the general criteria discussed in Subsection 5.8.1.1.
- For DP-SC containment under DBAs or DBTs (i.e., equivalent to design load combinations per U.S. NRC RG 1.136), the acceptable damage criteria are per ASME BPVC, Section III, Division, II, Subsection CC, Paragraph CC-3923, but not less than the superficial damage criteria per CNSC REGDOC-2.5.2 and IAEA SR No. 87 listed in Table 5-2 and Table 5-3.
- For DP-SC containment under Design Extension Event 1 as defined per IAEA SR No. 87, BDBAs tier 1 or Beyond Design Basis Threats (BDBTs) Tier 1 as defined per CNSC REGDOC-2.5.2, the acceptable damage criteria correspond to the moderate damage criteria listed in Table 5-2 and Table 5-3. These criteria conform to that of NEI 07-13.
- For DP-SC containment under Design Extension Event 2 as defined per IAEA SR No. 87, BDBAs tier 2 or BDBTs Tier 2 as defined per CNSC REGDOC-2.5.2, the acceptable damage criteria correspond to the severe damage criteria listed in Table 5-2.
- For DP-SC non-containment, the limits for moderate damage criteria in Table 5-2 and Table 5-3 are acceptable for DBAs or DBTs as listed in the design load combinations given

in U.S. NRC RG 1.243. Those limits are per ANSI/AISC N690 as endorsed and modified by Regulatory Position C11.1 of U.S. NRC RG 1.243.

- For impulsive loads, the strength available is at least 20 percent greater than the magnitude of any portion of the impulsive loading, which is approximately constant for a time equal to or greater than the first fundamental period of the structural member.
- In addition to the limits in Table 5-2 and Table 5-3, the maximum deformation should not result in the loss of intended function of the structural wall nor impair the safety Category I (i.e., safety related) function of other systems and components.
- Shock and vibratory effects due to impactive or impulsive loadings affecting the functionality of attached Safety Category 1 (i.e., safety-related) components at or at points away from the location of impact should also be evaluated.
- For impact loadings, impact locations evaluated should be such that the shear demand and flexural demand are maximized.
- Damage criteria for DP-SC structures subjected to impactive loads meet the criteria in Subsection 5.8.2.

Table 5-2: Structural Acceptance Criteria for Flexure in Terms of Support Rotations and for Shear in Terms of Ductility

Element Type	**Controlling Behavior** (1) (5)	**Superficial Damage**	**Limited, Moderate, Severe Damage**	**Limited Damage**	**Moderate Damage**	**Severe Damage**
			Ductility μ_d	**Support Rotation** **r_θ (deg)**(2) (6)	**Support Rotation** **r_θ (deg)**(2) (3) (7)	**Support Rotation** **r_θ (deg)**(3) (7)
SC Slabs and Walls (including DP-SC)	Out-of-Plane Flexure	Essentially Elastic Behavior (4)	10(6)	1	4	6
	Out-of-Plane Shear:					
	• Ties or Diaphragms spaced at no more than ½ t_{sc}		1.3			
	• Ties or Diaphragms spaced at more than ½ t_{sc}		1.0			
	Compression		1.0(8)			
SC Shear Walls, and Diaphragms	In-Plane Flexure (shear walls and diaphragms)		N/A	-	1.5	2

(including DP-SC) (9)	In-Plane Shear (shear walls)	Essentially Elastic Behavior (4)	3.0			
	In-Plane Shear (diaphragms)		1.5			

Notes:

(1) SC components (including DP-SC) shall be classified as flexure-controlled if their available strength for the limit state of flexural yielding is less than their available strength for the limit state of out-of-plane shear failure by at least 25%.

(2) When flexure controls, the criteria in terms of support rotations, from Table 5-2, and in terms of strains, from Table 5-3, are fulfilled simultaneously in order to control damage.

(3) These rotation criteria (in degrees) are in general consistent with those in the ASCE/SEI 59-11 (Reference 9-68), which does not specify allowable inelastic deformation in terms of ductility ratio-criteria for flexure.

(4) Essentially elastic behavior means elastic structural analysis using design strain acceptance criteria of 1% for steel plates and 0.35% for concrete in compression, which corresponds to superficial damage of elements. The permissible ductility ratio µd is 1.0.

(5) When impact/impulse loading results in net tension, shear capacity of concrete is not considered.

(6) 1 degree support rotation is related to buildings with internal explosions producing internal blast pressures or chamber pressurization. This is a global structural response and is similar to a structural drift criterion that governs the entire structure's integrity. This is a higher damage level than the essentially elastic response threshold defined for superficial damage. The limit of ductility of 3 may be used in lieu of support rotations of 1 degree complying with Regulatory Position C11.1.6 of U.S. NRC RG 1.243.

(7) This is a semi-global response criterion (i.e., for a wall or slab or part of the structure). The collapse of this structural member does not lead to the collapse of the entire structure.

(8) For additional information refer to Regulatory Position C11.1.5 of U.S. NRC RG 1.243.

(9) Per the acceptance criteria of IAEA SR No. 87 and CNSC REGDOC-2.5.2.

Table 5-3: Structural Acceptance Criteria – Allowable Strains for Steel

Structural Acceptance Criteria - Allowable Strains for Steel				
Material	**Strain Measure**	**Superficial Damage**	**Limited Damage**	**Moderate Damage**
Carbon Steel Plate	Membrane principal strain (tension)	0.010	0.025	0.050
	Local ductile tearing effective strain	N/A	$0.070/TF$ (1)	$0.140\ /\ TF$ (1)
304 Stainless Steel Plate	Membrane principal strain (tension)	0.010	0.033	0.067
	Local ductile tearing effective strain	N/A	$0.138/TF$ (1)	$0.275\ /\ TF$ (1)

Note:

(1) The tri-axiality factor, TF, is defined as

$$TF = \frac{\sigma_1 + \sigma_2 + \sigma_3}{\sigma_e}$$

Where σ_1, σ_2 and σ_3 are principal stresses and σe is effective or equivalent stress. Conservatively, the tri-axiality factor, TF, value is taken as 2 for DP-SC modules. The values in Table 5-2 and Table 5-3 are maximum values under given loading condition. Note that the acceptance criteria presented in Table 5-2 and Table 5-3 are applicable to large structural components impacted by large impulsive loading. The strain values for severe damage are not provided as it is difficult to measure strains at that level of damage.

5.8.2 Missile Impact Design for Local Failure

Local impact effects include perforation of the DP-SC structures. Perforation of DP-SC structures is not allowed. The faceplate thickness required to prevent perforation under impactive loads is at least 25% greater than that calculated using rational methods discussed in Subsection 5.8.2.2.

5.8.2.1 Explicit Dynamic Inelastic Analysis

Panels and faceplate thicknesses of DP-SC modules are designed for the load effects of impactive loads using explicit dynamic inelastic FE analysis software packages per NEI 07-13 recommendations.

Realistic explicit dynamic analysis is used to predict the local damage associated with the penetration of a missile into the wall resulting in local fracture in rear steel plate. NEI 07-13 allows the use of one of the following two methods to predict local damage:

1. Force Time-History Analysis Method: In this method, the impact force time-history is first determined based on the missile crushing characteristics and impulse conservation principles using the Riera method presented in the NEI 07-13. The computed force time-history is then applied to a mathematical model of the structure in a time-history analysis.
2. Missile-Target Interaction Analysis Method: In this method, a combined dynamic analysis model of both the missile and target is developed, and the dynamic response is determined

as an initial velocity problem. This method provides more accurate results than the Riera method.

Detailed continuum 3D FE model is used to depict the local performance of the DP-SC module system. The components of DP-SC module panels, including concrete, steel plates and connectors are explicitly modeled. The constitutive model for concrete material with a suitable failure criterion in shear, tension, and compression is selected to accurately simulate the concrete behavior under impact loading. The concrete constitutive model has a failure surface in shear, tension, and compression. The constitutive model for steel is selected to simulate the piece-wise linear plasticity behavior of steel material. The NEI 07-13 guides for the element erosion criterion are implemented into the numerical model.

The following additional numerical modeling guidelines are considered:

- Explicit inclusion of material dynamic increase factors in the material constitutive models, considering the material strain rate effects in accordance with NEI 7-13
- Modeling of interface between the steel plates and the concrete infill using appropriate interface/contact equations
- Use of appropriate boundary conditions that may allow a simplification of the explicit dynamic FE model for symmetry and structural continuity
- Use of suitable FE to model the steel plates and concrete infill
- Performance of a mesh sensitivity analysis (mesh aspect ratio and mesh size) to ensure that the utilized constitutive model is independent of the element size
- Limiting the element size for the concrete infill to the anticipated aggregate size used in the concrete
- Limiting the element size for steel plates to the thickness of the steel plate

5.8.2.2 Alternative Rational Methods

An alternative procedure using empirical equations based on physics and testing data may be used as follows:

DP-SC modules are designed to prevent local perforation. Scabbing is not a design limit state since it is prevented by the rear steel faceplates of DP-SC structures. Per ASME BPVC Section III, Division 2, Paragraph CC-3931, local areas for missile impact are defined as having a maximum diameter equal to 10 times the effective diameter of the impacting missiles, or $5\sqrt{t_{SC}}$ plus the effective diameter of the impacting missile, whichever is smaller, where t_{SC} and the effective missile diameter are in feet.

Subsection 5.8.2.2.1 illustrates the conservatism of the same methodology used for calculating the perforation resistance curve for NRIC missile impact tests (see Section 7.0).

5.8.2.2.1 Steel Plate Thickness Preventing Perforation

When the missile impact velocity (V_{imp}) is greater than the calculated perforation velocity of the concrete infill ($V_{p.conc}$), perforation of DP-SC structures by missiles is prevented by specifying steel faceplate thickness that is greater than the minimum steel plate thickness calculated per Subsection 5.8.2.2.1(d) per Section 7.4.4 of Reference 9-69.

(a) Concrete Infill Penetration Depth of DP-SC structures

The penetration depth $x_{c.sc}$ (in inch) for the concrete infill is calculated as follows:

$$x_{c.sc} = K_{sc} x_c \qquad [5\text{-}35]$$

(Equation (7-13) of Reference 9-69)

Where,
K_{sc}= penetration depth modification factor as defined as below:

$$K_{sc} = 2.073 - 0.661K + 0.688\left(\frac{\alpha_p d}{t_c}\right) + 0.835\left(\frac{x_c}{t_c}\right) \qquad [5\text{-}36]$$

(Equation (7-14) of Reference 9-69)

K = concrete penetrability factor defined as $\frac{180}{\sqrt{f_c'}}$ (f_c' in psi) per Equation (8) of Reference 9-70.

t_c = concrete infill thickness, in

α_p= missile deformability factor (0.60 for deformable missiles,1.0 for rigid missiles)

x_c= concrete penetration depth (in inch) calculated using the modified National Defense Research Council (NDRC) formula:

$$x_c = \sqrt{4KNW_p d\left(\frac{V_{imp}}{1000d}\right)^{1.80}} \qquad \text{for } \frac{x_c}{d} \leq 2.0 \qquad [5\text{-}37]$$

(Equation (4-1) of Reference 9-69)

$$x_c = KNW_p\left(\frac{V_{imp}}{1000d}\right)^{1.80} + d \qquad \text{for } \frac{x_c}{d} > 2.0 \qquad [5\text{-}38]$$

(Equation (4-2) of Reference 9-69)

N= nose shape factor (0.72 for flat-nosed, 0.84 for blunt-nosed, 1.0 for bullet-nosed)

W_p= missile weight in lbs

V_{imp}= missile impact velocity in ft/sec

d= missile diameter in in.

(b) Missile Perforation Velocity ($V_{p.conc}$)

The missile perforation velocity ($V_{p.conc}$) for the concrete infill can be calculated using the procedure described in NEI 07-13, Section 2.1.2.4. This procedure is combined into the following equations to compute directly $V_{p.conc}$ as listed below:

$$V_{p.conc} = 1000d\left(\frac{d}{1.44KW_pNK_{sc}^{2}}\left(2.2 \pm \sqrt{4.84 - 1.2\left(\frac{t_c}{\alpha_p d}\right)}\right)^{2}\right)^{\frac{5}{9}} \quad \text{for } \frac{t_c}{\alpha_p d} \le 2.65$$

[5-39] (Equation (7-15) of Reference 9-69)

$$V_{p.conc} = 1000d\left(\frac{d}{4KW_pNK_{sc}^{2}}\left(\frac{t_c}{1.29\alpha_p d} - 0.53\right)^{2}\right)^{\frac{5}{9}} \quad \text{for } 2.65 < \frac{t_c}{\alpha_p d} < 3.27$$

[5-40] (Equation (7-16) of Reference 9-69)

$$V_{p.conc} = 1000d\left(\frac{d}{KW_pNK_{sc}}\left(\frac{t_c}{1.29\alpha_p d} - (0.53 + K_{sc})\right)\right)^{\frac{5}{9}} \quad \text{for } \frac{t_c}{\alpha_p d} \ge 3.27$$

[5-41] (Equation (7-17) of Reference 9-69)

Where $V_{p.conc}$ is in ft/sec

(c) Missile Residual Velocity V_r

When the missile impact velocity V_{imp} is greater than the calculated perforation velocity of concrete infill $V_{p.conc}$, the residual velocity V_r for the missile and concrete frustum moving together is calculated using:

$$V_r = \sqrt{\left(\frac{W_p}{W_p + W_{cf}}\right)\left(V_{imp}^{2} - V_{p.conc}^{2}\right)}$$

[5-42] (Equation (7-18) of Reference 9-69)

Where,

V_r is in ft/sec

W_p = missile weight in lbs

W_{cf}= concrete frustum weight in lbs defined as

$$W_{cf} = \frac{1}{3}\pi\rho_c(t_c - x_{c.sc})(r_2^2 + r_1r_2 + r_1^2) \quad \text{for } x_{c.sc} < t_c$$

[5-43] (Equation (7-11) of Reference 9-69)

$$W_{cf} = 0 \quad \text{for } x_{c.sc} \ge t_c$$

[5-44] (Equation (7-11) of Reference 9-69)

ρ_c= concrete density, lbs/in^3

$r_1 = d/2$

$r_2 = r_1 + (t_c - x_{c.sc}) \tan\theta$ for $x_{c.sc} < t_c$ [5-45] (Equation (7-12) of Reference 9-69)

$r_2 = \mathrm{N/A}$ for $x_{c.sc} \geq t_c$ [5-46] (Equation (7-12) of Reference 9-69)

$$\theta = \frac{45^0}{\left(\frac{t_c}{d}\right)^{\frac{1}{3}}}$$ (in degrees) [5-47] (Equation (4) of Reference 9-69)

(d) Minimum steel faceplate thickness preventing perforation $t_{p.min}$

The minimum steel faceplate thickness required to prevent perforation of the rear steel plate by the missile and concrete plug moving together with the residual velocity V_r is calculated as follows:

$$t_{p.min} = 0.72\left(\frac{(12V_r)^2 m_t}{\frac{\pi}{2} d^2 \sigma_s}\right)$$ [5-48] (Equation (11) of Reference 9-71)

Where,

m_t= total mass of missile and concrete frustum defined as $(W_p + W_{cf}) / (386\ \mathrm{in/sec^2})$ per Equation (7-20) of Reference 9-69

σ_s= the von Mises yield criterion defined as follows per Equations (7-23) and (7-24) of Reference 9-69

$5.1F_y + 101000$ (psi) for $t_p \geq 0.25$ in.

$3.9F_y + 64000$ (psi) for $t_p < 0.25$ in.

Where F_y is in psi.

5.8.3 Impact or Impulse Design for Global Response

The global response of DP-SC structures subjected to impactive, or impulsive loads is determined by one of the following methods:

1. The dynamic effects are considered by calculating a dynamic load factor. In this case, the impulsive load resistance is considered to be at least equal to the peak of the impulsive load transient multiplied by the dynamic load factor, where the calculation of the dynamic load factor is based on the dynamic characteristics of the structure and impulsive load transient.
2. The dynamic effects of loads are considered by using impulse, momentum, and energy balance techniques. In this case, the strain energy capacity is limited by the ductility criteria in Subsection 5.8.1.3.

3. The dynamic effects of loads are considered by performing a time-history dynamic analysis. This method considers the mass and inertial properties as well as the nonlinear stiffnesses of the structural members under consideration. Simplified bilinear definitions of stiffness are acceptable using this method. The maximum predicted response using this method is governed by the ductility criteria in Subsection 5.8.1.3.
4. The shear strength under local loads considers reaction shear at the supports and punching shear adjacent to the load. Local loads may be impulsive or impactive, except that, for impactive loads, satisfaction of criteria for perforation should be used in place of punching shear requirements. In the case of the reaction shear (beam action condition) at the supports, the effective width of the critical section for the shear beam capacity at the supports is to be determined according to the zone of influence induced by the local loads instead of the entire width of the support. The zone of influence induced by the concentrated loads may be determined by analysis.

5.8.4 Aircraft Impact Evaluation

Aircraft impact evaluations are performed using the NEI 07-13 methodology. Per NEI requirements, the aircraft impact evaluations must demonstrate that the integrity of the containment, the fuel pool, and the systems needed to maintain cooling of fuel in the vessel and in the fuel pool is preserved from the physical shock and fire effects of the aircraft impact. For the BWRX-300 RB, this is achieved by adopting the following acceptance criteria:

1. Maintain the structural integrity of the RB during and after the impact
2. Prevent any damage in the RB which could allow pressurized or propagated fire and burning jet fuel inside the RB
3. Prevent any post-impact debris of concrete and steel components from falling into the reactor and fuel pool
4. Prevent any crane components from falling into the reactor and fuel pool

Two distinct types of structural failure modes are evaluated:

- Local failure caused by impact of the aircraft engines
- Global failure caused by impact of the entire aircraft

For DP-SC walls, the driving local failure mode is wall perforation, since the rear (non-impact side) steel plate prevents scabbing of the concrete prior to perforation. The assessment of local failure identifies whether the thicknesses of the wall and steel faceplates are sufficient to prevent wall perforation by engine components.

The global failure analysis investigates the structural integrity of the RB during and after the impact. The global stability analysis is performed using a High-Fidelity-Physics-Based Explicit computer simulation following the guidance of NEI 07-13. Specific requirements and approaches for aircraft impact explicit dynamic analyses are not in the scope of this report.

5.9 Design of Steel-Plate Composite Floors

[[SC slabs (including DP-SC slabs) built with two steel faceplates (top and bottom) of the same nominal thickness and material properties behave in a similar manner to SC walls (including DP-SC walls). As a result, ANSI/AISC N690, Appendix N9 can be extended to the design of DP-SC slabs as long as they meet the general provisions of Section N9.1.1, and those provided in Section 5.1 for DP-SC.

Due to the similarities in their behavior and failure mechanisms, DP-SC slabs can be modeled in accordance with Section 5.5 and equations listed in Section 5.7 for the estimation of the out-of-plane flexural, out-of-plane shear, in-plane shear, and axial strengths of DP-SC walls can be used for the DP-SC floors. This is supported by the experimental results presented in Reference 9-66 that are equally applicable to the out-of-plane flexure strength and out-of-plane shear strength of DP-SC walls and slabs. The experimental results from the NRIC program presented in Section 7.0 are also applicable to DP-SC walls and slabs, including mat foundations. {3}]]

5.10 Design and Detailing Requirements Around Openings

Design and detailing of the RB floor and wall penetrations and openings is coordinated with the fabricator and meets the requirements in ANSI/AISC N690, Appendix N9, Section N9.1.7, to the extent they apply to the construction of DP-SC modules.

5.11 Design of Steel-Plate Composite Connections

[[DP-SC modules splices and floor-to-wall, wall-to-wall and wall-to-mat foundation connections are designed to meet the requirements of ANSI/AISC N690, Section N9.4, ANSI/AISC 360-16 specifications, and the explanation of Design Guide 32 (Reference 9-72).

All DP-SC elements splices meet the applicable requirements of full-strength connections listed in ANSI/AISC N690, Section N9.4.2.

BWRX-300 large and heavy attachments or equipment inside the RB are supported using pre-installed cast-in place anchors, welded, or bolted to the steel module bottom (for slabs) or far-side faceplates (for walls).

The faceplates are to be locally strengthened as required. The design of DP-SC modules accounts for additional loadings of smaller attachments mounted directly to the faceplates after construction of the DP-SC walls (e.g., field run conduit and piping), where applicable.

For DP-SC panel-to-panel connections where the faceplates are continuous, or where continuity is provided through stiffener plates, the confinement action of the section, surrounded by the faceplates, represents a closed-filled-tube at intersections. For DP-SC module-to-module connections as shown in Figure 5-10, the available joint shear capacity at intersection is calculated using Equation [5-49] based on the research work shown in the equations (17 to 20b) of Reference 9-73.

$$V_{n.JS} = 0.6A_vF_y + 0.0316\beta A_c\sqrt{f_c'} \qquad [5\text{-}49]$$

Where,

f_c' is in ksi
F_y is in ksi
A_c = area of concrete in the connections, in^2

A_v = steel shear area used in joint shear capacity, in^2

$= t_{p.eq.JS} . t_{c\_hrz}$ (When checking joint shear across the DP-SC horizontal member)

$= t_{p.eq.JS} . t_{c\_vrt}$ (When checking joint shear across the DP-SC horizontal member)

$$t_{p.eq.JS} = \frac{t_{c\_vrt} \cdot t_{c\_hrz} \cdot t_{pd\_vrt} - \pi . D_{vrt}{}^{2} . t_{pd\_vrt} / 4}{t_{c\_vrt} \cdot t_{c\_hrz}} \qquad [5\text{-}50]$$

$t_{p.eq.JS}$ = Equivalent diaphragm plate thickness in the joint zone

t_{c_vrt} = Concrete infill thickness for DP-SC vertical member, in

t_{c_hrz} = Concrete infill thickness for DP-SC horizontal member, in

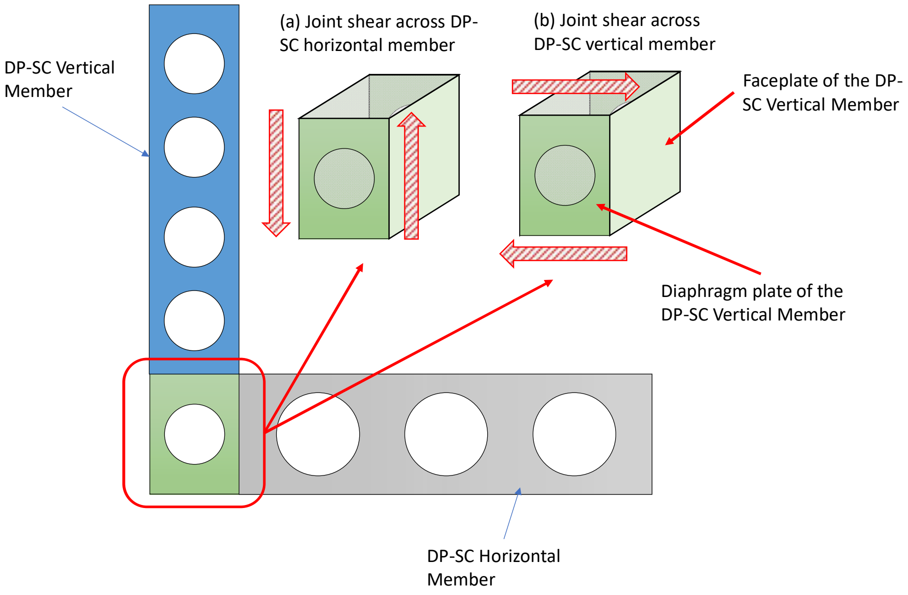
t_{pd_vrt} = Diaphragm plate thickness for DP-SC vertical member, in

D_{vrt} = Diaphragm hole diameter for DP-SC vertical member, in

β = 2 for members with $M_u/V_u\,d > 0.75$, where M_u and V_u are equal to the maximum moment and shear demands, respectively, along the member length, and d is equal to the member depth in the direction of bending

β = 20 for members with rectangular cross sections and $M_u/V_u\,d \leq 0.75$

Equation [5-49] is derived for low compressive axial loads and provides very conservative capacity for higher levels of compressive axial loads per Reference 9-73. Higher concrete contribution may be used based on (i) project-specific test data, or (ii) results of nonlinear inelastic analyses conducted using modeling approaches that are benchmarked against available test data and peer-reviewed. {3}]]



[[{3}]]

Figure 5-10: Illustration Showing Joint Shear Capacity of DP-SC Panel-to-Panel Connection

5.12 Effect of Curvature on Behavior of Steel-Plate Composite Structures

In curved wall applications, the most unique components of force demands are the out-of-plane moment and shear force caused by the curvature of a wall subjected to axial forces. These out-of-plane forces are not induced in straight (rectilinear) walls.

Wang et al (Reference 9-74) compared the results of flat walls and curved walls under constant compression load and cyclic in-plane and out-of-plane loading. The curvature effects were found to be negligible for a thickness-to-radius ratio no more than 0.5, i.e., radius-to-wall panel thickness of 2.0. The integrated RB curved walls are designed and detailed to have a radius-to-wall panel thickness greater than 2.0. Hence, the findings of Reference 9-74 are applicable to the integrated RB SC (including DP-SC) curved walls.

The curvatures of the integrated RB walls are included in the FE model. If the above thickness-to-radius ratio requirement is not met, the curvature effects can be addressed by performing a second-order analysis for the most critical elements.

Since the curvature effects are accounted for in the integrated RB analysis and because of the findings of Reference 9-74, Appendix N9 of ANSI/AISC N690 can be extended to curved walls.

5.13 Fire Rating and Capacity Under Fire Condition Evaluation

The design and evaluation criterion of structural steel components, DP-SC systems, and frames for fire conditions is based on the provisions provided in ANSI/AISC 360-22, Appendix 4 and ANSI/AISC N690, Appendix N4.

Structural members and components in steel buildings are qualified for the rating period in conformance with ASTM E119 (Reference 9-75) and ANSI/AISC N690. It is also permitted to demonstrate equivalency to such standard fire resistance ratings using the advanced analysis methods in Subsection 5.13.1.1 per ANSI/AISC 360-22, Appendix 4, Section 4.2 in combination with the fire exposure specified in ASTM E119 and ANSI/AISC N690 as the design-basis fire. Additionally, design by simple methods of analysis, per Subsection 5.13.1.2, is also permitted to be used where applicable per ANSI/AISC 360, Section 4.2 and ANSI/AISC N690, Appendix N4. The fire rating of BWRX-300 critical DP-SC components are identified per the following criteria:

- The exposure time required for the DP-SC component to increase the temperature levels on the unexposed side of the fire barrier to 139°C above the ambient temperature (per ASTM E119) (termed the thermal insulation requirement)
- The exposure time required for the DP-SC component to lose its load carrying capacity due to the degradation in the material strength at elevated temperature.
- The protected liner remains intact to prevent projection of water beyond the unexposed surface during the hose stream test, and additionally to prevent any smoke from passing through the barrier.

All BWRX-300 DP-SC panels are designed to have a fire resistance rating not less than three hours.

Requirements of Section 5.14 are met to prevent steam pressure build-up.

5.13.1 Design by Engineering Analysis

5.13.1.1 Design by Advanced Methods of Analysis

The advanced method of analysis includes both a thermal response and a mechanical response to the design-basis fire.

The design-basis fire exposure is as specified in ASTM E119 or Eurocode 1 (Reference 9-76). The exposure conditions need to be stipulated in terms of a time-temperature history, along with radiation and convection heat transfer parameters associated with the exposure, or as an incident heat flux as described in ASTM E119, or Eurocode 1.

The thermal response produces a temperature field in each structural element as a result of the design-basis fire and incorporates temperature-dependent thermal properties of the structural elements and fire-resistive materials, as defined per Section 5.2.

The mechanical response includes the forces and deformations in the structural system due to the thermal response calculated from the design-basis fire. The mechanical response considers explicitly the deterioration in strength and stiffness with increasing temperature, the effects of thermal expansions, inelastic behavior and load redistribution, large deformations, time-dependent effects, and uncertainties resulting from variability in material properties at elevated temperature. Support and restraint conditions (forces, moments, and boundary conditions) represent the behavior of the structure during a design-basis fire. Material properties are defined as per Section 5.2.

The resulting analysis addresses all relevant limit states, such as excessive deflections, connection ruptures, and global and local buckling, and demonstrates an adequate level of safety as required by the authority having jurisdiction.

5.13.1.2 Design by Simple Methods of Analysis

Where applicable, the nominal compressive strength for flexural-buckling in filled DP-SC walls, is computed in accordance with ANSI/AISC 360-22, Appendix 4, Section 4.2.4d.(d) and Equation A-4-12.

5.13.2 Design by Qualification Testing

This approach establishes standard fire resistance ratings of structural steel by calculations. Use of this approach is permitted in place of and/or as a supplement to published fire-resistive assemblies based on ASTM E119.

5.13.2.1 Fire Resistance Rating of Diaphragm Plate Steel-Plate Composite Walls

The fire resistance rating for unprotected DP-SC panels, meeting the requirements of ANSI/AISC N690, Appendix N9 and satisfying the following conditions adapted from ANSI/AISC 360-22, Appendix 4, Section 4.3, is determined in accordance with Equations [5-51] and [5-52].

(a) Wall slenderness ratio, L/t_{sc}, is less than or equal to 20

(b) Axial load ratio, P_u/P_n , is less than or equal to 0.2

(c) Wall thickness, t_{sc}, is greater than or equal to 8 in. (200 mm)

$$R = \left[-18.5\left(\frac{P_u}{P_n}\right)^{\left(0.24-\frac{L/t_{sc}}{230}\right)} + 15\right]\left(\frac{1.9t_{sc}}{8} - 1\right) \qquad [5\text{-}51]$$

$$R = \left[-18.5\left(\frac{P_u}{P_n}\right)^{\left(0.24-\frac{L/t_{sc}}{230}\right)} + 15\right]\left(\frac{1.9t_{sc}}{200} - 1\right) \text{ (SI Units)} \qquad [5\text{-}52]$$

where R is the fire rating in hours, L is the unsupported length of DP-SC panel and P_u is the required axial load in kips (N). P_n and t_{sc} are as defined in Chapter I of ANSI/AISC 360-22. The calculations of fire rating of DP-SC panels are based on ANSI/AISC 360-22, Appendix 4, Section 4.3.2g, for design by qualification testing.

5.14 Vent Holes Requirements

Vent holes are required for concrete-filled steel composite members, to relieve the build-up of steam or vapor pressure caused by water evaporation from heated concrete at elevated temperatures and fire incidents. The same requirement applies for DP-SC walls and slabs. The vent holes are designed per the methodology provided in Design Guide 38 (Reference 9-77). The vent hole size and spacing depend on the allowable pressure, concrete moisture content, vent hole spacing, and thermal gradient through the wall thickness.

The following are the minimum vent holes requirements to achieve for the BWRX-300 DP-SC structures:

- Vent holes are used to relieve the steam pressure.
- At least two vent holes are placed at top and bottom of the wall (story height) at each floor, with a maximum spacing of 12 ft (3.7m) on center in the orthogonal directions. Each set of vent holes are located on the alternative face relative to the adjacent set of holes, where possible.
- Maximum spacing between vent holes in floor modules is limited to 12 ft (3.7m) on center in the orthogonal directions. Each set of vent holes is located on the alternative face relative to the adjacent set of holes.
- Vent hole diameter is not to exceed the size of the concrete infill coarse aggregate or 13 mm, whichever is less.
- At the locations where vent holes are not possible, other mechanical methods of releasing the steam may be used to collect and transport the steam to vented locations.

5.14.1 Design of Vent Holes

Equation [5-53] is used to calculate the required vent hole size for a designated effective area. For effective area calculation purposes, vent holes are considered located in the middle of the effective area. The maximum allowable vapor pressure is equated to the maximum allowable hydrostatic pressure on the steel plates during concrete casting. This allowable hydrostatic pressure is calculated per Reference 9-78. The vapor generation rate, m, is determined based on the thickness of the dry concrete, T_{dc} and is calculated by dividing the amount of evaporated water content from the dry concrete thickness, T_{dc}, with the time duration in seconds associated with drying, t_{dc}. The discharge rate of every vent hole is conservatively taken equal to the vapor generation rate, m. The vapor generation rate and the allowable pressure based on the concrete pouring height are calculated using Equation [5-54] and Equation [5-55], respectively.

The following conditions were considered in developing the vent holes design equations:

- Temperature of vapor does not exceed (392°F) while traveling inside the wall until it reaches a vent hole (T = 392°F, $\gamma = 1.315$).
- Water content of concrete evaporates when the temperature exceeds 212°F.
- Flow of vapor through vent holes is reversible and isentropic.
- Vent holes have a square edge for calculation purposes.
- Generated vapor rate is equal to the vapor discharge.

Equation [5-56] is obtained after simplifying Equation [5-53] and taking into account all listed conditions.

$$A = \frac{m}{K_d P \sqrt{\frac{\gamma M_m}{\bar{R}T}\left(\frac{2}{\gamma + 1}\right)^{\left(\frac{\gamma+1}{\gamma-1}\right)}}} \tag{5-53}$$

$$m = \frac{s_1 s_2 T_{dc} \omega \rho_w}{t_{dc}} \tag{5-54}$$

$$P = \rho_c g h_c \tag{5-55}$$

$$A = 116 \frac{s_1 s_2 T_{dc} \omega \rho_w}{t_{dc} \rho_c h_c} \tag{5-56}$$

Where,

A = vent hole area, ft^2

K_d = discharge coefficient (a square edge hole = 0.62)

M_m = molar weight of water, lb/mol

P = allowable pressure, lb/ft-s^2

$\bar{R}$ = ideal gas constant, lb-ft^2/s^2-K-mol

T = maximum vapor temperature, K

T_{dc} = dry concrete thickness, ft (m)

g = gravitational acceleration, ft/s^2 (m/s^2)

h_c = concrete pouring height, ft (m)

m = vapor generation rate, lb/s

s_1 = horizontal spacing of vent holes, ft (m)

s_2 = vertical spacing of vent holes, ft (m)

t_{dc} = heating duration associated with the selected dry concrete thickness, s

γ = specific heat ratio

ρ_w = water density, lb/ft^3 (N/m^3)

ρ_c = concrete density, lb/ft^3(N/m^3)

ω = concrete water content, % by volume.

5.15 Corrosion Protection

The corrosion protection of DP-SC modules is met by one or a combination of the following approaches to meet the design life and decommissioning time of the plant:

- Corrosion tolerance of adding a sacrificial thickness by increasing the faceplate thickness
  - The additional sacrificial thickness is not considered in strength or stiffness estimates.
- Protective paint system suitable to the surrounding environment
  - The protective paint system is per International Organization for Standardization (ISO)-12944-5 (Reference 9-79) and ANSI/AISC 303 (Reference 9-80) requirements. Surface preparation and touch up painting are to meet The Society for Protective Coatings (SSPC) Manuals volumes 1 and 2 provisions and requirements (Reference 9-81 and Reference 9-82). All painting system are to be tested in accordance with ASTM D1014 (Reference 9-83) procedures.
- Membrane coating system.
- Impressed Current Cathodic Protection. The cathodic protection system is to meet ISO-12473 (Reference 9-84).

ASTM MNL20-2nd Edition (Reference 9-85) is used for all corrosion Tests and standards.

The corrosion protection of DP-SC modules will also conform to U.S. NRC RG 1.54, including the requirements for aging management of coatings.

5.16 Fabrication and Construction Requirements

The fabrication and erection requirements for non-containment DP-SC modules are per ANSI/AISC N690, Chapter NM. The acceptable dimensional tolerances for DP-SC modules are similar to those of conventional SC panels presented in ANSI/AISC N690, Section NM2.7(d) and are as follows:

- At diaphragm plate locations, on the flat surface away from the corners, the acceptance criteria for the perpendicular distance between the opposite steel plates is within plus or minus t_{sc}/200, rounded upward to the nearest 1/16 in. (2 mm), where t_{sc} is the design thickness and t_p is the faceplate thickness.
- In between the diaphragm locations, the acceptance criteria for the perpendicular distance between the opposite steel plates is within plus or minus t_{sc}/100, rounded upward to the

nearest 1/16 in. (2 mm). This tolerance check is to be performed along the free edge of the empty steel module.

Additional requirement established for the concrete compressive strength testing are provided in Section 3.2.2.1 of NEDO-33914-A. These requirements address NUREG/CR-7193 for the effect of small volume of concrete placed for the BWRX-300.

ANSI/AISC N690 implicitly accounts for the effects of locked-in stresses from initial imperfections and hydrostatic pressure exerted by the concrete pour during construction. These are accounted for by having a minimum plate thickness as per Section 5.1, minimum yield stress of the steel plates as mentioned in Section 5.2.2, meeting the non-slenderness requirement for the steel faceplates mentioned in ANSI/AISC N690, Section N9.1.3, and the waviness requirement for the steel faceplates after concrete casting per ANSI/AISC N690 Equation NM2-1.

5.17 Quality Control and Quality Assurance

BWRX-300 non-containment Seismic Category I DP-SC structures follow the requirements of ANSI/AISC N690, Chapter NN and Section NA5. U.S. NRC RG 1.28 is used for QA/QC in design, construction, inspection, and testing of steel and composite structures as required by U.S. NRC RG 1.243.

Requirements for placement and installation of ties in conventional SC modules are applicable to the diaphragm plates of DP-SC modules.

5.18 Aging Management, Inservice Inspection, and Testing Requirements for the Integrated RB

An inservice inspection and testing program is established for the DP-SC integrated RB to ensure the structure can fulfill its intended functions throughout its design service life. The examination program may also include requirements for additional examination beyond the regulatory requirements for critical components such as the below-grade RB exterior wall and mat foundation. The scope of this program includes all structural components in the RB other than those covered by Section 6.0 of this report.

The inservice inspection and testing program for the DP-SC integrated RB is similar to that described in the NUREG-2191, Chapter XI.S6 (Reference 9-86). In particular, the program consists of periodic visual inspections of the accessible areas of the RB by qualified personnel for pertinent aging effects, such as those described in ACI 349.3R (Reference 9-87) and SEI/ASCE 11 (Reference 9-88).

Failure Mode Effect Analysis (FMEA) will be performed to identify aging and degradation mechanisms associated with the integrated RB DP-SC construction, inspection processes to detect the abnormalities and proposed repair methods. The condition assessment of accessible steel faceplates can be performed by means of visual inspection as well as using applicable nondestructive testing techniques such as ultrasonic pulse-echo thickness measurement (typically used for steel liners). However, the ultrasonic pulse-echo thickness measurement method is not applicable for testing inaccessible steel faceplates such as the below-grade exterior wall of the RB.

The use the ultrasonic guided wave phased-array method via access ports installed on the inaccessible faceplate allows for the nondestructive testing of the back faceplate (currently being evaluated by the NRIC project). This method utilizes guided wave pulser/receiver equipment and a circular piezoelectric phased-array sensor to detect section loss caused by general or pitting corrosion, cracks, ruptures, dents, and corrosion/crack in welds.

As discussed in Section 5.15, corrosion tolerance may be used as a method of corrosion protection by adding an additional thickness to the faceplate thickness. Alternatively, the inaccessible steel faceplates can also be coated and the gap around the exterior walls filled with waterproofing materials to provide corrosion protection. The integrity of the inaccessible steel faceplates can therefore be maintained throughout the service life of the structure by monitoring the integrity of protective coatings or waterproofing system to assess corrosion potential. Corrosion of inaccessible faceplates can also be estimated by measuring the flexural strain to detect changes in the elastic neutral axis of the composite section due to material loss. This technique is, however, limited to evaluating the material loss due to corrosion only at locations instrumented with strain gauges which provide local damage detection.

The inservice visual inspection of concrete infill in DP-SC modules is not feasible, thus other applicable methods such as nondestructive examination techniques described in ACI 349.3R, Section 3.6.2 can be used.

As part of the NRIC project, the Electric Power Research Institute (EPRI) demonstrated the effectiveness of some potential nondestructive examination techniques on mockups/prototypes fabricated with DP-SC modules to inspect concrete placed between the faceplates. The techniques used for this demonstration included high-energy X-ray and low-frequency ultrasound testing.

EPRI concluded that the high-energy X-ray method can detect the presence of defects and honeycombs in concrete when imaging from both sides of the structure is performed but that it does not provide depth information of the honeycomb. EPRI recommended that the use of this technique be limited to an as-needed basis in areas where defects/cracks are suspected.

The low-frequency ultrasound is performed with a low-frequency ultrasound shear wave array to detect contact between the concrete and steel interface and to detect defects within the concrete. The results of the demonstration tests performed by EPRI indicated that this method allows the inspection of the contact between the steel plate and the concrete, and detection of flaws within the concrete core. However, the effectiveness of this technique is limited to a faceplate thickness of 8 mm. Beyond that thickness, information regarding the concrete could not be obtained. To overcome this limitation, a recommendation was made to prepare inspection areas where a portion of the steel plate, slightly larger than the size of the test array, is replaced with a (8 mm) steel faceplate thickness. Alternatively, making windows of exposed concrete for examination would eliminate the limitation presented by the presence of thicker plates (more than 8 mm) steel faceplate. The windows also permit the use of other techniques such as impact echo, impulse response, surface sounding, and ultrasonic pulse velocity tests to inspect the concrete.

Another potential technique that may be used for the inspection of the concrete infill includes the use embedded ultrasonic sensors that enable determining the relative changes of ultrasonic wave velocity traveling between the two steel faceplates. A drop in the wave velocity indicates that a defect is present within the path of the ultrasonic waves in concrete.

As demonstrated by testing carried out as part of the NRIC project, techniques for inservice inspection and testing that may be deployed for the BWRX-300 DP-SC modules include:

- Ultrasonic guided wave phased-array (screening of defects within steel plates)

- High-energy X-ray (location of voids and foreign material within concrete)
- Low-frequency ultrasound (evaluation of steel plate contact and defects within the concrete)

Additional methods may be implemented after further evaluation during detailed design.

As per the structures monitoring program described in NUREG-2191, Section XI.S6, baseline preservice inspection data will be established by testing during original construction. Baseline inspections including non-destructive examination measurements for the methods identified as part of the aging management program need to be collected at the time of original construction to be used as part of data collection used for trending analysis with respect to subsequent inspections.

The material properties and other parameters to be measured as a baseline data for specific DP-SC modules (e.g., RPV pedestal) will be confirmed based on the outcomes of the FMEA that summarizes the pertinent aging effects, including irradiation embrittlement. A detailed neutron fluence analysis will be performed to identify the locations experiencing high levels of neutron irradiation. Baseline material testing results listed below will be required as part of Certified Material Test Report for DP-SC structures exposed to high levels of neutron irradiation exceeding the threshold level identified to potentially change the mechanical properties of carbon steels (i.e., $1x10^{17}$ neutrons/cm^2 as per NUREG-1509 (Reference 9-89)). By exceeding this threshold, these locations will potentially be prone to neutron irradiation embrittlement.

In addition to chemical analyses and tensile testing of the steel materials used in the faceplates of the DP-SC RPV pedestal, baseline data of the impact testing (either by the drop weight tests or Charpy V-notch impact test), need to be collected for future trending analysis. Impact testing shall conform to one of the following tests:

- The nil-ductility transition temperature in accordance with ASTM E208 (Reference 9-90)
- The Charpy V-notch impact test in accordance with ASTM A370/ASME SA-370 (Reference 9-91)

Based on the outcomes of the inservice inspections, any identified aging effects are evaluated by qualified personnel against predefined acceptance criteria. The acceptance criteria are derived from applicable codes and standards including ACI 349.3R, ACI 318, SEI/ASCE 11, and ANSI/AISC 360-16 specifications as well as the findings from ongoing testing programs. The program also includes periodic testing of ground water samples to assess the impact of any changes in the water chemistry on below-grade portions of the RB. If protective coatings are used, the program is to cover the protective coating monitoring and maintenance during plant operation.

The frequency of inspections of all structural components, protective coatings and ground water quality for the integrated RB is established according to U.S. NRC RG 1.160 with a maximum interval of 5 years as per ACI 349.3R and NUREG-2191. This program supports a plant-specific aging management plan for the DP-SC integrated RB (including items governed by section 6.0 of this report) to provide timely detection and mitigate aging effects. The aging management program begins with the plant commissioning followed by periodic inservice inspection and testing at predefined intervals up to the plant decommissioning.

6.0 PROPOSED DESIGN APPROACH FOR BWRX-300 STEEL-PLATE COMPOSITE CONTAINMENT VESSEL (SCCV)

6.1 Introduction

The general requirements and rules of ASME BPVC, 2021 Edition, Section III, Division 2, Subsection CC, Subsubarticles CC-1110 to CC-1130 are applicable to the BWRX-300 DP-SC containment (SCCV). The proposed design, fabrication, construction, examination and testing requirements presented in this section for the SCCV are adapted from the ASME BPVC, 2021 Edition, Section III, Division 2, Article CC-2000 to CC-6000. These proposed requirements meet the safety goals established by the NRC and CNSC for ensuring the protection of public health and safety and the environment.

The design code applicability is shown in Figure 4-1. As shown in Figure 4-1, the containment boundary includes the containment vessel, including the mat foundation inside the containment and the containment top slab, and all penetration assemblies or appurtenances attached to the containment vessel.

The SCCV DP-SC modules, including the inner and outer faceplates, diaphragm plates, steel headed stud anchors (see Section 5.3) and concrete infill, are part of the containment pressure boundary. In addition to being part of the containment pressure boundary, the modules inner faceplate (i.e., at the containment side) also serves as the leak-tight liner (i.e., containment leakage barrier). Requirements presented in this Section are applicable to the SCCV DP-SC modules, with the exception of leak tightness requirements. Leak tight requirements related to liners are only applicable to the inner faceplate of the DP-SC modules (i.e., containment side). For the SCCV DP-SC modules design parameters, refer to Section 5.1.

6.2 Materials

The requirements for the SCCV DP-SC modules materials follow ASME BPVC, Section III, Division 2, Subsection CC, Article CC-2000, as applicable, in addition to the NRC staff regulatory guidance reported in U.S. NRC RG 1.136. Applicable Subarticles, Subsubarticles, Paragraphs, Subparagraphs, or Subsubparagraphs referenced in Article CC-2000, are followed to the extent they apply to DP-SC modules without reinforcing steel or prestressing tendons. Reinforcing steel bars, where used in SCCV DP-SC connections regions, shall meet the material requirements in ASME BPVC, Section III, Division 2, Subsection CC, Subarticle CC-2300. The following subsections present the proposed requirements specific to the BWRX-300 SCCV.

6.2.1 Concrete Infill

The self-consolidating concrete infill of SCCV DP-SC modules meets the requirements of ASME BPVC, Section III, Division 2, Subsection CC, Subarticle CC-2200 with the following modifications:

- The requirement for the maximum size of coarse aggregate in the concrete infill (CC-2222.1(g)) is limited to maintain acceptable fresh properties of self-consolidating concrete. In particular, the self-consolidating concrete mixture is qualified using tests including static and dynamic segregation resistance and passing ability tests as per Subparagraph CC-2232.3.

Basis of selection of self-consolidating concrete: based on ASME BPVC, Section III, Division 2, Subsection CC, Subparagraph CC-2232.3, the use of self-consolidating concrete is permitted for areas where conditions make manual consolidation difficult. The basis of selection of self-consolidating concrete for the general use in the SCCV is to achieve the required workability and consistency of concrete through the diaphragm holes and around shear studs (particularly for horizontal modules) without segregation or excessive bleeding as per Subparagraph CC-2232.1. This is especially important since the visual inspection of the concrete infill is not feasible after the concrete placement in the DP-SC modules. The self-consolidated concrete mixture used in the integrated RB (including the SCCV) is designed according to the procedure described in ACI 237 (Reference 9-92) and qualified based on ASTM standard test methods specified in U.S. NRC RG 1.136, Section C.1.

- The water-soluble chloride content of the DP-SC modules concrete is limited to 0.06% by mass of total cementitious materials. This value is the maximum specified value for concrete placed in direct contact with prestressing steel as specified in ASME BPVC, Section III, Division 2, Subsection CC, Subparagraph CC-2231.2 and is selected to minimize the possibility of corrosion of the steel plates and shear studs.
- The exposure categories in Table CC-2231.7.1-1 are applicable to the BWRX-300 SCCV, where "concrete" is replaced with "DP-SC concrete infill". The category for corrosion protection of steel materials in DP-SC modules follow those for reinforcement steel.

6.2.2 Steel Materials

All DP-SC steel faceplates and diaphragm plates used in the BWRX-300 SCCV meet ASME BPVC, Section III, Division 2, Subsection CC, Subarticle CC-2500 requirements in addition to the following:

- The design of the inner faceplate of DP-SC modules that serves as the leak barrier meets the material requirements of Subarticle CC-2500. Given the fabrication sequence of the DP-SC modules, the outer faceplate and the diaphragm plate also meet the same Subarticle CC-2500 requirements.
- The effect of elevated temperatures on the mechanical properties of steel materials of DP-SC modules is determined in accordance with ASME BPVC, Section II, Part D.

6.2.3 Welding Materials

All welding materials conform to the requirements of ASME BPVC, Section III, Division 2, Subsection CC, Subarticle CC-2600.

Additional welding requirements are discussed in Sections 6.13 through 6.15.

6.2.4 Material for Embedment Anchors

If used, steel materials classified as load bearing steel materials are to meet the requirements of ASME BPVC, Section III, Division 2, Subsection CC, Subarticle CC-2700. Examples of these materials may include embedded anchors used to support the attachments to the faceplates and ensure the proper load transfer as well as stiffeners used in the DP-SC connection areas.

6.3 Effective Stiffness, Geometric and Material Properties of Diaphragm Plate Steel-Plate Composite Modules for Finite Element Analysis

Based on Subsubarticle CC-3320 of ASME BPVC, Section III, Division 2, elastic behavior is the accepted basis for predicting internal forces, displacements, and stability of the containment shells.

The effective stiffnesses, geometric and material properties, for operational and accidental conditions, of SCCV elements are computed as shown in Section 5.5.

6.4 Damping Values

Damping values specified for SC walls in Tables 1 and 2 of U.S. NRC RG 1.61 are used to account for the dissipation of energy in the SCCV DP-SC elements. These values are consistent with the stiffness properties assigned to the SCCV developed following the approach in Section 5.5 of this report.

6.5 Design Loads and Load Combinations for Steel-Plate Composite Containment Vessel

The loading criteria provisions outlined in ASME BPVC, Section III, Division 2, Subarticle CC-3200 supplemented by U.S. NRC RG 1.136 are applicable to the SCCV and are followed in the analysis of the structure.

6.5.1 Structural Thermal Analysis

[[Analyses for load combinations involving accidental thermal loads are performed using a conservative linear through-section temperature profile. In this type of analysis, the thermal load is developed considering the stress-free reference temperature. The maximum temperature is applied on the face of the DP-SC module subjected to accidental thermal condition and is reduced linearly across the thickness to reach normal temperature at the opposite face of the DP-SC module subjected to no accidental thermal conditions, considering both winter and summer conditions.

The analyses for load combinations involving accidental thermal loads also include heat transfer analyses. The heat transfer analyses are conducted using the geometric and material properties specified in Section 6.3 to estimate the temperature histories and through-section temperature profiles produced by the thermal accident conditions. These temperature histories and through-section temperature profiles are considered in the structural FE analyses.

Alternative to using the properties of Section 6.3 in heat transfer analysis, explicit models as discussed in Section 5.5.1 may be used to estimate the temperature histories and through-section temperature profiles. The BWRX-300 heat transfer analysis is conducted using the explicit models approach to estimate through thickness temperature time histories counting for time lag effects between the different materials.

The concrete temperature limitations for normal operational and accidental conditions meet those specified in ASME BPVC, Section III, Division 2, Subsection CC, Subsubarticle CC-3440. {3}]]

6.6 Design Allowables and Acceptance Criteria for Steel-Plate Composite Containment Vessel

[[The provisions of ASME BPVC, Section III, Division 2, Subsection CC, Subarticle CC-3400 are not fully applicable to the BWRX-300 SCCV. The acceptance criteria and allowable stresses for a

DP-SC containment are different than for a concrete containment, and thus allowables and acceptance criteria are developed for the SCCV, for factored and service loads.

The stress/strain acceptance criteria for the design of the BWRX-300 SCCV are presented in Table 6-1. These allowables are based on criteria in Tables CC-3432-1 and CC-3432-2 of ASME BPVC, Section III, Division 2, Subsection CC modified to include the allowable stresses for the steel component of DP-SC modules. The stress/strain acceptance criteria in Table 6-1 allow the SCCV to remain elastic under service load combinations and below the range of general yield under factored loads. {3}]]

Table 6-1: Acceptance Criteria for BWRX-300 Steel-Plate Composite Containment Vessel

(a) Allowable Stress/Strain Limits for Factored Loads

Material	Force Classification	Type of Force Action	Criteria for Factored Loads	
			Stress Limit	Strain Limit, if any
Concrete	Primary	Membrane	$0.60f_c'$	-
		Membrane + Bending (2)	$0.75f_c'$	-
	Primary + Secondary (1)	Membrane	$0.75f_c'$	-
		Membrane + Bending (2)	$0.85f_c'$ (3)	-
Steel Plates	Primary	Membrane or Membrane + Bending (2)	$0.90F_y$	-
	Primary + Secondary (1)	Membrane or Membrane + Bending (2)	-	$2\varepsilon_y$ (4)

(1) The primary portion of this calculated stress shall not exceed the allowable stress applicable when primary stress acts alone.
(2) The membrane portion of this calculated stress shall not exceed the allowable stress applicable when membrane stress acts alone.
(3) The maximum allowable primary-plus-secondary membrane and bending compressive stress of 0.85f'c corresponds to a limiting strain of 0.002 in./in (0.002 mm/mm). The concrete allowable stresses for factored compression loads shall be reduced, if necessary, to maintain structural stability per Subparagraph CC-3421.1 of ASME BPVC, Section III, Division 2.
(4) Limit for mechanical (net) strain due to primary forces, which is calculated by subtracting strain induced by secondary force (e.g., thermal strain) from the total strain as per Subsubparagraph CC-3422.1(e) of ASME BPVC, Section III, Division 2. For analysis purposes, ϵ_y is defined as the yield stress divided by Young's modulus.

(b) Allowable Stresses for Service Loads

Material	Force Classification	Type of Force Action	Criteria for Service Loads
			Stress Limit
Concrete	Primary	Membrane	$0.30f_c$'
		Membrane + Bending (2)	$0.45f_c$'
	Primary + Secondary (1)	Membrane	$0.45f_c$'
		Membrane + Bending (2)	$0.60f_c$'
Steel Plates	Primary	Membrane or Membrane + Bending (2)	$0.50F_y$ (3) (4)
	Primary + Secondary (1)	Membrane or Membrane + Bending (2)	$0.67F_y$ (3) (4

(1) The primary portion of this calculated stress shall not exceed the allowable stress applicable when primary stress acts alone.
(2) The membrane portion of this calculated stress shall not exceed the allowable stress applicable when membrane stress acts alone.
(3) Where the steel plates are under tension stress, the stress limit may be increased by 50%, with an upper limit of $0.9F_y$ when the temporary pressure loads during the test condition are combined with other loads in the load combination.
(4) Where the steel plates are under compression stress, the stress limit may be increased by 33%, with an upper limit of $0.9F_y$ when the temporary pressure loads during the test condition are combined with other loads in the load combination.

6.7 Required Strength (Demand) Calculations

[[The SCCV design demands are obtained from the linear elastic FE analysis discussed in Section 4.0. The required strength for each demand type is averaged over panel sections no larger than twice the section thickness, t_{sc}, in length and width. In the vicinity of openings and penetrations, and in connection regions, the required strength is averaged over panel sections no larger than the section thickness, t_{sc}, in length and width.

The required strengths of DP-SC modules are denoted as follows and as illustrated in Figure 6-1:

S_{rx} = required membrane axial strength per unit width in direction x, kip/ft (kN/m)

S_{ry} = required membrane axial strength per unit width in direction y, kip/ft (kN/m)

S_{rxy} = required membrane in-plane shear strength per unit width, kip/ft (kN/m)

M_{rx} = required out-of-plane flexural strength in direction x, kip-in/ft (kN.m/m)

M_{ry} = required out-of-plane flexural strength in direction y, kip-in/ft (kN.m/m)

M_{rxy} = required twisting moment strength per unit width, kip-in/ft (kN.m/m)

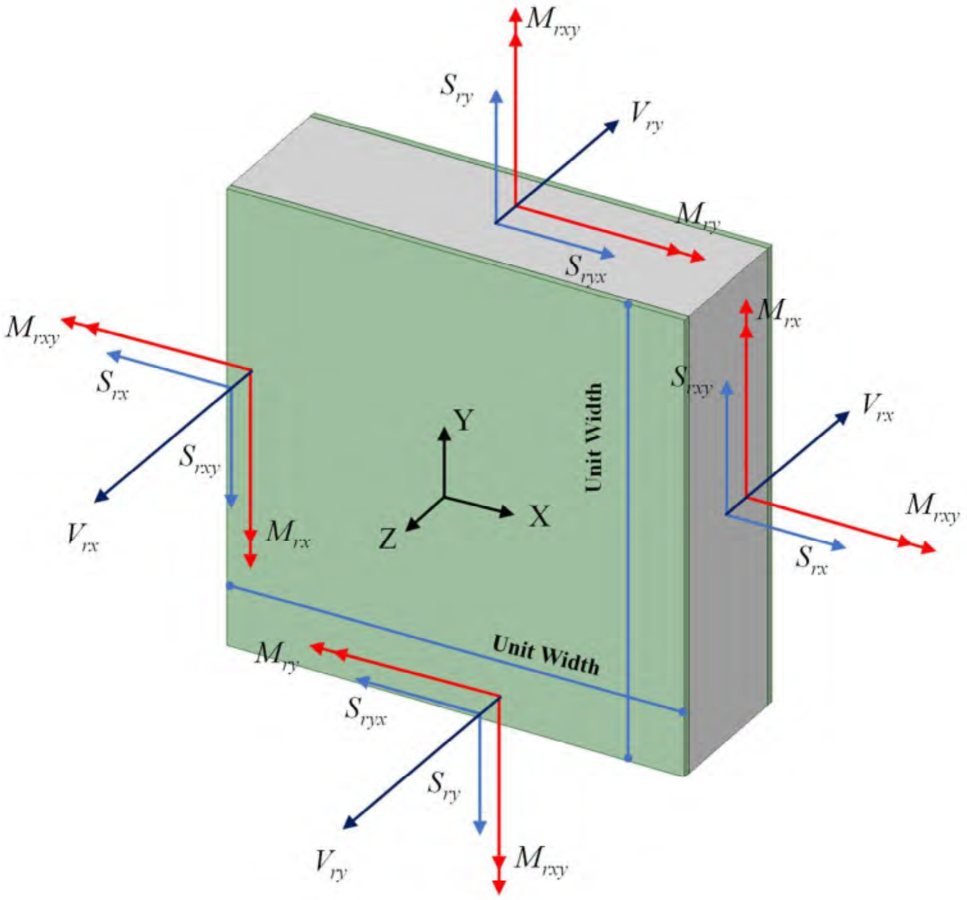
V_{rx} = required out-of-plane shear strength per unit width along edge parallel to direction y, kip/ft (kN/m)

V_{ry} = required out-of-plane shear strength per unit width along edge parallel to direction x, kip/ft (kN/m)

x, y = local coordinate axes associated with the FE model.

In-plane membrane forces and out-of-plane moments interaction of containment DP-SC members is calculated per the methodology shown in Subsections 6.7.1, 6.7.2, and 6.7.3. The factored loads and service loads stresses are calculated and compared to the limits in Section 6.6. For these calculations, the diaphragm plate contributions to the section axial tension strength and flexural strength are conservatively not considered.

The out-of-plane shear design under factored loads and service loads is per the methodology in Section 6.8.{3}]]



[[{3}]]

Figure 6-1: Element Member Force and Moment Demands

6.7.1 Principal Stresses

[[The DP-SC sections are divided into two notional halves, an inside half and an outside half. Each half consists of one faceplate and half of the concrete infill thickness as described in Reference 9-93. The section principal forces (maximum principal force, S_{p1}, and minimum principal force S_{p2}) for each notional half are calculated as follows:

$$S_{p1,2} = \frac{S'_x + S'_y}{2} \pm \sqrt{\left(\frac{S'_x - S'_y}{2}\right)^2 + {S'_{xy}}^2} \qquad [6\text{-}1]$$

Where,

Positive $S_{p1,2}$ = tensile stresses and negative $S_{p1,2}$ = compressive stresses

$S'_x = \frac{S_{rx}}{2} \pm \frac{M_{rx}}{0.9 t_{sc}}$

S_{rx} = membrane force per unit width in direction x

M_{rx} = bending moment per unit width about direction x

t_{sc} = section thickness of DP – SC containment, in (m)

$$S'_{y} = \frac{S_{ry}}{2} \pm \frac{M_{ry}}{0.9t_{sc}}$$

S_{ry} = membrane force per unit width in direction y

M_{ry} = bending moment per unit width about direction y

S'_{x} = membrane force per unit width in direction x for each notional half

S'_{y} = membrane force per unit width in y direction y for each notional half

$$S'_{xy} = \frac{S_{rxy}}{2} \pm \frac{M_{rxy}}{0.67t_{sc}}$$

S_{rxy} = membrane in-plane shear force per unit width

M_{rxy} = twisting moment per unit width]]

6.7.2 Steel Plates

[[For each notional half, the section principal forces described in Subsection 6.7.1 are used to calculate the principal stresses in the corresponding steel faceplate, $\sigma_{p1,2}$. The principal stresses in each steel faceplate, $\sigma_{p1,2}$, are used to calculate the von Mises stress, σ_{VM}. The calculated von Mises stress, σ_{VM}, for each steel faceplate is not to exceed the allowable stresses for factored load combinations summarized in Table 6-1 and allowable stresses for service loads summarized in Table 6-2.

(a) $S_{p1} > 0$ and $S_{p2} > 0$

When both S_{p1} and S_{p2} are greater than 0, the principal stresses and von Mises stress in the steel faceplate (of the corresponding notional half) are calculated as follows:

$$\sigma_{p1} = \frac{S_{p1}}{t_p} \qquad [6\text{-}2]$$

$$\sigma_{p2} = \frac{S_{p2}}{t_p} \qquad [6\text{-}3]$$

$$\sigma_{VM} = \sqrt{\sigma_{p1}{}^2 - \sigma_{p1}\sigma_{p2} + \sigma_{p2}{}^2} \qquad [6\text{-}4]$$

(b) $S_{p1} > 0$ and $S_{p2} < 0$

When one of the section principal forces is less than 0, the contribution of the concrete compressive strength is relied upon to resist the corresponding section principal forces. In this case, the principal stresses and the von Mises stress in the steel faceplate (of the corresponding notional half) are calculated as follows:

$$\sigma_{p1} = \frac{S_{p1}}{t_p} \qquad [6\text{-}5]$$

$$\sigma_{p2} = \frac{S_{p2}}{\left(E_s t_p + 0.85 E_c \frac{t_c}{2}\right)} E_s \qquad [6\text{-}6]$$

$$\sigma_{VM} = \sqrt{\sigma_{p1}{}^2 - \sigma_{p1}\sigma_{p2} + \sigma_{p2}{}^2} \qquad [6\text{-}7]$$

(c) $S_{p1} < 0$ and $S_{p2} < 0$

When both section principal forces are less than 0, the contribution of the concrete compressive strength is relied upon to resist both forces. In this case, the principal stresses and von Mises stress in the steel faceplate (of the corresponding notional half) are calculated as follows:

$$\sigma_{p1} = \frac{S_{p1}}{\left(E_s t_p + 0.85 E_c \frac{t_c}{2}\right)} E_s \qquad [6\text{-}8]$$

$$\sigma_{p2} = \frac{S_{p2}}{\left(E_s t_p + 0.85 E_c \frac{t_c}{2}\right)} E_s \qquad [6\text{-}9]$$

$$\sigma_{VM} = \sqrt{\sigma_{p1}{}^2 - \sigma_{p1}\sigma_{p2} + \sigma_{p2}{}^2} \qquad [6\text{-}10]$$

{3}]]

6.7.3 Concrete Infill

[[For each notional half, the section principal forces described in Subsection 6.7.1 are used to calculate the principal stresses in the corresponding concrete infill, $\sigma_{c1,2}$. The calculated principal stresses, $\sigma_{c1,2}$, are not to exceed the allowable stresses for concrete for factored load combinations summarized in Table 6-1 and allowable stresses for service loads summarized in Table 6-2. Concrete tensile strength is not relied upon to resist flexural and membrane tension as per ASME BPVC, Section III, Division 2, Subsection CC, Subparagraph CC-3421.2.

(a) $S_{p1} \geq 0$ and $S_{p2} \geq 0$

When both S_{p1} and S_{p2} are greater than 0, the principal stresses, $\sigma_{c1,2}$, in the concrete infill (of the corresponding notional half) are 0.

(b) $S_{p1} \geq 0$ and $S_{p2} < 0$

When one of the section principal forces is less than 0, the concrete compressive strength is relied upon to resist the section principal forces and the principal stresses in the concrete infill (of the corresponding notional half) are calculated as follows:

$$\sigma_{c1} = 0 \qquad [6\text{-}11]$$

$$\sigma_{c2} = \frac{S_{p2}}{\left(E_s t_p + 0.85 E_c \frac{t_c}{2}\right)} E_c \qquad [6\text{-}12]$$

(c) $S_{p1} < 0$ and $S_{p2} < 0$

When both section principal forces are less than 0, the concrete compressive strength is relied upon to resist the section principal forces and the principal stresses in the concrete infill (of the corresponding notional half) are calculated as follows:

$$\sigma_{c1} = \frac{S_{p1}}{\left(E_s t_p + 0.85 E_c \frac{t_c}{2}\right)} E_c \qquad [6\text{-}13]$$

$$\sigma_{c2} = \frac{S_{p2}}{\left(E_s t_p + 0.85 E_c \frac{T_c}{2}\right)} E_c \qquad [6\text{-}14]^{\{3\}}]]$$

6.8 Section Capacities of Steel-Plate Composite Elements

Membrane forces (i.e., tensile axial, compressive axial, tangential shear), twisting moment, and out-of-plane flexural moments are evaluated using the methodology in Section 6.7 for the allowables in Section 6.6 for factored and service loads.

6.8.1 One-Way Out-of-Plane Shear Strength

6.8.1.1 Allowable Stresses for Factored Loads

The computation of one-way (out-of-plane) shear strength of the SCCV DP-SC panels is as shown in Subsections 5.7.5.1 and 5.7.5.2 for factored loads.

6.8.1.2 Allowable Stresses for Service Loads

Similar to the approach in ASME BPVC, Section III, Division 2, Subparagraph CC-3431.3, for one-way out-of-plane shear strength under service loads:

a) Use 50% of capacities computed as discussed in Subsections 5.7.5.1, and 5.7.5.2.

b) Use 67% of capacities computed as discussed in Subsections 5.7.5.1, and 5.7.5.2 where pressure loads due to testing exist.

c) Use 67% of capacities computed as discussed in Subsections 5.7.5.1, and 5.7.5.2 where secondary forces (e.g., thermal) are included. However, a separate check with no secondary forces induced demands is required using 50% of capacities computed per Subsections 5.7.5.1, and 5.7.5.2 only as in (a) above.

6.8.2 Two-Way (Punching) Shear Strength

6.8.2.1 Allowable Stresses for Factored Loads

The two-way (punching) shear strength of the SCCV DP-SC panels under localized concentrated loads is calculated as shown in Subsection 5.7.5.3 for factored loads.

6.8.2.2 Allowable Stresses for Service Loads

Similar to the approach in ASME BPVC, Section III, Division 2, Subparagraph CC-3431.3, for two-way (punching) shear strength under service loads:

a) Use 50% of capacities computed as discussed in Subsection 5.7.5.3.

b) Use 67% of capacities computed as discussed in Subsection 5.7.5.3 where pressure loads due to testing exist.

c) Use 67% of capacities computed as discussed in Subsection 5.7.5.3 where Secondary forces (e.g., thermal) are included. However, a separate check with no secondary forces induced demands is required using 50% of capacities computed per Subsection 5.7.5.3 as in (a) above.

6.8.3 Out-of-Plane Shear Interaction Checks

6.8.3.1 Out-of-Plane Shear Interaction for Factored Loads

The out-of-Plane (radial) shear interaction check for the SCCV DP-SC panels is calculated as shown in Subsection 5.7.6 for factored loads.

6.8.3.2 Out-of-Plane Shear Interaction for Service Loads

Similar to the approach in ASME BPVC, Section III, Division 2, Subparagraph CC-3431.3, for one-way shear interaction under service loads, for equation [5-32]:

a) Use 50% of V_c and $V_{c\,conc}$ as defined in Subsection 5.7.6.
b) Use 67% of V_c and $V_{c\,conc}$ as defined in Subsection 5.7.6 where pressure loads due to testing exist.
c) Use 67% of V_c and $V_{c\,conc}$ as defined in Subssection 5.7.6 where secondary forces (e.g., thermal) are included. However, a separate check with no secondary forces induced demands is required using 50% of V_c and $V_{c\,conc}$ as defined in Subsection 5.7.6 as in (a) above.

6.9 Allowable Bearing Stress of Containment Steel-Plate Composite elements

6.9.1.1 Allowable Stresses for Factored Loads

Under Factored loads, per ASME BPVC, Section III, Division 2, Subparagraph CC-3421.9, the maximum bearing stress in concrete shall not exceed $0.60\ f_c'$.

6.9.1.2 Allowable Stresses for Service Loads

Similar to the approach in ASME BPVC, Section III, Division 2, subparagraph CC-3431.3, under Service loads, the maximum bearing stress in concrete shall not exceed $0.30\ f_c'$.. Where pressure loads due to testing exist, the maximum bearing stress in concrete shall not exceed $0.40\ f_c'$.

Under Service loads, where Secondary forces (e.g., thermal) included, the maximum bearing stress in concrete shall not exceed $0.40\ f_c'$. However, a separate check with no secondary forces induced demands is required with a maximum bearing stress in concrete of $0.30\ f_c'$.

6.10 Impulsive and Impactive Design

The BWRX-300 SCCV is designed for impulsive and impactive loads per the regulatory guidelines of NUREG-0800 SRP 3.8.1, Appendix A.

ASME BPVC, Section III, Division 2 provisions are not fully applicable to DP-SC containment. Shear requirements and deformation limits for the containment design are determined as shown in Section 5.8.

6.11 Design of Brackets and Attachments

Similar to ASME BPVC, Section III, Division 2, Subsection CC, Subarticles CC-3125, CC-3650, and CC-3750 requirements, brackets and attachments connected to the SCCV structure are designed and analyzed using accepted techniques applicable to beams, columns, and weldments such as those illustrated in ANSI/AISC N690 and ANSI/AISC 360-16.

6.12 Design and Detailing of Penetrations and Openings

The design and detailing of the SCCV penetrations and openings is coordinated with the fabricator and meets the requirements of ASME BPVC, Section III, Division 2, Subsection CC, Subsubarticle CC-3740 to the extent applicable to DP-SC modules.

6.12.1 Design and Detailing Requirements of Large Openings

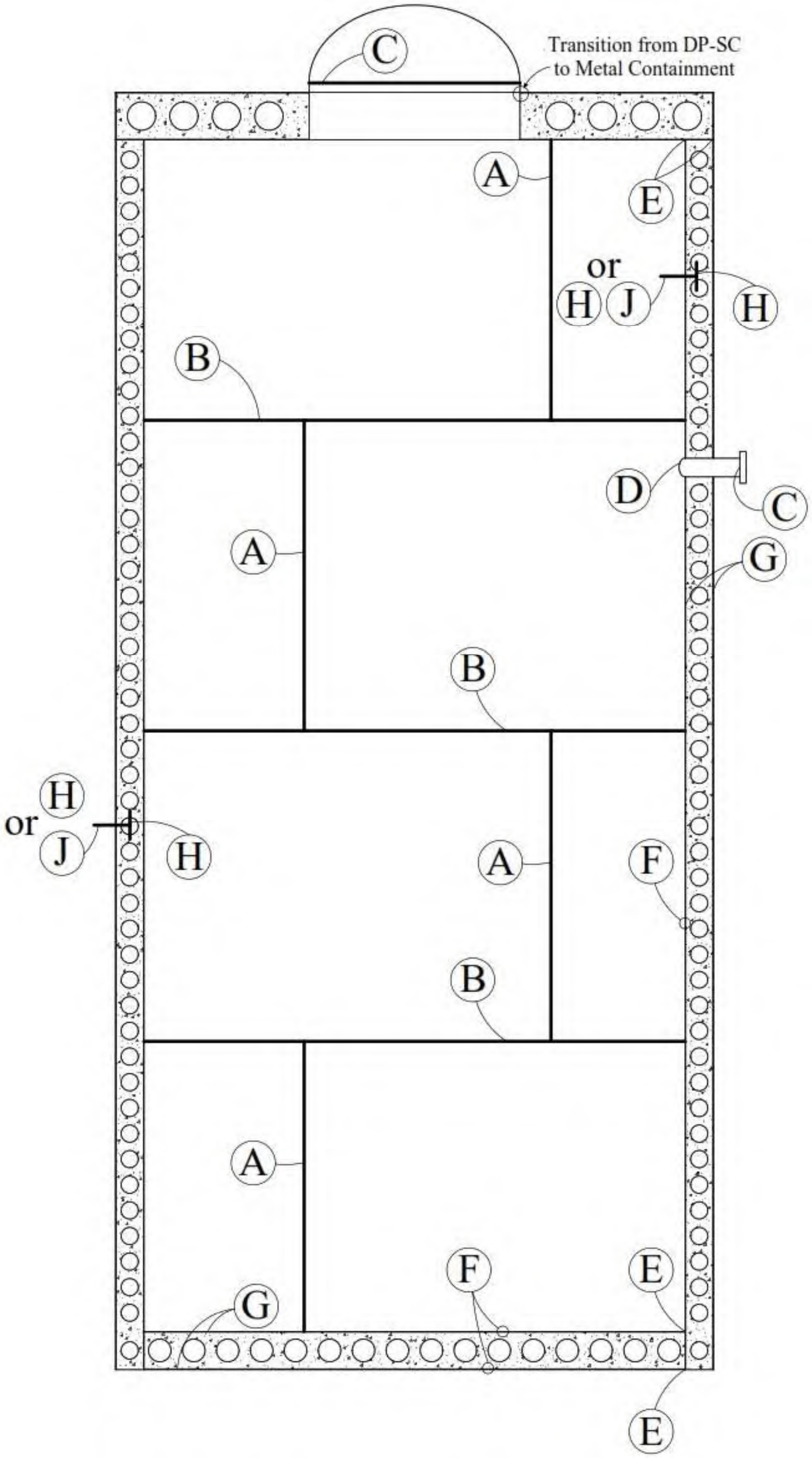
Design and detailing of large openings is in accordance with the provisions of ANSI/AISC N690, Section N9.1.7b.

6.12.2 Design and Detailing Requirements Around Bank of Small Penetrations and Openings

Design and detailing of bank of small openings is in accordance with the provisions of ANSI/AISC N690, Section N9.1.7c.

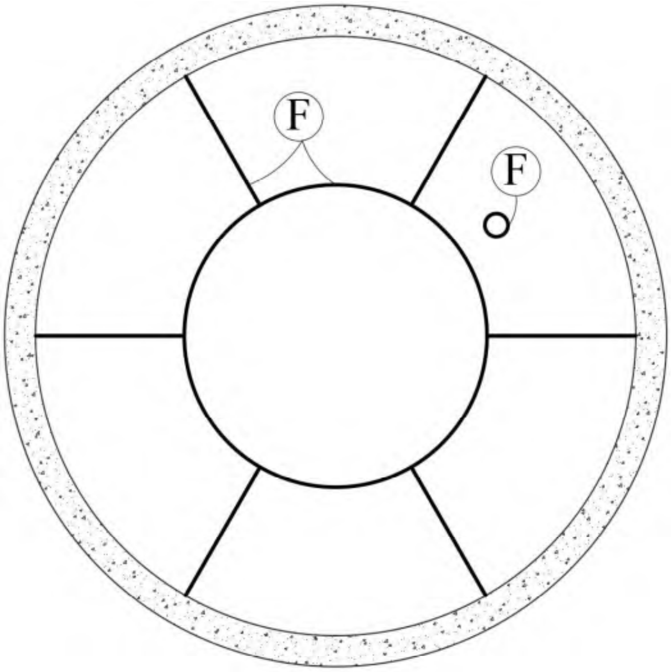
6.13 Welded Construction of Diaphragm Plate Steel-Plate Composite Containment

[[The term category as used herein defines the location of a joint in the DP-SC containment vessel and illustrates some acceptable details. The joints included in each category are designated as A, B, C, D, E, F, G, H, and J. Figure 6-2 illustrates the typical joint locations within the BWRX-300 DP-SC containment vessel.{3}]]



(a) Section Elevation View

[[{3}]]



(b) Basemat Plan View

Notes:

(1) For definitions of joint categories, see Table 6-2

(2) Welding categories annotated on the DP-SC inner faceplates are also applicable to outer faceplates as stated in Table 6-2

(3) Unequal faceplates thickness transitions follow the requirements of ASME Section III, Division 2, Paragraph CC-3843

(4) Transition from DP-SC containment to metal containment:

  a. Metal sections not backed by concrete shall meet all the design requirements of ASME BPVC, Section III, Division 1 and shall consider the concrete confinement. Metal sections may be attached to DP-SC by any connection elements capable of transferring the design loads designed per Section 6.14.

  b. Metal sections backed up by compressible material to provide local flexibility shall meet all design requirements of ASME BPVC, Section III, Division 1 in the region where compressible material is present. Where the sections attach to concrete backed or embedded members, only the requirements of Section 6.0 apply.

[[{3}]]

Figure 6-2: Illustration of Typical Welded Joint Locations for all Joint Categories

Table 6-2: Weld Categories Applicability to Diaphragm Plate Steel-Plate Composite (DP-SC) Containment Vessel

Weld Category	Definition	Permissible Types of Welded Joints and Rules for Making Welded Joint$^{(1)}$	Required Examination of Welds$^{(3-6)}$
[[Category A	Longitudinal welded joints within the DP-SC inner or outer faceplates	• All welded joints of Category A and B shall be full penetration butt joints. The joints may be single or double welded. • Backup bars, if used, shall be continuous and any joints in the backup bars shall be made with full penetration welds. When structural shapes are used as backups, these requirements shall apply.	Category A and B welds shall be radiographed in accordance with ASME Section III, Division 2, Subsection CC, Paragraph CC-5531, except where backup bars are used. Category A and B welds with backup bars shall be examined by ultrasonic examination plus liquid penetrant or magnetic particle examination methods for the full length of the weld.
Category B	Circumferential welded joints within the DP-SC inner or outer faceplates		
Category C	Detailed descriptions and requirements for this category are covered in ASME BPVC, Section III, Division 1	Detailed descriptions and requirements for this category are covered in ASME BPVC, Section III, Division 1.	Detailed requirements for this category are covered in ASME BPVC, Section III, Division 1.
Category D	Welded joints connecting penetration nozzles in the inner and outer faceplates	Welded joints of Categories D, E, F, G, H, and J shall be single or double welded. Backup bars are permitted. Backup bars, when used, shall be continuous and any joints in the backup bars shall be made with full penetration welds. When	Category D butt welds shall be radiographed in accordance with ASME Section III, Division 2, Subsection CC, Paragraph CC-5531, except where backup bars are used. Category D butt welds with backup bars shall be examined by ultrasonic examination plus liquid penetrant or magnetic particle examination methods for the full length of the weld. Where the Category D weld around the insert plate is within a distance from the center of the opening equal

		structural shapes are used as backups, these requirements shall apply.	to the diameter of the opening, the weld shall be 100% radiographed in that area. All butt welds in the insert plate shall be 100% radiographed. When the joint detail does not permit radiographic examination to be performed, ultrasonic examination plus liquid penetrant or magnetic particle examination of the completed weld may be substituted for the radiographic examination. Other Category D welds shall be examined by the magnetic particle or ultrasonic examination method for the full length of the weld.
Category E	Welded joints connecting flat DP-SC inner or outer faceplate to elements of spherical, cylindrical, or conical DP-SC inner faceplate sections, or for intersection of DP-SC faceplates sides to sides, or sides to bottoms		Category E welds shall be examined by ultrasonic examination plus liquid penetrant or magnetic particle examination methods for the full length of the weld.
Category F	Welded joints connecting inner or outer DP-SC floor, roof, or basemat faceplates together and to faceplates transition sections. Welded joints in DP-SC inner and outer faceplates sealing localized holes used for concrete pouring or as welding access windows		Category F welds shall be examined by ultrasonic examination plus liquid penetrant or magnetic particle examination methods for the full length of the weld.
Category G	Welded joints connecting DP-SC diaphragm plates, embedded in the concrete infill, to DP-SC inner and outer faceplates, or for stiffener plates embedded in the concrete and welded to DP-SC diaphragm plates and/or DP-SC faceplates		Full penetration Categories G and H welds shall be examined by ultrasonic examination plus liquid penetrant or magnetic particle examination methods for the full length of the weld. Except for the exposed ends of the welds, which require only visual examination, Categories G and H welds

Category H	Welded joints connecting attachments (including anchors) to the inner or outer DP-SC faceplates, and welded joints connecting embedment anchors to attachments or other embedment anchors		shall be examined by magnetic particle or liquid penetrant method for the full length of the weld with the following exceptions: (1) 10% (2) of the partial penetration welds, that have a groove depth or throat dimensions equal to or less than 1 in. (25 mm), shall be inspected by magnetic particle examination or liquid penetrant examination. The remainder of the weld need only be visually examined. (2) Fillet welds to faceplates that have throat dimensions less than 1⁄2 in. (13 mm) need only be visually examined. (3) Faceplates anchor welds need only be visually examined. All Categories G and H welds exclusive of those described above shall be visually examined.
Category J	Welded joints connecting embedments to inner or outer DP-SC faceplates that are penetrating the inner or outer faceplates		Category J welds shall be examined by ultrasonic examination plus liquid penetrant or magnetic particle examination methods for the full length of the weld.

Notes:

(1) See Figure 6-3 for typical weld categories.

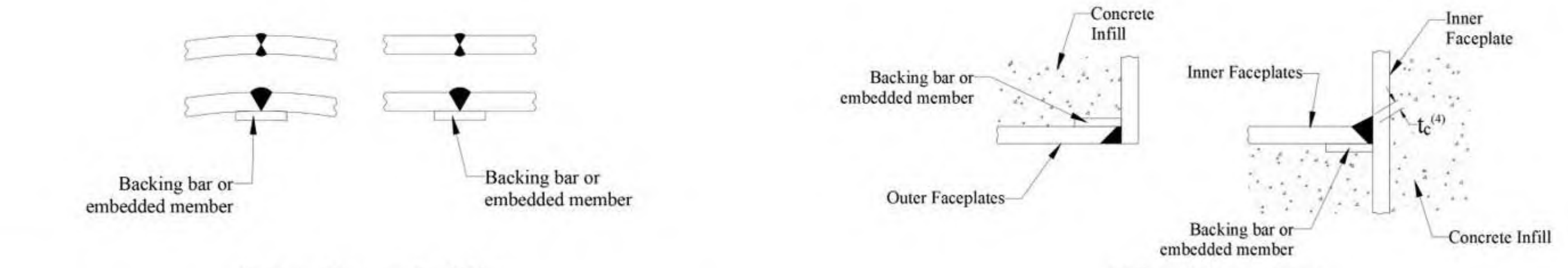
(2) This examination shall be either 10% of each weld or 100% of one weld in 10 and the reduction and increase in the ultrasonic testing rate are to follow ANSI/AISC N690, Sections NN5.5e and NN5.5f.

(3) Weld procedure, acceptance criteria, and documentation are to follow ASME BPVC, Section III, Division 2, Subsection CC requirements.

(4) All DP-SC inner faceplate welds, except attachment welds that do not penetrate the inner faceplate, shall be leak tested in accordance with ASME BPVC, Section III, Division 2, Subsection CC, Paragraph CC-5536 for the full length of the weld.

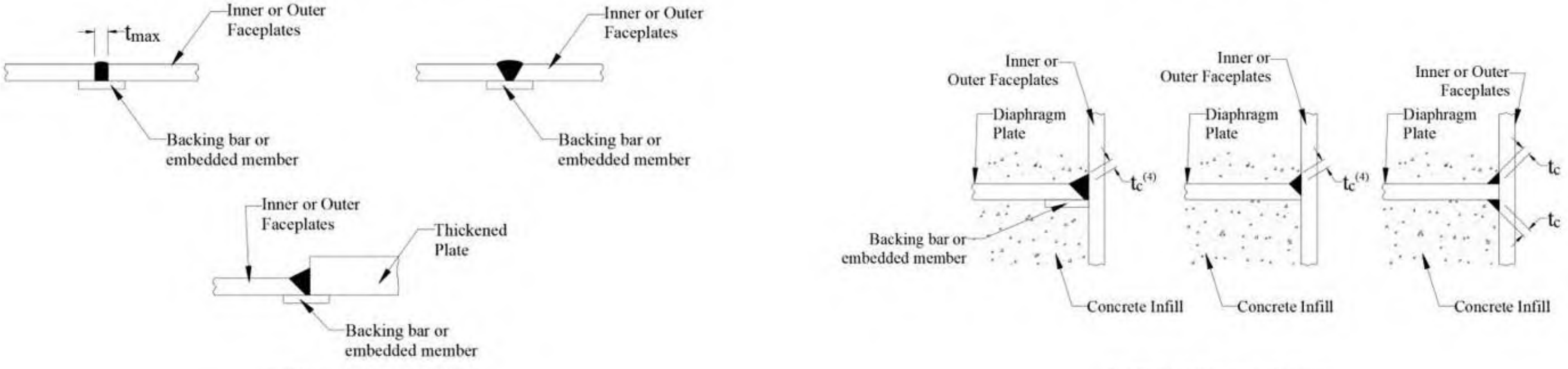
(5) For all austenitic welds, liquid penetrant shall be substituted for magnetic particle examination.

(6) Temporary attachment weld removal areas shall be inspected and shall meet the requirements of ASME BPVC, Section III, Division 2, Subsection CC, Paragraph CC-2533, and the removal area shall be examined by the magnetic particle or liquid-penetrant method.{3}]]



(i) Typical Categories A or B Joint

(ii) Typical Category E Joint



(iii)Typical Category F Joint

(iv)Typical Category G Joint

Notes:

1. (1) Typical Category D Joint is as per Figure CC-4542.2-1 for nozzles over 3 in. (75 mm) diameter and Figure CC-4542.2-2 for nozzles 3 in. (75 mm) diameter and under.
2. (2) Typical Category H Joint is as per Figure CC-4542.2-6.
3. (3) Typical Category J Joint is as per Figure CC-4542.2-7.
4. (4) For all welding categories fillet reinforcement weld, t_c, shall be provided when welding to inner faceplate only.
5. (5) For definition of symbols, t_c and t_{max}, see ASME BPVC, Section III, Division 2, Subparagrpah CC-3842.10.

[[-- {3}]]

Figure 6-3: DP-SC Typical Welded Joint Details

6.14 Design of Steel-Plate Composite Connections

ASME BPVC, 2021 Edition, Section III, Division 2, Subsection CC does not include requirements for the design of SC connections. The requirements of ANSI/AISC N690, Appendix N9, Section N9.4 are adapted as described in Section 5.11, to the design of the SCCV splices, slab-to-wall and wall-to-mat foundation connections.

6.15 Fabrication and Construction Requirements

The fabrication and construction requirements for the SCCV DP-SC modules follow ASME BPVC, Section III, Division 2, Subsection CC, Article CC-4000, as applicable, in addition to the Regulatory Guidance of Position 10 reported in RG 1.136 related to CC-4240 Concrete Curing. Applicable Subarticles, Subsubarticles, Paragraphs, Subparagraphs, or Subsubparagraphs referenced in Article CC-4000, are followed to the extent they apply to DP-SC modules without reinforcing steel or tendons. Leak tightness requirement related to liners are only applicable to the inner faceplate (i.e., containment side) of DP-SC modules.

The following sections of ASME BPVC, Section III, Division 2, Subsection CC, Article CC-4000 are not applicable to the construction and fabrication of DP-SC modules:

- CC-4122.3 Prestressing System Material and CC-4400 Fabrication and Installation of Prestressing Systems

  Reason for non-applicability: Prestressing systems are not used in the construction of the SCCV.

- CC-4230 Preplaced Aggregate Concrete and CC-4270 Repairs to Concrete

  Reason for non-applicability: Repairing concrete using preplaced aggregate concrete is not applicable to the construction of DP-SC modules.

  Concrete consolidation and filling are verified through mockups per CC-4226.3 requirements. Visual inspection of DP-SC modules is difficult. Detectors of concrete filling, vent holes, cameras, telltale tubes are used to ensure proper concrete filling of modules.

- CC-4250 Formwork and Construction Joints, except CC-4251.3

  Reason for non-applicability: Temporary formworks are not required for DP-SC modules construction. SC modules are used as permanent concrete forms. Therefore, only CC-4251.3 is applicable to SC construction.

  Concrete construction joints are not used in DP-SC modules construction. Only cold formed joints between concrete lifts exist that require no surface preparation. Faceplates and diaphragm plates ensure reinforcement continuity through the cold formed joints.

The requirements of the following CC-4000 subsections are amended to adapt them to the construction and fabrication of DP-SC modules:

- CC-4226.3 Placeability Tests

  Basis of amendment: Mock-up specimens for the placeability tests contain representatively complicated portions of SCCV configurations, such as special joints with surrounding structures, penetration sleeves, horizontal stiffener plate, and other embedment. Concrete mix, pumps, other equipment, and procedures used in the tests are as similar as practically possible to those used in the actual construction of the SCCV.

- Weld joints applicable to DP-SC construction are defined in Table 6-2. These categories shall be used in lieu of Paragraph CC-4542 rules for making welded joints including Subparagraphs CC-4542.1 and CC-4542.2 applicable to concrete liner.

The following additional requirements are established for the design of the BWRX-300 SCCV:

- Empty DP-SC modules are to be properly stiffened not to cause excessive deformations or distortions during the construction and concrete placement.
- Concrete filling procedures are demonstrated using construction mockups to secure filling and consolidation especially beneath the penetration sleeves and horizontal components (i.e., slabs and mat foundation).
- In addition to the tolerance requirements in Section 5.16, the Construction Specification shall delineate the tolerance requirements for fabrication and construction of DP-SC SCCV. The Designer shall ensure that the tolerances specified in the Construction Specification are compatible with the design assumptions. The SCCV analysis shall consider deviations in modules geometry due to the fabrication and erection tolerances, which are stated in ASME Section III, Division 2, Paragraph CC-4522, and any additional tolerances stated in the Construction Specification.
- Consideration shall be given to the limitations of interpass temperatures for quenched and tempered material to avoid detrimental effects on the mechanical properties.
- The requirement of ASME BPVC, Section III, Subsubparagraph CC-4532.2.1 (e) is revised as follows for the DP-SC SCCV: “The identification of welders or welding operators is not required for non-structural attachment welds provided that the Fabricator or Constructor maintains a system to permit the Inspector to verify that all such attachment welds were made by qualified welders or welding operators.”
  Structural attachments will utilize the same practices for documentation provided in Subsubparagraph CC-4532.2.1(c).

6.16 Construction Testing and Examination Requirements, Including Weld Examination and Qualification for Diaphragm Plate Steel-Plate Composite Modules

This section discusses construction testing and examination requirements of DP-SC components, tests and examinations of materials including steel, concrete and welds, and qualifications of personnel performing the tests and examinations.

The requirements for construction testing and inspection of materials and welds of ASME Section III, Division 2, Subsection CC, Article CC-5000 are followed, where applicable. Concrete and concrete constituents are examined and tested in accordance with Subarticle CC-5200 including the following modifications:

- Concrete used in DP-SC modules is exempted from visual inspection requirements and therefore can be inspected using nondestructive testing techniques as described in Section 5.18. The nondestructive tests can either be performed directly on the concrete surface (where possible) or through the faceplate depending on the technique being used to detect hidden defects, honeycombing, and voids.

- To monitor concrete during placement in highly congested areas (e.g., connections), cameras can be installed inside the fabricated steel modules to assess the concrete flow/consolidation. These cameras can remain embedded in the concrete infill after hardening. Alternatively, the demonstration of the filling and consolidation of concrete can be achieved on site through the testing of mock-up specimens as per ASME BPVC, Section III, Division 2, Subsection CC, Article CC-4000, Subparagraph CC-4226.3.
- Additional concrete sampling requirements (beyond those described in ASME BPVC, Section III, Division 2, Subsection CC, Article 5000, Subparagraph CC-5232.3 for the compressive strength testing program) provided in Section 3.2.2.1 of NEDO-33914-A are used to address NUREG/CR-7193 for the effect of small volume of concrete placed for the BWRX-300.

Welds examination is in accordance with Subarticle CC-5500, considering the following modifications:

- Where radiographic examination is required and the joint detail does not permit the examination to be performed (i.e., due to configuration of the SCCV, if backup bars are used per Subparagraph CC-4542.1, or obstruction of the headed studs), magnetic particle or ultrasonic examination method for the full length of the weld can be used as allowed by Paragraph CC-5521.
- Leak testing required by Subparagraph CC-5521(e) and described in Paragraph CC-5536 is limited to the inner steel faceplate welds (except attachment welds that do not penetrate the inner faceplate), and is to be completed prior to concrete infill placement.
- Required examination for different welding categories shall follow the requirements described in the Table 6-2 instead of Paragraph CC-5521 requirements.

6.17 Steel-Plate Composite Containment Vessel Pre-Service Inspection and Testing Requirements

The SCCV SIT follows the requirement of ASME BPVC, Section III, Division 2, Subsection CC, Article CC-6000 as applicable. Applicable Subarticles, Subsubarticles, Paragraphs, Subparagraphs, or Subsubparagraphs referenced in Article CC-6000, are followed to the extent they apply to DP-SC modules without reinforcing steel or tendons. Leak tightness requirement related to liners are only applicable to the inner faceplate (i.e., containment side) of DP-SC modules.

The following ASME BPVC, Section III, Division 2, Subsection CC, Article CC-6000 sections related to containment pre-service inspection and testing are not applicable to the SCCV:

- Concrete visual inspection as spalling or unusual cracking of the concrete required by CC-6210
- CC-6225: Crack Measurements
- CC-6350: Surface Cracking
- Concrete visual inspection for permanent damage to the concrete structure as required by CC-6410(b)
- CC-6420: Surface Cracks

- Reporting a summary and discussion of crack measurements as required by CC-6530(c)

Reason for non-applicability: DP-SC construction has an advantage of having the main reinforcement plates exposed and thus strain measurements and damage detection can be performed easily during the pressure test. However, concrete surface crack measurements and mapping, and concrete surface visual inspection are not applicable to DP-SC construction as the concrete is inaccessible and enclosed within the steel faceplates. This is similar to inaccessible concrete behind the liner in concrete containment. SCCV structural integrity is verified by comparing the displacement measurements to the analytical model predictions following ASME BPVC, Section III, Division 2, Subsection CC, Subsubarticles CC-6160 and CC-6510. Furthermore, faceplate strain measurements are compared to the analytical model predictions for the prototype containment (i.e., BWRX-300 first tested unit treated as a prototype containment as per ASME Section III, Subsubarticle CC-6150 definition).

Mock-up tests are performed per ASME BPVC, Section III, Division 2, Subsection CC, Article CC-4000, Subparagraph CC-4226.3 to confirm and demonstrate the filling and consolidation of concrete. The mock-up specimens contain representative portions of SCCV configurations, such as special joints with surrounding structures, penetration sleeves, horizontal stiffener plate, and other embedment. Concrete mix, pumps, other equipment, and procedures used in the tests are as similar as practically possible to those used in the actual construction of the SCCV.

6.18 Effect of Curvature on Behavior of Steel-Plate Composite Containment Vessel

As discussed in Section 5.12, the SCCV wall curvature is included in the integrated RB FE model.

Faceplates rolling and bending shall follow ASME BPVC, Section III, Division 2, Subsection CC, Paragraph CC-4521 requirements.

6.19 Corrosion Protection of Diaphragm Plate Steel-Plate Composite Modules

The corrosion protection approach discussed in Section 5.15 is applicable to the SCCV structure.

6.20 Fire Resistance of Diaphragm Plate Steel-Plate Composite Modules

The BWRX-300 SCCV is designed to have a 3-hour fire resistance rating. The design and evaluation criterion for fire protection of the SCCV are as described in Section 5.13.

6.21 Vent Hole Requirements

The SCCV vent hole requirements are the same as those for non-containment DP-SC structures discussed in Section 5.14 with the following exceptions:

- Vent holes are only used on the external faceplate of the containment walls and slabs.
- Vent holes are not used on the internal faceplates of the leak boundary.
- Vent holes are not used on the internal face of the water storage tanks and pools.
- Vent holes are not used on the external face plated facing the soil.

6.22 Steel-Plate Composite Containment Vessel Inservice Inspection and Testing Requirements

The inservice inspection and testing program supports the aging management plan for the integrated RB described in Section 5.18. The aging management plan includes the details of the inservice inspection and testing methodologies.

A pre-service and periodic inservice inspection and testing program is established for the SCCV to meet the requirements of ASME Section XI, Division 1, Subsections IWE and IWL, as per 10CFR50, 50.55a (b)(2)(viii) and (b)(2)(ix). The pre-service examinations are performed prior to plant startup following the completion of the SIT. The inservice inspections of the SCCV, including penetrations, are performed after the completion of SIT and following plant outages (such as refueling shutdowns or maintenance shutdowns) in accordance with ASME Section XI, Subsections IWE and IWL and before each periodic ILRT in accordance with Appendix J to 10 CFR 50. In accordance with 10 CFR 50.55a(g)(4) and ASME Section XI, Subsection IWE, the accessible inner and outer faceplates, welds and their integral attachments are subject to inservice inspection. The DP-SC diaphragm plates, headed stud anchors, embedments, and their welds are inaccessible after concrete infill placement, and, therefore, are exempted from the inservice inspection examination requirements of Article IWE-2000 as per IWE-1220(b), for embedded or inaccessible portions of containment vessels, parts, and appurtenances that meet the requirements of the original Construction Code. Subsequently, the requirements listed in IWE-1232 are not applicable to these components. All welds of the diaphragm plates and headed stud anchors will be examined before concrete infill placement in accordance with Section 6.16. As part of the inner and outer faceplates inservice inspection, any indication of separation of the DP-SC faceplates from its stud anchor to the concrete infill, or separation of the anchor from the concrete, the bulging (inward or outward curvature) of the faceplates shall require corrective action or engineering evaluation to meet the requirements of IWE-3122 prior to continued service.

For the purposes of inservice inspection, Subsections IWE and IWL of ASME Section XI are used where applicable to SCCV DP-SC modules. Metallic components of the SCCV DP-SC modules (inner and outer faceplates, diaphragm plates, headed stud anchors, and welds), that are pressure retaining components and their integral attachments, shall meet the inservice inspection, repair, and replacement requirements applicable to Class MC components as defined in ASME Section XI, Subsection IWE. DP-SC concrete infill shall meet the inservice inspection, repair, and replacement requirements applicable to Class CC concrete containment pressure retaining components as defined in ASME Section XI, Subsection IWL. Note that the SCCV DP-SC modules, including the inner and outer faceplates, diaphragm plates, headed stud anchors, and concrete infill are part of the containment pressure boundary, whereas the inner faceplate only act as a leak-tight barrier, as explained in Section 6.1.

The following are the considerations for the inservice inspection and testing of the SCCV concrete infill:

- According to ASME BPVC, Section XI, Division 1, Subsection IWL, Subsubarticle IWL-1220, portions of the concrete surface that are covered by the faceplates are exempted from visual examination. This exemption applies to all concrete infill used in the SCCV due to their inaccessibility for visual examination.

Critical locations within the SCCV, such as areas around penetrations and/or at stress concentrations, are also exempted from visual examination. Potential examination techniques at these areas include the use of acoustic emission monitoring during the SIT and subsequent ILRTs to detect and localize cracking activities of the concrete infill. The acoustic emission technique has been extensively used in the crack detection and quantification of concrete structures and its effectiveness was also extended to monitoring the health monitoring of SC shear walls (Reference 9-94). Recently, this approach was successfully implemented in pressure-induced damage monitoring in prestressed concrete of a 1:3 scale nuclear containment structure (VeRCoRs mock-up) in France (Reference 9-95).

- If conditions exist after visual examination in accessible areas of the faceplates that indicate the presence of or result in the degradation of the inaccessible concrete, other means of inspection, such as the nondestructive examination techniques described in Section 5.18, can be used to evaluate the condition of concrete.
- Testing mock-up specimens (used during construction) exposed to similar conditions as the SCCV can also provide a means for destructive testing (e.g., core testing) to evaluate the condition of the concrete infill over time as a result of aging degradation effects.

6.23 SCCV Beyond Design Basis Evaluation

This section provides guidance on the BWRX-300 approach for meeting the SCCV structural integrity requirements in:

- 10 CFR 50, Appendix A, GDC 50, "Containment Design Basis," related to the containment structural capacity for design-basis internal pressures presented in Subsection 6.23.1
- 10 CFR 50.44(c)(5) related to the combustible gas control presented in Subsection 6.23.2

6.23.1 Ultimate Pressure Capacity of Steel-Plate Composite Containment Vessel

[[The SCCV and the containment metal components are designed to accommodate, without exceeding the design leakage rate and with sufficient margin, the calculated pressure and temperature conditions caused by a LOCA. The internal pressure capacity is a deterministically based estimate of the maximum internal pressure, beyond the design pressure, at which the containment structure is still able to maintain its structural and functional integrity preventing a failure leading to a significant release of fission products. The evaluation is focused only on the containment structural capacity, and does not address effects on other connected components, such as the piping and other equipment attached to the SCCV. The evaluation of the internal pressure capacity of the SCCV and the containment metal components also addresses major containment penetrations, such as the containment closure head, vent lines and major piping penetrations.

In accordance with the regulatory guidance of NUREG-0800, SRP 3.8.1, the ultimate pressure capacity of the containment is a measure of the safety margin above the design-basis conditions. Ultimate containment pressure can be computed from the results of static FE analysis following the guidelines of Regulatory Position 1 of U.S. NRC RG 1.216.

The analysis is performed on a 3D nonlinear FE model that uses either layered composite shell elements or shell elements representing the steel of the DP-SC modules and solid elements representing the concrete infill. The nonlinear constitutive behavior of the steel is based on the specified minimum yield strength and a stress-strain relationship beyond yield for the specific grade of the steel material. The nonlinear stress-strain constitutive relationship for the concrete considers only the response in compression and does not consider the tensile strength of the concrete. The stress-strain constitutive models that are used represent the nonlinear material behavior corresponding to the DBA temperature.

The model includes penetrations in the SCCV that are larger than one half of its thickness. Smaller penetrations and penetration closure components are separately evaluated using refined FE sub-models.

The initial loads on the containment are established considering an elastic response under dead and design-basis internal pressure loads at design-basis temperature. Nonlinear overall response of the containment is then calculated by applying incremental static pressure loading until reaching failure criteria. The pressures corresponding to initial yielding of the SCCV steel plates and steel components such as the closure head, hatch etc. are recorded.

The analysis considers quasi-static internal pressures. Results of nonlinear dynamic analysis are used to establish a reasonable pressure capacity value accounting for dynamic effects.

The pressure capacity of the containment is established based on the criteria in Regulatory Position 1 of U.S. NRC RG 1.216. The pressure capacity analysis is based on attaining a pressure generated maximum hoop membrane strain in the steel plates of DP-SC modules away from discontinuities of 1 percent, over a gauge length of at least one times the wall thickness. This is consistent with the limit specified in Position 1 of U.S. NRC RG 1.216 for the reinforced concrete containments. In accordance with Clause C.3.1 of CSA N287.3, the internal pressure capacity of the containment is more than twice the DBA internal pressure. {3}]]

6.23.2 Steel-Plate Composite Containment Vessel Robustness Against Combustible Gas Pressure Loads

[[In accordance with the regulatory guidance of NUREG-0800, SRP 3.8.1, evaluations are performed to demonstrate that the containment structural integrity is maintained under loads resulting from combustible gases generated by metal-water reactions of the fuel cladding. These structural integrity analyses meet the requirements specified in Regulatory Position 5 of U.S. NRC RG 1.7 and Regulatory Position 2 of U.S. NRC RG 1.216.

The SCCV containment is evaluated for the pressures resulting from an accident that releases hydrogen generated from 100% fuel clad metal-water reaction (Pg1). Per guidance of U.S. NRC RG 1.216, Regulatory Position 2, the evaluations consider Pg1 pressure magnitudes of at least 310 kPa (45 psig) gauge in combination with dead loads.

The containment response under the combination of Pg1 and dead loads are obtained from the results of analysis performed on a 3D FE model that uses either layered composite shell elements or shell elements representing the steel of the DP-SC modules and solid elements representing the concrete infill. The model includes penetrations in the SCCV that are larger than one half of its thickness.

Per guidance of U.S. NRC RG 1.216, Regulatory Position 2, linear elastic or nonlinear FE analyses may be performed. The tensile strength of the concrete is not considered, and the constitutive behavior of the concrete infill is represented by the nonlinear stress-strain curve in compression.

Steel and concrete mechanical properties are used that correspond to the temperature resulting from the hydrogen-generation event.

Consistent with the guidance of Regulatory Position 5 of U.S. NRC RG 1.7 for reinforced concrete containments, the SCCV acceptance criteria are limited to demonstrating that strains in the inner plates of DP-SC modules satisfy the factored load acceptance criteria of 1 percent strain over a gauge length of at least one times the wall thickness.

Pressures resulting from uncontrolled hydrogen burning (Pg2) and post-accident inerting (Pg3) are not applicable for the BWRX-300 as discussed in NEDC-33911P-A. {3}]]

6.23.3 Steel-Plate Composite Containment Vessel Behavior Following a Severe Accident

Per U.S. NRC SECY-93-087 , the BWRX-300 containment under the more likely severe accident conditions shall:

- Maintain its role as a reliable leak-tight barrier for approximately 24 hours following the onset of core damage
- Continue to provide a barrier against the uncontrolled release of fission products following the initial 24-hour period

The containment robustness to meet these requirements is evaluated following the methods provided in Regulatory Position 3 of U.S. NRC RG 1.216.

The BWRX-300 design minimizes generation of combustible, non-condensable gases from corium-concrete interaction.

6.23.3.1 Evaluations for 24-Hour Period Following the Onset of Core Damage

[[Evaluations are performed to demonstrate that the containment can maintain its role of leak-tight barrier for approximately 24 hours following the onset of core damage. Per requirements of SECY-93-087, these evaluations consider pressure and temperature loadings associated with more likely severe accident challenges identified by considering sequences of plant damage states that represent 90% or more of the core damage frequency. A single pair or a reduced set of pairs of pressure and corresponding temperature loadings are identified that envelop the entire set of pressure and temperature loadings associated with the identified plant damage sequencies.

Analyses of global and local FE models are performed to calculate the enveloping containment response for the reduced set of pairs of pressure and corresponding temperature loadings. The containment global responses under the enveloping pair(s) of internal pressure and temperature loads are obtained from the results of nonlinear analysis performed on a 3D nonlinear FE model that uses either composite layered shell elements or shell elements representing the steel of the DP-SC modules and solid elements representing the concrete infill. The model includes penetrations in the SCCV that are larger than one half of its thickness.

Per guidance of U.S. NRC RG 1.216, Regulatory Position 2, a linear elastic constitutive behavior may be considered for the DP-SC modules. The tensile strength of the concrete is not considered, and the constitutive behavior of the concrete infill is represented by the nonlinear stress-strain curve in compression. Steel and concrete material properties are used that correspond to the considered temperature load.

Consistent with the guidance in Regulatory Position 3 of U.S. NRC RG 1.216 for reinforced concrete containments, the SCCV ability to maintain its role as a reliable leak-tight barrier is demonstrated by meeting factored load category limits. Under the enveloping pressure and corresponding temperature loadings, the SCCV is demonstrating the deterministic performance goal for the first 24 hours following the onset of core damage by meeting the factored load category stress and strain limits in Table 6-1, including the evaluation of the containment for stability or buckling of other metal components not backed by concrete. This is consistent with the factored load category requirements in ASME Code, Section III, Division 2, Subsection CC, Subsubarticle CC-3720 liner strain limits. {3}]]

6.23.3.2 Evaluation for Period Following Initial 24 Hours After the Onset of Core Damage

[[The deterministic performance goal after the initial 24-hour period is demonstrated by showing one of the following:

1. The maximum pressure and temperature following the initial 24-hour period are enveloped by the maximum pressure and temperature during the initial 24-hour period; or
2. The maximum pressure and temperature following the initial 24-hour period meet the factored load category stress and strain limits in Table 6-1; or
3. The calculated release for the more likely severe accident challenges, following the initial 24-hour period, meets site-specific design criteria for fission product released from the containment, in accordance with the requirements of 10 CFR 100.21 and 10 CFR 50.34, for sufficient time to allow implementation of emergency measures.

For alternative 2 above, structural integrity evaluations are performed using results of nonlinear analyses of global and local FE models. Per guidance of U.S. NRC RG 1.216, Regulatory Position 2, a linear elastic constitutive behavior can be considered for the plates of DP-SC modules. The tensile strength of the concrete is not considered, and the constitutive behavior of concrete infill is represented by the nonlinear stress-strain curve in compression. Steel and concrete material properties are used that correspond to the considered temperature loads. {3}]]

7.0 NATIONAL REACTOR INNOVATION CENTER (NRIC) DEMONSTRATION PROJECT OVERVIEW

NRIC demonstration project is a collaboration between various nuclear industry stakeholders, including GEH and Purdue University, for testing the DP-SC design, including application to containment, to be used with BWRX-300. The confirmatory prototype tests are performed on specimens made of Steel Bricks™ representing DP-SC modules manufactured using a proprietary and unique process.

Other types of DP-SC modules, such as the ones shown in Figure 3-5 and Figure 3-6, have the same overall performance characteristics as Steel Bricks™. As a result, the confirmatory test results obtained for Steel Bricks™ discussed in Section 7.3 are applicable to other types of DP-SC modules.

7.1 Objective of the NRIC Project

The NRIC ACT Demonstration Project is comprised of two phases. NRIC Phase 1 (Detailed Design and Structural Performance Testing) and NRIC Phase 2 (Construction, Testing, Decommissioning Activity and Quality Control).

The main objectives of the NRIC Demonstration Project (NRIC Project) include:

- Demonstration of the structural performance of DP-SC modules,
- Development and demonstration of the efficient fabrication, installation, and construction processes for use of DP-SC and in particular Steel Bricks™ for nuclear applications, and
- Advancing the technical readiness level of the DP-SC technology and establishing regulatory process development.

The objectives of the confirmatory prototype tests (NRIC Phase 1) are to evaluate the performance of DP-SC modules for various loading conditions applicable for containment (i.e., pressure-retaining) and non-containment applications. A total of 14 Steel Bricks™ scaled prototype specimens are constructed and tested. The scaled prototypes are designed to be representative of the following components:

1. Mat foundation
2. Inner cylindrical shaft (i.e., SCCV wall)
3. Inside cylindrical shaft (i.e., SCCV wall)-to-mat foundation connection
4. Outer cylindrical shaft (i.e., RB exterior wall)-to-mat foundation connection
5. RB exterior wall

The confirmatory test results are to support:

- Applicability of ANSI/AISC N690, Appendix N9 with modifications in Section 5.0 for the design and construction of SC structures made of DP-SC modules
- Applicability of the proposed design approach presented in Section 6.0 for the design and construction of containment structures DP-SC modules

7.2 NRIC Phase 1 Test Plan

7.2.1.1 NRIC Phase 1 Prototype Testing

Table 7-1 summarizes the prototype testing for NRIC Phase 1 selected to support the technical evaluation of the modified ANSI/AISC requirements provided in Section 5.0 of this report. Further details of the Prototype Test Plan for each test are presented in subsequent sections. Full details including loading, specimen geometry and materials are presented in the NRIC Prototype Test Plan.

Figure 7-1 and Figure 7-2 show the test specimens for out-of-plane shear for mat foundation, Figure 7-3 shows bi-axial tension test specimens for SCCV, Figure 7-4 shows in-plane shear test specimens for SCCV-to-mat foundation connection, Figure 7-5 shows in-plane shear + out-of-plane shear test specimen for RB-to-mat foundation connection and Figure 7-6 shows missile impact test specimens for the RB.

The prototype test specimens are scaled to facilitate testing using the existing loading assemblies available at the testing laboratory. All test specimen geometric properties are scaled based on SC section sizes and steel plate thicknesses comparable to the conceptual design section properties of the BWRX-300 full-scale structure. Self-consolidating concrete was used as concrete infill in the NRIC Phase 1 testing specimens. Hence the NRIC confirmatory test conclusions are directly applicable to the BWRX-300 integrated RB design.

The specimens are approximately 1:2, 1:3, or 1:6 scale depending on the loading and estimated capacity. The scaling refers to the geometric size of the test specimen.

Pre-test calculations and numerical simulations using FE analysis were performed to calculate the capacities of the specimens and ensure they were within the limits of the testing apparatus. These calculations were based on ANSI/AISC N690 code provisions, with modifications as applicable. Material properties taken directly from material test reports, which are usually higher than the specified minimum code/standard properties, were used in the pre-test calculations to provide predictions of the expected specimen capacities. However, the acceptance criteria are based on the nominal capacities calculated based on specific minimum steel and concrete material strengths without the resistance factor ϕ and compared with experimental results.

NEDO-11209-A, GEH quality assurance program, was implemented during the testing program which was performed using a graded approach to fabrication and testing activities. GEH inspection reports demonstrating procurement and manufacturing traceability, and GEH witness test reports were documented. Testing plan and results were reviewed and accepted per NEDO-11209-A.

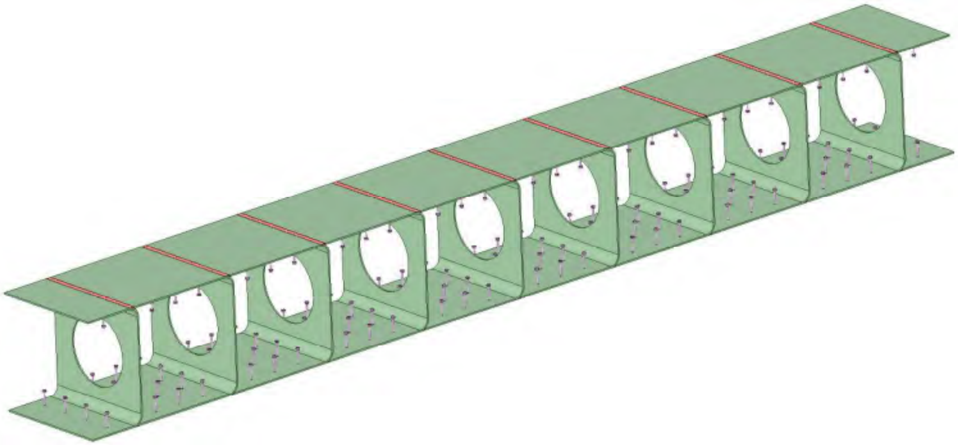


Figure 7-1: Out-of-Plane Shear Test Specimen -
Diaphragm Plate Orientation Parallel to Loading (OOPV-1)

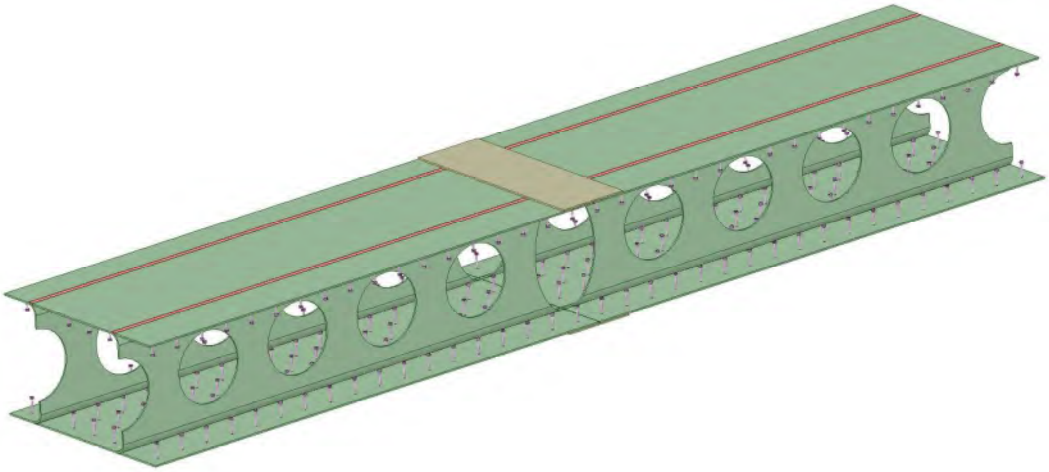


Figure 7-2: Out-of-Plane Shear Test Specimen -
Diaphragm Plate Orientation Perpendicular to Loading (OOPV-2)

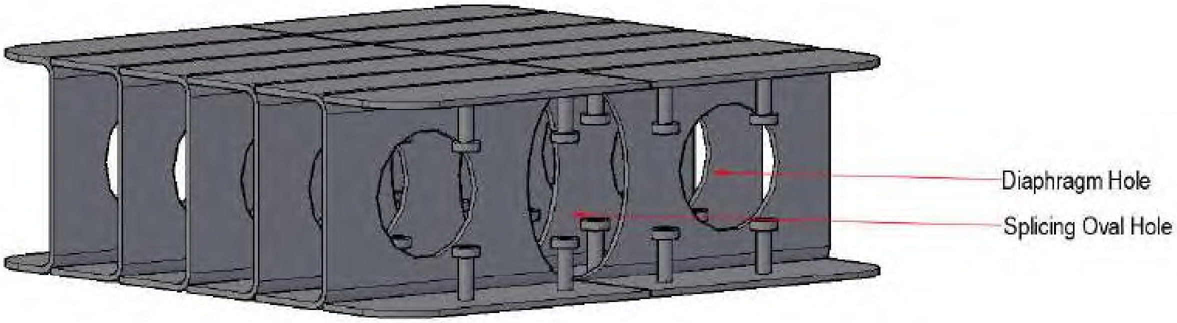


Figure 7-3: Bi-Axial Tension Test Specimen

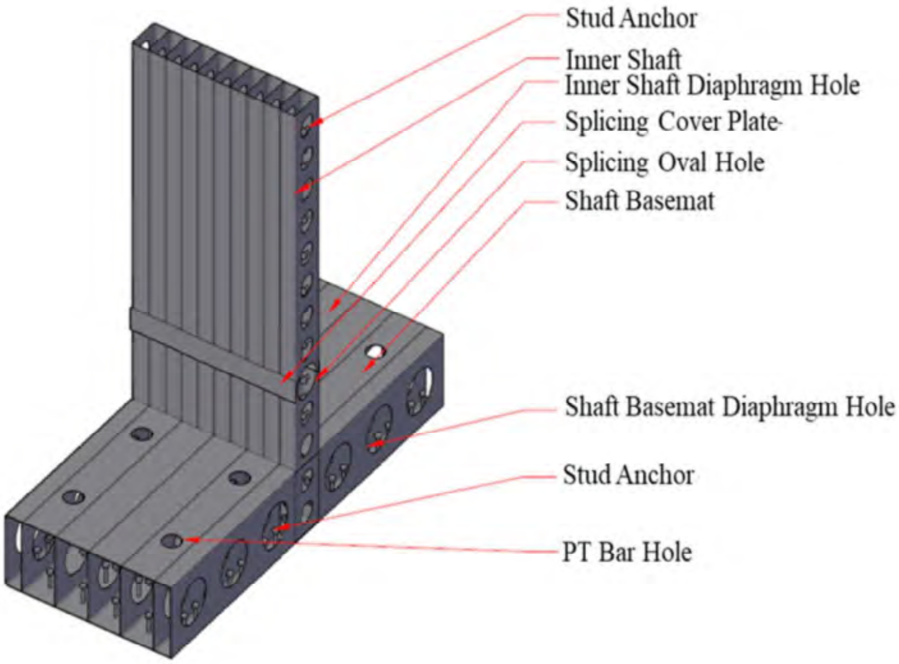


Figure 7-4: In-Plane Shear Test Specimen

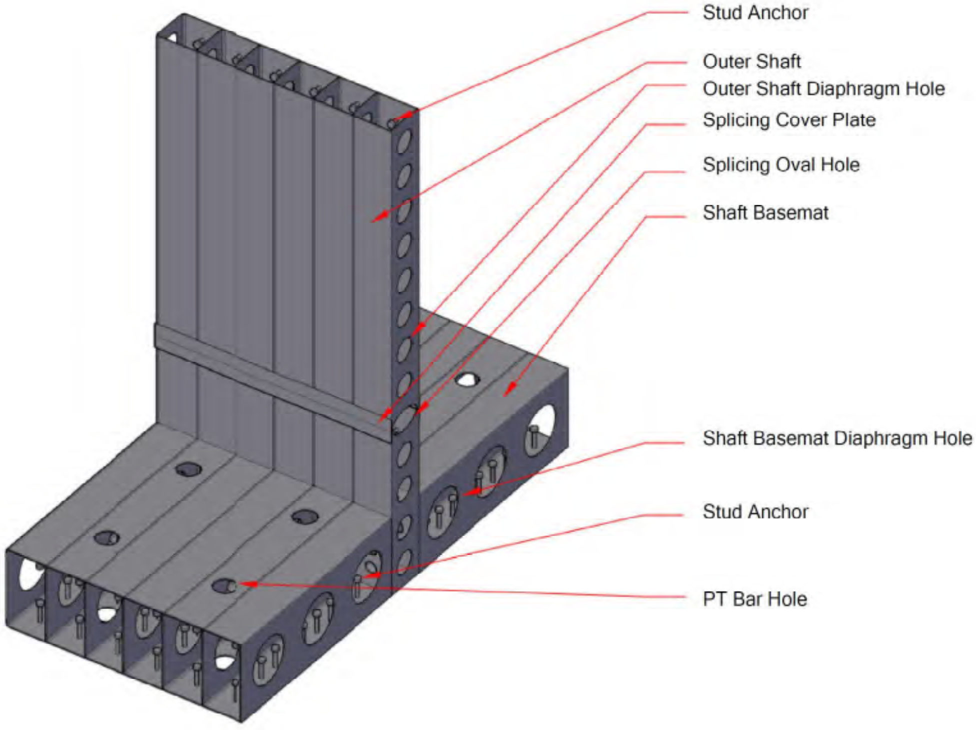


Figure 7-5: In-Plane Shear + Out-Of-Plane Shear Test Specimens

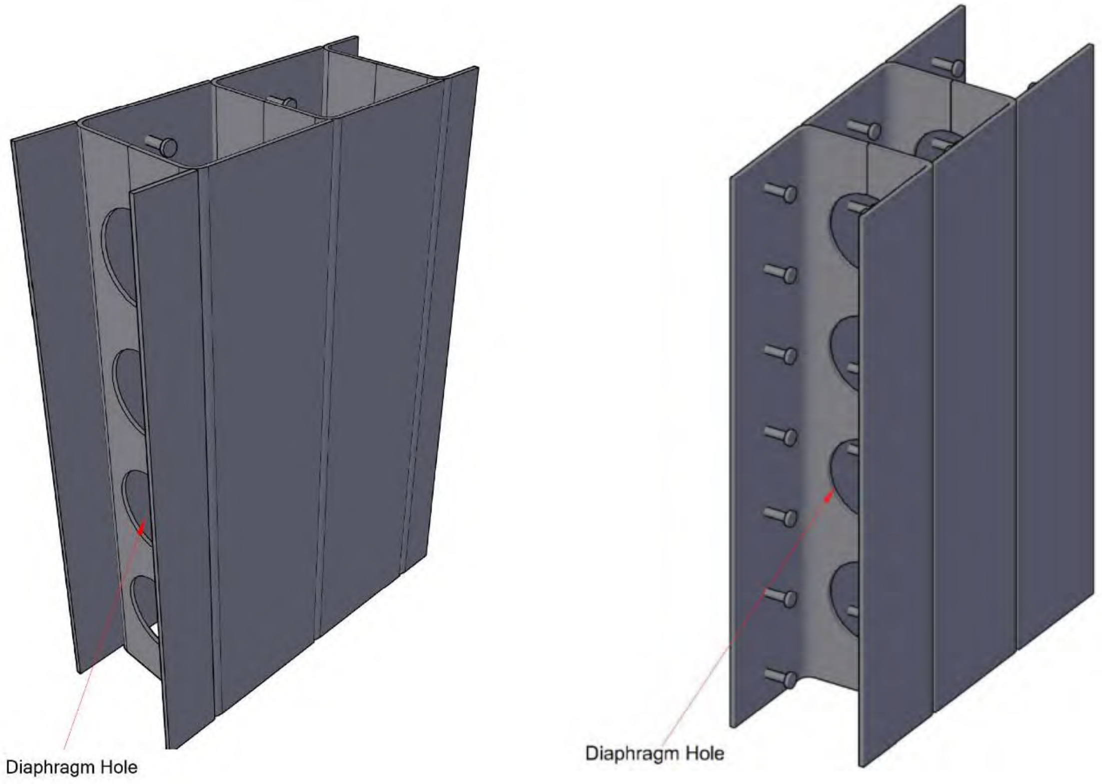


**Figure 7-6: Missile Impact Test Specimens –
Impact Location at Center Diaphragm Plate (IMP-D) (left) -
Impact Location Between Two Adjacent Diaphragm Plates (IMP-C) (right)**

Table 7-1: Summary of Steel-Plate Composite Modules with Diaphragm Plates NRIC Phase 1 Prototype Loading Tests

Test	Prototype	Test Objective	Number of Tests	Scale	Specimen	Loading Type* - Orientation	Thermal Effect
Out-Of-Plane Shear (OOPV)	Mat foundation	Confirm that the out-of-plane strength of DP-SC modules can be calculated conservatively using ANSI/AISC N690 or ACI 349 code provisions before undergoing failure due to out-of-plane shear / bending loading.	2	1:2	OOPV-1	M – Diaphragm plate parallel to loading	Ambient
					OOPV-2	M – Diaphragm plate perpendicular to loading	
Bi-Axial Tension	SCCV	Confirm that the DP-SC constructed SCCV wall and the corresponding splice detail can develop yield strength before undergoing failure due to bi-axial tension simulating effects of accident pressure and concurrent thermal loading conditions.	3	1:3	BA-1-AMB	T – Orientation 1	Ambient
					BA-1-TH	T – Orientation 1	Thermal
					BA-2-TH	T – Orientation 2	Thermal
In-Plane Shear (IPV)	SCCV-to-mat foundation connection	Confirm that the DP-SC constructed SCCV-to-mat foundation connection detail and the nearby SCCV wall-to-wall splice can develop the in-plane flexural capacity of the DP-SC constructed SCCV wall before undergoing failure due to cyclic loading simulating the effects of earthquakes along with concurrent accident thermal loading.	2	1:3	IPV-1	C	Ambient
					IPV-2	C	Thermal
In-Plane Shear + Out-Of-Plane Shear (IPV+OOPV)	RB-to-mat foundation connection	Confirm that the DP-SC constructed RB exterior wall-to-mat foundation connection detail and the nearby DP-SC constructed RB wall-to-wall splice can develop their in-plane flexural capacity, in accordance with the interaction between in-plane strength and out-of-plane strength, before undergoing failure from sustained out-of-plane loading.	2	1:3	IPV+ OOPV-1	C 40% OOPV	Ambient
					IPV+ OOPV-2	C 54% OOPV	
Missile Impact	RB	Confirm that the modified three step design method can conservatively estimate the projectile / missile impact resistance of DP-SC walls.	5	1:6	IMP-D-1 IMP-D-2	I – on center diaphragm plate	Ambient
					IMP-C-3 IMP-C-4 IMP-C-5	I – between two adjacent diaphragm plates	

*Loading Type Key: M – Monotonic Shear C – Cyclic Shear T – Tension I – Missile Impact

7.2.2 Out-Of-Plane Shear (OOPV)

7.2.2.1 Test Objective

The out-of-plane shear (OOPV) tests aim to confirm that the out-of-plane strength of DP-SC modules can be calculated conservatively using ANSI/AISC N690 or ACI 349 code provisions, as applicable, before undergoing failure due to out-of-plane shear / bending loading.

7.2.2.2 Acceptance Criteria

The acceptance criteria for the out-of-plane shear tests are as follows:

1. The specimens will develop flexural yielding before shear failure. That is, yielding of the tension faceplate will occur prior to shear failure.
2. The load carrying capacity of the specimens will be equal to or greater than the load associated with the nominal flexural capacity (M_n) calculated using ANSI/AISC N690 or ACI 349 code equations, whichever applies to the configuration. Nominal capacity is computed using specified minimum steel and concrete material strengths,
3. The specimens exhibit some ductility before failure achieving a minimum ductility ratio of 3.0.

7.2.2.3 Specimen Details

The specimens are illustrated schematically in Figure 7-1 and Figure 7-2. There are two 1:2 scaled specimens (OOPV-1 and OOPV-2) representing two different orientations of diaphragm plate.

Orientation OOPV-1 (Figure 7-1) is used to represent diaphragm plates oriented parallel to the loading (transverse to the longitudinal direction of the specimen). Orientation OOPV-2 (Figure 7-2) is used for diaphragm plates oriented perpendicular to the loading (parallel to the longitudinal direction of the specimen). Specimen OOPV-2 includes a horizontal (longitudinal) splice with cover plates and an oval-shaped splicing hole to represent the actual construction of the mat foundation in the BWRX-300.

7.2.2.4 Test Set-Up

The test subjects the specimens to monotonic loading in a four-point bending test at ambient temperature with a shear span-to-section thickness ratio of 2.5 designed to develop flexural yielding before shear failure. The loading simulates the effects of reactions from the soil foundation support on the mat foundation.

Yielding is established using strain gauges attached to the tension faceplate at locations near the midspan subjected to maximum bending moment. The specimens are loaded until the specified load carrying capacity and displacement per the acceptance criteria are achieved.

7.2.2.5 Calculated Capacities

For the out-of-plane shear test OOPV-1, diaphragm plates oriented parallel to the loading, nominal shear capacity is based on ANSI/AISC N690 code provisions, as presented in Subsection 5.7.5.1, Equation [5-26]. The nominal flexural capacity is calculated based on ANSI/AISC N690 code provisions, as presented in Subsection 5.7.3.1, Equation [5-19].

For the out-of-plane shear test OOPV-2 with diaphragm plates oriented perpendicular to the loading, the nominal shear capacity is calculated based on modified ANSI/AISC N690 code provisions as provided in Reference 9-66 (refer to Subsection 5.7.5.2, Equations [5-28] to [5-31]). The nominal flexural capacity is calculated based on ACI 349 code provisions as developed and verified by Reference 9-64 (refer to Subsection 5.7.3.2, Equation [5-20]).

The governing failure mode for both tests is expected to be flexural yielding of the steel faceplates. The calculated nominal capacities are compared with the experimental strengths.

7.2.3 Bi-Axial Tension

7.2.3.1 Test Objective

The bi-axial tension tests aim to confirm that the DP-SC constructed SCCV wall and corresponding splice detail can develop yield strength before undergoing failure due to bi-axial tension, simulating the effects of accident pressure and concurrent thermal loading conditions.

7.2.3.2 Acceptance Criteria

The acceptance criteria for the bi-axial tests are as follows:

1. The bi-axial specimen under the ambient condition shall reach the yield strength of the steel faceplates accounting for the bi-axial stress state.
2. The bi-axial specimen under the accidental thermal condition shall reach the yield strength of the steel faceplates for the bi-axial stress state and the elevated temperature.

7.2.3.3 Specimen Details

The specimen is illustrated schematically in Figure 7-3. There are three 1:3 scale specimens and all are identical in the geometry and material properties.

The specimen design includes a central splice with a CJP and oval-shaped hole to simulate the joint between different DP-SC units.

7.2.3.4 Test Set-up

Differences in the three tests are primarily the loading orientations and the existence of thermal effects (refer to Table 7-1). For Orientation 1, the applied tension along the brick width will be twice compared to that along the brick length. For Orientation 2, the applied tension along the brick length will be twice compared to that along the brick width.

The applied tension force magnitudes follow a 2:1 ratio to reproduce the membrane stress of a cylindrical shell structure under internal pressure. The load is increased monotonically in stages up to load representative of the BWRX-300 accidental design pressure. The specimens are loaded until the steel plates undergo yielding per the acceptance criteria.

For the tests with thermal loading, one-sided heating is applied to the prototype specimens. The elevated temperature is representative of BWRX-300 accident thermal loading. As the specimens are 1:3 scaled structures compared to the full-scale inner shaft, the heating time is modified so the scaled specimens have a similar through-thickness temperature profile to the full-scale structure.

7.2.3.5 Calculated Capacities

For the bi-axial tension test, the nominal strength is calculated according to the von Mises yield criteria, which is typically used and referenced in ASME BPVC. The calculated nominal capacity is compared with the experimental strengths.

7.2.4 In-Plane Shear (IPV)

7.2.4.1 Test Objective

The In-Plane Shear (IPV) tests aim to confirm that the DP-SC constructed SCCV-to-mat foundation connection detail and the nearby SCCV wall-to-wall splice can develop the in-plane flexural capacity of the DP-SC constructed SCCV wall before undergoing failure due to cyclic loading, simulating the effects of earthquakes along with concurrent accident thermal loading.

7.2.4.2 Acceptance Criteria

The acceptance criterion for the in-plane shear tests is as follows:

1. Develop the in-plane flexural capacity, defined as the plastic moment capacity, M_P, of the DP-SC constructed SCCV wall segment simplified as a concrete-filled composite member.

7.2.4.3 Specimen Details

The specimen is illustrated schematically in Figure 7-4. There are two 1:3 scale specimens and all are identical in the geometry and material properties. The wall of the specimen includes a splice with cover plates and an oval-shaped splicing hole representative of the joint between units.

7.2.4.4 Test Set-up

The specimens are subjected to increasing cyclic in-plane shear simulating the effects of seismic loading; one at ambient temperature (IPV-1) and the other at an elevated temperature simulating accidental thermal loading conditions (IPV-2).

Force-controlled cycles are applied to measure the elastic response and displacement-controlled cycles are applied in the inelastic range as illustrated in Figure 7-7. Testing continues until the specimen fails due to concrete crushing or fracture of the steel plates/connections, or until the lateral load resistance reduces below 80% of the lateral load capacity.

For the test with thermal loading (IPV-2), one-sided heating is applied to the prototype specimen as per the bi-axial tension test as discussed in Subsection 7.2.3.4. The thermal loads are then maintained, and the specimen is subjected to lateral loading in the same manner as specimen IPV-1.

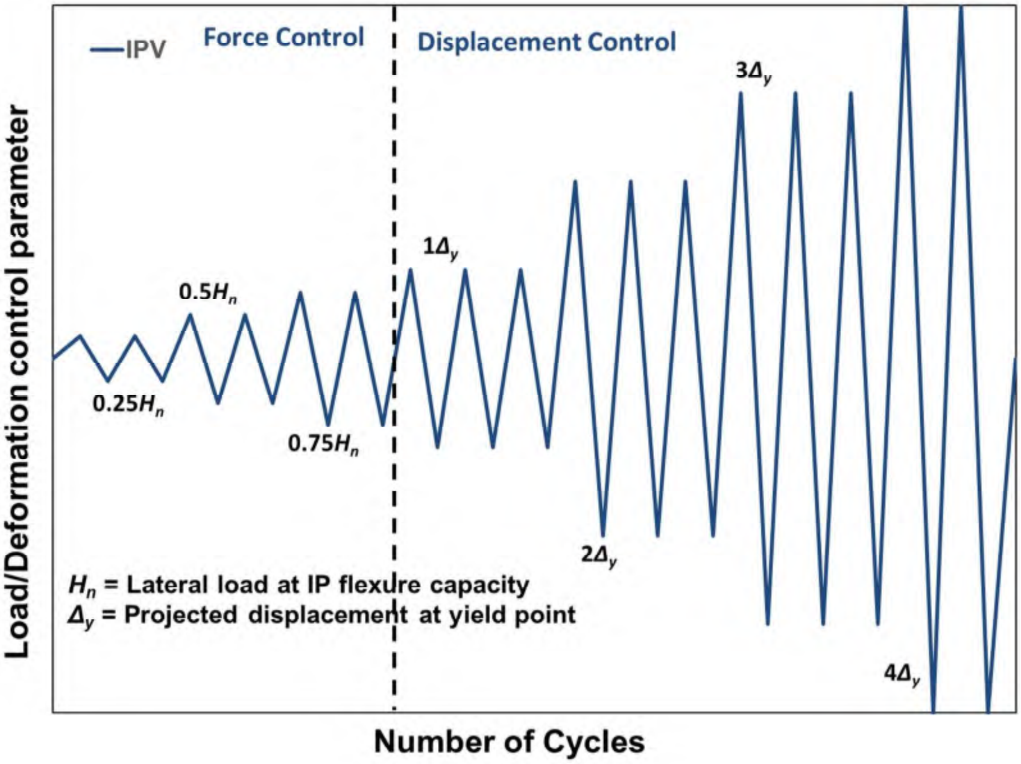


Figure 7-7: Lateral Loading Protocol for In-Plane Shear Tests

7.2.4.5 Pre-Test Calculated Capacities

For the in-plane shear test (IPV), the nominal in-plane shear capacity is calculated based on ANSI/AISC N690 code provisions. The nominal in-plane flexural capacity is calculated based on the plastic moment capacity (M_P) of the simplified concrete-filled composite wall using the plastic stress distribution method referenced in ANSI/AISC 360-16. The governing failure mode is expected to be in-plane flexural failure. The calculated nominal capacities are compared with the experimental strengths.

7.2.5 In-Plane Shear + Out-Of-Plane Shear (IPV+OOPV)

7.2.5.1 Test Objective

The in-plane shear + out-of-place shear (IPV+OOPV) tests aim to confirm that the DP-SC constructed RB exterior wall-to-mat foundation connection detail and the nearby RB wall-to-wall splice can develop their in-plane flexural capacity, in accordance with the interaction between in-plane strength and out-of-plane strength, before undergoing failure due to sustained out-of-plane loading. This test simulates lateral earth pressure and cyclic in-plane loading simulating earthquake effects.

7.2.5.2 Acceptance Criteria

The acceptance criterion for the in-plane shear + out-of-plane shear tests is as follows:

1. Develop the in-plane flexural capacity calculated based on the linear interaction between in-plane and out-of-plane flexure capacities.

7.2.5.3 Specimen Details

The specimen is illustrated schematically in Figure 7-5. The two 1:3 scale specimens are identical in the geometry and material properties. The wall of the specimen includes a splice with cover plates and an oval-shaped splicing hole representative of the joint between different units.

7.2.5.4 Test Set-up

The out-of-plane loading is monotonically applied in force-control mode until the desired out-of-plane force is achieved. The out-of-plane loading is then held constant while the specimen is subjected to incremental cyclic loading in the in-plane direction as illustrated in Figure 7-8. The in-plane load is applied under force-control for elastic cycles and displacement-control for post-yield cycles. Testing continues until the specimen fails due to concrete crushing or fracture of the steel plates/ connections, or until the lateral load resistance reduces below 80% of the lateral load capacity.

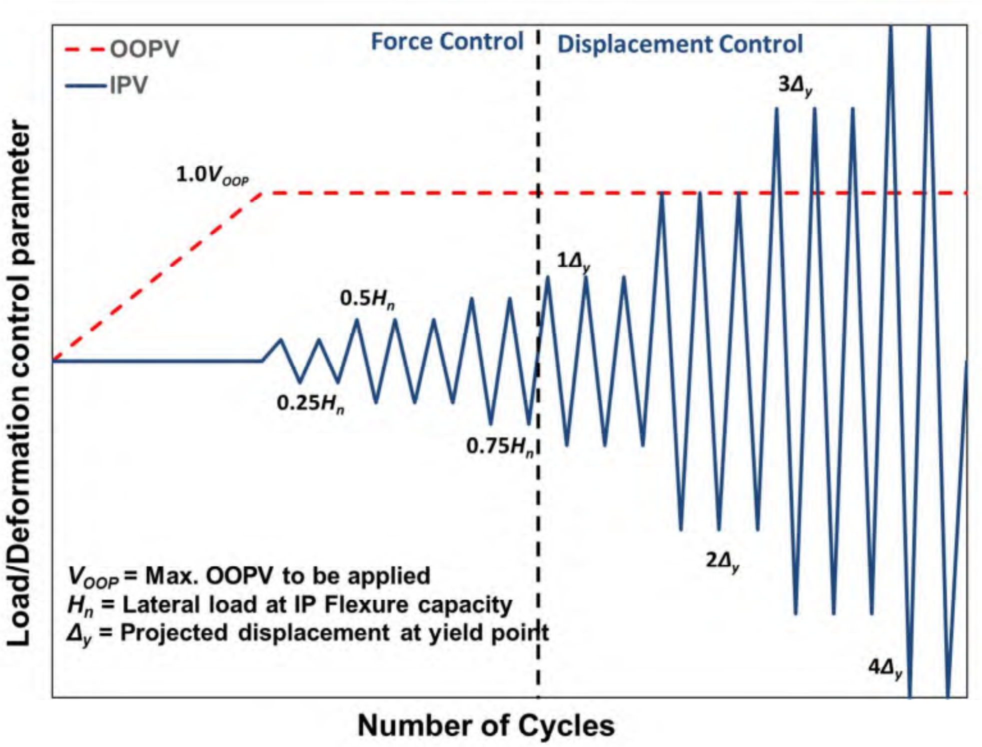


Figure 7-8: Loading Protocol for In-Plane Shear+ Out-of-Plane Shear Tests

7.2.5.5 Calculated Capacities

For the in-plane shear + out-of-plane shear test (IPV+OOPV), the various capacities are calculated as follows:

- Nominal in-plane shear capacity is calculated based on ANSI/AISC N690 code provisions
- Nominal out-of-plane shear capacity is calculated based on modified ANSI/AISC N690 code provisions provided in Reference 9-66 (refer to Subsection 5.7.5.2, Equations [5-28] to [5-31])

- Nominal in-plane flexural capacity is calculated based on the plastic moment capacity (M_P) of the simplified concrete-filled composite wall using the plastic stress distribution method referenced in ANSI/AISC 360-16
- Nominal out-of-plane flexural capacity is calculated based on ACI 349 code provisions as developed and verified by Reference 9-64 (refer to Subsection 5.7.3.2, Equation [5-20])

The calculated nominal capacities are compared with the experimental strengths. Flexural yielding is expected to be the governing failure mode in both in-plane and out-of-plane directions for both specimens; that is the specimens are expected to develop the flexural capacity at the base before the shear capacity is achieved. It is expected that the application of out-of-plane forces will reduce the in-plane capacity of the specimens. The actual reduction in capacity is ascertained from the experimental results and plotted on the interaction diagram as illustrated in Figure 7-9. In Figure 7-9 the linear interaction (yellow) between the in-plane and out-of-plane flexure is a conservative estimation while the parabolic interaction (purple) is expected to be closer to the actual experimental response. The data points for the two experiments are expected to lie above the linear interaction curve for the tests to satisfy the acceptance criteria.

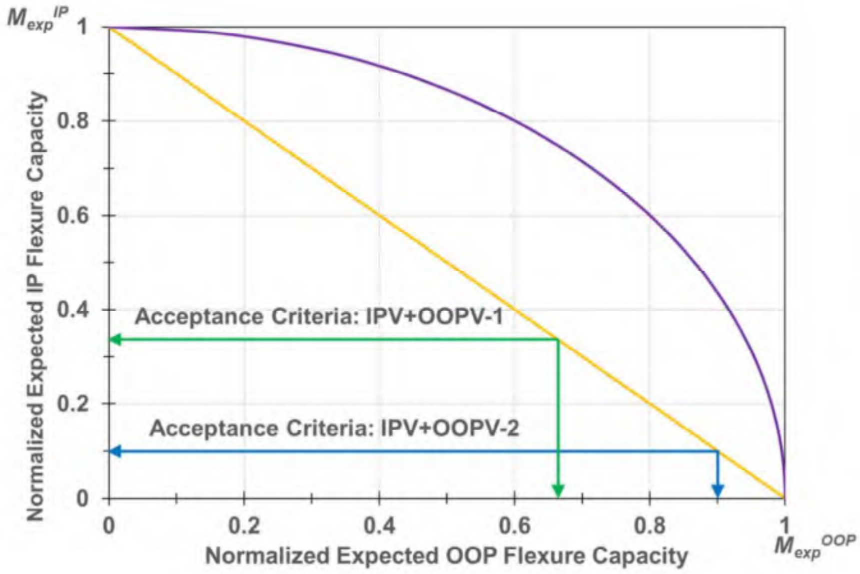


Figure 7-9: Illustration of Interaction between In-Plane and Out-of-Plane Flexural Capacities

7.2.6 Missile Impact

7.2.6.1 Test Objective

The missile impact tests aim to confirm that the modified three step design method (Reference 9-69) can conservatively estimate the projectile/missile impact resistance of DP-SC walls.

7.2.6.2 Acceptance Criteria

The acceptance criterion for the missile impact tests is as follows:

1. Experimental results for missile perforation resistance of small-scale DP-SC specimens are conservative with respect to the estimated missile perforation resistance calculated by the Modified Design Method for DP-SC walls (Reference 9-69).

7.2.6.3 Specimen Details

The specimens are illustrated schematically in Figure 7-6 and are representative of a BWRX-300 RB wall. There are five 1:6 scale specimens that are designed with two different orientations to enable impact loading to be applied from a missile impacting at different locations on the DP-SC specimen. Missile impact is on the center diaphragm plate (two specimen tests designated IMP-D) or between two adjacent diaphragm plates (three specimen tests designated IMP-C). The specimens have identical material properties.

7.2.6.4 Test Set-up

The test subjects the specimens to impact loading from a nondeformable flat-nosed missile with a projectile diameter of 1 inch (25.4 mm) and a weight of 2 lbs (0.9 Kg). The main test parameters in the testing program are impact location and impact velocity.

A high-speed camera is used to capture the instance of the projectile impact on the prototype wall specimens and to measure the actual projectile impact velocity. Damage to the front and rear of the specimens is quantitatively and qualitatively recorded and analyzed upon completion of each test. Qualitative measures include the nature of the damage (e.g., bulging or tearing of rear faceplate). Quantitative measures include the projectile penetration depth and the rear steel faceplate bulging depth.

7.2.6.5 Calculated Capacities

Figure 7-10 shows typical stages in local failure mechanisms of SC walls due to missile impact to illustrate the range of damage modes from bulging to full perforation of the back faceplate. The actual test specimens are expected to exhibit increasing damage with increasing missile velocity.

For the missile impact tests, the perforation resistance curve generated by the Modified Design Method (Reference 9-69) for a 1-inch (25.4 mm) diameter missile is used to determine the expected velocity required to perforate the specimens for the missile weight of 2 lbs (0.9 Kg). For the Modified Design Method, refer to Subsection 5.8.2.2.1, Equations [5-33] to [5-36]. Expected damage modes are compared with the experimental results.

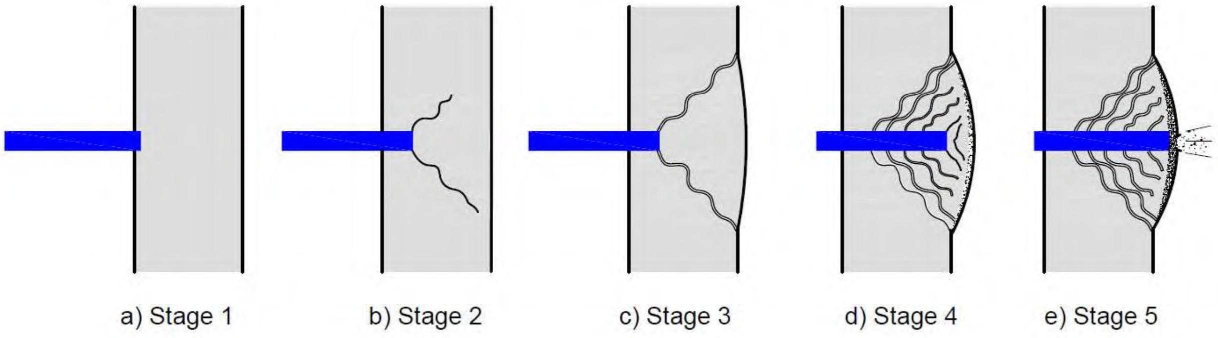


Figure 7-10: Stages in Local Failure Mechanisms of SC walls subject to Missile Impact (Adopted from Reference 9-69)

7.3 NRIC Confirmatory Prototype Phase 1 Test Results

Summaries of the NRIC Phase 1 Prototype Test results are presented in Table 7-2 and in the following subsections. Full details are presented in the NRIC Prototype Test Report (Reference 9-96). As shown in Table 7-2, all specimens met both the acceptance criteria (A) and (B).

Table 7-2: NRIC Prototype Summary Test Results

Test	Specimen	Behavior	Acceptance Criterion (A)	Acceptance Criterion (B)
			$R_{exp}/\phi R_{n\text{-}meas}$	$R_{exp}/R_{n\text{-}nom}$
OOPV	**OOPV-1**	Out-of-Plane flexure	1.61	1.93
	OOPV-2	Out-of-Plane flexure	1.45	1.74
Bi-Axial	**BA-1-AMB**	Bi-axial tension	1.11	1.24
	BA-1-TH	Bi-axial tension + thermal	1.11	1.24
	BA-2-TH	Bi-axial tension + thermal	1.11	1.24
IPV	**IPV-1**	In-plane flexural capacity	1.58	1.82
	IPV-2	In-plane flexural capacity + thermal	1.54	1.74
IPV+OOPV	**IPV+OOPV-1**	In-plane + out-of-plane shear	1.24	1.41
	IPV+OOPV-2	In-plane + out-of-plane shear	1.44	1.67
Missile Impact	**IMP-D-1,** **IMP-D-2** **IMP-C-3** **IMP-C-4** **IMP-C-5**	Missile impact resistance	See Section 7.3.5	N/A

Notes:

(A) Evaluation for original Acceptance Criterion (A) per NRIC Prototype Test Report (Reference 9-96)

$R_{exp}/\ \phi\ R_{n\text{-}meas} \geq 1$

(B) Evaluation for alternative Acceptance Criterion (B)

$R_{exp}/R_{n\text{-}nom} \geq 1$

Where:

- R_{exp} is the experimental strength obtained from the test.
- $R_{n\text{-}meas}$ is the calculated experimental strength, calculated per the code-based/proposed equations developed in Section 5.7 using 'measured' material properties obtained from the Certified Material Test Report (and properties derived from the measured material properties).
- ϕ is the resistance factor, also termed capacity or strength reduction factor.
- $R_{n\text{-}nom}$ is the nominal strength, i.e., M_n (flexure), or V_n (shear), calculated per the code-based/proposed equations developed in Section 5.7 using nominal or specified material properties (and properties derived from nominal).

7.3.1 Out-of-Plane Shear (OOPV)

7.3.1.1 OOPV-1 Test Results

The OOPV-1 specimen was subjected to a maximum load that exceeded the calculated nominal flexural capacity. The test was terminated at this point although the specimen had not failed or lost its load carrying capacity. Steel yielding at the bottom faceplate and diaphragm plate occurred close to the flexural capacity. The specimen developed flexural yielding without undergoing any shear failure or fracture failure.

Thus, the acceptance criteria described in Subsection 7.2.2.2 were met for the OOPV-1 test.

7.3.1.2 OOPV-2 Test Results

The OOPV-2 specimen was subjected to a maximum load that exceeded the calculated nominal flexural capacity. The test was terminated at this point although the specimen had not failed or lost its load carrying capacity. Steel yielding at the bottom faceplate and diaphragm plate occurred close to the flexural capacity. The specimen developed flexural yielding without undergoing any shear failure or fracture failure.

Thus, the acceptance criteria described in Subsection 7.2.2.2 were met for the OOPV-2 test.

7.3.2 Bi-Axial Tension

7.3.2.1 BA-1 AMB Test Results

For bi-axial test BA-1-AMB at ambient temperature, the applied tension along the brick width is twice compared to that along the brick length (designated Orientation 1). The maximum tensile force from the experiment exceeded the nominal strength. The results show that the specimen can reach the yield strength of the steel faceplates accounting for the bi-axial stress state.

Thus, the acceptance criteria described in Subsection 7.2.3.2 were met for the BA-1-AMB test.

7.3.2.2 BA-1-TH Test Results

For bi-axial test BA-1-TH under the heated condition, the applied tension along the brick width is twice compared to that along the brick length (designated Orientation 1). The maximum tensile force from the experiment exceeded the nominal strength. The results show that the specimen can reach the yield strength of the steel faceplates accounting for the bi-axial stress state and elevated temperature.

Through-thickness temperature measurements were taken during the test at various thermocouple locations. Mechanical loading was initiated after the through-thickness thermal gradient was achieved. All temperatures exceeded the minimum through-thickness temperature requirement.

Due to safety concerns, the experiment was stopped when the specimen reached the expected strength.

Thus, the acceptance criteria described in Subsection 7.2.3.2 were met for the BA-1-TH test.

7.3.2.3 BA-2-TH Test Results

For bi-axial test BA-2-TH under the heated condition, the applied tension along the brick length is twice compared to that along the brick width (designated Orientation 2). The maximum tensile force from the experiment exceeded the nominal strength. The results show that the specimen can reach the yield strength of the steel faceplates accounting for the bi-axial stress state and elevated temperature.

Through-thickness temperature measurements were taken during the test at various thermocouple locations. Mechanical loading was initiated after the through-thickness thermal gradient was achieved. All temperatures exceeded the minimum through-thickness temperature requirement.

Due to safety concerns, the experiment was stopped when the specimen reached the expected strength.

Thus, the acceptance criteria described in Subsection 7.2.3.2 were met for the BA-2-TH test.

7.3.3 In-Plane Shear (IPV)

7.3.3.1 IPV-1 Test Results

The IPV-1 specimen was subjected to a maximum load that exceeded the nominal in-plane flexural capacity.

Steel yielding of the first flange (end) plate occurred during the force-controlled loading phase, and later at the web (face) plate during the displacement-controlled loading phase (refer to Figure 7-7 for illustration of loading cycles). The governing failure mode was in-plane flexural failure. There was no sign of shear failure prior to flexural failure.

The results confirm that the plastic stress distribution method can conservatively estimate the in-plane flexural capacity.

Thus, the acceptance criterion described in Subsection 7.2.4.2 was met for the IPV-1 test.

7.3.3.2 IPV-2 Test Results

The IPV-2 specimen was subjected to a maximum load that exceeded the nominal in-plane flexural capacity.

Steel yielding of the flange (end) plate occurred during the force-controlled loading phase, and later at the web (face) plate during the displacement-controlled loading phase (refer to Figure 7-7 for illustration of loading cycles).

Through-thickness temperature measurements were taken during the test at various thermocouple locations. Mechanical loading was initiated after the through-thickness thermal gradient was achieved. All temperatures exceeded the minimum through-thickness temperature requirement.

The IPV-2 results show that the application of the through-thickness thermal gradient reduces the experimental strength compared to the IPV-1 results. The in-plane capacity from the IPV-2 test still exceeds the nominal in-plane flexural capacity.

The governing failure mode was in-plane flexural failure. There was no sign of shear failure prior to flexural failure. The results confirm that the plastic stress distribution method can conservatively estimate the in-plane flexural capacity.

Thus, the acceptance criterion described in Subsection 7.2.4.2 was met for the IPV-2 test.

7.3.4 In-Plane Shear + Out-of-Plane Shear (IPV+OOPV)

7.3.4.1 IPV+OOPV-1 Test Results

The initial out-of-plane shear force was applied and maintained throughout the duration of the test.

The IPV+OOPV-1 specimen was subjected to a maximum in-plane load which exceeded the nominal in-plane flexural capacity. Steel yielding of the flange (end) plate followed by the web (face) plate during the force-controlled out-of-plane loading phase (refer to Figure 7-8 for illustration of loading cycles).

The results confirm that the plastic stress distribution method can conservatively estimate the in-plane flexural capacity.

When the experimental data points are plotted on the in-plane – out-of-plane interaction diagram (as illustrated in Figure 7-9), points lie above the linear interaction line.

Thus, the acceptance criterion described in Subsection 7.2.5.2 was met for the IPV+OOPV-1 test.

7.3.4.2 IPV+OOPV-2 Test Results

The initial out-of-plane shear force was applied and maintained throughout the duration of the test.

The IPV+OOPV-2 specimen was subjected to a maximum in-plane load which exceeded the nominal in-plane flexural capacity. Steel yielding of the flange (end) plate followed by the web (face) plate during the force-controlled out-of-plane loading phase (refer to Figure 7-8 for illustration of loading cycles).

The results confirm that the plastic stress distribution method can conservatively estimate the in-plane flexural capacity.

When the experimental data points are plotted on the in-plane – out-of-plane interaction diagram (as illustrated in Figure 7-9), points lie above the linear interaction line.

Thus, the acceptance criterion described in Subsection 7.2.5.2 was met for the IPV+OOPV-2 test.

7.3.5 Missile Impact

The test specimens exhibited increasing damage with increasing missile velocity. The expected and actual test results are summarized in Table 7-3. Four of the test specimens stopped the missile while only specimen IMP-C-4 was perforated as expected. Specimen IMP-C-3 stopped the missile as expected. Perforation by the missile was expected for tests IMP-D-1, IMP-D-2 and IMP-C-5 based on the perforation resistance curve. However, the resistance of the specimens to impact was stronger and the missile was stopped with bulging damage mode. Comparison of test results for

IMP-C-4 (perforated) and IMP-D-2 (stopped), which were both conducted at the same missile velocity, demonstrate the additional missile impact resistance provided by the diaphragm plate.

Thus, the test results confirm the impact resistance of DP-SC modules and demonstrate that the Modified Design Method (Reference 9-69) is conservative.

Thus, the acceptance criterion described in Subsection 7.2.6.2 was met for the missile impact test.

Table 7-3: Missile Impact Summary Tests Results

Specimen	Calculated Expected Result(1)	Simulated Expected Result(2)	Test Result	Damage Mode
IMP-D-1	Perforation	Stop	Stopped	Bulging
IMP-D-2	Perforation	Perforation	Stopped	Bulging
IMP-C-3	Stop	Stop	Stopped	Bulging
IMP-C-4	Perforation	Perforation	Perforated	Perforation
IMP-C-5	Perforation	Perforation	Stopped	Bulging

(1) Modified Design Method (Reference 9-69)

(2) Numerical Simulation

7.4 NRIC Phase 2

NRIC Phase 2 tests are not under the purview of this report.

8.0 CONCLUSION

GEH is seeking approval from the NRC and acceptance from the CNSC for the proposed design method of DP-SC modules of the BWRX-300 Seismic Category I (Canadian Seismic Category A) RB and containment structures, including the proposed codes and standards and requirements provided in Sections 5.0 and 6.0 of this report.

The design of the BWRX-300 RB and other non-containment Seismic Category I structures is governed by ANSI/AISC N690 as modified per U.S. NRC RG 1.243 and the modified rules discussed in Section 5.0. As stated in Section 5.0 of the report, the ANSI/AISC N690, Appendix N9 requirements can extend to the design, analysis, fabrication, construction, inspection, examination and testing of DP-SC constructed floors since their structural behavior and failure mechanisms are identical to those of walls when constructed to meet the general provisions of Section N9.1.1 of ANSI/AISC N690.

The provisions of ANSI/AISC N690, Appendix N9 as modified per U.S. NRC RG 1.243 and the proposed design rules discussed in Section 5.0, are extended to the design of BWRX-300 curved DP-SC walls. This is based on results of experimental and analytical evaluations that show the curvature effects are negligible for SC walls with radius-to-wall panel thickness ratios similar to those of the integrated RB walls.

The BWRX-300 containment is still considered a ASME BPVC, Section III, Division 2 containment and is designed per the rules in Section 6.0 adapted from ASME BPVC, 2021 Edition, Section III, Division 2, Subsection CC, Articles CC-1000 through CC-6000, for materials, design, fabrication, construction, inspection, examination, and testing, including Division 2 Appendices, to the extent they apply to an SC containment without reinforcing steel or tendons. The SCCV pre-service inspections, including inservice inspections throughout the life of the plant follow ASME BPVC, Section XI. Leak tests are performed in accordance with 10 CFR 50 Appendix J. Section 6.0 provides the proposed design rules for the SCCV that address the particularities of DP-SC elements and are in compliance with the safety and performance objectives of the regulatory requirements.

As discussed in Section 7.0, the design approaches provided in Sections 5.0 and 6.0 of this report are supported by the conclusions of the NRIC Demonstration Project Prototype tests, which confirm that the load carrying capacities of DP-SC modules are equal to or exceed the loads associated with the nominal capacity.

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ENCLOSURE 2

M240080

NEDO-33926, Revision 2, BWRX-300 Steel-Plate Composite Containment Vessel (SCCV) and Reactor Building (RB) Structural Design – Non-Proprietary Information

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GE Hitachi Nuclear Energy

NEDO-33926
Revision 2
April 2024

Non-Proprietary Information

Licensing Topical Report

BWRX-300 Steel-Plate Composite (SC) Containment Vessel (SCCV) and Reactor Building Structural Design

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

REVISION SUMMARY

Revision Number	Description of Change
0	Initial Issue
1	Updated to reclassify selected content as non-proprietary including Figures 3-1, 3-2, and 3-4; Sections 5.18 and 6.22; and Table 6-1.
2	• Revised to incorporate the following response to NRC Requests for Additional Information No. 018 (RAI-10121-R1):NRC RAI 2.1.2-1 (Question 1) deleted Subsection 2.1.2 since the 10 CFR 100.21 requirements are outside the scope of this report and added Subsection 2.2.7 to address conformance to the regulatory guidance of NUREG-0800, SRP 19.0. • NRC RAI 5.3-1 (Question 2) revised Section 5.3 to clarify that steel headed studs contribute to the composite action of Diaphragm Plate Steel-Plate Composite (DP-SC) modules, to provide the methodology used to quantify the contribution of diaphragm plates and steel headed studs to the DP-SC composite actions, and to provide the design and detailing requirements for the steel headed studs. Subsection 5.3.1 is added to provide methodology used to determine shear connectors capacity. Section 5.4 and Subsection 5.7.5.2 are revised to capture the changes in Section 5.3. Subsection 5.7.6 is revised to provide the methodology for evaluating the interaction of the idealized diaphragm plates under out-of-plane and interfacial shear stresses. • NRC RAI 5.4-1 (Question 3) revised Section 5.4 by deleting the statement “Tie plates or bars may be added for additional stiffness and strength.” • NRC RAI 5.5.1-1 (Question 4) revised Subsections 5.5.1 and 6.5.1 to provide clarity on the BWRX-300 methodology and modeling approach for heat transfer analysis. • NRC RAI 5.7.2-1 (Question 5) revised Subsection 5.7.2 to clarify the applicability of Equation [5-19] (previously Equation [5-16]) to temperature limits and temperature-dependent properties listed on Subsections 5.2.1 and 5.2.2. • NRC RAI 5.8-1 (Question 6) revised Table 5-1 and Table 5-3, footnote 1 included, to remove non-Steel-plate Composite (non-SC) or DP-SC materials that are outside the scope of this report. • NRC RAI 5.8-1 (Question 6) revised Subsection 5.8.1.3 and Table 5-2, footnotes included, to provide clarity on levels of damage and deformation limits for normal and severe environmental load combinations, and for abnormal and extreme environmental load combinations; and to provide acceptance criteria for SC slabs and SC walls, including DP-SC.

	• NRC RAI 5.8-1 (Question 6) revised Subsection 5.8.3 by adding bullet #4 to address conformance to Regulatory Position C11.1.8.3 of U.S. NRC RG 1.243. • NRC RAI 5.18-1 (Question 7) revised Section 5.18 to describe the plan for identifying and developing measured baseline data to facilitate the evaluation, monitoring and trending of applicable aging effects for DP-SC modules. Proposed changes to Section 5.18 in response to audit observations #16, 68 and 69 are superseded by the response to RAI 5.18-1 (Question 7). • NRC RAI 6.2-1 (Question 8) revised Section 6.2 to clarify that materials used in the SCCV DP-SC modules meet the general requirements of ASME BPVC, Section III, Division 2, Subarticle CC-2000 as applicable to DP-SC modules without reinforcing steel or prestressing tendons. • NRC RAI 6.2-1 (Question 8) revised Subsection 6.2.4 to clarify the specific SCCV load bearing steel materials this section applies to. • NRC RAI 6.13-1 (Question 9) revised Subsection 2.1.1.14 to point to Sections 6.2 and 6.15 for the SCCV quality control and quality assurance requirements, and Sections 6.13, 6.14, 6.15 and 6.16 to provide a figure equivalent to Figure CC-3831-1 of ASME Section III, Division 2 that is representative of SCCV DP-SC welded joints to clarify the DP-SC permitted welded joint types and welding examination requirements. • NRC RAI 6.22-1 (Question 10) revised Section 6.22 to provide the characterization of the SCCV components for the purposes of inservice inspection in accordance with 10 CFR 50.55a(g)(4). • NRC RAI 7.2-1 (Question 11) revised Subsections 7.2.1.1, 7.2.2.2, 7.2.2.5, 7.2.3.5, 7.2.4.5, 7.2.5.1, 7.2.5.2, 7.2.5.5, 7.3, 7.3.1.1, 7.3.1.2, 7.3.2.1, 7.3.2.2, 7.3.2.3, 7.3.3.1, 7.3.3.2, 7.3.4.1, 7.3.4.2 and the last paragraph of Section 8.0 to refer to the revised acceptance criterion and nominal strength consistent with code terminology and added Table 7-2 to provide a summary of the NRIC Prototype test results. Revised to incorporate the following responses to NRC audit observations: • Audit observation #3 revised Sections 5.1, 5.3, 5.7.1, 5.7.2, 5.11, 5.13, 5.13.1.2, 5.13.2.1, 5.18, 6.11, 6.14, 7.2.4.5 and 7.2.5.5 to specify the edition of the ANSI/AISC 360 referenced, deleted the reference to ANSI/AISC 360 related to Equation [5-19] (previously Equation [5-16]) and deleted the first paragraph of Section 5.4. • Audit observation #3 revised Sections 5.18 and 9.0 to replace NUREG-1801 with NUREG-2191.

	• Audit observation #3 revised Section 9.0 to update the revisions of U.S. NRC RG 1 136, U.S. NRC RG 1.26 and NUREG-0800, SRP 3.8.3 to the latest and to list the 2016 edition of ANSI/AISC 360. • Audit observation #4 revised Subsection 2.1.1.5 to clarify how the design will meet the requirements of 10 CFR 50.150. • Audit observation #5 revised Subsection 2.1.1 to specify that the design will meet the requirements of the regulations and guidance discussed in the section. • Audit observation #6 revised Subsection 2.1.1.15 (previously Subsection 2.1.1.14) to demonstrate compliance with regulations for Type B and Type C local leak rate tests. • Audit observation #7 revised Subsection 2.1.1.16 (previously Subsection 2.1.1.15) to demonstrate how the Operational Basis Earthquake (OBE) requirements in “10 CFR Part 50, Appendix S” for plant shutdown and load combinations are met. • Audit observation #8 revised Subsections 2.2.2, 2.2.3 and Section 6.1 to clarify that the SCCV is designed, fabricated, constructed, inspected, examined and tested to applicable portions of ASME BPVC, Section III, Division 2 requirements along with the modified requirements outlined in Section 6.0 of this report. • Audit observation #9 revised Subsection 2.3.6 and Section 9.0 to clarify that the DP-SC damping values are based on values provided for SC walls in Tables 1 and 2 of U.S. NRC RG 1.61, Revision 2. • Audit observation #10 revised Section 5.5 to specify that analysis for load combinations involving accident thermal conditions will include heat transfer analysis, deleted the last paragraph in Section 5.5 and added Subsection 5.5.1 to discuss methodology used for performing the heat transfer analysis. Section 5.5.1 was later updated per RAI 5.5.1-1 (Question 4). • Audit observation #11 revised Section 4.0 to clarify the code jurisdictional boundary for the Reactor Building (RB) walls and floors connections. • Audit observation #13 revised Subsection 7.2.1.1 to add a paragraph on GEH’s Quality Assurance (QA) program that was implemented during the NRIC testing program and used to review and accept test results. • Audit observation #14 revised Section 3.4 to describe the curved assemblies of DP-SC modules, and Section 6.18 to specify the requirements for faceplates rolling and bending. • Audit observation #16 revised Section 5.18 to add a discussion on the failure mode effect analysis that will be performed to identify

	aging and degradation mechanisms, inspection processes and proposed repair methods for DP-SC modules. • Audit observation #20 revised Section 5.18 to add a discussion on the failure mode effect analysis that will be performed to identify aging and degradation mechanisms, inspection processes and proposed repair methods for DP-SC modules. • Audit observation #21 revised Section 5.18 to provide acceptable techniques for inservice inspection and testing of DP-SC modules. • Audit observation #22 revised the first two bullets of Section 1.1 to clarify that the purpose of this report is to seek regulatory approval for the use of DP-SC structural elements for the construction of the integrated RB. • Audit observation #23 revised Subsection 2.1.1 to provide a statement of compliance to 10 CFR 50 Appendix A, General Design Criterion (GDC) 52 in Subsection 2.1.1.12, revised Subsection 2.1.1.15 (previously Subsection 2.1.1.14) to specify the applicable GDCs, including GDC 52, met by the containment provisions for periodic integrated leakage rate testing and listed U.S. NRC RG 1.163 as a reference in Section 9.0. • Audit observation #24 revised Subsections 2.1.1.5, 2.1.1.8 and 2.2.8 (previously Subsection 2.2.7) to remove all references to site-specific aircraft impact assessments. • Audit observation #25 revised Subsection 2.1.1.3 by deleting the statements of compliance to 10 CFR 50.55a(f) and 10 CFR 50.55a(g) requirements not applicable to the scope of this report. • Audit observation #25 revised Subsection 2.1.1.15 (previously Subsection 2.1.1.14) by deleting the reference to Section 6.17. • Audit observation #25 revised Section 4.4 by specifying the edition of ASME BPVC Section XI to be followed for the containment pre-service and periodic inservice inspection and testing program. • Audit observation #25 revised Section 9.0 by updating Reference 9-1 to be specific to ASME Section III, Division 2, 2021 Edition and deleting the U.S. NRC RG 1.192 and RG 1.147 references not applicable to the scope of this report. • Audit observation #26 revised Section 4.3 to (1) clarify the design philosophy used for the RB DP-SC design provisions (2) to confirm that external pressure loads resulting from pressure variation inside or outside the containment (P_v) are considered under the normal operating pressure load (P_o) (3) to replace “MSLB” by “LOCA” (4) to update “Seismic Loads (E)” to “Seismic Loads (Es)” (5) to add a paragraph on OBE Seismic loads (E_o) (6) to clarify local load effects considered for the containment (7) to clarify why loads resulting from relief valve or other high

	energy device actuation and prestress loads are not applicable for the containment. • Audit observation #26 revised Section 9.0 by listing ANSI/ANS-2.23 as a reference. • Audit observation #28 revised Section 6.22 to provide clarity on the SCCV components that will be examined in accordance with Subsection IWE. The audit observation revision of Section 6.22 is superseded by the response to RAI 6.22-1 (Question 10). • Audit observation #29 revised Sections 3.4 and 5.1 to specify that DP-SC faceplates and diaphragm plates can have different thicknesses, clarified the parameters listed in Section 3.4 and updated Figure 5-1. • Audit observation #30 revised Section 5.1 to clarify the basis for the BWRX-300 DP-SC thickness limitations. • Audit observation #31 revised Section 5.1 to specify that the minimum reinforcement ratio for DP-SC modules is per ANSI/AISC N690, Section N9.1.1.(c). • Audit observation #31 revised Section 5.2.1 to (1) delete the concrete compressive strength statement from the first paragraph, (2) to specify that self-consolidating concrete is used in the integrated RB DP-SC modules and (3) that the self-consolidating concrete compressive strength is a function of reinforcement ratio per draft ANSI/AISC N690-XX added as Reference 9-59 in Section 9.0 in the absence of the published version. • Audit observation #32 revised Section 5.3 to indicate that steel headed stud anchors will not be used in accessible tight locations and to provide clarity on how the stud anchors diameter, height and spacing are determined, and Section 6.1 to indicate that stud anchors may not always be needed. These changes were overridden by the response to RAI 5.3-1 (Question 2). • Audit observation #33 revised Subsections 5.2.1 and 6.2.1 to indicate that self-consolidated concrete is used in the integrated RB DPSC modules, and Subsection 7.2.1.1 to clarify that self-consolidating concrete was used as concrete infill in the NRIC Phase I testing specimens. • Audit observation #34 revised Subsection 5.7.2 to correct the compressive strength resistance factor from 0.9 to 0.75. • Audit observation #38 revised Section 5.6 by deleting the last paragraph, and Section 9.0 by deleting the Revision 1 Reference 9-57 related to Sarraj's alternative component model. • Audit observation #39 revised Subsection 5.7.5.1 to correct the equation in the first bullet to "Equation (a) in Table 22.5.5.1," and to add "W_{sc} in Figure 5-1" in the (a) statement.

	• Audit observation #40 revised Subsection 5.7.5.2 to clarify that V_{conc} is calculated using Equations [5-26] and [5-27] (previously Equations [5-23] and [5-24]). • Audit observation #42 revised Subsection 5.7.5.1 to clarify how the nominal tensile strength of diaphragm segments between diaphragm openings are determined. • Audit observation #43 revised Table 5-2 to clarify the damage level or ductility criteria that will be used to determine design adequacy for the stated load cases where the structures are allowed to have permanent, plastic deformations. Changes to Table 5-2 and associated footnotes were superseded by the response to RAI 5.8-1 (Question 6). • Audit observation #44 revised the first bullet in Subsection 5.8.1.3 to clarify how the reference to ACI 349.4R will be replaced with U.S. NRC RG 1.243, CNSC REGDOC-2.5.2, Version 1, and International Atomic Energy Agency (IAEA) Safety Reports Series No 87. First bullet was later updated per response to RAI 5.8-1 (Question 6). • Audit observation #45 revised the second paragraph in Subsection 5.8.2.2 to identify the basis for the definition of local areas for missile impact and to clarify the units for $5\sqrt{(tsc)}$. • Audit observation #46 revised Subsection 5.8.2.2.1 to add Section 7.4.4 in the first paragraph, to define the parameters t_c and V_r , to correct Equations [5-43] and [5-48] (previously Equations [5-41] and [5-46]), to clarify the unit for $x_{c.sc}$, ρ_c , $V_{p.conc}$ and F_y, to add Equation [5-47] and to provide the basis for the parameters "K", m_t , σ_s and Equations [5-35] to [5-48] (previously Equations [5-33] to [5-46]). • Audit observation #49 revised Section 5.11 to clarify the definition of A_v in Equation [5-49] (previously Equation [5-47]), to provide an illustrative figure (Figure 5-10) of SC connections to which Equation [5-49] is intended to be applied and to clarify the applicability of Equation [5-49] to compressive axial loads. • Audit observation #50 revised Section 5.13 and Subsections 5.13.1.1 and 5.13.2 to remove all references to ANSI/UL 263 and to add the criteria for identifying the fire rating of DP-SC components. • Audit observation #51 revised Section 5.13 to address the modifications stated in Appendix N4 of ANSI/AISC N690 and to define the parameter "L" in Equations [5-51] and [5-52] (previously Equations [5-48] and [5-49]). • Audit observation #52 removed the proprietary designation from Sections 5.16 and 6.4.

	• Audit observation #53 revised Section 5.16 by adding a paragraph at the end of the section to clarify how potential locked-in stresses in the faceplates and diaphragm plates from initial imperfections and hydrostatic pressure exerted by the concrete pour during construction are accounted for in the design. • Audit observation #54 revised Section 5.1 to clarify the maximum allowable plate thickness for DP-SC modules and Subsection 5.2.1 to include the requirements from second public review draft of ANSI/AISC N690 (dated October 9, 2023), Section N9.1.1(e) related to compressive strength of concrete. • Audit observation #55 revised Subsection 5.2.1 to clarify the concrete temperature limitations for normal operational and accidental conditions, Subsection 5.2.2 to clarify how the effect of elevated temperatures on mechanical properties of steel materials of DP-SC modules is determined, Subsection 5.13.1.1 to point to Section 5.2 of the report in the third paragraph, and to Section 4.2 for how material properties are defined. • Audit observation #58 revised the last bullet in Section 6.2.1 to indicate that the word “concrete” in Table CC-2231.7.1-1 is to be replaced by “DP-SC concrete infill”. • Audit observation #59 revised Subsection 6.2.2 to remove the word “hollow”. • Audit observation #60 revised Section 6.5 to clarify that the loading criteria provisions are supplemented by U.S. NRC RG 1.136 and to remove the proprietary designation. • Audit observation #61 revised Tables 6-1(a) and 6-1(b) to include footnote (1) against the “Primary + Secondary” force classification for Steel Plates, Table 6-1(a) footnotes (1)-(4) and the first paragraph of Subsection 6.7.3 to clarify that the DP-SC concrete tensile strength is not relied upon to resist flexural and membrane tension. • Audit observation #62 revised the T_{sc} parameter in Subsection 6.7.1 to t_{sc} for consistency with other sections. • Audit observation #63 revised Subsection 6.7.2 to replace steel plates with steel faceplates and to point to the allowable stresses for service loads summarized in Table 6-2. • Audit observation #64 revised Subsection 6.7.3 to provide the equation for σ_{c2} for case (c). • Audit observation #65 revised Subsection 6.7.1 to define the DP-SC notional halves, to clarify that positive principal stresses are tensile and negative principal stresses are compressive and to update Equation [6-1] membrane force and bending moment parameters.

	• Audit observation #65 revised Subsections 6.7.2 and 6.7.3 to point to the allowable stresses for service loads summarized in Table 6-2. • Audit observation #66 revised Section 6.7 to clarify how the in-plane membrane forces and out-of-plane moments interaction and the out-of-plane shear of containment DP-SC members are calculated. • Audit observation #66 deleted Subsections 6.8.1 to 6.8.3and 6.8.5 related to the uniaxial tensile, compressive, flexural and tangential shear strength and revised Section 6.8 to specify that these parameters are evaluated using the procedure in Section 6.7 and the allowables provided in Section 6.6. • Audit observation #66 revised the number of Subsection 6.8.4 to 6.8.1 and added Subsections 6.8.1.1 and 6.8.1.2 to define the allowable stresses for factored loads and service loads, respectively, for one-way out-of-plane shear strength. • Audit observation #66 revised the number of Subsection 6.8.6 to 6.8.2 and added Subsections 6.8.2.1 and 6.8.2.2 to define the allowable stresses for factored loads and service loads, respectively, for punching shear. • Audit observation #66 revised the number of Section 6.9 to Subsection 6.8.3 and added Subsections 6.8.3.1 and 6.8.3.2 to discuss the out-of-plane shear interaction for factored loads and service loads, respectively. • Audit observation #66 added a new Section 6.9 to discuss the allowable bearing stress of containment steel-plate composite elements. • Audit observation #67 revised the first paragraph in Section 6.15 to replace “with the exception reported” with “in addition to the Regulatory Guidance of Position 10 reported” and to correct U.S. NRC RG 1.36 to RG 1.136. • Audit observation #68 revised the last but one paragraph of Section 6.17 to add a reference to ASME Section III, Paragraphs CC-6160 and CC-6510 and to clarify that the BWRX-300’s first unit will be treated as a prototype containment as per Paragraph CC-6150 definition. • Audit observation #69 changes to Section 6.22 are superseded by the response to RAI 6.22-1 (Question 10). • Audit observation #70 removed the proprietary designation of Section 6.23 and revised the section to specify GDC 50. • Audit observation #71 revised the last paragraph of Subsection 5.7.5.1, and Subsections 7.2.1.1, 7.2.2.2, 7.2.2.5, 7.2.3.5, 7.2.4.5, 7.2.5.5, 7.3.1.1, 7.3.1.2, 7.3.2.1, 7.3.2.2, 7.3.2.3, 7.3.3.1, 7.3.3.2,

	7.3.4.1, 7.3.4.2, and Section 8.0 to clarify that experimental strength are compared to the calculated nominal strength. • Audit observation #75 revised the second bullet of Section 1.1 to add a reference to Section 5.0. • Audit observation #76 revised Section 4.3 to define “Seismic Loads (Es)” as “SSE or DBE Seismic Loads (Es).” • Audit observation #77 revised the publication date of U.S. NRC RG 1.136 to February 2021, the referencing of ANSI/AISC N690-XX and the title of the M230099 Enclosure 2 in Section 9.0. • Audit observation #78 removed the proprietary designation of the following Sections and Subsections: 5.6, 5.7.3.1, 5.7.4, 5.7.5.3, 5.7.6, 5.10, 5.12, 6.3, 6.8, 6.8.1.1, 6.8.1.2, 6.8.2.1, 6.8.2.2, 6.8.3.1, 6.8.3.2, 6.9.1.1, 6.9.1.2, 6.15, 6.16, 6.17, 6.18 and 6.23.3. Revised to incorporate the following responses to NRC requests for additional information to support NRC acceptance review of the report, M230099, Enclosure 1: • Item #1 added the NRIC Prototype Test Report as a reference in Sections 7.3 and 9.0. • Item #3 revised Bullet (A) in Section 3.4, added the last two paragraphs in Section 3.4 and revised Figures 3-5 and 3-6 (previously Figures 3-6 and 3-7) to provide clarity on the different configurations and composite action of DP-SC modules. • Item #3 added a paragraph in Section 4.0 to discuss connections and attachment welds of DP-SC modules. • Item 4 removed the reference to ACI 349.4R and added a reference to U.S. NRC RG 1.243, REGDOC-2.5.2 and IAEA Safety Reports Series No, 87 in Subsection 5.8.1.3 and Section 9.0, and specified a design strain acceptance criterion of 0.35% for concrete compression in footnote (4) of Table 5-2. Revised to incorporate the following licensing and technical updates: • Acronyms and Acronym Table are updated. • Sections 1.1 and 1.2 are revised to clarify the intent of this report. • The statements of compliance in Subsections 2.1.1.1, 2.1.1.3, 2.1.1.4, 2.1.1.6, 2.1.1.9, 2.1.1.11, 2.1.1.14 and 2.1.1.16 are updated to provide more clarity. • The statements of conformance in Subsections 2.2.4, 2.2.5, 2.3.2, 2.3.3, 2.3.5, 2.3.7, 2.3.8, 2.3.9, 2.3.10, 2.3.11 and 2.3.12 are updated to provide more clarity. • Conformance to U.S. NRC RG 1.54 is discussed in newly added Subsection 2.3.4.

	• The statement of compliance in Subsection 2.4.2 and the statements of compliance to REGDOC-2.5.2, Sections 7.12.1 and 8.6, in Subsection 2.4.3 are updated to provide more clarity. • The statement of compliance to REGDOC-2.6.3, Section 4.3, in Subsection 2.4.4 is updated to provide more clarity. • Subsections 2.5.1 to 2.5.3 are updated to provide more clarity on how CSA N291, CSA N287 and CSA N289 requirements are met. • Subsections 2.5.4 to 2.5.6 are added to discuss compliance with CSA N293, CSA N286 and CSA N299. • Figure 3-1 and Figure 3-2 are updated to reflect latest Power Block layout and structures. • The integrated RB structures overview in Section 3.3 is updated. • Figure 3-3 and Figure 3-4 are updated to identify the DP-SC components of the integrated RB. • Figure 3-5 is deleted. • Fourth paragraph in Section 3.4 is revised to align with updated Section 5.4. • Sections 4.0 and 4.2 are updated to provide more clarity on the BWRX-300 overall analysis, design and modeling approach. • The last but one paragraph of Section 4.4 is updated to clarify the ASME code edition considered. • The last paragraph of Section 4.4 is moved to Subsections 2.1.1.14 and 2.5.5. • Equation [5-14] (previously Equation [5-11]) is updated. • Figure 5-4 and Figure 5-5 are updated. • Equation [5-15] (previously Equation [5-12]) and associated parameters are updated. • Parameters of Equation [5-23] (previously Equation [5-20]) are updated. • The concrete compressive strength units in Subsection 5.7.5.1 are updated. • The first paragraph of Sections 5.9, 5.17 and 5.18 are updated. • Section 5.12 is updated to indicate that curved walls research findings are applicable to the integrated RB SC, including DP-SC, curved walls. • The concrete and water density parameters in Subsection 5.14.1 are updated. • Section 5.15 is updated to address RG 1.54. • Section 6.2 is revised to provide a technical update on the local use of reinforcing steel bars in SCCV connections regions.

	• Section 6.3 is revised to remove the ANSI/AISC N690 reference. • First bullet in Section 6.15 is deleted. • Equation numbers in Section 5.0 are updated due to the addition of two new equations per response to RAI 5.3-1 (Question 2). • Reference numbers are updated. • “Steel Bricks^{TM}” is replaced with “DP-SC” in the first paragraph of Section 7.0. Revised to incorporate the following editorial changes: • “Intent” is replaced with “Safety and performance objectives” in Section 1.2, in Subsections 2.2.3, 2.2.4, 2.2.5, 2.2.6, 2.3.7 and in Section 8.0. • “Meeting” is replaced with “in conformance with” or “conforms to” in Subsections 2.2.1, 2.3.1, 2.3.2 and 2.3.10. • “In-service” is replaced with “Inservice” throughout the report. • Typographical errors in the sixth and seventh bullets of Subsection 2.2.6 and in Sections 2.4, 2.4.1, 2.4.2, 2.4.3, 2.4.4, 4.2 and 6.15 are corrected. • “Is in compliance with” is replaced with “conforms to the guidance of” in Subsection 2.3.6. • “Requirements” is replaced with “guidance” in Subsection 2.3.7. • “Surfaces” is deleted and “RB SC modules” is replaced with “RB DP-SC modules” in Section 2.6. • “Safety-related” is replaced with “systems and components required for accidents mitigation and safe shutdown” and “referred to as DP-SC” is added in Section 3.1. • “Safety-related” is removed from Section 2.5, the second paragraph of Section 3.3 and from the second bullet of Section 7.1. • “SC pedestal” is replaced with “DP-SC pedestal” in the fourth paragraph of Section 3.3. • “Delay” is replaced with “control” in the third paragraph of Section 3.4. • The missing “0” is added to the caption of Figure 4-1. • The first paragraph of Section 5.0 is deleted since conformance to U.S. NRC RG 1.243 is addressed in Subsection 2.3.12 and the second paragraph is split in two. • “Spanning” is added to Figure captions 5-4 and 5-5 (previously Figure 5-2 and Figure 5-3). • “SC modules/walls” are replaced by “DP-SC modules/walls” in Subsection 5.8.2.1 and 5.8.4.

	• The reference to CSA N291 and CSA N287 is removed from Section 5.8 since the conformance of the impactive and impulsive design to the CSA requirements is now addressed in Subsection 2.4.3. • The conformance to REGDOC-2.6.3 is removed from Section 5.18 since it is stated in Section 2.4.4. • A pointer is added to Section 5.1 in Section 6.1. • "DP-SC" is added in the first sentence of Section 6.2.2. • The reference to REGDOC-2.5.2 is removed from Section 6.10 since the conformance of the impactive and impulsive design to the CSA requirements is now addressed in Subsection 2.4.3. • Title of Section 6.16 is revised. • Second paragraph in Section 6.17 is revised and reformatted. • The reference to REGDOC-2.5.2 is removed from Section 6.22 and Subsections 6.23.3 and 6.23.3.2 since the conformance is now addressed in Section 2.4.3. • "Subsubarticle" is replaced with Paragraph, Subparagraph or Subsubparagraph in Sections 4.3, 5.8.2.2, 6.6 and 6.7.3. • "Design" is removed from the fourth line, third column of Table 7-1.

Acronyms and Abbreviations

Term	Definition
3D	Three-Dimensional
ACI	American Concrete Institute
ACT	Advanced Construction Technology
ANSI	American National Standard Institute
AISC	American Institute of Steel Construction
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BDBA	Beyond Design Basis Accident
BPVC	Boiler and Pressure Vessel Code
BWR	Boiling Water Reactor
CEPSS	Containment Equipment and Piping Support Structure
CJP	Complete Joint Penetration
CNSC	Canadian Nuclear Safety Commission
CP	Construction Permit
CSA	CSA Group
DBA	Design Basis Accident
DBE	Design Basis Earthquake
DBT	Design Basis Threat
DEC	Design Extension Condition
DEE	Design Extension Event
DP-SC	Diaphragm Plate Steel-Plate Composite
EPRI	Electric Power Research Institute
ESBWR	Economic Simplified Boiling Water Reactor
FE	Finite Element
FMEA	Failure Mode Effect Analysis
GDC	General Design Criterion
GEH	GE Hitachi Nuclear Energy
HGNE	Hitachi-GE Nuclear Energy, Ltd.

Term	Definition
IAEA	International Atomic Energy Agency
ILRT	Integrated Leak Rate Test
IN	Information Notice
IPV	In-Plane Shear
ISO	International Organization for Standardization
LOCA	Loss-Of-Coolant-Accident
LRFD	Load and Resistance Factor Design
NDRC	National Defense Research Council
NEI	Nuclear Energy Institute
NRC	Nuclear Regulatory Commission
NRIC	National Reactor Innovation Center
OBE	Operating Basis Earthquake
OOPV	Out-Of-Plane Shear
PCCS	Passive Containment Cooling System
QA	Quality Assurance
QC	Quality Control
RB	Reactor Building
RG	Regulatory Guide
RPV	Reactor Pressure Vessel
SASSI	System for Analysis of Soil-Structure Interaction
SC	Steel-Plate Composite
SCCV	Steel-Plate Composite Containment Vessel
SEI	Structural Engineering Institute
SIT	Structural Integrity Test
SMR	Small Modular Reactor
SR	Safety Reports
SRP	Standard Review Plan
SRV	Safety Relief Valve
SSCs	Structures, Systems, and Components
SSE	Safe Shutdown Earthquake

Term	Definition
SSI	Soil-Structure Interaction
SSPC	The Society for Protective Coatings

1.0 INTRODUCTION

1.1 Purpose

This licensing topical report is being furnished to the U.S. Nuclear Regulatory Commission (U.S. NRC) and the Canadian Nuclear Safety Commission (CNSC) for their collaborative reviews to support licensing activities for the deployment of the GE Hitachi Nuclear Energy (GEH) BWRX-300 structural design using Steel-Plate Composite (SC) modules with diaphragm plates for the integrated Reactor Building (RB) housing the Steel-Plate Composite Containment Vessel (SCCV) and containment internal structures.

The purpose of this licensing topical report includes the following:

- U.S. NRC approval and CNSC acceptance is requested for the design approach and methodology of Diaphragm Plate Steel-Plate Composite (DP-SC) structural elements for the GEH BWRX-300 Seismic Category I (Canadian Seismic Category A) SCCV and RB structures that demonstrates compliance with the safety and performance objectives of established regulatory requirements.
- U.S. NRC approval is requested for the requirements for the material, fabrication, construction, inspection, examination and testing of DP-SC modules for the GEH BWRX-300 SCCV and RB structures presented in Sections 5.0 and 6.0 that demonstrate compliance with the safety and performance objectives of established U.S. regulatory requirements.
- CNSC acceptance is requested for the requirements for the material, fabrication, construction, inspection, examination and testing of DP-SC modules for the GEH BWRX-300 SCCV and RB structures described in Sections 5.0 and 6.0, and the alternative requirements discussed in Section 2.5 specific to Canadian sites, that demonstrate compliance with the safety and performance objectives of established Canadian regulatory requirements
- U.S. NRC design-specific approval is requested for the use of:
  - Proposed criteria and requirements for materials, design, fabrication, construction, inspection, examination, and testing for the BWRX-300 SCCV adapted from the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) 2021 Edition, Section III, "Rules for Construction of Nuclear Facility Components," Division 2, "Code for Concrete Containments," Subsection CC, "Concrete Containments," Articles CC-1000 through CC-6000, including Division 2 Appendices (Reference 9-1).
  - Modified criteria and requirements to American National Standard Institute (ANSI)/American Institute of Steel Construction (AISC) N690-18 (Reference 9-2), Chapters NM, NN, and Appendix N9 for material, design, analysis, fabrication, construction, inspection, examination, and testing of BWRX-300 non-containment Seismic Category I structural members, including slabs and curved walls, built using DP-SC modules.
- CNSC acceptance is requested for the use of:

- Proposed design criteria and requirements for the BWRX-300 SCCV adapted from the ASME BPVC, 2021 Edition, Section III, Division 2, Subsection CC, Articles CC-1000 through CC-6000, including Division 2 Appendices, and the alternative material, fabrication, construction, inspection, examination, testing and quality assurance requirements specific to Canadian sites discussed in Section 2.5.2.
- Modified criteria and requirements to ANSI/AISC N690-18, Chapters NM, NN, and Appendix N9 for material, design, analysis, fabrication, construction, inpection, examination and testing of BWRX-300 non-containment Seismic Category A structural members, including slabs and curved walls, built using DP-SC modules, and the alternative material, fabrication, construction, inspection, examination, testing and quality assurance requirements specific to Canadian sites discussed in Section 2.5.1.

1.2 Scope

The scope of this document includes the following:

- Regulatory evaluation of compliance of the proposed design rules to applicable U.S. regulations, regulatory guidance of NUREG-0800, and Regulatory Guides (RGs), presented in Sections 2.1, 2.2 and 2.3, respectively
- Regulatory evaluation of compliance of the proposed design rules to applicable Canadian requirements, codes, and standards, and proposed alternative requirements specific to Canadian sites, presented in Sections 2.4 and 2.5
- Description of generic issues relevant to the scope of this report, presented in Section 2.6
- General description of the BWRX-300 integrated RB structures and a general overview of SC structural elements and technical justification for the proposed use of DP-SC modules for the integrated RB structures, presented in Section 3.0
- Overall structural analysis and design approach for the BWRX-300 integrated RB, including analysis method, structural modeling, loads and load combinations, and design code jurisdictions, presented in Section 4.0
- Technical evaluation of the proposed design parameters and requirements applicable to the proposed use of DP-SC modules for the BWRX-300 non-containment SC structures and a demonstration of how the proposed design approach meets the safety and performance objectives of applicable codes, presented in Section 5.0
- Technical evaluation of the proposed design parameters and requirements applicable to the proposed use of DP-SC modules for the BWRX-300 SCCV and a demonstration of how the proposed design approach meets the safety and performance objectives of applicable codes, presented in Section 6.0
- Summary of the National Reactor Innovation Center (NRIC) Demonstration Program Prototype test conclusions, presented in Section 7.0 confirming the proposed design approaches discussed in Sections 5.0 and 6.0
- Radiation shielding function requirements are not under the purview of this report.

2.0 REGULATORY EVALUATION

2.1 U.S. NRC Regulatory Requirements and Guidance

U.S. NRC regulatory requirements and guidance are evaluated to determine compliance or to justify the BWRX-300 specific approaches to compliance, where applicable.

2.1.1 10 CFR 50 Regulations

2.1.1.1 10 CFR 50.34(f)

10 CFR 50.34(f), "Additional TMI-related requirements," requires license applications to provide sufficient information to describe the nature of the studies required, how they are conducted, and a program to ensure that the results of these studies are factored into the final design of the facility, and the studies must be submitted as part of the final safety analysis report. This includes the capability of the containment to resist: (1) those loads that are generated by pressure and dead loads during an accident that releases hydrogen generated from 100-percent fuel clad metal-water reaction and accompanied by either hydrogen burning or added pressure from post-accident inerting; and (2) those loads that are generated as a result of an inadvertent full actuation of a post-accident inerting hydrogen control system, excluding seismic or Design Basis Accident (DBA) loadings. The following requirements are evaluated as they are related to containment structural integrity:

Regulatory Requirement:10 CFR 50.34(f)(3)(v)(A)(1) requires that containment integrity be maintained for steel containments by meeting the requirements of ASME BPVC, Section III, Division 1, Subarticle NE 3220, Service Level C Limits and for concrete containments by meeting the requirements of the ASME BPVC, Section III, Division 2. The specific code requirements for each type of containment will be met for a combination of dead load and an internal pressure of 45 psig. Modest deviations from these criteria will be considered by the NRC Staff, if good cause is shown by an applicant. Systems necessary to ensure containment integrity shall also be demonstrated to perform their function under these conditions.

> Statement of Compliance: The ASME BPVC, Section III, Division 1 requirements are met in the design of the BWRX-300 containment metal closure head and other Class MC components. The proposed containment material, design, fabrication, construction, inspection, examination and testing requirements presented in Section 6.0 of the report are adapted from the ASME BPVC, Section III, Division 2 requirements and ensure the containment structural integrity in compliance with the requirements of 10 CFR 50.34(f)(3)(v)(A)(1).

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50.34(f).

2.1.1.2 10 CFR 50.44

10 CFR 50.44, "Combustible gas control for nuclear power reactors," 10 CFR 50.44(c), Requirements for future water-cooled reactor applicants and licensees, apply to all water-cooled reactor Construction Permits (CPs) or operating licenses under this part, and to all water-cooled reactor design approvals, design certifications, combined licenses, or manufacturing licenses under Part 52 of this chapter, any of which are issued after October 16, 2003.

Regulatory Requirement: 10 CFR 50.44(c)(5), Structural analysis, requires that an applicant must perform an analysis that demonstrates containment structural integrity. This demonstration must use an analytical technique that is accepted by the NRC and include sufficient supporting justification to show that the technique describes the containment response to the structural loads involved. The analysis must address an accident that releases hydrogen generated from 100 percent fuel clad coolant reaction accompanied by hydrogen burning. Systems necessary to ensure containment integrity must also be demonstrated to perform their function under these conditions.

> Statement of Compliance: 10 CFR 50.44 (c)(1) through (c)(4) compliance is addressed in NEDC-33911P-A, "BWRX-300 Containment Performance," (Reference 9-3). The design requirements for the BWRX-300 containment structural integrity analysis performed to demonstrate the survivability of the containment to the structural loads generated from an accident where a 100 percent fuel clad coolant reaction accompanied by hydrogen burning occurs are provided in Section 6.0.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50.44(c)(5).

2.1.1.3 10 CFR 50.55a

10 CFR 50.55a(b), "Use and conditions on the use of standards," requires that systems and components of boiling water-cooled nuclear power reactors must meet the requirements of the ASME BPVC and the ASME OM Code (Reference 9-4) as specified in this paragraph (b).

Regulatory Requirement: 10 CFR 50.55a(b) includes applicability to the BWRX-300 SCCV as a pressure-retaining component.

> Statement of Compliance: Based on the justification provided in Section 6.22 of this report, the proposed inspection and testing approach provides an acceptable level of quality and safety when applied to the materials, design, fabrication, construction, inspection, examination, and testing of the BWRX-300 SCCV.

10 CFR 50.55a(g)(4), "Pre-service and inservice inspection requirements" requires that inservice inspection of Class CC concrete containments and metallic shell and penetration liners of concrete containments shall be performed in accordance with the applicable edition of the ASME BPVC, Section XI, Division 1, "Rules for Inspection and Testing of Components of Light-Water-Cooled Plants," (Reference 9-5), Subsections IWE and IWL, as incorporated by reference and subject to conditions stated in this regulation.

Regulatory Requirement: The most recent standard applicable to the BWRX-300 SCCV approved by the NRC in 10 CFR 50.55a(a)(1)(ii), ASME BPVC, Section XI, Division 1.

> Statement of Compliance: As discussed in Section 6.22 of this report, the pre-service and inservice inspection requirements of the SCCV meet the requirements of ASME Section XI, Division 1, complying with the requirements of 10 CFR 50.55a(g)(4).

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50.55a.

2.1.1.4 10 CFR 50.65

10 CFR 50.65, "Requirements for monitoring the effectiveness of maintenance at nuclear power plants," requires monitoring of the performance or condition of Structures, Systems, and Components (SSCs) against licensee-established goals, in a manner sufficient to provide reasonable assurance that these SSCs, as defined in Paragraph (b) of this section, are capable of fulfilling their intended functions. These goals shall be established commensurate with safety and,

where practical, take into account industrywide operating experience. When the performance or condition of an SSC does not meet established goals, appropriate corrective action shall be taken. This includes structures monitoring and maintenance requirements for Seismic Category I structures.

Regulatory Requirement: 10 CFR 50.65 requires safety-related SSCs that are relied upon to remain functional during and following design-basis events to ensure the integrity of the reactor coolant pressure boundary, the capability to shut down the reactor and maintain it in a safe shutdown condition, or the capability to prevent or mitigate the consequences of accidents that could result in potential off-site exposure.

> Statement of Compliance: An inservice inspection and maintenance program is established for the BWRX-300 Seismic Category I integrated RB structures to ensure the structures can fulfill their intended functions throughout their design service life in compliance with 10 CFR 50.65. Inspection methodology for the DP-SC non-containment structures and the SCCV are discussed in Sections 5.18 and 6.22 of this report.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50.65.

2.1.1.5 10 CFR 50.150

10 CFR 50.150, “Aircraft impact assessment,” each applicant listed shall perform a design-specific assessment of the effects on the facility of the impact of a large, commercial aircraft. Using realistic analyses, the applicant shall identify and incorporate into the design those design features and functional capabilities to show that, with reduced use of operator actions, the reactor core remains cooled, or the containment remains intact and spent fuel cooling or spent fuel pool integrity is maintained. The assessment must be based on the beyond design basis impact of a large, commercial aircraft used for long distance flights in the U.S., with aviation fuel loading typically used in such flights, and an impact speed and angle of impact considering the ability of both experienced and inexperienced pilots to control large, commercial aircraft at the low altitude representative of a nuclear power plant’s low profile.

Regulatory Requirement: A design-specific aircraft impact of a large, commercial aircraft assessment on the facility is required to ensure that (i) The reactor core remains cooled, or the containment remains intact; and (ii) Spent fuel cooling or spent fuel pool integrity is maintained.

> Statement of Compliance: The BWRX-300 design applies the Nuclear Energy Institute’s (NEI’s) methodology in NEI 07-13 (Reference 9-6) for aircraft crash evaluations and explicit dynamic analysis methods, where appropriate, to evaluate the consequences of regulatory defined threats on a BWRX-300 reactor site as discussed in Subsection 5.8.4 of this report. Specific requirements and approaches for aircraft impact explicit dynamic analyses are not in the scope of this report. The beyond design basis evaluation will demonstrate that the BWRX-300 design includes adequate design features that allow the containment to remain intact, and the fuel pool to maintain structural integrity for safe operations.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50.150.

2.1.1.6 10 CFR 50 Appendix A, GDC 1

Regulatory Requirement: 10 CFR 50 Appendix A, General Design Criterion (GDC) 1, “Quality standards and records,” requires that SSCs important to safety shall be designed, fabricated, erected, and tested to quality standards commensurate with the importance of the safety functions to be performed. Where generally recognized codes and standards are used, they shall be identified and evaluated to determine their applicability, adequacy, and sufficiency, and shall be supplemented or modified as necessary to assure a quality product in keeping with the required safety function. A Quality Assurance (QA) program shall be established and implemented in order to provide adequate assurance that these SSCs will satisfactorily perform their safety functions. Appropriate records of the design, fabrication, erection, and testing of SSCs important to safety shall be maintained by or under the control of the nuclear power unit licensee throughout the life of the unit.

> Statement of Compliance: As described in this report, the BWRX-300 Seismic Category I SSCs are designed, fabricated, erected, and tested to quality standards commensurate with the importance of their safety functions in accordance with generally recognized codes and standards, and under an approved QA program with approved control of records. The use of the proposed modifications to ANSI/AISC N690 and ASME BPVC addressing the materials, design, fabrication, construction, inspection, examination, and testing for the BWRX-300 Seismic Category I integrated RB are evaluated in Sections 5.0, 6.0 and 7.0 of this report to demonstrate their applicability, adequacy, and sufficiency.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix A, GDC 1.

2.1.1.7 10 CFR 50 Appendix A, GDC 2

10 CFR 50 Appendix A, GDC 2, "Design bases for protection against natural phenomena," requires that SSCs important to safety shall be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions. The design bases for these SSCs shall reflect: (1) Appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated; (2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena; and (3) the importance of the safety functions to be performed.

> Statement of Compliance: The BWRX-300 Seismic Category I integrated RB, including containment, is designed to withstand the effects of natural phenomena such as earthquakes, tornadoes and tornado missiles without loss of capability to perform its safety functions. Loads and load combinations considered in the design are discussed in Section 4.3 of this report.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix A, GDC 2.

2.1.1.8 10 CFR 50 Appendix A, GDC 4

10 CFR 50 Appendix A, GDC 4, "Environmental and dynamic effects design bases," requires that SSCs important to safety shall be designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation, maintenance, testing, and postulated accidents, including Loss-Of-Coolant Accidents (LOCAs). These SSCs shall be appropriately protected against dynamic effects, including the effects of missiles, pipe whipping, and discharging fluids, that may result from equipment failures and from events and conditions outside the nuclear power unit. However, dynamic effects associated with postulated pipe ruptures in nuclear power units may be excluded from the design basis when analyses reviewed and

approved by the Commission demonstrate that the probability of fluid system piping rupture is extremely low under conditions consistent with the design basis for the piping.

> Statement of Compliance: Loads and load combinations considered in the design BWRX-300 Seismic Category I integrated RB include normal operating, testing, accident pressure and reaction loads that may result from equipment or piping failures as discussed in Section 4.3 of this report. For sites where nonterrorism-related aircraft crashes cannot be screened out, site-specific loading will be developed consistent with Regulatory Position C.8.a(4) of U.S. NRC RG 1.136 (Reference 9-7) for the SCCV and Regulatory Position C.2.2.6 of U.S. NRC RG 1.243 (Reference 9-8) for the RB.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix A, GDC 4.

2.1.1.9 10 CFR 50 Appendix A, GDC 16

10 CFR 50 Appendix A, GDC 16, "Containment design," requires that reactor containment and associated systems shall be provided to establish an essentially leak-tight barrier against the uncontrolled release of radioactivity to the environment and to assure that the containment design conditions important to safety are not exceeded for as long as postulated accident conditions require.

> Statement of Compliance: The BWRX-300 SCCV enclosing the Reactor Pressure Vessel (RPV) and the containment internal structures is leak-tight, with the inner steel faceplate of the DP-SC modules serving as the leak barrier. The design of the containment penetrations that follows the requirements in Section 6.12 of this report also includes leak-tight isolation design features, including containment isolation valve, blind flanges, hatches, and electrical penetrations. The design and detailing of the SCCV penetrations and openings are coordinated with the fabricator to meet the code requirements.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix A, GDC 16.

2.1.1.10 10 CFR 50 Appendix A, GDC 50

10 CFR 50 Appendix A, GDC 50, "Containment design basis," requires that the reactor containment structure, including access openings, penetrations, and the containment heat removal system shall be designed so that the containment structure and its internal compartments can accommodate, without exceeding the design leakage rate and with sufficient margin, the calculated pressure and temperature conditions resulting from any LOCA. This margin shall reflect consideration of: (1) the effects of potential energy sources which have not been included in the determination of the peak conditions, such as energy in steam generators and as required by 10 CFR 50.44 energy from metal-water and other chemical reactions that may result from degradation but not total failure of emergency core cooling functioning; (2) the limited experience and experimental data available for defining accident phenomena and containment responses; and (3) the conservatism of the calculational model and input parameters.

> Statement of Compliance: The containment design is based upon consideration of a full spectrum of postulated accidents that would result in the release of reactor coolant to the containment. The BWRX-300 containment structural design includes sufficient margin to account for uncertainties from a full spectrum of postulated accidents that would result in the release of reactor coolant to the containment. The containment ultimate pressure capacity

discussed in Subsection 6.23.1 will demonstrate compliance to 10 CFR 50, Appendix A, GDC 50.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix A, GDC 50.

2.1.1.11 10 CFR 50 Appendix A, GDC 51

10 CFR 50 Appendix A, GDC 51, "Fracture prevention of containment pressure boundary," requires that the reactor containment boundary shall be designed with sufficient margin to assure that under operating, maintenance, testing, and postulated accident conditions: (1) its ferritic materials behave in a nonbrittle manner; and (2) the probability of rapidly propagating fracture is minimized. The design shall reflect consideration of service temperatures and other conditions of the containment boundary material during operation, maintenance, testing, and postulated accident conditions, and the uncertainties in determining: (1) material properties; (2) residual, steady-state, and transient stresses; and (3) size of flaws.

> Statement of Compliance: The BWRX-300 containment possesses ductility and energy absorbing capacity which permits inelastic deformation without failure under design basis transients and accidents. The design material selection reflects consideration of service temperatures and other conditions of the pressure boundary during operation, maintenance, testing, and design basis accident conditions, and the uncertainties in determining: (a) material properties; (b) residual, steady-state, and transient stresses; and (c) the size of flaws. The containment seismic design is qualified to meet the ductility detailing and design requirements for steel and SC structures of ANSI/AISC N690, with the supplementary guidance of U.S. NRC RG 1.243. Additionally, the ductility is confirmed by the ultimate capacity analysis of the BWRX-300 containment described in Section 6.23.1 and results of the NRIC tests discussed in Section 7.0.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix A, GDC 51.

2.1.1.12 10 CFR 50 Appendix A, GDC 52

10 CFR 50 Appendix A, GDC 52, "Capability for Containment Leakage Rate Testing," requires that the reactor containment and other equipment which may be subjected to containment test conditions shall be designed so that period integrated leakage rate testing can be conducted at containment design pressure.

> Statement of Compliance: As stated in NEDC-33911P-A and in Section 6.22 of this report, the BWRX-300 containment is designed with provisions to conduct periodic integrated leakage rate testing at containment design pressure to comply with 10 CFR 50, Appendix J and the guidance of U.S. NRC RG 1.163 (Reference 9-9).

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix A, GDC 52.

2.1.1.13 10 CFR 50 Appendix A, GDC 53

10 CFR 50 Appendix A, GDC 53, "Provisions for containment testing and inspection," requires that the reactor containment shall be designed to permit: (1) appropriate periodic inspection of all important areas, such as penetrations; (2) an appropriate surveillance program; and (3) periodic testing at containment design pressure of the leak tightness of penetrations which have resilient seals and expansion bellows.

> Statement of Compliance: The BWRX-300 containment and associated penetrations have provisions for conducting individual leakage rate tests on applicable penetrations. Penetrations and other important areas are visually inspected, and pressure tested for leak tightness at periodic intervals in accordance with 10 CFR 50, Appendix J as stated in NEDC-33911P-A, Section 2.2.7 and in Section 6.22 of this report.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix A, GDC 53.

2.1.1.14 10 CFR 50 Appendix B

10 CFR 50 Appendix B, "Quality assurance criteria for nuclear power plants and fuel reprocessing plants," requires, by the provisions of § 50.34, to include in its preliminary safety analysis report a description of the QA program to be applied to the design, fabrication, construction, and testing of the SSCs of the facility. Every applicant for an operating license is required to include, in its final safety analysis report, information pertaining to the managerial and administrative controls to be used to assure safe operation. Nuclear power plants and fuel reprocessing plants include SSCs that prevent or mitigate the consequences of postulated accidents that could cause undue risk to the health and safety of the public. This appendix establishes QA requirements for the design, manufacture, construction, and operation of those SSCs. The pertinent requirements of this appendix apply to all activities affecting the safety-related functions of those SSCs; these activities include designing, purchasing, fabricating, handling, shipping, storing, cleaning, erecting, installing, inspecting, testing, operating, maintaining, repairing, refueling, and modifying.

> Statement of Compliance: NEDO-11209-A, "GE Hitachi Nuclear Energy Quality Assurance Program Description," (Reference 9-10) complies with ASME NQA-1, "Quality Assurance Requirements for Nuclear Facility Applications," (Reference 9-11). The NRC Staff reviewed the QA measures implemented by GEH in Section 1.0 of Reference 9-10 and concluded that the organizational changes in Reference 9-10 continue to meet the guidance in 10 CFR Part 50, Appendix B. Computer programs used in the structural analyses of the BWRX-300 integrated RB are verified in accordance with NEDO-11209-A. NRIC test plans and results are also reviewed and accepted in accordance with NEDO-11209-A as discussed in Subsection 7.2.1.1. The SCCV quality control and quality assurance requirements are discussed in Sections 6.2 and 6.15 of this report consistent with the requirements of 10 CFR 50 Appendix B.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix B.

2.1.1.15 10 CFR 50 Appendix J

10 CFR 50 Appendix J, "Primary reactor containment leakage testing for water-cooled power reactors," requires that primary reactor containments shall meet the containment leakage test requirements set forth in this appendix. These test requirements provide for pre-operational and periodic verification by tests of the leak-tight integrity of the primary reactor containment, and systems and components which penetrate containment of water-cooled power reactors and establish the acceptance criteria for these tests. The purposes of the tests are to assure that: (a) leakage through the primary reactor containment and systems and components penetrating primary containment shall not exceed allowable leakage rate values as specified in the technical specifications or associated bases; and (b) periodic surveillance of reactor containment penetrations and isolation valves is performed so that proper maintenance and repairs are made during the service life of the containment and systems and components penetrating primary

containment. These test requirements may also be used for guidance in establishing appropriate containment leakage test requirements in technical specifications or associated bases for other types of nuclear power reactors.

> Statement of Compliance: The BWRX-300 design includes provisions for periodic integrated leakage rate testing, and local leak rate test for the SCCV (type A testing) and containment penetrations (type B testing), in compliance with the requirements of 10 CFR 50 Appendix A, GDC 52, GDC 53 and 10 CFR 50, Appendix J as discussed in NEDC-33911P-A and in Sections 4.3 and 6.22 of this report.

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix J.

2.1.1.16 10 CFR 50 Appendix S

10 CFR Part 50, Appendix S, "Earthquake engineering criteria for nuclear power plants," requires that for Safe Shutdown Earthquake (SSE) ground motions, SSCs will remain functional and within applicable stress, strain, and deformation limits. The required safety functions of SSCs must be assured during and after the vibratory ground motion through design, testing, or qualification methods. The evaluation must take into account Soil-Structure Interaction (SSI) effects and the expected duration of the vibratory motion.

> Statement of Compliance: The compliance of the BWRX-300 seismic design to the requirements of 10 CFR 50, Appendix S is evaluated in NEDO-33914-A, "BWRX-300 Advanced Civil Construction and Design Approach," (Reference 9-12), Section 2.3. The SSE ground motion used in the analysis of the integrated RB structures is site-specific and is developed per the methodology discussed in NEDO-33914-A. NEDO-33914-A provides additional requirements for the development of the SSE ground motion and seismic SSI analysis to address the deeply embedded design of the RB. Section 4.0 of this report provides an overview of the BWRX-300 SSI analyses, including seismic analysis, performed to evaluate demands on the structures, and of the integrated RB Finite Element (FE) model used in the analyses. Floor response spectra or acceleration time histories obtained from the seismic SSI analysis are used to qualify systems and components required to remain functional during and following an SSE. Complying with the requirements of 10 CFR 50, Appendix S, Operating Basis Earthquake (OBE) loads and load combinations are considered in the BWRX-300 design when the OBE is set larger than 1/3 of the site-specific SSE. For U.S. sites, the OBE is selected by the applicant based on the site conditions to serve as reference for shutdown of the plant per criteria in ANSI/ANS-2.23 (Reference 9-13).

Therefore, the BWRX-300 design will meet the requirements of 10 CFR 50 Appendix S.

2.2 NUREG-0800 Standard Review Plan (SRP) Guidance

2.2.1 NUREG-0800, SRP 3.5.3

NUREG-0800, SRP 3.5.3, "Barrier Design Procedures," (Reference 9-14), provides review guidance to the NRC Staff responsible for the review of procedures utilized in the design of Seismic Category I structures to withstand the effects of missile impact to ensure conformance with 10 CFR 50, GDC 2 and 4. This includes the following specific areas of review:

- Procedures utilized for the prediction of local damage in the impacted area
    - This includes the estimation of the depth of penetration.

- Procedures utilized for the prediction of the overall response of the barrier or structures due to the missile impact
    - This includes the assumptions on acceptable ductility ratios where elasto-plastic behavior is relied upon, and procedures for estimation of forces, moments, and shear induced in the barrier by the impact force of the missile.
- Adequacy of missiles' parameters considered

Statement of Conformance: The BWRX-300 design considers local and global effects of impactive loads as discussed in Sections 5.8 and 6.10 of this report in conformance with the regulatory guidance of SRP 3.5.3.

2.2.2 NUREG-0800, SRP 3.8.1

NUREG-0800, SRP 3.8.1, "Concrete Containment," (Reference 9-15), provides review guidance to the NRC Staff responsible for structural analysis reviews for concrete containments. Although this SRP section is not directly applicable to the design of the SCCV, the guidance is reviewed to determine what remains relevant for the NRC Staff to consider in their review. This includes the following specific areas of review:

- Descriptive information, including plans and sections of the containment structure, to establish that sufficient information is provided to define the primary structural aspects and elements relied upon to perform the containment function, including structural and functional characteristics
- Design codes, standards, specifications, regulations, RGs, and other industry standards that are applied in the design fabrication, construction, testing, and inservice surveillance of the containment
- Information pertaining to the applicable design loads and various combinations thereof, with emphasis on the extent of compliance with ASME BPVC requirements
- Design and analysis procedures used for the containment with emphasis on the extent of compliance with ASME BPVC requirements
- Design limits imposed on the various parameters that quantify the structural behavior of the containment, with emphasis on the extent of compliance with ASME BPVC requirements
- Materials that are used in construction of the containment with emphasis on the extent of compliance with ASME BPVC requirements
- Quality Control (QC) program that is proposed for the fabrication and construction of the containment, with emphasis on the extent of compliance with ASME BPVC requirements
- Any special design provisions (e.g., providing sufficient physical access, providing alternative means for identification of conditions in inaccessible areas that can lead to degradation, or providing remote visual monitoring of high-radiation areas) to accommodate inservice inspection
- Pre-operational structural testing program for the completed containment and for individual components, such as personnel and equipment locks and hatches, which includes

the objectives of the test program and acceptance criteria, with emphasis on the extent of compliance with ASME BPVC requirements, including inservice surveillance programs

Statement of Conformance: For code applicability, the BWRX-300 SCCV is designed, fabricated, constructed, inspected, examined and tested to applicable portions of ASME BPVC, Section III, Division 2 requirements along with the modified requirements outlined in Section 6.0 of this report. The code jurisdictional boundary for application of the proposed design approach presented in Section 6.0 to the SCCV is shown in Figure 4-1. The proposed design approach for the BWRX-300 SCCV meets the safety and performance objectives of the regulatory guidance of SRP 3.8.1.

2.2.3 NUREG-0800, SRP 3.8.2

NUREG-0800, SRP 3.8.2, “Steel Containment,” (Reference 9-16), provides review guidance to the NRC Staff responsible for structural analysis reviews for steel containments. Although this SRP section is not directly applicable to the design of the SCCV, the guidance is reviewed to determine what remains relevant for the NRC Staff to consider in their review. This includes the following specific areas of review:

- Descriptive information, including plans and sections of the containment structure, to establish that sufficient information is provided to define the primary structural aspects and elements relied upon to perform the containment function, including structural and functional characteristics, including steel components of concrete containments that resist pressure and are not backed by structural concrete (e.g., the containment head in a Boiling Water Reactor (BWR))
- Design codes, standards, specifications, regulations, RGs, and other industry standards that are applied in the design fabrication, construction, testing, and inservice surveillance of the containment
- Information pertaining to the applicable design loads and various combinations thereof, with emphasis on the extent of compliance with ASME BPVC requirements
- Design and analysis procedures used for the containment, with emphasis on the extent of compliance with ASME BPVC requirements
- Design limits imposed on the various parameters that quantify the structural behavior of the containment, with emphasis on the extent of compliance with ASME BPVC requirements
- Materials that are used in construction of the containment, with emphasis on the extent of compliance with ASME BPVC requirements
- QC program that is proposed for the fabrication and construction of the containment, with emphasis on the extent of compliance with ASME BPVC requirements, including nondestructive examination of the materials, including tests to determine their physical properties, welding procedures, and erection tolerances
- Any special construction techniques, if proposed, to determine their effects on the structural integrity of the completed containment
- Pre-operational structural testing program for the completed containment and for individual components, such as personnel and equipment locks and hatches, which includes

the objectives of the test program and acceptance criteria, with emphasis on the extent of compliance with ASME BPVC requirements, including inservice surveillance programs

- Special testing and inservice surveillance requirements proposed for new or previously untried design approaches, and for new reactors, it is important to accommodate inservice inspection of critical areas.

Statement of Conformance: For code applicability, the BWRX-300 SCCV is designed, fabricated, constructed, inspected, examined and tested to applicable portions of ASME BPVC, Section III, Division 2 requirements, along with the modified requirements outlined in Section 6.0 of this report. The code jurisdictional boundary for application of the proposed design approach presented in Section 6.0 to the SCCV is shown in Figure 4-1. The proposed design approach for the BWRX-300 SCCV meets the safety and performance objectives of the regulatory guidance of SRP 3.8.2. Design of Class MC components of the containment is not in the scope of this report as discussed in Section 4.0 of the report.

2.2.4 NUREG-0800, SRP 3.8.3

NUREG-0800, SRP 3.8.3, “Concrete and Steel Internal Structures of Steel or Concrete Containments” (Reference 9-17), provides review guidance to the NRC Staff responsible for structural analysis reviews. This includes the following specific areas of review:

- Descriptive information, including plans and sections of the various internal structures, to establish that sufficient information is provided to define the primary structural aspects and elements relied upon to perform the safety-related functions of these structures
- Capability of the internal structures to resisting loads and load combinations to which they may be subjected and should not become the initiator of an LOCA, with the structures able to mitigate its consequences by protecting the containment and other engineered safety features from the accident’s effects such as jet forces and whipping pipes
- Plant designs may also use modular construction methods for the major containment internal structures:
    - With wall modules typically constructed from large, prefabricated sections of steel plates spaced apart with intermittent steel members, joined with other modules at the site, and then filled with concrete
    - With the concrete fill used in wall modules either structural concrete with reinforcement (composite construction) or fill concrete of low strength without reinforcement, or heavy concrete for radiation shielding
    - With floor modules consisting of prefabricated steel members and plates combined with poured concrete to create a composite section, and the structural module design, fabrication, configuration, layout, and connections may be reviewed on a case-by-case basis
- Design codes, standards, specifications, and RGs, as well as industry standards that are applied in the design, fabrication, construction, testing, and surveillance of the containment structures
- Applicable design loads and associated load combinations

- Design and analysis procedures used for the containment internal structures, with an emphasis on the extent of compliance with the applicable codes as indicated in Subsection II.2 of SRP 3.8.3
- Design limits imposed on the various parameters that quantify the structural behavior of the various interior structures of the containment, particularly with respect to stresses, strains, deformations, and factors of safety against structural failure, with emphasis on the extent of compliance with the applicable codes indicated in Subsection II.5 of SRP 3.8.3
- Materials used in the construction of the containment internal structures, including concrete ingredients, reinforcing bars and splices, structural steel, and various supports and anchors
- QC program proposed for the fabrication and construction of the containment internal structures, including nondestructive examination of the materials to determine physical properties, placement of concrete, and erection tolerances
- Special, new, or unique construction techniques, such as the use of modular construction methods, if used
- For Seismic Category I structures inside containment, information on structures monitoring and maintenance requirements, including inservice inspection of critical areas, special design provisions (e.g., sufficient physical access, alternative means for identification of conditions in inaccessible areas that can lead to degradation, remote visual monitoring of high-radiation areas) to accommodate inservice inspection of containment internal structures, and post-construction testing and inservice surveillance programs for containment internal structures such as periodic examination of inaccessible areas

Statement of Conformance: Following the guidance of NUREG-0800, SRP 3.8.3, Subsection II.2, the analysis and design, fabrication, construction and testing of the containment internal structures is in accordance with ANSI/AISC N690 with the supplementary guidance of U.S. NRC RG 1.243. The proposed modified ANSI/AISC N690 design rules for the BWRX-300 SC (including DP-SC) containment internal structures presented in Section 5.0 of this report meet the safety and performance objectives of the regulatory guidance of SRP 3.8.3.

2.2.5 NUREG-0800, SRP 3.8.4

NUREG-0800, SRP 3.8.4, “Other Seismic Category I Structures” (Reference 9-18), provides review guidance to the NRC Staff responsible for structural analysis reviews. This includes specific areas of review that are applicable to the RB Seismic Category I structure surrounding the containment, including the following:

- Descriptive information, including plans and sections of each structure, to establish that there is sufficient information to define the primary structural aspects and elements relied upon for the structure to perform the intended safety function, and the relationship between adjacent structures, including the separation provided or structural ties, if any
- Design codes, standards, specifications, RGs, and other industry standards that are applied in the design, fabrication, construction, testing, and surveillance of Seismic Category I structures
- Applicable design loads and various load combinations

- Design and analysis procedures used for Seismic Category I structures focusing on the extent of compliance with American Concrete Institute (ACI) 349 (Reference 9-19), with supplemental guidance by U.S. NRC RG 1.142 (Reference 9-20) for concrete structures and ANSI/AISC N690 supplemented by U.S. NRC RG 1.243 for steel structures
- Design limits imposed on the various parameters that serve to quantify the structural behavior of each structure and its components, with specific attention to stresses, strains, gross deformations, and factors of safety against structural failure, and for each load combination specified, the allowable limits compared with the acceptable limits delineated in Subsection II.5 of SRP 3.8.4
- Materials used in the construction of Seismic Category I structures, including concrete ingredients, reinforcing bars and splices, and structural steel and anchors
- QC parameters that are proposed for the fabrication and construction of Seismic Category I structures, including nondestructive examination of the materials to determine physical properties, placement of concrete, and erection tolerances
- Special construction techniques, such as modular construction methods, if used
- Information on structures monitoring and maintenance requirements, including accommodation for inservice inspection of critical areas, any special design provisions (e.g., providing sufficient physical access, providing alternative means for identification of conditions in inaccessible areas that can lead to degradation, remote visual monitoring of high-radiation areas). Post-construction testing and inservice surveillance programs, such as periodic examination of inaccessible areas, monitoring of ground water chemistry, and monitoring of settlements and differential displacements

Statement of Conformance: Following the guidance of NUREG-0800, SRP 3.8.4, the analysis and design, fabrication, construction, inspection, examination and testing of the RB structure is in accordance with the ANSI/AISC N690 with the supplementary guidance of U.S. NRC RG 1.243. The proposed ANSI/AISC N690 modified design rules for the BWRX-300 RB presented in Section 5.0 of this report meet the safety and performance objectives of the regulatory guidance of SRP 3.8.4.

2.2.6 NUREG-0800, SRP 3.8.5

NUREG-0800, SRP 3.8.5, “Foundations,” (Reference 9-21), provides review guidance to the NRC Staff relating to the foundations of all Seismic Category I structures. This includes the following specific areas of review:

- Descriptive information, including plans and sections of each foundation, to establish that sufficient information is provided to define the primary structural aspects and elements relied on to perform the foundation function
    - Major plant Seismic Category I foundations that are reviewed, together with associated descriptive information, includes concrete structure foundation, containment enclosure building foundation, auxiallry building foundation and other Seismic Category I foundations.

- Codes, standards and specifications, RGs, and other industry standards that are applied in the design, fabrication, construction, testing, and surveillance of Seismic Category I foundations
- Applicable design loads and various load combinations
- Design procedures used for Seismic Category I foundations other than containment, focusing on the extent of compliance with ACI 349, with supplemental guidance by U.S. NRC RG 1.142 for concrete structures and ANSI/AISC N690 supplemented by U.S. NRC RG 1.243 for steel structures
- Structural acceptance criteria limits imposed on the various parameters that serve to quantify the structural behavior of each foundation, emphasizing the extent the allowable limits and the factors of safety against overturning and sliding to ensure adequate safety margins
- Materials, QC, and special construction used in the construction of Seismic Category I foundations, including concrete ingredients, reinforcing bars, structural steel, and rock anchors
- Testing and inservice surveillance programs focusing on any special design provisions (e.g., providing sufficient physical access, furnishing alternative means for identification of conditions in inaccessible areas that can lead to degradation, conducting remote visual monitoring of high-radiation areas) to accommodate inservice inspection of Seismic Category I foundations

Statement of Conformance: The proposed design approach for the portion of the common mat foundation supporting the BWRX-300 integrated RB is discussed in Section 5.0 of this report. Similarly, the proposed design approach for the portion of the common mat foundation supporting the BWRX-300 SCCV is discussed in Section 6.0. The proposed approaches in Sections 5.0 and 6.0 meet the safety and performance objectives of the regulatory guidance of SRP 3.8.5.

2.2.7 NUREG-0800, SRP 19.0

NUREG-0800, SRP 19.0, “Probabilistic Risk Assessment and Severe Accident Evaluation for Reactors,” (Reference 9-22), provides review guidance to the NRC staff of the applicant’s design-specific probabilistic risk assessment and deterministic evaluation of design features for the prevention or mitigation of severe accidents. The structural performance of the containment under severe accident loads encompasses: (1) the applicant’s assessment of the Level C (or factored load) pressure capability of the containment in accordance with 10 CFR 50.44(c)(5); (2) the applicant’s demonstration of the containment capability to withstand the pressure and temperature loads induced by the more likely severe accident scenarios as stipulated in SECY-93-087, “Policy, Technical, and Licensing Issues Pertaining to Evolutionary and Advanced Light-Water Reactor Designs,” Section I.J (Reference 9-23); (3) the applicant’s containment structural fragility assessment for overpressurization; and (4) the applicant’s assessment of the seismic capacity of the containment structure in meeting the expectation documented in SECY-93-087, Section II.N.

Statement of Conformance: The BWRX-300 containment structural performance under beyond design basis and severe accident loads related to the containment ultimate pressure capacity combustible gases, and containment ability to maintain leak-tight barrier following the onset of core damage is evaluated following the regulatory guidance of SRP 19.0 as described in Section 6.23. As stated in Subsection 6.23.3, the BWRX-300 containment is designed to maintain its structural integrity under severe accidents complying with SRP 19.0 and meeting the containment structural performance goals stipulated in SECY-93-087. The plant-specific probabilistic risk assessment and severe accident evaluations that will demonstrate the survivability of the containment and its robustness against the four conditions specified in SRP 19.0 will be presented in Chapter 19 and Section 15.6, respectively, of each plant-specific final safety analysis report in conformance with the regulatory guidance of SRP 19.0.

2.2.8 NUREG-0800, SRP 19.5

NUREG-0800, SRP 19.5, “Adequacy of Design Features and Functional Capabilities Identified and Described for Withstanding Aircraft Impacts,” (Reference 9-24), provides review guidance to the NRC Staff to perform a design-specific assessment of the effects on the facility of the impact of a large commercial aircraft. Using realistic analysis, the applicant shall identify and incorporate into the design those design features and functional capabilities to show that, with reduced use of operator actions: (1) the reactor core remains cooled, or the containment remains intact; and (2) spent fuel cooling or spent fuel pool integrity is maintained.

Statement of Conformance: The BWRX-300 design applies the methodology in NEI 07-13 for aircraft crash evaluations and explicit dynamic analysis methods, where appropriate, to evaluate the consequences of regulatory defined threats on a BWRX-300 reactor site as discussed in Subsection 5.8.4 of this report. Specific requirements and approaches for aircraft impact explicit dynamic analyses are not in the scope of this report. The beyond design basis evaluation will demonstrate that the BWRX-300 design includes adequate design features that allow the containment to remain intact, and the fuel pool to maintain structural integrity for safe operations in conformance with SRP 19.5.

2.3 Regulatory Guides

2.3.1 Regulatory Guide 1.7

RG 1.7, “Control of Combustible Gas Concentrations in Containment Following a Loss of Coolant Accident” (Reference 9-25), describes methods acceptable to the NRC Staff for implementing the regulatory requirements of 10 CFR 50.44 for reactors subject to the provisions of Sections 50.44(b) or 50.44(c) with regard to control of combustible gases generated by Beyond Design Basis Accident (BDBA) that could be a risk significant threat to containment integrity. For applicants and holders of a water-cooled reactor CP or operating license under 10 CFR 50 that are docketed after October 16, 2003, containments must have an inerted atmosphere or limit combustible gas concentrations in containment during and following an accident that releases an equivalent of combustible gas as would be generated from a 100% fuel clad coolant reaction, uniformly distributed, to less than 10% (by volume) and must maintain containment structural integrity.

Statement of Conformance: The criteria and approach presented in Subsection 6.23.2 for demonstrating the containment structural integrity under loads resulting from combustible gases generated by metal-water reactions of the fuel cladding conform to the guidance of Regulatory Position 5 of U.S. NRC RG 1.7.

2.3.2 Regulatory Guide 1.26

RG 1.26, "Quality Group Classifications and Standards for Water , Steam , and Radioactive Waste Containing Components of Nuclear Power Plants" (Reference 9-26), describes methods acceptable to the NRC Staff for use in implementing the regulatory requirements of 10 CFR 50 Appendix A, GDC 1, "Quality Standards and Records," with regard to a quality classification system related to specified national standards that may be used to determine quality standards acceptable to the NRC Staff for components containing water, steam, or radioactive material in light water cooled nuclear power plants.

> Statement of Conformance: The BWRX-300 containment is classified as Quality Group B and its design complies with the requirements of 10 CFR 50 Appendix A, GDC 1. The BWRX-300 containment design discussed in Section 6.0 of the report conforms to the guidance of U.S. NRC RG 1.26.

2.3.3 Regulatory Guide 1.28

RG 1.28, "Quality Assurance Program Criteria (Design and Construction)," for addressing 10 CFR 50 Appendix B QA requirements, as it applies to the RB and SCCV, describes methods that the staff of the U.S. NRC considers acceptable for complying with the provisions of 10 CFR Part 50, Appendix B, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants," for establishing and implementing a QA program for the design and construction of nuclear power plants and fuel reprocessing plants. 10 CFR Part 50, Appendix A, GDC 1 and 10 CFR 50.34(a)(7) provide a description of the QA program to be applied to the design, fabrication, construction, and testing of the SSCs of the facility, and a discussion of how the applicable requirements of Appendix B to 10 CFR Part 50 Appendix B will be satisfied.

> Statement of Conformance: The BWRX-300 SSCs are designed, fabricated, erected, and tested to quality standards commensurate with the importance of the safety functions to be performed in accordance with NEDO-11209-A, which complies with NRC approved ASME NQA-1 and conforms to the guidance of U.S. NRC RG 1.28.

2.3.4 Regulatory Guide 1.54

RG 1.54, "Service Level I, II, III and In-Scope License Renewal Protective Coatings Applied to Nuclear Power Plants" (Reference 9-27), describes a method that the staff of the U.S. NRC considers acceptable for complying with NRC requirements for the selection, application, qualification, inspection, and maintenance of protective coatings applied to nuclear power plants.

> Statement of Conformance: As stated in Sections 5.15 and 6.19 of the report, the selection, application, qualification, inspection, and maintenance of coatings used for corrosion protection of the containment and non-containment DP-SC modules will conform to the guidance of U.S. NRC RG 1.54.

2.3.5 Regulatory Guide 1.57

RG 1.57, "Design Limits and Loading Combinations for Metal Primary Reactor Containment System Components" (Reference 9-28), describes an approach to the NRC Staff to consider an acceptable for use in satisfying the requirements of General Design Criteria 1, 2, 4, and 16, as specified in 10 CFR Part 50 Appendix A, "General Design Criteria for Nuclear Power Plants." The leak tightness of the containment structure must be tested at regular intervals during the life of the plant, in accordance with the provisions of 10 CFR Part 50, Appendix J, "Primary Reactor Containment Leakage Testing for Water-Cooled Power Reactors." In addition, for certain reactors specified in 10 CFR 50.34(f), 10 CFR 50.34(f)(3)(v)(A) and (B) require steel containments to meet specific provisions of the ASME BPVC when subjected to loads resulting from fuel damage, metal-water reactions, hydrogen burning, and inerting system actuations.

> Statement of Conformance: The design limits, load combinations, and leak tightness of the containment closure head, and other Class MC components conform to the guidance of U.S. NRC RG 1.57. Design limits, load combinations, and leak tightness of Class MC components of the containment backed by concrete are discussed in Sections 4.0 and 6.0 of this report.

2.3.6 Regulatory Guide 1.61

RG 1.61, "Damping Values for Seismic Design of Nuclear Power Plants" (Reference 9-29), describes an acceptable damping value that the NRC Staff can use in reviewing the seismic response analysis of Seismic Category I nuclear power plant SSCs in accordance with 10 CFR Part 50, GDC 2, and requires that SSCs important to safety be designed to withstand the effects of natural phenomena such as earthquakes without losing the ability to perform their safety functions. Such SSCs must also be designed to accommodate the effects of and be compatible with the environmental conditions associated with normal operation and postulated accidents. Appendix S specifies the requirements for the implementation of GDC 2 with respect to earthquakes.

> Statement of Conformance: OBE and SSE damping values for the SCCV and the non-containment Seismic Category I DP-SC elements are based on the values provided for SC walls in Tables 1 and 2 of U.S. NRC RG 1.61. The response level considered for the generation of in-structure response spectra conforms to the guidance U.S. NRC RG 1.61.

2.3.7 Regulatory Guide 1.136

RG 1.136, "Materials, Construction, and Testing of Concrete Containments", describes an approach that is acceptable to the NRC Staff to meet regulatory requirements for materials, design, construction, fabrication, examination, and testing of concrete (reinforced or prestressed) containments in nuclear power plants.

10 CFR Part 50 Appendix A provides minimum requirements for the principal design criteria that establish the necessary design, fabrication, construction, testing, and performance requirements for SSCs important to safety to provide reasonable assurance that the facility can be operated without undue risk to the health and safety of the public. GDC 1, 2, 4, 16, and 50 are applicable to U.S. NRC RG 1.136.

> Statement of Conformance: The BWRX-300 SCCV is designed, fabricated, erected, inspected, examined and tested to quality standards commensurate with the importance of the safety functions to be performed in accordance with generally recognized codes and standards, and under an approved QA program with approved control of records. The safety and performance objectives of the regulatory guidance of U.S. NRC RG 1.136 for materials, design, construction, fabrication, examination, and testing of concrete containments are met by following the SCCV design approach provided in Section 6.0.

2.3.8 Regulatory Guide 1.160

RG 1.160, "Monitoring the Effectiveness of Maintenance at Nuclear Power Plants" (Reference 9-30), describes methods that are acceptable to NRC Staff for demonstrating compliance with the provisions of Section 50.65, "Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants," of 10 CFR Part 50. 10 CFR 50.34(b)(6)(iv) requires an operating license to include a final safety analysis report that includes plans for conduct of normal operations, including maintenance, surveillance, and periodic testing of SSCs.

> Statement of Conformance: As stated in Sections 5.18 and 6.22, an inservice inspection and testing program is established to satisfy the general requirements for examination of the integrated RB to ensure the structure can fulfill its intended functions throughout the design service life of the BWRX-300, in compliance with 10 CFR 50.65 and conforming to the guidance of U.S. NRC RG. 1.160.

2.3.9 Regulatory Guide 1.199

RG 1.199, "Anchoring Components and Structural Supports in Concrete" (Reference 9-31), describes a method acceptable to the NRC Staff for compliance with regulations for the design, installation, testing, evaluation, and QA of anchors (steel embedment's) used for component and structural supports in concrete. 10 CFR Part 50, Appendix A, GDC 1, 2, and 4; 10 CFR Part 50 Appendix B; and 10 CFR 50 Appendix S are applicable.

> Statement of Conformance: Load bearing steel materials may be used in the connections and for some attachments that require embedment anchors/stiffeners. If used, design of load bearing steel materials embedded in DP-SC structures will meet the requirements of ASME BPVC, 2021 Edition, Section III, Division 2, Subsection CC and conform to the regulatory guidance of U.S. NRC RG 1.199.

2.3.10 Regulatory Guide 1.216

RG 1.216, "Containment Structural Integrity Evaluation for Internal Pressure Loadings Above Design-Basis Pressure" (Reference 9-32), describes the methods that the NRC Staff considers acceptable for: (1) predicting the internal pressure capacity for containment structures above the DBA pressure; (2) demonstrating containment structural integrity related to combustible gas control; and (3) demonstrating containment structural integrity through an analysis that specifically addresses the Commission's performance goals related to the prevention and mitigation of severe accidents. 10 CFR 50, Appendix A, GDC 50, "Containment Design Basis," requires that the reactor containment structure and its internal compartments can accommodate, without exceeding the design leakage rate and with sufficient margin, the calculated pressure and temperature conditions caused by an LOCA.

> Statement of Conformance: The leak tightness evaluation of the containment structure, including the SCCV, containment closure head, and other Class MC components, under beyond design basis internal pressure loads conforms to the guidance of U.S. NRC RG 1.216 as discussed in Section 6.23.

2.3.11 Regulatory Guide 1.217

RG 1.217, "Guidance for the Assessment of Beyond-Design-Basis Aircraft Impacts for Aircraft Impact Assessment" (Reference 9-33), describes a method that the NRC Staff considers acceptable regarding the consideration of aircraft impacts for new nuclear power reactors. In particular, this RG endorses the methodologies described in the industry guidance document, NEI 07-13, "Methodology for Performing Aircraft Impact Assessments for New Plant Designs," Revision 8, dated April 2011. The objective of the aircraft impact rule is to require nuclear power plant designers to rigorously assess their designs to identify design features and functional capabilities that could provide additional inherent protection to withstand the effects of an aircraft impact. The NRC expects this rule to result in new nuclear power reactor facilities that are inherently more robust with regards to an aircraft impact than if they were designed in the absence of the aircraft impact rule. The rule provides an enhanced level of protection beyond that which is provided by the existing adequate protection requirements applicable to currently operating power reactors.

> Statement of Conformance: The BWRX-300 design applies the methodology in NEI 07-13 for the beyond design basis aircraft crash evaluations as discussed in Subsection 5.8.4 of this report. Specific requirements and approaches for aircraft impact explicit dynamic analyses are not in the scope of this report. The beyond design basis evaluation will demonstrate that the containment remains intact, and the fuel pool structural integrity is maintained for safe operations in conformance with the guidance of U.S. NRC RG 1.217.

2.3.12 Regulatory Guide 1.243

RG 1.243, "Safety-Related Steel Structures and Steel-Plate Composite Walls for Other Than Reactor Vessels and Containments," describes a method acceptable to the NRC Staff for compliance with regulations for the design, fabrication, and erection of safety-related steel structures and SC walls for other than reactor vessels and containments. 10 CFR Part 50, Appendix A, GDC 1, 2, and 4; 10 CFR 50 Appendix B; and 10 CFR Appendix S are applicable. This guide endorses, with exceptions and clarifications, the procedures and standards of the ANSI/AISC N690 code.

> Statement of Conformance: The analysis, design, fabrication, construction, inspection, examination and testing of the non-containment Seismic Category I DP-SC structures discussed in Section 5.0 of the report follow the regulatory guidance of U.S. NRC RG 1.243.

2.4 CNSC Regulatory Requirements and Guidance

CNSC regulatory requirements and guidance are evaluated to determine compliance, to establish the use of the graded approach, or justify an alternative approach, where applicable. The information below is provided to assist the CNSC in their review with the purpose of soliciting feedback in support of licensing activities for the deployment of the BWRX-300 in Canada, and for the purpose of facilitating collaborative review by the NRC and CNSC regarding the proposed use of SC materials for the BWRX-300 Seismic Category A integrated RB. This information is complementary to details provided in the Licence to Construct Application. As outlined in the application, design principles for the BWRX-300 structures are provided in a graded manner commensurate to their importance to safety. Use of the graded approach is considered for the GEH BWRX-300 SC materials, in accordance with REGDOC-1.1.5, "Supplemental Information for Small Modular Reactor Proponents" (Reference 9-34) used in conjunction with REGDOC-1.1.2, "Licence Application Guide: Licence to Construct a Reactor Facility" (Reference 9-35).

2.4.1 CNSC Regulatory Document REGDOC-1.1.2

REGDOC-1.1.2, "Licence Application Guide: Licence to Construct a Reactor Facility"

Regulatory Requirement: REGDOC-1.1.2, Section 4.3.2 includes requirements for presenting information on procedures that will be implemented for the construction and commissioning of the reactor facility in accordance with REGDOC-2.3.1, “Conduct of Licensed Activities: Construction and Commissioning Programs” (Reference 9-36). The requirement includes the overall process to be followed to satisfactorily complete the concrete work during the construction phase, including fabrication and placing requirements for reinforcing systems of concrete containments and confinements to comply with the relevant design and construction drawings.

> Statement of Compliance: Requirements in Sections 5.16 and 6.15 of this report contribute to the compliance of REGDOC-1.1.2, Section 4.3.2 for the fabrication and construction of the integrated RB structures, including the SCCV. Information in Sections 5.16 and 6.15 is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-1.1.2, Section 4.3.2 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-1.1.2, Section 4.5.5 describes the requirements for presenting relevant information on the design of the site layout and on civil engineering works and structures associated with the nuclear facility, with sufficient detail for CNSC staff to verify that the design is in accordance with Sections 7.15 and 8.6.2 of REGDOC-2.5.2, “Design of Reactor Facilities: Nuclear Power Plants” (Reference 9-37).

> Statement of Compliance: This report contributes to the compliance of REGDOC-1.1.2, Section 4.5.5, by providing the design approaches for the integrated RB structures, including the SCCV. Information in Sections 5.0 and 6.0 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-1.1.2, Section 4.5.5 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-1.1.2, Section 4.5.6 includes requirements for relevant information on pressure- or fluid-retaining SSCs in accordance with REGDOC-2.5.2, including pressure boundary standards and codes.

> Statement of Compliance: This report contributes to the compliance of REGDOC-1.1.2, Section 4.5.6 for pressure- or fluid-retaining SSCs by providing the material, design, construction and inspection requirements for the SCCV in Section 6.0. Information in Section 6.0 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-1.1.2, Section 4.5.6 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-1.1.2, Section 4.5.9 describes the requirements for presenting information on safety systems as defined in REGDOC-2.5.2, which includes SSCs supporting containment and means of confinement to limit the consequences of anticipated operational occurrences or DBAs.

> Statement of Compliance: The proposed design approach for the SCCV structure, which acts as a leak-tight pressure boundary and provides radiation shielding, presented in Section 6.0 of

this report contributes to the compliance of REGDOC-1.1.2, Section 4.5.9. Information in Section 6.0 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-1.1.2, Section 4.5.9 as described in this report and in conjunction with information presented in the Licence to Construct Application.

2.4.2 CNSC Regulatory Document REGDOC-1.1.5

REGDOC-1.1.5, *Supplementary Information for Small Modular Reactor Proponents*

Regulatory Requirement: REGDOC-2.5.2, Section 3.1 details the use of the graded approach, which an applicant may use to address CNSC requirements in a manner that is commensurate with the novelty, complexity and potential for harm that the activity represents. The graded approach is a method or process by which elements such as the level of analysis, the depth of documentation and the scope of actions necessary to comply with the requriements are commensurate with the following:

- Relative risks to health, safety, security, the environment, and the implementation of international obligations to which Canada has agreed
- Characteristics of a facility or activity

Statement of Compliance: This report contributes to the compliance of REGDOC-1.1.5, Section 3.1 for the acceptability of use of DP-SC modules for the construction of the integrated RB structures. Information in Sections 5.0 and 6.0 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-1.1.5, Section 3.1 as described in this report and in conjunction with information presented in the Licence to Construct Application.

2.4.3 CNSC Regulatory Document REGDOC-2.5.2

REGDOC-2.5.2, “Design of Reactor Facilities: Nuclear Power Plants”

Regulatory Requirement: REGDOC-2.5.2, Section 5.4 requires identification of the codes and standards that are used for the plant design, and an evaluation of those codes and standards for applicability, adequacy, and sufficiency to the design of required SSCs.

Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 5.4 for the identification of codes and standards used for the BWRX-300 integrated RB structural design. Information in Sections 5.0 and 6.0 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 5.4 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 6.1.1 requires that the design provides multiple physical barriers to the uncontrolled release of radioactive materials to the environment, which include the containment.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 6.1.1 for integrity of physical barriers to ensure defense-in-depth is maintained. The integrated RB proposed design requirements presented in Sections 5.0 and 6.0 of this report ensure the safety functions of the structure under design basis and beyond design basis conditions. Information in Sections 5.0 and 6.0 is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 6.6.1 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 6.6 requires development of a facility layout that considers postulated initiating events to enhance protection of required SSCs with the final design reflecting an assessment of options, demonstrating that an optimized configuration has been sought for the facility layout.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 6.6 for the BWRX-300 facility layout. Information on the facility layout is presented in Section 3.0. BWRX-300 overall design approach, design loads and load combinations are presented in Section 4.0. Design requirements for protection against external and internal impactive hazards are addressed in Sections 5.8, 5.13, 6.10, 6.20, and 6.23. Information in this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2 Section 6.6 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Sections 7.4.1 and 7.4.2 require that SSCs important to safety be designed and located in a manner that minimizes the probability and effects of hazards (e.g., fires and explosions) caused by external or internal events, and that all natural and human-induced external hazards that may be linked with significant radiological risk be identified. External hazards which the plant is designed to withstand are to be selected and classified as DBAs or Design Extension Conditions (DECs) as subset of BDBAs.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Sections 7.4.1 and 7.4.2 for internal and external hazards assessed for the BWRX-300 integrated RB. Information in Sections 3.0, 4.0, 5.8, 5.13, 6.10, 6.20, and 6.23 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Sections 7.4.1 and 7.4.2 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 7.7 requires that all pressure-retaining SSC be protected against overpressure conditions, and be classified, designed, fabricated, erected, inspected, and tested in accordance with established standards. Section 7.7 also requires that, for DECs, relief capacity be sufficient to provide reasonable confidence that pressure boundaries credited in severe accident management will not fail.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 7.7 for pressure-retaining SSCs. The loads and load combinations discussed in Section

4.3 and the proposed design requirements for the SCCV presented in Section 6.0 ensure the SCCV can perform its safety functions under design basis and beyond design basis conditions. Information in Sections 4.3 and 6.0 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 7.7 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 7.12.1 requires that provisions for fire safety be included in design of buildings and structures.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 7.12.1 for DP-SC modules fire protection. Information in Sections 5.13 and 6.20 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2 Section 7.12.1 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirements: REGDOC-2.5.2, Section 7.13.1 requires that the seismically qualified SSCs important to safety be qualified to a Design Basis Earthquake (DBE), that the design of these SSCs meets the DBE criteria to maintain all essential attributes, such as pressure boundary integrity, leak tightness and operability in the event of a DBE and that SSCs credited to function during and after a BDBA be capable of performing their intended function under the expected condition.

> Statement of Compliance: The proposed design rules presented in Sections 5.0 and 6.0 of this report ensure that the pressure boundary integrity, leak tightness and structural integrity of the integrated RB, and the safety functions of SSCs, are maintained during and following DBE and BDBAs. Information in this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 7.13.1 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 7.15.1 requires that the environmental effects be considered in the design of civil structures and the selection of construction materials, and that the choice of construction material be commensurate with the design service life and potential life extension of the plant.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 7.15.1 for design of the integrated RB structures. Environmental effects are considered in the design of the structures as demonstrated by the loads discussed in Section 4.3 and the alternative design requirements presented in Sections 5.0 and 6.0. Information in Sections 5.0 and 6.0 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 7.15.1 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 7.15.2 requires that the design enables implementation of periodic inspection programs for structures important to safety in order to verify that the as-constructed structures meet their functional and performance requirements.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 7.15.2 for inservice inspection and testing of the integrated RB structures, including the SCCV. Information in Sections 5.18 and 6.22 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 7.15.2 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 7.15.3 requires that the lifting and handling of large and heavy loads, particularly those containing radioactive material be considered in the design.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 7.15.3 for the design of the integrated RB structures. Information in Sections 5.8 and 6.10 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 7.15.3 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 7.17 requires that the design takes due account of the effects of aging and wear on SSCs, including additional requirements provided in REGDOC-2.6.3, “Aging Management” (Reference 9-38).

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 7.17, including the additional requirements provided in REGDOC-2.6.3 (addressed in Subsection 2.4.4), for aging and wear. Information in Sections 5.18 and 6.22 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 7.17 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 7.22 requires that the design provides physical features such as protection against Design Basis Threats (DBTs), in accordance with the requirements of the Nuclear Security Regulations.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 7.22 for robustness against malevolent acts. Information in Sections 5.0 and 6.0 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 7.22 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.5.2, Section 8.6 requires that each nuclear power reactor be installed within a containment structure, to minimize the release of radioactive materials to the environment during operational states and DBAs. Containment is to also assist in mitigating the consequences of DECs. In particular, the containment and its safety features are to be able to perform their credited functions during DBAs and DECs, including melting of the reactor core. To the extent practicable, these functions shall be available for events more severe than DECs.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.5.2, Section 8.6 for the BWRX-300 containment. As described in Section 3.0, the BWRX-300 containment is completely enclosed within the RB to protect it from external hazards and to minimize the release of radioactive materials to the environment during operational states and DBAs. Design requirements presented in Sections 5.0 and 6.0 of the report ensure the safety functions of the RB and SCCV during DBAs and DECs and meet the requirements of Section 8.6.12 for containment leak-tightness and control of fission products release following the onset of core damage. Information in Sections 5.0 and 6.0 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.5.2, Section 8.6 as described in this report and in conjunction with information presented in the Licence to Construct Application.

2.4.4 CNSC Regulatory Document REGDOC-2.6.3

REGDOC-2.6.3, "Aging Management"

Regulatory Requirement: REGDOC-2.6.3, Section 2 requires that the design considers aging and obsolescence of SSCs, including systematic and integrated approaches to aging management.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.6.3, Section 2 for aging and obsolescence management of SSCs. Information in Sections 5.18 and 6.22 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.6.3, Section 2 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.6.3, Section 3 requires that appropriate measures be taken in design to facilitate proactive and effective aging management throughout the lifetime of the reactor facility.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.6.3, Section 3 for proactive strategy for aging management. Information in Sections 5.18 and 6.22 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.6.3, Section 3 as described in this report and in conjunction with information presented in the Licence to Construct Application.

Regulatory Requirement: REGDOC-2.6.3, Section 4.3 requires that a document screening process be used to establish a list of SSCs to be included in the scope of the overall integrated aging management program framework.

> Statement of Compliance: This report contributes to the compliance of REGDOC-2.6.3, Section 4.3 for screening and selection of SSCs for inclusion in the scope of the overall integrated aging management program. Information in Sections 5.18 and 6.22 of this report is complementary to the information in the Licence to Construct Application.

Therefore, the BWRX-300 design meets the requirements of REGDOC-2.6.3, Section 4.3 as described in this report and in conjunction with information presented in the Licence to Construct Application.

2.5 Canadian Codes and Standards

The following CSA Group (CSA) standards govern the design, construction, inspection and testing of the BWRX-300 nuclear structures categorized in accordance with the Canadian regulatory guidance as Seismic Category A.

2.5.1 CSA N291 Standard

The design and construction of the BWRX-300 non-containment Seismic Category A structures, including the RB structures surrounding the containment and the containment internal structures, meet the safety and performance objectives of CSA N291 (Reference 9-39) standard following the regulatory guidance of REGDOC-2.5.2, Sections 7.15.1 and 8.6.8.

The design of the BWRX-300 non-containment Seismic Category A structures is in accordance with Clause 6.1.2 of CSA N291 that permits the use of alternate design methods not covered by the CSA standards that do not provide guidance for the design of SC structures. By following the provisions of ANSI/AISC N690, Appendix N9, supplemented by the regulatory guidance of U.S. NRC RG 1.243 and the proposed design rules provided in Section 5.0 of this report, the design, construction, testing and inspection of the BWRX-300 non-containment DP-SC structures ensure a level of safety and performance commensurate with the requirements of CSA N291, CSA S16 (Reference 9-40) (for steel) and CSA A23.1/A23.2 (Reference 9-41) and CSA A23.3 (Reference 9-42) (for concrete) design standards. The BWRX-300 design for impactive and impulsive loads discussed in Section 5.8 of the report satisfies the requirements of CSA N291, Clauses 6.1.3, A.2.2 and A.2.3 in addition to the local and global response criteria of Clause A.5.

For BWRX-300 Small Modular Reactors (SMRs) built in Canada, specifically for non-containment Seismic Category A structures, applicable CSA N291 material, fabrication, construction, inspection, examination, testing and quality assurance requirements may be followed as an alternative to the requirements presented in Section 5.0 of the report, as shall be specified in a project specific implementation specification.

Per the guidance of REGDOC-2.6.3, Section 2.2, the approach implemented for the aging management of non-containment Seismic Category A structures in Canada follow the requirements of CSA N291, Clause 10.

2.5.2 CSA N287 Standard Series

Per the guidance of Section 7.15.1 and Appendix A of REGDOC-2.5.2, the design and construction of the BWRX-300 SCCV meet the applicable safety and performance objectives of the CSA N287 series of standards for concrete containment structures for nuclear power plants, including:

- General requirements of CSA N287.1 (Reference 9-43)
- Material requirements of CSA N287.2 (Reference 9-44)
- Design requirements of CSA N287.3 (Reference 9-45)
- Construction, fabrication and installation requirements of CSA N287.4 (Reference 9-46)
- Construction examination and testing requirements of CSA N287.5 (Reference 9-47)

The CSA N287 series of standards does not include provisions for SC containments. Clause 4.3 of CSA N287.3 permits the use of alternate design methods for design of concrete containments in Canada. The SCCV material, design, construction, fabrication, inspection and examination requirements discussed in Section 6.0 of this report ensure a level of safety and performance commensurate with CSA N287 standard series. As noted in Subsection 6.23.1 of this report, the internal pressure capacity of the BWRX-300 containment is at least twice the DBA internal pressure in accordance with CSA N287.3. The BWRX-300 design for impactive and impulsive loads discussed in Section 5.8 of the report satisfies the local and global response criteria of CSA N287.3, Clause B.4.

In accordance with the regulatory guidance of REGDOC-2.5.2, Section 7.15.2, the BWRX-300 containment requirements for:

- Pre-operational pressure and leakage rate testing in Section 6.17 meet the applicable provisions of CSA N287.6 (Reference 9-48)
- Inservice examination and testing in Section 6.22 meet the applicable provisions of CSA N287.7 (Reference 9-49)

The aging management and maintenance programs implemented for the BWRX-300 containment follow the requirements of CSA N287.8 (Reference 9-50).

For BWRX-300 SMRs built in Canada, applicable CSA N287 material, fabrication, construction, inspection, examination, testing and quality assurance requirements may be followed as an alternative to the requirements presented in Section 6.0 of the report, as shall be specified in a project specific implementation specification. Additional Canadian site-specifc requirements related to the containment examination and testing, aging management and maintenance programs, beyond those discussed in Section 6.22, will also be addressed in the project specific implementation specification.

2.5.3 CSA N289 Standard Series

Per Section 7.13 of REGDOC-2.5.2, the seismic qualification of the BWRX-300 structures meets the applicable requirements of the CSA N289 standard series. The specific requirements for seismic analysis of the deeply embedded BWRX-300 integrated RB structures provided in Section 5.0 of NEDO-33914-A meet the safety objectives of CSA N289.3 (Reference 9-51). The seismic design of the BWRX-300 structures meets the safety objectives of CSA N289.3, Clause 7 and the applicable requirements of CSA N291, Clause 6.10 for the seismic design of non-containment Seismic Category A structures and CSA N287.3, Clause 11 for the seismic design of concrete containments. The beyond design basis seismic robustness of the integrated RB is evaluated following the guidance of CSA N289.1, Annex F.

2.5.4 CSA N293

Per Section 7.12.1 of REGDOC-2.5.2, the BWRX-300 DP-SC containment and non-containment Seismic Category A structures are designed to be fire resistant as discussed in Sections 5.13 and 6.20 of the report. The fire resistance rating of the BWRX-300 containment and non-containment Seismic Category A structures is evaluated per the methodology presented in Section 5.13 of the report and will comply with the fire resistance rating requirements of CSA N293 (Reference 9-52).

2.5.5 CSA N286 Standard Series

The requirements of the CSA N286 series for the life cycle activities management of the BWRX-300 DP-SC containment and non-containment structures in Canada are applicable and shall be followed.

Computer programs used in the analyses of the BWRX-300 integrated RB structures are verified in accordance with NEDO-11209-A which complies with CSA N286.7 (Reference 9-53).

2.5.6 CSA N299 Standard Series

The CSA N299 (Reference 9-54) quality assurance program requirements for the supply of items and services of BWRX-300 DP-SC non-containment structures in Canada may be followed as an alternative to the requirements presented in Section 5.0, as shall be specified in a project specific implementation specification.

2.6 Generic Issues

The following generic issues are provided based on their relevance to the scope of this report, and an up-to-date evaluation of generic issues is to be provided during future licensing activities by GEH in support of a 10 CFR 50 CP application or by a license applicant for requesting an operating license under 10 CFR 50.

NUREG/CR-7193, “Evaluations of NRC Seismic Structural Regulations and Regulatory Guidance, and Simulation Evaluation Tools for Applicability to Small Modular Reactors (SMRs),” (Reference 9-55) for the design of deeply embedded SMRs identified specific areas of concerns related to the subgrade characterization, development of proper input parameters for the SSI analysis, and stability of deeply embedded SMRs.

The innovative approaches presented in NEDO-33914-A, Sections, 3, 4, and 5 address these concerns ensuring a proper design of the deeply embedded BWRX-300 integrated RB.

U.S. NRC Information Notice (IN) 86-99 (Reference 9-56) issued on December 8, 1986, Supplement 1: Degradation of Steel Containments in response to the discovery of significant corrosion on the external surface of the carbon steel drywell in the sand bed region of the Oyster Creek plant. Corrosion protection of the SCCV surfaces is discussed in Section 6.19 of this report.

U.S. NRC IN 89-79 (Reference 9-57) issued on December 1, 1989, degraded coatings, and the corrosion of steel containment vessel. Duke Power Company reported significant coating damage and base metal corrosion on the outer surface of the steel shell of the McGuire Unit 2 containment which was discovered during a pre-integrated leak rate test inspection. Subsequently, Duke Power identified similar degradation of the McGuire Unit 1 containment, which is essentially identical to the Unit 2 structure. The NRC regulations (Appendix J to 10 CFR Part 50) require that a general visual inspection of the accessible surfaces in the containment be performed before each integrated leak rate test. The purpose of this inspection is to identify any evidence of structural deterioration or other problems that may affect containment integrity or leak tightness. As a result of these and other inspections, several instances of containment wall thinning due to corrosion have been discovered during the past 3 years at operating power reactors. However, the visual inspections done in connection with the integrated leak rate tests are only required to be performed three times in each 10-year period. In addition, because of the physical arrangement of plant systems, the steel in the annular spaces of some containments may not be easily accessible to the visual inspections associated with leak tests. Considering the frequency and severity of recent instances of containment degradation due to corrosion, additional efforts to inspect steel containment surfaces potentially susceptible to corrosion may be prudent.

The corrosion protection of the integrated RB DP-SC modules is addressed in Sections 5.15 and 6.19 of this report. The inservice inspection of the integrated RB structures is addressed in Sections 5.18 and 6.22.

3.0 DESCRIPTION OF THE BWRX-300 INTEGRATED REACTOR BUILDING

3.1 Background

The BWRX-300 integrated RB consists of the RB structure enclosing the containment, the containment structure comprised of the SCCV, containment closure head and other Class MC components, and the containment internal structures. The integrated RB is the only BWRX-300 Seismic Category I structure.

The BWRX-300 integrated RB is constructed using SC modules to maximize its safety performance during the operational and decommissioning life of the plant and to optimize the construction cost and schedule. The BWRX-300 integrated RB is deeply embedded so that the majority of the RPV, SCCV structure, and other important systems and components required for accidents mitigation and safe shutdown are located below grade to mitigate the effects of possible external events, including aircraft impact and adverse weather.

Current design codes do not address the use of SC systems as a containment pressure boundary. Therefore, design rules for the SCCV are proposed in Section 6.0 that are based on the ASME BPVC, Section III, Rules for Construction of Nuclear Facility Components, Division 2, Code for Concrete Containments, Subsection CC, Concrete Containments, Articles CC-1000 through CC-6000, for materials, design, fabrication, construction, examination and testing for the BWRX-300 SCCV, including Division 2 Appendices to the extent they apply to an SC containment without reinforcing steel or tendons. Design rules for the RB and containment internal structures that are not part of the containment pressure boundary follow existing codes and standards for design of SC structures with proposed modifications provided in Section 5.0 to cover design elements beyond the scope of current codes and standards.

The SC modules used in the construction of the BWRX-300 integrated RB consist predominantly of SC modules with diaphragm plates referred to as DP-SC modules (see Section 3.4 for details). The proposed design approaches for the RB, containment internal structures and SCCV using these SC modules are supplemented by a test program that is being performed under the NRIC Advanced Construction Technology (ACT) project in the United States. This program is known as the NRIC Demonstration Project and is described in Section 7.0.

3.2 BWRX-300 General Description

The BWRX-300 is an approximately 300 MWe, water-cooled, natural circulation SMR utilizing simple safety systems driven by natural phenomena. It is being developed by GEH in the USA and Hitachi-GE Nuclear Energy Ltd. (HGNE) in Japan. It is the tenth generation of the BWR. The BWRX-300 is an evolution of the U.S. NRC-licensed, 1,520 MWe Economic Simplified Boiling Water Reactor (ESBWR). Target applications include base load electricity generation and load following electrical generation.

The BWRX-300 containment design is based upon GEH BWR experience and fleet performance, including the following features:

- Containment size comparable to a small BWR drywell
- Containment peak accident pressure and temperatures within existing BWR experience base

- Containment load simplified when compared to conventional BWRs with pressure suppression containments
- Nitrogen inerted containment same as BWR Mark I and Mark II containments
- Pressure and temperature during normal operation maintained by fan coolers, similar to existing BWRs
- Upon loss of active containment cooling, heat removal achieved by the Passive Containment Cooling System (PCCS)

The BWRX-300 Power Block consists of several structures as shown in Figure 3-1. Each structure houses components that perform the various functions which result in the generation of electricity in the Turbine Building. The integrated RB is the circular structure in Figure 3-1. The integrated RB houses the main function of steam generation and is separated from the rest of the Power Block structures by seismic gaps, limiting the physical interaction between its structure and the adjacent Power Block structures during a seismic event. Figure 3-2 provides a Three-Dimensional (3D) view of the Power Block Structures. The Power Block layout shown in Figures 3-1 and 3-2 is for information only and may be optimized and changed based on the site-specific conditions.

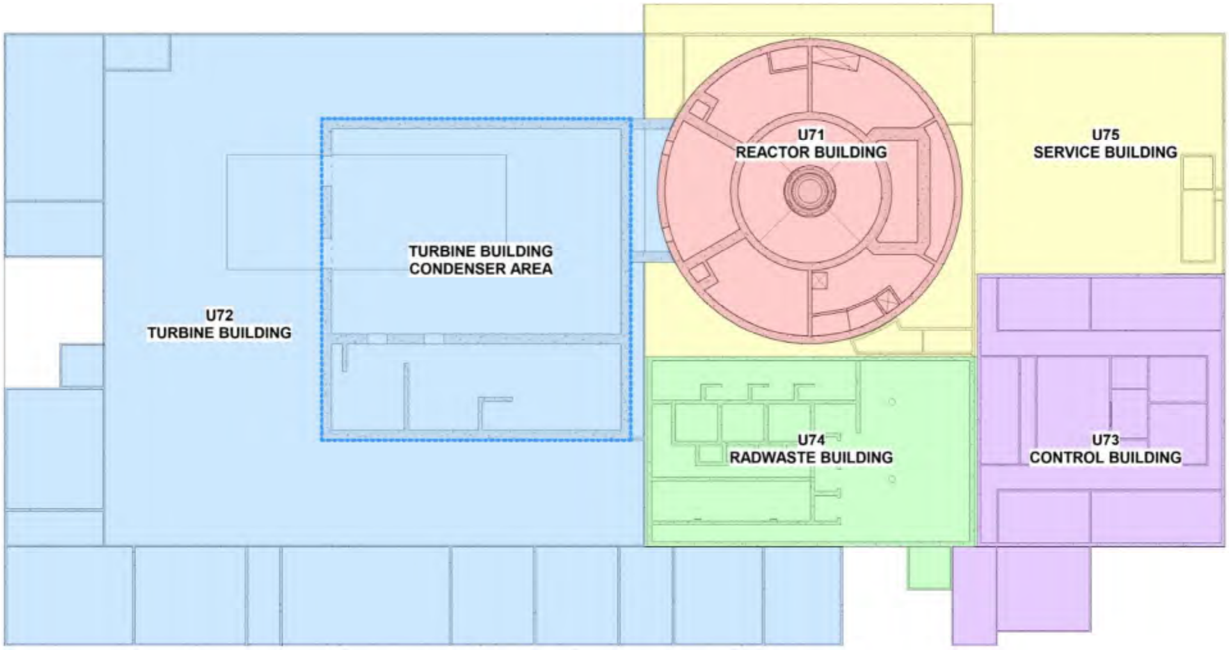

Figure 3-1: BWRX-300 Power Block Plan View

* For information only. Layout may be optimized and changed based on site-specific conditions.

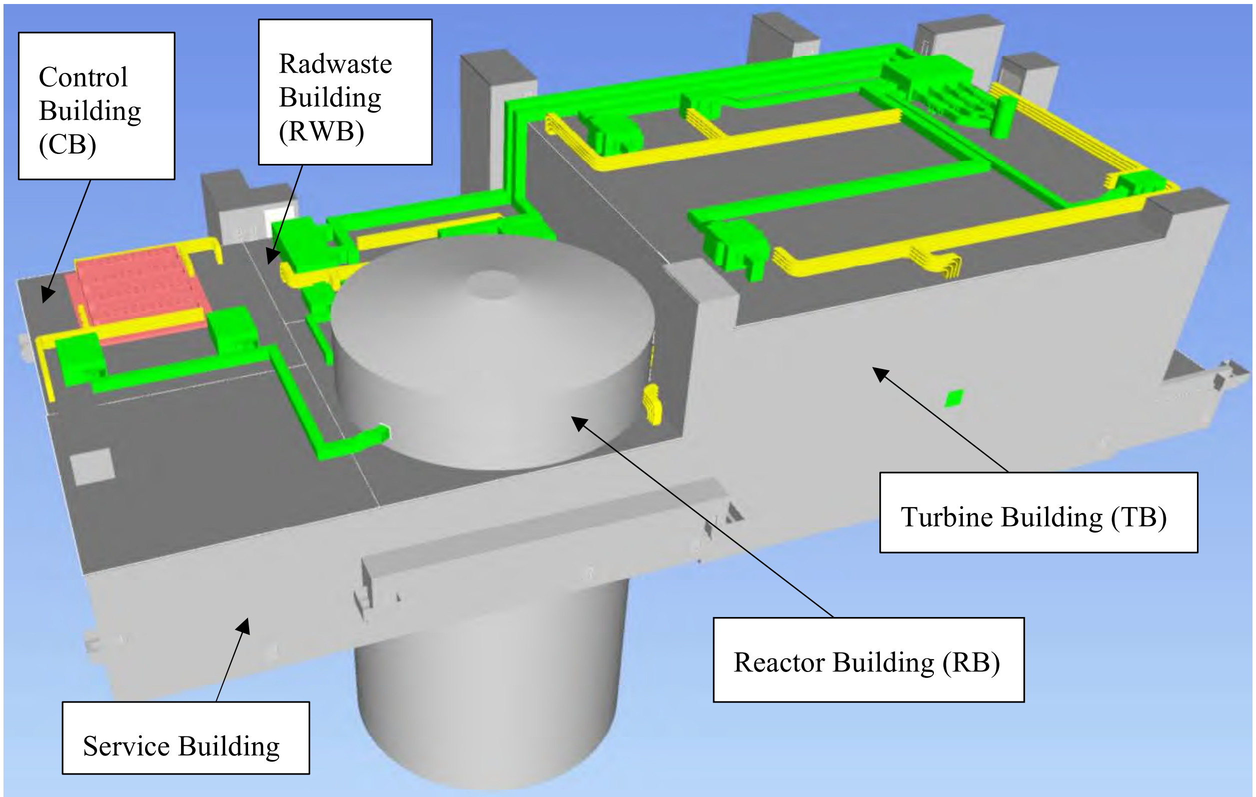

Figure 3-2: BWRX-300 Power Block Three-Dimensional View

* For information only. Layout may be optimized and changed based on site-specific conditions.

3.3 Integrated Reactor Building Structures Overview

The BWRX-300 RB structure is a cylindrical-shaped, shear wall building that is deeply embedded to an approximate depth of 36 meters below grade. Figure 3-3 and Figure 3-4 show the 3D and orthogonal representation, respectively, of a typical integrated RB cross-section and depict the finished grade level. In these figures, the boundary of the RB structure is shown in red and the containment is shown in green.

The walls, floors, roof, and mat foundation of the RB structure are primarily constructed using DP-SC modules. The below-grade portion of the RB houses the containment and containment internal structures as well as the RPV and safety systems, and the majority of vital and non-vital power supplies and equipment. The above grade portion of the RB structure houses the refueling floor, refueling and fuel handling systems, fuel pool, water needed for the BWRX-300 passive cooling systems, and polar crane. The RB protects the containment structure from external hazards (i.e., wind loads, fires, floods, tornado loads, aircraft hazard, missiles) and external beyond design basis scenarios (i.e., aircraft impact, blast impact).

The SCCV portion of the containment consists of a cylindrical wall, mat foundation and top slab constructed using DP-SC modules. The metal containment closure head and other metal components (i.e., personnel/equipment hatches, mechanical and electrical penetrations) not backed by concrete at the containment boundary are ASME Class MC components.

The SCCV houses the containment internal structures which includes the DP-SC pedestal that supports the RPV, the Containment Equipment and Piping Support Structure (CEPSS), main steam pipes and other safety important equipment. The SCCV also houses the bioshield SC wall that together with the RPV pedestal provides shielding around the fuel core. The bioshield is a standalone structure separated from the RPV pedestal by a seismic gap. The bioshield is designed per the requirements of ANSI/AISC N690 as supplemented by U.S. NRC RG 1.243 in addition to Section 5.12 of this report. The bioshield and SCCV walls support the lower elevation containment steel platforms at Levels -21 m and -29 m as shown in Figure 3-4.

The RB, containment and containment internal structures are integrated at the DP-SC mat foundation. The RB and SCCV structures are also integrated at the wing walls and floor slabs, including the pool slab and walls. Floor slabs that integrate the RB exterior wall and SCCV wall are connected with either rigid, semi-rigid, pinned or released connections. Connections are designed per the requirements in Sections 5.11, 6.11, and 6.14 of this report. Failure of these connections has no impact on the pressure-retaining function of the containment. The BWRX-300 integrated RB including walls, floors, and RB roof act in an integrated manner to provide suitable load path for gravity and lateral loads.

[[ ]]

Figure 3-3: Three-Dimensional Depiction of Integrated Reactor Building

*For information only. Integrated RB layout is based on current design. Layout may change as the design progresses.

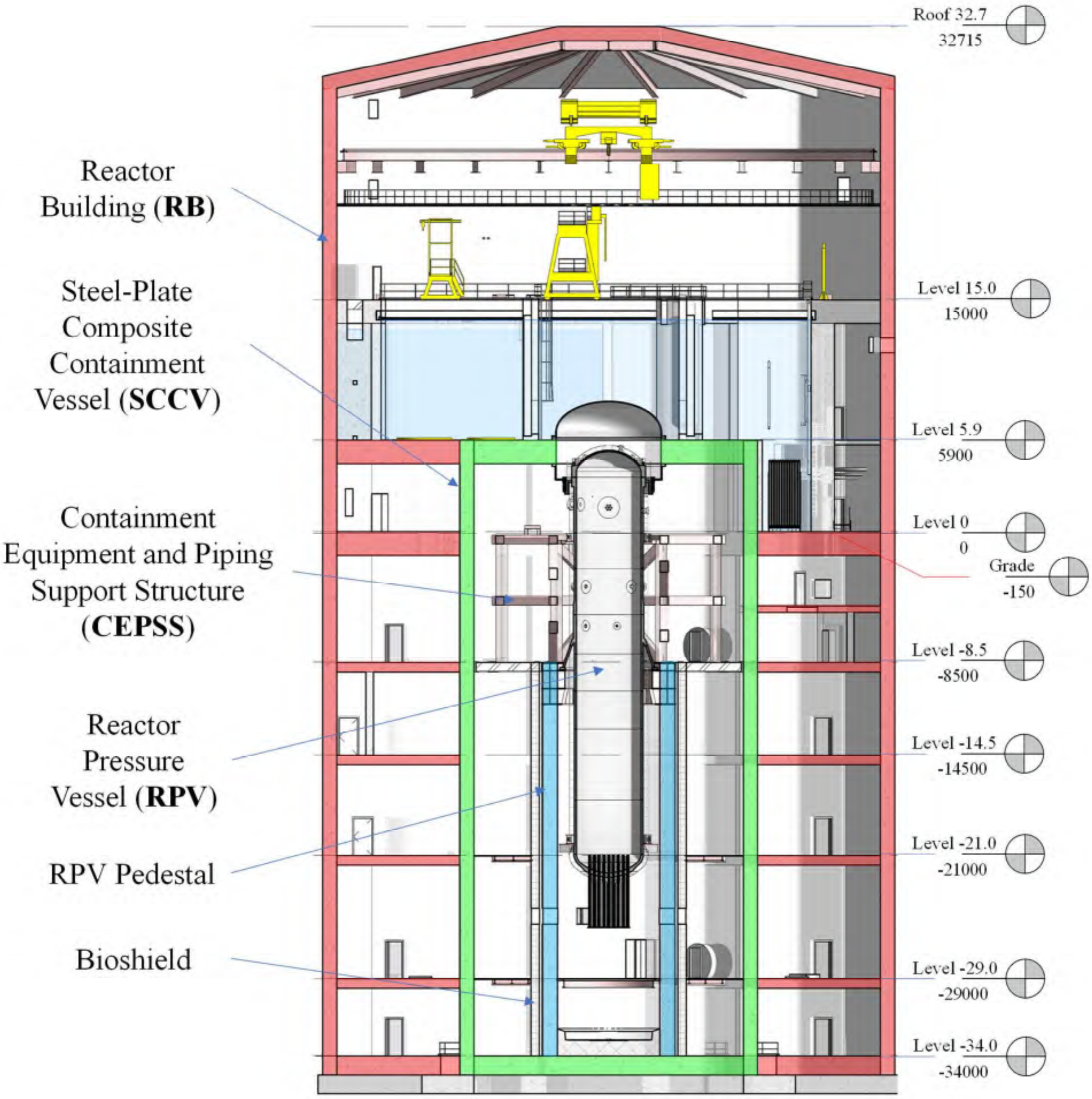

Figure 3-4: Section View of Integrated Reactor Building

*For information only. Integrated RB layout is based on current design. Layout may change as the design progresses. Elevations provided in m/mm.

3.4 Steel-Plate Composite Structures

SC structures are proven structural systems with demonstrated structural performance that enable ease of fabrication and construction and have been widely used in the commercial and nuclear industry.

SC structural modules are constructed by placing concrete between two steel faceplates that serve as the main reinforcement and permanent formwork. Steel ties and steel anchors, such as steel headed stud anchors, are used in the SC modules to develop the composite action between the concrete and the faceplates and to maintain the strain compatibility between the concrete and steel.

SC modules can be categorized into two groups based on the steel ties' configuration as illustrated in Figure 3-5. In the first group (Figure 3-5(a)), discrete tie bars, having round or rectangular cross-section, are used to connect the two faceplates and provide the composite action. This type of SC modules is referred to in this report as "conventional SC modules". Before concrete casting, the stiffness and strength of the empty modules are provided by the ties along with the steel faceplates. After concrete casting, the ties provide structural integrity to the composite section by preventing delamination of the plain concrete core and serving as out-of-plane shear reinforcement. Additional shear stud anchors may be used to anchor the steel faceplates to the concrete infill and control faceplates local buckling. SC walls may have sleeves for penetrations and embedded plates for attachments. Conventional SC modules have first been employed in Japan for construction of containment internal structures of a number of operating pressurized water reactors. In the U.S, the Westinghouse designed and U.S. NRC certified AP1000® pressurized water reactor uses conventional SC structural modules.

In the second group (Figure 3-5(b)), continuous diaphragm plates with holes to allow the flow of concrete are used to attach the two faceplates and provide the composite action between the steel faceplates and the concrete core. This type of SC modules is referred to in this report as Diaphragm Plate Steel-Plate Composite (DP-SC) modules. Before concrete casting, the diaphragm plates and steel faceplates provide stiffness and strength to the empty steel modules. When compared to conventional SC designs, DP-SC modules can have greater stiffness and stability in the empty module configuration due to the continuous support provided by the diaphragm plates to the steel faceplates. After concrete casting, the diaphragm plates provide structural integrity to the composite section by preventing delamination of the plain concrete core. Additionally, the diaphragm plates and headed studs steel anchors provide composite action between the steel faceplates and the concrete infill, and out-of-plane shear reinforcement for the composite section.

As shown in Figure 3-5(b), DP-SC modules can be built by welding a series of components:

(A) Multi-web components: straight or curved faceplates are connected by multi-diaphragm plates

(B) Single web I-shape components: built-up or hot rolled I-beams having web holes, or castellated and cellular beams

(C) Single web U-shape components: steel channels having web holes, or Steel Bricks™ where a steel plate is first profiled and then bent into an L shape, after which the L-shaped elements are welded to each other to make U-shaped bricks

A DP-SC module system, including Steel Bricks™, consists of multiple components (or bricks) arranged and welded together to form a module. Each component consists of an individual steel element. The DP-SC modules are spliced together to form structural walls, floors, or mat foundation sections as shown in Figure 3-6. The DP-SC faceplates can be straight or curved in the multi-web DP-SC modules. For straight modules, the diaphragm plates are welded directly to the planar faceplates per the design configuration. For curved modules, faceplates are rolled first, then the diaphragm plates are welded to the curved faceplates to create a curved multi-web DP-SC subassembly. For multi-web DP-SC components, the DP-SC faceplate can have a different thickness and/or steel grade as compared to the diaphragm plate due to design demands or shielding requirements.

For all DP-SC configurations, the stiffness depends on the faceplates and the concrete infill as discussed in Section 5.5. The steel faceplates and diaphragm plates contribute to the out-of-plane flexural capacity, whereas the diaphragm plates develop the out-of-plane shear capacity. The in-plane shear capacity is developed by the steel faceplates.

The diaphragm plates are either welded to the steel faceplates to develop their capacity as in configuration (A), hot-rolled as in configuration (B), or made of the same plate and bent then welded with Complete-Joint-Penetration (CJP) welds as in configuration (C). In either configuration (A, B, or C), the structural performance of the components is equivalent, as each configuration consists of faceplates and fully developed diaphragm plates.

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Figure 3-5: Different Configurations of Steel-Plate Composite Structural Modules

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Figure 3-6: Diaphragm Plate Steel-Plate Composite Module System

In conventional SC construction, welding of ties (i.e., rectangular, or round bars) is a manual process which can be time consuming. In the DP-SC module construction, the welding process can be automated. DP-SC modules can be used in floor construction where additional holes at the top faceplate can be provided to allow filling and flow of concrete in the plane of the floor. These holes can be sealed later if leak tightness is a design requirement.

4.0 BWRX-300 OVERALL ANALYSIS AND DESIGN APPROACH

The BWRX-300 Seismic Category I integrated RB is designed to meet the serviceability, strength, and stability requirements for all possible load combinations under the categories of normal operation and DBA in compliance with the requirements of 10 CFR 50 Appendix A, GDC 4 and CNSC REGDOC-2.5.2, Sections 7.15.1 and 7.7. The robustness of the design to prevent potential release of radioactivity to the public and environment under BDBAs and DECs is considered in compliance with the regulatory guidance of SRP 19.5 and the requirements of CNSC REGDOC-2.5.2, Sections 7.7, 7.15.1, 7.22, and 8.6.

Design codes jurisdictions are illustrated in Figure 4-1. The analysis, design, construction and maintenance of:

- The Seismic Category I DP-SC structures, excluding the SCCV pressure boundary, are governed by the provisions of ANSI/AISC N690, endorsed and modified per U.S. NRC RG 1.243, and the modified design rules discussed in Section 5.0 of this report.
- The SCCV containment boundary is governed by the provisions in Section 6.0.
- The RPV pedestal and internal steel structures are designed according to ANSI/AISC N690 including the modified design rules for the BWRX-300 non-containment DP-SC structures provided in Section 5.0.
- The containment metal closure head and Class MC components are governed by the provisions of ASME BPVC, 2021 Edition, Section III, Division 1, Subsection NE for Class MC and are beyond the scope of this report.

The connections of the RB walls and floors to the outer face of the SCCV wall are designed per Section 5.0 of this report, with the exception of attachment welds. Attachment welds to the SCCV outer face are designed per Section 6.11, and follow the quality assurance, welding procedures, and inspection requirements of Sections 6.13, 6.15 and 6.16.

This section presents the overall approach for the structural analysis and design of BWRX-300 Seismic Category I structures that include the BWRX-300 containment, containment internal structures, and the RB structure surrounding the containment. Demands from global design loads are obtained from analyses of a linear elastic FE model of the RB integrated structures presented in Section 4.2.

Different types of analyses performed on the FE model of the integrated RB structures to calculate design demands from different loads and load combinations.

Design demands from localized loads are obtained from separate analysis of refined models of the affected portions of the RB integrated structures.

4.1 One-Step Analysis Approach

Since the integrated RB is deeply embedded, the interaction of the structure with the surrounding subgrade is important for its structural integrity and its response under static and dynamic loads. The interaction with the surrounding subgrade determines the boundary conditions at the interfaces of the RB below-grade exterior wall and mat foundation thus affecting the response and stress distribution of the deeply embedded structure subjected to global design loads.

In accordance with the guidance of NEDO-33914-A, Section 5.1, the one-step approach, as defined in Section 3.1.2 of American Society of Civil Engineers (ASCE)/Structural Engineering Institute (SEI) 4-16 (Reference 9-58) is implemented for the design of the BWRX-300 integrated RB to adequately account for the effects of interaction of the deeply embedded structure with the surrounding subgrade.

A set of different linear elastic analysis cases are performed on FE models of the integrated RB, described in Section 4.2, that have the same node and FE type configurations and differ only in the assigned structural properties depending on the type of analysis and the considered load conditions. The use of linear elastic models with identical FE configuration enables the demands obtained from different analysis cases to be combined on an element-by-element basis for the applicable design load combinations per governing design codes.

Seismic demands for the design of the BWRX-300 Seismic Category I structure are obtained from seismic SSI analyses that consider the interaction of the integrated RB with the surrounding subgrade and adjacent Power Block structures. Quasi-dynamic SSI analyses provide design demands for the combination of gravity loads with static soil and rock pressure loads, including overburden pressures from the surrounding Power Block foundations, by applying a very low-frequency ground motion excitation on the SSI model to simulate (1-g) gravity load. Following the guidelines of NEDO-33914-A, Section 5.0, the seismic and static 1-g SSI analyses are performed using the System for Analysis of Soil-Structure Interaction (SASSI) method.

The interaction with the surrounding subgrade determines the boundary conditions at the interfaces of the integrated RB and the subgrade which affects, in turns, the structural response and stress distribution from other mechanical and temperature design loads. To account for the stiffness of the subgrade surrounding the RB, stiffness impedance sub-structuring methodology is used for:

- Static analyses of internal static and quasi-static design loads that affect the global response of the deeply embedded integrated RB
- Thermal stress analyses of normal operating and DBA temperature loads

In the SSI and subgrade stiffness impedance sub-structuring analyses, the subgrade is represented by layered half-space continuum. To account for the soil nonlinear behavior and the variation of subgrade conditions, the seismic SSI analyses are performed for a set of profiles of dynamic subgrade properties compatible with the strains generated by design earthquake ground motions developed following the guideline of NEDO-33914-A, Section 5.2.4. The static 1-g SSI and subgrade stiffness impedance analyses use equivalent linear subgrade static properties developed following the guidelines of NEDO-33914-A, Section 5.2.1.

Contact spring elements model the conditions at the interfaces of the RB below-grade exterior wall and mat foundation with the surrounding subgrade. Stiffness properties are assigned to these contact springs that provide conservative demands for the design of the integrated RB structures.

4.2 Integrated Reactor Building Finite Element Model

A 3D FE model of the integrated RB is developed for the one-step approach analyses following the modeling guidelines of NEDO-33914-A, Section 5.1.1. The model adequately represents the configuration of all main load carrying structural members of the integrated RB structures and meets the mesh refinement and quality attributes required for accurate calculation of structural stress demands.

Openings and penetrations smaller than half the DP-SC wall or slab thickness are not included in the integrated RB FE model in accordance with ANSI/AISC N690, Appendix N9. Openings and penetrations larger than the associated DP-SC wall or slab thickness are modeled explicitly, and other openings and penetrations are evaluated for modeling depending on the applicable loads and potential impact on the structural design at the opening/penetration location. Finer meshes are used around penetrations and openings in accordance with ANSI/AISC N690 and ASME BPVC, Section III to enable accurate computations of the stress demands for design of the opening/penetration locations.

Where semi-rigid connections are used, they are represented by six linear springs, with three translational and rotational stiffnesses each, at each pair of near coincident nodes of the connecting DP-SC members. Section 5.6 describes the method used to calculate the stiffness properties assigned to the springs representing the semi-rigid connections between the DP-SC members, if applicable. The stiffness properties of springs representing the semi-rigid connections between the SCCV wall, and the RB wing walls and slabs are calculated as discussed in Subsection 6.3.

The SCCV and RB walls, slabs and mat foundation are modeled using thick shell elements with an equivalent thickness, elastic modulus, Poisson’s ratio and material density calibrated to match the stiffness and mass properties of DP-SC modules. Effective stiffness properties are assigned to the DP-SC elements for the analyses of load combinations that exclude accidental thermal loads. For load conditions that include the high accidental temperatures, reduced stiffness is considered to account for the effects of concrete cracking on the redistribution of forces and moments.

Effective and reduced stiffnesses of non-containment DP-SC members are calculated as described in Section 5.5. Section 6.3 discusses the methodology for calculation of effective and reduced stiffness properties of the SCCV shell elements.

Damping values assigned to the RB and SCCV DP-SC structures and components in the integrated RB FE model are discussed in Sections 5.5 and 6.4, respectively.

4.3 Design Loads and Load Combinations

Loads and load combinations used in the design of the BWRX-300 integrated RB are in accordance with:

- ASME BPVC, 2021 Edition, Section III, Division 2, Subsection CC, Subsubarticle CC-3230, supplemented by U.S. NRC RG 1.136 for the SCCV
- ANSI/AISC N690, Section NB2.5 Load and Resistance Factor Design (LRFD) provisions for the RB steel and DP-SC structures supplemented with load combinations specified in U.S. NRC RG 1.243 that prescribes more conservative load factors

The following are the main design loads considered in the design of the BWRX-300 containment and other Seismic Category I structures:

- Dead Load (D)

  Dead load (D) includes the self-weight of the structural members and the weight of permanently attached equipment, tanks, machinery, cranes, and elevators, including fluid contained within the piping and equipment under normal operating conditions. It also includes the weight of distributed systems, including piping, conduits and cable trays. Demands due to dead loads are obtained from the results of 1-g SSI analyses.

- Hydrostatic Loads (F)

  The hydrostatic loads (F) include the vertical and lateral hydrostatic pressures of liquids contained in the RB pools acting on the surfaces of pool walls and slabs. Vertical hydrostatic loads on pool slabs are considered in the 1-g SSI analysis as gravity inertia loads by adding the liquid weight to the shell elements of the pool floors. Design demands from lateral hydrostatic pressures are obtained from separate static analyses by applying pressure loads with amplitude linearly increasing with the liquid depth on the pool wall shell elements.

- Live Load (L)

  Live loads (L) include floor area loads, laydown loads, equipment handling loads, rated capacity of cranes, and similar items. Demands due to live loads are calculated from results of separate subgrade impedance analyses.

- Static Earth and Groundwater Pressure Loads (H)

  Earth pressure loads (H) include loads due to the weight of soil (including groundwater in soil) on the RB outer cylinder wall and lateral soil pressures due to surcharge loads applied on the ground surface in the proximity of the RB. Design demands from static earth pressure loads associated with dry weight of the soil, including the overburden loads from the surrounding structures are obtained from results of SSI 1-g analyses.

  The design considers the groundwater loads as a static pressure loading on the RB mat foundation and below-grade exterior wall. Additional earth pressure loads (H) may be applied on the below-grade exterior wall of RB structural model to account for pressures from potentially unstable blocks of rock mass or in-situ rock pressures and pressures distributions that cannot be modeled by the 1-g SSI analysis. Design demands from groundwater loads and additional rock pressure loads are obtained from separate static analyses with prescribed boundary conditions.

- Normal Operating and Testing and Accident Pressure Loads (P_o, P_t and P_a)

  The normal operating pressure load (P_o) includes the internal containment pressures during normal operating conditions. External pressure loads resulting from pressure variation either inside or outside the containment (P_v), as defined in ASME BPVC Section III, Division 2, Subsection CC, Subparagraph CC-3221.1, are considered under the P_o load case. The test pressure load (P_t) includes the internal pressure load applied to the containment during Structural Integrity Test (SIT) or Integrated Leak Rate Test (ILRT).

  DBA internal pressure load (P_a) resulting from a LOCA is considered. Quasi-static pressures resulting from this event is applied on the containment structure. Although the DBA pressures (P_a) resulting from LOCA are dynamic in nature, the internal accident pressure loads are represented by quasi-static pressure loads. The quasi-static pressure loads include dynamic load factor amplifications to account for dynamic response effects.

  Demands from normal operating and testing and accident pressure loads are obtained from the results of subgrade impedance analyses of RB integrated FE model.

- Crane Load (C)

Crane loads (C) include the maximum wheel loads of the crane and the vertical, lateral and longitudinal forces induced by the moving crane. Static and quasi-static subgrade impedance analyses provide design demands from crane loads. The most critical position of the crane and the lifted load is considered for the design. The critical crane position is determined based on the results of sensitivity static analyses performed on a fixed base RB FE model.

- Normal Operating and Accident Reaction Loads (R_o and R_a)

  The design of the containment and RB structures considers nozzle, equipment and piping reaction loads due to the plant operation under normal operating and DBA conditions. These local loads are applied as point loads at nozzle, equipment support and pipe support locations to calculate demands for the design of the containment and RB structures.

- Severe Wind and Tornado Wind Loads (W and W_t)

  The severe wind load (W) and extreme tornado wind load (W_t) are considered by the design as static pressure loads applied on the exterior of the RB structure. Design demands due to wind and tornado wind pressure loads are obtained from static subgrade impedance analyses.

- Severe and Extreme Precipitation Event Loads (S, R, and S_x)

  Severe snow and rain loads (S and R) and extreme precipitation event design loads (S_x) are considered in the design and are applied, as applicable, as a pressure to the RB roof shell elements. Since the snow and rain have only local effect on the RB structural response, design load demands from these loads can be obtained from the results of fixed base static analyses.

- SSE or DBE Seismic Loads (E_s)

  The design of RB integrated structure considers the following seismic load (E_s) demands:

  - Seismic inertia load demands that are obtained directly from results of one-step seismic SSI analyses
  - Seismic lateral pressure load demands that include structure-soil-structure interaction effects with surrounding Power Block structures and foundations, that are also obtained directly from results of one-step seismic SSI analyses
  - Additional torsion load demands obtained from a separate quasi-static analysis
  - Hydrodynamic pressure load demands including impulsive hydrodynamic pressures associated with the rigid mass inertia response of the liquid, and convective or sloshing pressures associated with the low-frequency response at the pool water surface

  The one-step seismic SSI analyses provide earthquake load (E_s) demands from:

  - Hydrodynamic loads on the RB pool floors
  - Impulsive hydrodynamic pressures on the pool walls due to the horizontal components of the design ground motion

  Additional static analysis cases are performed to calculate demands from hydrodynamic pressure loads that are not captured by the one-step approach seismic SSI analyses of the

RB, including sloshing pressure loads and breathing mode hydrodynamic pressures due to the vertical earthquake component.

Additional quasi-static analysis cases may also be performed, where additional dynamic earth pressure loads are applied on the below-grade exterior walls of the integrated RB structural model as quasi-static pressures to account for loads from potentially unstable rock blocks.

- OBE Seismic Load (E_o)

  These loads are generated by the OBE. The OBE ground motion is only associated with plant shutdown and inspection. OBE loads and load combinations are considered only when the OBE is set larger than 1/3 of the site-specific SSE as stated in Subsection 2.1.1.16.

- Normal Operating and DBA Thermal Loads (T_o and T_a)

  Thermal stress analyses performed on subgrade impedance sub-structuring models provide structural design demands from:

  - Normal operating thermal loads (T_o) that consist of steady-state linear temperature profiles through the containment and RB slabs and walls
  - DBA thermal loads (T_a) resulting from accident conditions from LOCAs and heat-up of fuel pool

  The LOCA accident thermal loads (T_a) are accompanied by the corresponding accident pressure loads (P_a). The heat-up of the fuel pool is also considered as a separate DBA event from LOCA DBA events.

  Normal and accident temperature loads (T_o and T_a) consider ambient (outdoor) temperatures for both Winter and Summer conditions. Operating temperatures for interior rooms consider environmental requirements of operating equipment.

- Local Load Effects on Containment

  The design considers local load effects on the containment due to high-energy line breaks during a DBA, including jet impingement load generated by the postulated accident (R_{rj}/Y_j), missile impact load, such as pipe whip generated by or during the postulated accident (R_{rm}/Y_m), loads on the structure generated by the reaction of the broken high-energy pipe during the postulated accident (R_{rr}/Y_r), and blast loads (R_b) that may be postulated due to instantaneous break of a large pipe. These local loads are applied on the integrated RB model to calculate demands for the design of the containment and RB structures. Local refined models with appropriate boundary conditions based on the response of the global model are used, as needed.

- Internal Flooding Loads (H_a)

  The design of integrated RB structures considers the loads associated with the post-accident internal flooding of the containment following a DBA. The hydrostatic loads from the maximum possible water level are applied as pressures to the affected walls and mat foundation and applicable loads are also used for design of containment metal components.

- Loads Resulting from Relief Valve or Other High Energy Device Actuation (G)

The BWRX-300 does not have Safety Relief Valves (SRVs), therefore, SRV loads are not applicable to the BWRX-300 design.

- Loads Resulting from the Application of Prestress

  The BWRX-300 integrated RB structures do not include prestressed structural components. As a result, prestress loads are not applicable to the BWRX-300 design.

4.4 Overall Design Approach

Acceptance criteria for the design of the RB DP-SC structures, including welded and bolted connections, are in accordance with ANSI/AISC N690, Appendix N9, as endorsed by the regulatory guidance of US NRC RG1.243, and the modified design rules in Section 5.0. Acceptance criteria for the design of the SCCV are discussed in Section 6.6.

Design procedures and acceptance criteria for the containment internal structures are the same as those for the RB structure. Design procedures and acceptance criteria for the containment mat foundation are the same as those for the SCCV. The mat foundation portion outside of the containment boundary is designed to ANSI/AISC N690, supplemented by U.S. NRC RG 1.243.

Since design requirements in ANSI/AISC N690, Appendix N9 are limited to traditional SC walls, modified and compensatory detailing and design requirements were developed for the integrated RB DP-SC structures. Section 5.0 presents these proposed modified and compensatory measures and addresses the applicability of ANSI/AISC N690 to the design of the DP-SC floors and curved walls. These modified rules allow the use of the most current methods and technology while meeting the safety goals established by the NRC for ensuring the protection of public health and safety and the environment.

The proposed design approach and rules for the BWRX-300 SCCV are presented in Section 6.0. ASME BPVC, Section III, Division 2, Subsection CC establishes rules for material, design, fabrication, construction, examination, and testing for prestressed and reinforced concrete containments. ASME Subsection CC is not directly applicable to SC containments due to some fundamental differences between SC containments and prestressed and reinforced concrete containments. One of the fundamental differences being that SC containments do not require a separate liner plate on their inside surfaces to serve as leak barrier. In the case of SC containments, the inner steel faceplate of the containment serves as the leak barrier, with the composite SC section (i.e., outer and inner faceplates, diaphragm plate, and concrete infill working together) serving as the pressure-retaining boundary for the containment. The outer containment faceplate is not considered as part of the leak-tight barrier. Consequently, concrete cracking inside the SC containment, bounded by steel plates on the inside and outside surfaces, is less significant for the containment design or performance.

To address the particularities of DP-SC elements, ASME BPVC, 2021 Edition, Section III, Division 2 Articles CC-1000 through CC-6000 and the Division 2 Appendices were reviewed for changes or additions that need to be made to allow and provide appropriate requirements for the use of a DP-SC containment vessel. All Division 2 Appendices are followed to the extent they apply to a DP-SC containment without reinforcing steel or tendons.

The BWRX-300 containment is still considered a ASME BPVC, Section III, Division 2 containment. The applicable sections of the remaining ASME BPVC consistent with the Section III division 2 edition, such as Section II; Section III, Subsection NCA; Section V; and Section IX are followed to the extent they apply to a DP-SC containment without reinforcing steel or tendons. ASME BPVC, Section XI incorporated by reference in 10 CFR 50.55a(g)(4) 18 months before the date of issuance of the operating license for the initial 120-month ISI interval as described in 10 CFR 50.55a(g)(4)(i) is followed for the containment pre-service and periodic ISI and testing program.

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Figure 4-1: BWRX-300 Integrated Reactor Building Design Codes Jurisdictions

* Integrated RB layout is based on current design. Layout may change as the design progresses.

5.0 MODIFIED DESIGN RULES FOR NON-CONTAINMENT STEEL-PLATE COMPOSITE STRUCTURES

This section presents the modified design rules for the BWRX-300 non-containment DP-SC structures adapted from ANSI/AISC N690 and adjusted to address the particularities of DP-SC construction. They include the modified ANSI/AISC N690, Appendix N9 design equations used to compute the DP-SC sectional capacities that account for the contribution of diaphragm plates.

This section also addresses the effects of curvature on SC (including DP-SC) walls, and the applicability of the ANSI/AISC N690 modified rules to SC (including DP-SC) horizontal modules. Only those provisions that differ from ANSI/AISC N690 are discussed in this section.

The modified design rules presented in this section are supported by the NRIC prototype testing data discussed in Section 7.0, and current literature and design methods.

5.1 Design Parameters

As shown in Figure 5-1, the fundamental aspects of DP-SC modules are:

(i) spacing between diaphragm plates W_{sc}, in (mm)
(ii) depth t_{sc}, in (mm)
(iii) concrete infill depth t_c, in (mm)
(iv) DP-SC faceplate and diaphragm plate thickness t_p, in (mm) (1)
(v) steel faceplate and diaphragm plate yielding strength F_y, ksi (MPa) (1)
(vi) diaphragm hole diameter D, in (mm)
(vii) diaphragm hole spacing S, in (mm)
(viii) studs anchor tensile strength F_{uta}, ksi (MPa)
(ix) stud anchor diameter d_{st}, in (mm)
(x) stud length l_{st}, in (mm)
(xi) studs anchor transversal spacing (perpendicular to diaphragm plate direction) s_t, in (mm)
(xii) studs anchor longitudinal spacing (parallel to diaphragm plate direction), s_l, in (mm)
(xiii) concrete compressive strength f_c', ksi (MPa)

Note:

(1) DP-SC faceplate and diaphragm plates can have different thicknesses and use different steel grades in the range allowed by the applicable design code/standard. Design equations presented in this report use the same t_p and F_y for DP-SC faceplate and diaphragm plates. These equations can be modified as required to reflect the design parameters for each DP-SC component.

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Figure 5-1: Dimensions of Diaphragm Plate Steel-Plate Composite modules

The minimum and maximum depths, t_{sc}, of DP-SC modules are in accordance with ANSI/AISC N690, Appendix N9, Section N9.1.1a provisions. The minimum steel plate thickness, t_p, is 0.25 in (6.4 mm). Maximum allowable plate thickness is 1.5 in (38.1 mm) per ANSI/AISC N690, Section N91.1.1(b). In accordance with Section N9.1.1a of ANSI/AISC N690, any DP-SC section thickness greater than 60 in (1500 mm) is to be justified by experimental or numerical results to demonstrate the applicability and conservatism of Appendix N9 provisions to sections with greater section thicknesses.

The minimum reinforcement ratio is 0.015 per ANSI/AISC N690, Appendix N9, Section N9.1.1.(c). The maximum reinforcement ratio for the DP-SC walls is taken as 0.10 following the requirements of draft ANSI/AISC N690-XX (Reference 9-59), Section N9.1.1.(c) and ANSI/AISC 360-22 (Reference 9-60), Section I1.6.

The hole diameter of DP-SC panels is limited to a maximum of 0.6 times the panel thickness, t_{sc}. The spacing between the diaphragm plate holes centerlines is limited to a minimum of 0.9 times t_{sc}.

5.2 Materials

5.2.1 Concrete Infill

Self-consolidating concrete is used for the integrated RB DP-SC modules.

Per draft ANSI/AISC N690-XX (Reference 9-59), Section N9.1.1(e), the self-consolidating concrete compressive strength, f_c', is a function of reinforcement ratio, ρ, and specified minimum yield stress of faceplates, F_y. as follows:

$$max\begin{pmatrix} 4ksi \\ [0.04 + 0.80\rho]F_y \end{pmatrix} \leq f_c' \leq 10ksi$$

[5-1]

$$max\begin{pmatrix} 28MPa \\ [0.04 + 0.80\rho]F_y \end{pmatrix} \leq f_c' \leq 70MPa$$

Where,

ρ = reinforcement ratio $= \frac{2t_p}{t_{sc}}$

Aggregates used in high-density concrete for radiation shielding purposes conform to American Society for Testing and Materials (ASTM) C637 (Reference 9-61), per ACI 349.

The concrete temperature limitations for normal operational and accidental conditions meet those specified in ACI 349, Appendix E, Section E.4. Reduction in concrete mechanical properties at elevated temperature is per ANSI/AISC N690, Appendix N4.

5.2.2 Steel Plates

The yield strength, F_y, of the steel plates of DP-SC modules ranges from 50 ksi (350 MPa) to 65 ksi (450 MPa) per the requirements of ANSI/AISC N690, Section N9.1.1.

The effect of elevated temperatures on the mechanical properties of steel materials of DP-SC modules is determined in accordance with ANSI/AISC N690, Section NB3.3.

5.3 Composite Action

The faceplates of DP-SC modules are anchored using shear connectors. Draft ANSI/AISC N690-XX (Reference 9-59), Appendix N9.1.4 defines shear connectors as ties and steel headed stud anchors that may serve as shear connectors to achieve composite action (i.e., diaphragm plates and steel headed stud anchors for the BWRX-300). The diaphragm plates of DP-SC modules act as ties preventing splitting of sections and serving as out-of-plane shear reinforcement. Requirements for composite action in this section are per draft ANSI/AISC N690-XX (Reference 9-59), Appendix N9, Section N9.1.4.

The BWRX-300 construction uses yielding steel headed stud anchors in all composite construction. As per ANSI/AISC N690, Appendix N9, Section N9.1.4a user note, the requirements for steel headed stud anchors are provided in ANSI/AISC 360-16 (Reference 9-62), Sections I8.1 and I8.3, including any modifications of ANSI/AISC N690, Chapter NI. Both diaphragm plates and steel headed stud anchors serve as shear connectors that achieve the composite action as shown in Section 5.3.1 below. The diaphragm plates and steel headed stud anchors are designed and detailed to meet the requirements of draft ANSI/AISC N690-XX (Reference 9-59), Appendix N9, Section N9.1.4b for the directions perpendicular and parallel to the diaphragm plates span. Furthermore, the steel headed stud anchors of DP-SC panels are designed to meet ANSI/AISC N690, Appendix N9, Section N9.1.3 for faceplate slenderness requirements.

In localized areas, where the faceplate slenderness requirements and the composite action requirements of ANSI/AISC N690, Appendix N9, Section N9.1.3 and draft ANSI/AISC N690-XX (Reference 9-59), Appendix N9, Section N9.1.4b respectively are met by the idealized diaphragm plates alone, steel headed stud anchors may not be used in order to facilitate the construction of DP-SC modules.

5.3.1 Shear Connectors Capacity

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Figure 5-2: Faceplate and tensile rib yielding strength development.

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Figure 5-3: Tributary area equivalent to Q_{cv}^{sum}

5.4 Diaphragm Requirements

The spacing of the modules diaphragm plates is limited to 1.0 times the panel thickness, t_{sc}, similar to maximum tie spacing in ANSI/AISC N690 and ACI 349 for reinforced concrete. Diaphragm plates shall meet draft ANSI/AISC N690-XX (Reference 9-59), Appendix. N9, Section N9.5.1, tie requirements.

5.5 Determination of Effective Stiffness of Steel-Plate Composite Elements

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5.5.1 Heat Transfer Analysis

Heat transfer analyses can be conducted using the geometric and material properties calculated in Section 5.5 to estimate the temperature histories and through-section temperature profiles produced by the thermal accident conditions in accordance with ANSI/AISC N690, Appendix N9, Section N9.2.4, as endorsed by regulatory guidance of U.S. NRC RG 1.243.

Alternatively, using an approach similar to that of ANSI/AISC 360-22, Appendix 4, Section 4.2.4c, an explicit model, representing the different components of steel plates, discretized studs, concrete infill, and contact between different components, simulating both thermal and mechanical responses of temperature-dependent properties of the steel plates and concrete infill can be used to estimate the temperature time histories and through-section temperature profiles produced by the thermal accident conditions for the different thermal gradient scenarios to calculate maximum corresponding structural demands (e.g. axial and/or flexure), both globally and locally. Material properties assigned to this model are developed per the provisions of ANSI/AISC 360-22, Appendix 4, Section 4.2.3, as modified per N690-18, Appendix N4. Following this approach, the BWRX-300 heat transfer analysis is conducted using explicit models for estimating the through thickness temperature time histories accounting for time lag effects between the different materials.

5.5.2 Damping Values

Damping values specified for SC walls in Tables 1 and 2 of U.S. NRC RG 1.61 are used to account for the dissipation of energy in the non-containment DP-SC elements. These values are consistent with the stiffness properties assigned to the non-containment DP-SC elements developed as described in Section 5.5.

5.6 Effective Stiffness of Semi-Rigid Connections

To model the behavior of the semi-rigid connections, an approach is adopted using a component-based model explained in Article 6.3 of Eurocode 3, Part 8 (Reference 9-63). The component-based model uses the behavior of the individual components within a connection (e.g., bolts, welds, endplate, column flange) to build a realistic representation of a connection’s load-deformation characteristic and thus the equivalent connection translational and rotational stiffnesses can be computed.

5.7 Section Capacities of Steel-Plate Composite Elements

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Figure 5-4: Unit Width Design Strip Spanning Along the Direction of Diaphragm Plates

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Figure 5-5: Unit Width Design Strip Spanning Perpendicular to the Direction of Diaphragm Plates

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Figure 5-6: Sectional Capacity of Different Directions

5.7.1 Uniaxial Tensile Strength

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5.7.2 Compressive Strength

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5.7.3 Out-of-Plane Flexural Strength

5.7.3.1 Perpendicular to Diaphragm Span

For DP-SC sections in the direction perpendicular to the diaphragm plate span (see Figure 5-5), the design flexural strength, $\phi_b M_n$, per unit width is determined for the limit state of yielding using Equation [5-22] for the available flexural strength, a similar equation to ANSI/AISC N690, Equation A-N9-19:

$$\phi_b M_n = \phi_b F_y (A_s^F)(0.9 t_{sc}) \qquad [5\text{-}22]$$

Where,

A_s^F = gross cross-sectional area of faceplate in tension due to flexure per unit width, in^2/ft (mm^2/m)

F_y = specified minimum yield stress of faceplate, ksi (MPa)

t_{sc}= panel thickness, in (mm)

ϕ_b= resistance factor for flexure = 0.90

The results of the NRIC OOPV-1 specimen test, as summarized in Section 7.0, confirm that Equation [5-22] conservatively estimates the out-of-plane flexural capacity.

5.7.3.2 Parallel to Diaphragm Span

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Figure 5-7: Stress and Force Distribution Across Diaphragm Plate Steel-Plate Composite Panel Section to Compute Out-of-Plane Flexural Capacity (Adopted from Reference 9-64)

5.7.4 In-Plane Shear Strength

The in-plane shear strength of DP-SC sections is calculated per ANSI/AISC N690, Section N9.3.4, based on the limit state of yielding of the faceplates.

5.7.5 Out-of-Plane Shear Strength

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5.7.5.1 Perpendicular to Diaphragm Span

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5.7.5.2 Parallel to Diaphragm Span

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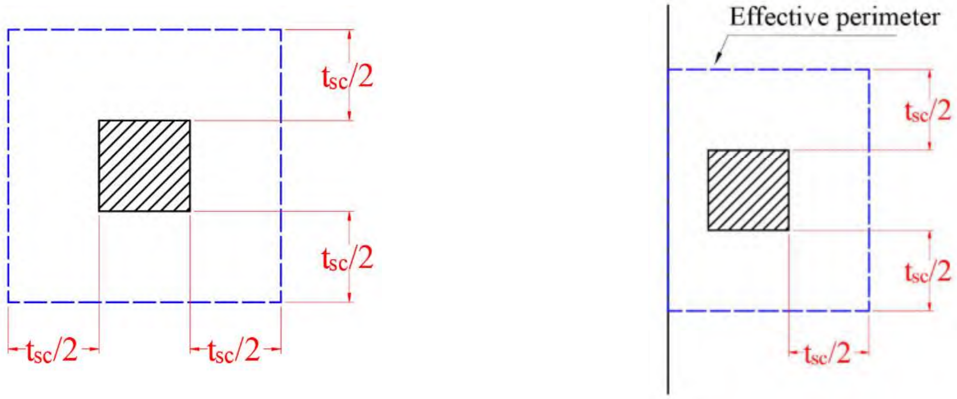
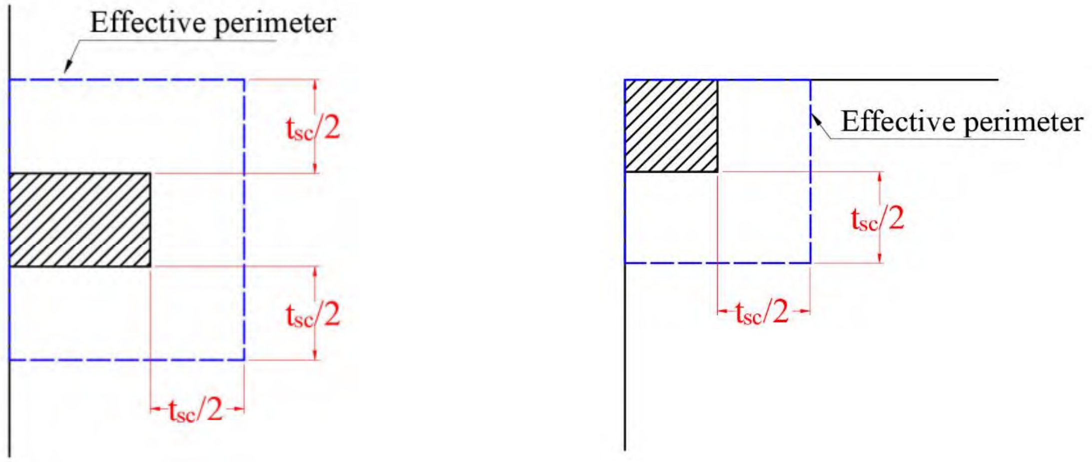
Figure 5-8: Idealized Reduced Section (Tie width)

5.7.5.3 Two-Way (Punching) Shear

For punching shear, the shear strength is calculated as the minimum of the out-of-plane shear strength in both directions, if different (e.g., along and across the direction of the diaphragm plates in case of DP-SC modules), multiplied by the perimeter of the punching shear length at a distance $t_{sc}/2$ around the face of the concentrated load as shown in Figure 5-9.



(a) Center Concentrated load (b) Concentrated load Near Edge



(c) Edge Concentrated Load (d) Corner Concentrated Load

Figure 5-9: Punching Shear Effective Perimeter

5.7.6 Out-of-Plane Shear Force Interaction

The out-of-plane shear forces interaction is calculated per draft ANSI/AISC N690-XX (Reference 9-59), Section N9.3.6a conditions using the following Equation [5-34] for DP-SC sections.

$$\left(\left(\frac{V_r - V_{c\,conc}}{V_c - V_{c\,conc}}\right)_x + \left(\frac{V_r - V_{c\,conc}}{V_c - V_{c\,conc}}\right)_y\right)^2 + \left(\frac{\sqrt{(V_{rx})^2 + \left(V_{ry}\right)^2} \Big/ 0.9t_{sc}}{lQ_{cv}^{sum} \Big/ W_{sc} \times S}\right)^2 \leq 1.0 \qquad [5\text{-}34]$$

Where,

V_r = Out-of-plane one-way shear demand per unit width of composite section in local x (V_{rx}) and y (V_{ry}) directions, kip/ft (kN/m)

$V_{c\,conc}$ = available out-of-plane shear strength contributed by concrete per unit width of section ($0.75\ V_{conc}$), kip/ft (kN/m)

V_c = Out-of-plane one-way shear strength per unit width of composite section in local x (V_{cx}) and y (V_{cy}) directions, ($0.75\ V_{no}$), kip/ft (kN/m)

$Q_{cv}^{sum} = Q_{cv}^{dp} + Q_{cv}^{sa}$

$Q_{cv}^{sa} = \sum Q_{cv}$, the sum of steel headed stud anchors shear capacities contribution is taken for headed stud anchors in a panel having dimensions of S by W_{sc}, kip (N). Where studs are not used in localized areas, $Q_{cv}^{sa} =$ zero

Q_{cv}= Headed stud anchor shear capacity computed per ANSI/AISC N690, Appendix N9, Section N9.1.4a, kip (N)

$Q_{cv}^{dp} = \phi * 0.6 * Fy * t_p * (S - D)$, kip (N), where ϕ =0.9

S = diaphragm hole spacing, in. (mm)

D = diaphragm hole diameter, in. (mm)

W_{sc}= spacing between diaphragm plates, in. (mm)

l = unit width of module, 12 in/ft (1000 mm/m)

x = subscript relating symbol to the local x-axis

y = subscript relating symbol to the local y-axis

For the perpendicular to diaphragm span direction, where the spacing of the shear reinforcement is bigger than $0.5t_{sc}$, and V_c is governed by steel contribution only, $V_{c\,conc}$ is taken equal to zero.

5.7.7 In-Plane Membrane Forces and Out-of-Plane Moments Interaction

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5.8 Design for Impactive and Impulsive Loads

DP-SC panels are designed to resist the effects of impulse loadings from pipe rupture and the impact of missiles resulting from pipe rupture, tornadoes, aircraft impact or any other missile.

In accordance with NUREG-0800, SRP 3.5.3, the design for impactive loads satisfies the criteria for both local effects and overall structural response as discussed in Subsections 5.8.2 and 5.8.3. For aircraft impact, see Subsection 5.8.4.

5.8.1 Design Allowable

5.8.1.1 General

- DP-SC panels are designed to resist loads in the normal and severe environmental load categories to stay essentially elastic.

- DP-SC panels designed to resist impulse loads and dynamic effects in the abnormal, extreme environmental, and abnormal and extreme environmental categories are allowed to have permanent, plastic deformations. Design adequacy is controlled by limiting the support rotation and ductility, as well as steel and concrete strains.

5.8.1.2 Allowable Stresses

Dynamic increase factors based on the strain rates involved are applied to static material strengths of steel and concrete for purposes of determining section strength but are not to exceed those specified in Table 5-1, adapted from NEI 07-13.

The dynamic increase factors are limited to 1.0 for all materials where the dynamic load factor associated with the impactive, or impulsive loading is less than 1.2.

Table 5-1: Dynamic Increase Factors for Diaphragm Plate Steel-Plate Composite Modules

Materials	Dynamic Increase Factor	
	Yield Strength	Ultimate Strength
Carbon steel plate	1.29	1.10
Stainless steel plate	1.18	1.00
Concrete compressive strength	—	1.25
Concrete shear strength	—	1.10

5.8.1.3 Allowable Limits

- Damage criteria for DP-SC structures subjected to impactive/impulsive loads, in addition to other simultaneously acting loads (e.g., gravity loads), are presented in Table 5-2, when separate material strains are not available, and Table 5-3. The damage criteria are based on U.S. NRC RG 1.243, ASME BPVC, Section III, Division 2, U.S. NRC RG 1.136, CNSC REGDOC-2.5.2, and International Atomic Energy Agency (IAEA) Safety Reports (SR) series No. 87 (Reference 9-67), and meet the general criteria discussed in Subsection 5.8.1.1.
- For DP-SC containment under DBAs or DBTs (i.e., equivalent to design load combinations per U.S. NRC RG 1.136), the acceptable damage criteria are per ASME BPVC, Section III, Division, II, Subsection CC, Paragraph CC-3923, but not less than the superficial damage criteria per CNSC REGDOC-2.5.2 and IAEA SR No. 87 listed in Table 5-2 and Table 5-3.
- For DP-SC containment under Design Extension Event 1 as defined per IAEA SR No. 87, BDBAs tier 1 or Beyond Design Basis Threats (BDBTs) Tier 1 as defined per CNSC REGDOC-2.5.2, the acceptable damage criteria correspond to the moderate damage criteria listed in Table 5-2 and Table 5-3. These criteria conform to that of NEI 07-13.
- For DP-SC containment under Design Extension Event 2 as defined per IAEA SR No. 87, BDBAs tier 2 or BDBTs Tier 2 as defined per CNSC REGDOC-2.5.2, the acceptable damage criteria correspond to the severe damage criteria listed in Table 5-2.
- For DP-SC non-containment, the limits for moderate damage criteria in Table 5-2 and Table 5-3 are acceptable for DBAs or DBTs as listed in the design load combinations given

in U.S. NRC RG 1.243. Those limits are per ANSI/AISC N690 as endorsed and modified by Regulatory Position C11.1 of U.S. NRC RG 1.243.

- For impulsive loads, the strength available is at least 20 percent greater than the magnitude of any portion of the impulsive loading, which is approximately constant for a time equal to or greater than the first fundamental period of the structural member.
- In addition to the limits in Table 5-2 and Table 5-3, the maximum deformation should not result in the loss of intended function of the structural wall nor impair the safety Category I (i.e., safety related) function of other systems and components.
- Shock and vibratory effects due to impactive or impulsive loadings affecting the functionality of attached Safety Category 1 (i.e., safety-related) components at or at points away from the location of impact should also be evaluated.
- For impact loadings, impact locations evaluated should be such that the shear demand and flexural demand are maximized.
- Damage criteria for DP-SC structures subjected to impactive loads meet the criteria in Subsection 5.8.2.

Table 5-2: Structural Acceptance Criteria for Flexure in Terms of Support Rotations and for Shear in Terms of Ductility

Element Type	Controlling Behavior (1) (5)	Superficial Damage	Limited, Moderate, Severe Damage	Limited Damage	Moderate Damage	Severe Damage
			Ductility μ_d	Support Rotation r_θ (deg)(2) (6)	Support Rotation r_θ (deg)(2) (3) (7)	Support Rotation r_θ (deg)(3) (7)
SC Slabs and Walls (including DP-SC)	Out-of-Plane Flexure	Essentially Elastic Behavior (4)	10(6)	1	4	6
	Out-of-Plane Shear:					
	- Ties or Diaphragms spaced at no more than ½ t_{sc}		1.3			
	- Ties or Diaphragms spaced at more than ½ t_{sc}		1.0			
	Compression		1.0(8)			
SC Shear Walls, and Diaphragms	In-Plane Flexure (shear walls and diaphragms)		N/A	-	1.5	2

(including DP-SC) (9)	In-Plane Shear (shear walls)	Essentially Elastic Behavior (4)	3.0			
	In-Plane Shear (diaphragms)		1.5			

Notes:

(1) SC components (including DP-SC) shall be classified as flexure-controlled if their available strength for the limit state of flexural yielding is less than their available strength for the limit state of out-of-plane shear failure by at least 25%.

(2) When flexure controls, the criteria in terms of support rotations, from Table 5-2, and in terms of strains, from Table 5-3, are fulfilled simultaneously in order to control damage.

(3) These rotation criteria (in degrees) are in general consistent with those in the ASCE/SEI 59-11 (Reference 9-68), which does not specify allowable inelastic deformation in terms of ductility ratio-criteria for flexure.

(4) Essentially elastic behavior means elastic structural analysis using design strain acceptance criteria of 1% for steel plates and 0.35% for concrete in compression, which corresponds to superficial damage of elements. The permissible ductility ratio μd is 1.0.

(5) When impact/impulse loading results in net tension, shear capacity of concrete is not considered.

(6) 1 degree support rotation is related to buildings with internal explosions producing internal blast pressures or chamber pressurization. This is a global structural response and is similar to a structural drift criterion that governs the entire structure's integrity. This is a higher damage level than the essentially elastic response threshold defined for superficial damage. The limit of ductility of 3 may be used in lieu of support rotations of 1 degree complying with Regulatory Position C11.1.6 of U.S. NRC RG 1.243.

(7) This is a semi-global response criterion (i.e., for a wall or slab or part of the structure). The collapse of this structural member does not lead to the collapse of the entire structure.

(8) For additional information refer to Regulatory Position C11.1.5 of U.S. NRC RG 1.243.

(9) Per the acceptance criteria of IAEA SR No. 87 and CNSC REGDOC-2.5.2.

Table 5-3: Structural Acceptance Criteria – Allowable Strains for Steel

Structural Acceptance Criteria - Allowable Strains for Steel				
Material	**Strain Measure**	**Superficial Damage**	**Limited Damage**	**Moderate Damage**
Carbon Steel Plate	Membrane principal strain (tension)	0.010	0.025	0.050
	Local ductile tearing effective strain	N/A	0.070/TF (1)	0.140 / TF (1)
304 Stainless Steel Plate	Membrane principal strain (tension)	0.010	0.033	0.067
	Local ductile tearing effective strain	N/A	0.138/TF (1)	0.275 / TF (1)

Note:

(1) The tri-axiality factor, TF, is defined as

$$TF = \frac{\sigma_1 + \sigma_2 + \sigma_3}{\sigma_e}$$

Where σ_1, σ_2 and σ_3 are principal stresses and σe is effective or equivalent stress. Conservatively, the tri-axiality factor, TF, value is taken as 2 for DP-SC modules. The values in Table 5-2 and Table 5-3 are maximum values under given loading condition. Note that the acceptance criteria presented in Table 5-2 and Table 5-3 are applicable to large structural components impacted by large impulsive loading. The strain values for severe damage are not provided as it is difficult to measure strains at that level of damage.

5.8.2 Missile Impact Design for Local Failure

Local impact effects include perforation of the DP-SC structures. Perforation of DP-SC structures is not allowed. The faceplate thickness required to prevent perforation under impactive loads is at least 25% greater than that calculated using rational methods discussed in Subsection 5.8.2.2.

5.8.2.1 Explicit Dynamic Inelastic Analysis

Panels and faceplate thicknesses of DP-SC modules are designed for the load effects of impactive loads using explicit dynamic inelastic FE analysis software packages per NEI 07-13 recommendations.

Realistic explicit dynamic analysis is used to predict the local damage associated with the penetration of a missile into the wall resulting in local fracture in rear steel plate. NEI 07-13 allows the use of one of the following two methods to predict local damage:

1. Force Time-History Analysis Method: In this method, the impact force time-history is first determined based on the missile crushing characteristics and impulse conservation principles using the Riera method presented in the NEI 07-13. The computed force time-history is then applied to a mathematical model of the structure in a time-history analysis.
2. Missile-Target Interaction Analysis Method: In this method, a combined dynamic analysis model of both the missile and target is developed, and the dynamic response is determined

as an initial velocity problem. This method provides more accurate results than the Riera method.

Detailed continuum 3D FE model is used to depict the local performance of the DP-SC module system. The components of DP-SC module panels, including concrete, steel plates and connectors are explicitly modeled. The constitutive model for concrete material with a suitable failure criterion in shear, tension, and compression is selected to accurately simulate the concrete behavior under impact loading. The concrete constitutive model has a failure surface in shear, tension, and compression. The constitutive model for steel is selected to simulate the piece-wise linear plasticity behavior of steel material. The NEI 07-13 guides for the element erosion criterion are implemented into the numerical model.

The following additional numerical modeling guidelines are considered:

- Explicit inclusion of material dynamic increase factors in the material constitutive models, considering the material strain rate effects in accordance with NEI 7-13
- Modeling of interface between the steel plates and the concrete infill using appropriate interface/contact equations
- Use of appropriate boundary conditions that may allow a simplification of the explicit dynamic FE model for symmetry and structural continuity
- Use of suitable FE to model the steel plates and concrete infill
- Performance of a mesh sensitivity analysis (mesh aspect ratio and mesh size) to ensure that the utilized constitutive model is independent of the element size
- Limiting the element size for the concrete infill to the anticipated aggregate size used in the concrete
- Limiting the element size for steel plates to the thickness of the steel plate

5.8.2.2 Alternative Rational Methods

An alternative procedure using empirical equations based on physics and testing data may be used as follows:

DP-SC modules are designed to prevent local perforation. Scabbing is not a design limit state since it is prevented by the rear steel faceplates of DP-SC structures. Per ASME BPVC Section III, Division 2, Paragraph CC-3931, local areas for missile impact are defined as having a maximum diameter equal to 10 times the effective diameter of the impacting missiles, or $5\sqrt{t_{SC}}$ plus the effective diameter of the impacting missile, whichever is smaller, where t_{SC} and the effective missile diameter are in feet.

Subsection 5.8.2.2.1 illustrates the conservatism of the same methodology used for calculating the perforation resistance curve for NRIC missile impact tests (see Section 7.0).

5.8.2.2.1 Steel Plate Thickness Preventing Perforation

When the missile impact velocity (V_{imp}) is greater than the calculated perforation velocity of the concrete infill ($V_{p.conc}$), perforation of DP-SC structures by missiles is prevented by specifying steel faceplate thickness that is greater than the minimum steel plate thickness calculated per Subsection 5.8.2.2.1(d) per Section 7.4.4 of Reference 9-69.

(a) Concrete Infill Penetration Depth of DP-SC structures

The penetration depth $x_{c.sc}$ (in inch) for the concrete infill is calculated as follows:

$$x_{c.sc} = K_{sc} x_c \qquad [5\text{-}35]$$

(Equation (7-13) of Reference 9-69)

Where,

K_{sc}= penetration depth modification factor as defined as below:

$$K_{sc} = 2.073 - 0.661K + 0.688\left(\frac{\alpha_p d}{t_c}\right) + 0.835\left(\frac{x_c}{t_c}\right) \qquad [5\text{-}36]$$

(Equation (7-14) of Reference 9-69)

K = concrete penetrability factor defined as $\frac{180}{\sqrt{f_c'}}$ (f_c' in psi) per Equation (8) of Reference 9-70.

t_c = concrete infill thickness, in

α_p= missile deformability factor (0.60 for deformable missiles,1.0 for rigid missiles)

x_c= concrete penetration depth (in inch) calculated using the modified National Defense Research Council (NDRC) formula:

$$x_c = \sqrt{4KNW_p d\left(\frac{V_{imp}}{1000d}\right)^{1.80}} \quad \text{for } \frac{x_c}{d} \leq 2.0 \qquad [5\text{-}37]$$

(Equation (4-1) of Reference 9-69)

$$x_c = KNW_p\left(\frac{V_{imp}}{1000d}\right)^{1.80} + d \quad \text{for } \frac{x_c}{d} > 2.0 \qquad [5\text{-}38]$$

(Equation (4-2) of Reference 9-69)

N= nose shape factor (0.72 for flat-nosed, 0.84 for blunt-nosed, 1.0 for bullet-nosed)

W_p= missile weight in lbs

V_{imp}= missile impact velocity in ft/sec

d= missile diameter in in.

(b) Missile Perforation Velocity ($V_{p.conc}$)

The missile perforation velocity ($V_{p.conc}$) for the concrete infill can be calculated using the procedure described in NEI 07-13, Section 2.1.2.4. This procedure is combined into the following equations to compute directly $V_{p.conc}$ as listed below:

$$V_{p.conc} = 1000d\left(\frac{d}{1.44KW_pNK_{sc}{}^2}\left(2.2 \pm \sqrt{4.84 - 1.2\left(\frac{t_c}{\alpha_p d}\right)}\right)^2\right)^{\frac{5}{9}} \quad \text{for } \frac{t_c}{\alpha_p d} \le 2.65$$

[5-39] (Equation (7-15) of Reference 9-69)

$$V_{p.conc} = 1000d\left(\frac{d}{4KW_pNK_{sc}{}^2}\left(\frac{t_c}{1.29\alpha_p d} - 0.53\right)^2\right)^{\frac{5}{9}} \quad \text{for } 2.65 < \frac{t_c}{\alpha_p d} < 3.27$$

[5-40] (Equation (7-16) of Reference 9-69)

$$V_{p.conc} = 1000d\left(\frac{d}{KW_pNK_{sc}}\left(\frac{t_c}{1.29\alpha_p d} - (0.53 + K_{sc})\right)\right)^{\frac{5}{9}} \quad \text{for } \frac{t_c}{\alpha_p d} \ge 3.27$$

[5-41] (Equation (7-17) of Reference 9-69)

Where $V_{p.conc}$ is in ft/sec

(c) Missile Residual Velocity V_r

When the missile impact velocity V_{imp} is greater than the calculated perforation velocity of concrete infill $V_{p.conc}$, the residual velocity V_r for the missile and concrete frustum moving together is calculated using:

$$V_r = \sqrt{\left(\frac{W_p}{W_p + W_{cf}}\right)\left(V_{imp}{}^2 - V_{p.conc}{}^2\right)}$$

[5-42] (Equation (7-18) of Reference 9-69)

Where,

V_r is in ft/sec

W_p = missile weight in lbs

W_{cf}= concrete frustum weight in lbs defined as

$$W_{cf} = \frac{1}{3}\pi\rho_c(t_c - x_{c.sc})(r_2^2 + r_1r_2 + r_1^2) \quad \text{for } x_{c.sc} < t_c$$

[5-43] (Equation (7-11) of Reference 9-69)

$$W_{cf} = 0 \quad \text{for } x_{c.sc} \ge t_c$$

[5-44] (Equation (7-11) of Reference 9-69)

ρ_c= concrete density, lbs/in^3

$r_1 = d/2$

$$r_2 = r_1 + (t_c - x_{c.sc}) \tan\theta \qquad \text{for } x_{c.sc} < t_c$$

[5-45]
(Equation (7-12) of Reference 9-69)

$$r_2 = \text{N/A} \qquad \text{for } x_{c.sc} \geq t_c$$

[5-46]
(Equation (7-12) of Reference 9-69)

$$\theta = \frac{45^0}{\left(\frac{t_c}{d}\right)^{\frac{1}{3}}} \qquad \text{(in degrees)}$$

[5-47]
(Equation (4) of Reference 9-69)

(d) Minimum steel faceplate thickness preventing perforation $t_{p.min}$

The minimum steel faceplate thickness required to prevent perforation of the rear steel plate by the missile and concrete plug moving together with the residual velocity V_r is calculated as follows:

$$t_{p.min} = 0.72\left(\frac{(12V_r)^2 m_t}{\frac{\pi}{2} d^2 \sigma_s}\right)$$

[5-48]
(Equation (11) of Reference 9-71)

Where,

m_t= total mass of missile and concrete frustum defined as $(W_p{+}W_{cf})/\ (386\ \text{in/sec}^2)$ per Equation (7-20) of Reference 9-69

σ_s= the von Mises yield criterion defined as follows per Equations (7-23) and (7-24) of Reference 9-69

$5.1F_y + 101000$ (psi) for $t_p \geq 0.25$ in.

$3.9F_y + 64000$ (psi) for $t_p < 0.25$ in.

Where F_y is in psi.

5.8.3 Impact or Impulse Design for Global Response

The global response of DP-SC structures subjected to impactive, or impulsive loads is determined by one of the following methods:

1. The dynamic effects are considered by calculating a dynamic load factor. In this case, the impulsive load resistance is considered to be at least equal to the peak of the impulsive load transient multiplied by the dynamic load factor, where the calculation of the dynamic load factor is based on the dynamic characteristics of the structure and impulsive load transient.
2. The dynamic effects of loads are considered by using impulse, momentum, and energy balance techniques. In this case, the strain energy capacity is limited by the ductility criteria in Subsection 5.8.1.3.

3. The dynamic effects of loads are considered by performing a time-history dynamic analysis. This method considers the mass and inertial properties as well as the nonlinear stiffnesses of the structural members under consideration. Simplified bilinear definitions of stiffness are acceptable using this method. The maximum predicted response using this method is governed by the ductility criteria in Subsection 5.8.1.3.
4. The shear strength under local loads considers reaction shear at the supports and punching shear adjacent to the load. Local loads may be impulsive or impactive, except that, for impactive loads, satisfaction of criteria for perforation should be used in place of punching shear requirements. In the case of the reaction shear (beam action condition) at the supports, the effective width of the critical section for the shear beam capacity at the supports is to be determined according to the zone of influence induced by the local loads instead of the entire width of the support. The zone of influence induced by the concentrated loads may be determined by analysis.

5.8.4 Aircraft Impact Evaluation

Aircraft impact evaluations are performed using the NEI 07-13 methodology. Per NEI requirements, the aircraft impact evaluations must demonstrate that the integrity of the containment, the fuel pool, and the systems needed to maintain cooling of fuel in the vessel and in the fuel pool is preserved from the physical shock and fire effects of the aircraft impact. For the BWRX-300 RB, this is achieved by adopting the following acceptance criteria:

1. Maintain the structural integrity of the RB during and after the impact
2. Prevent any damage in the RB which could allow pressurized or propagated fire and burning jet fuel inside the RB
3. Prevent any post-impact debris of concrete and steel components from falling into the reactor and fuel pool
4. Prevent any crane components from falling into the reactor and fuel pool

Two distinct types of structural failure modes are evaluated:

- Local failure caused by impact of the aircraft engines
- Global failure caused by impact of the entire aircraft

For DP-SC walls, the driving local failure mode is wall perforation, since the rear (non-impact side) steel plate prevents scabbing of the concrete prior to perforation. The assessment of local failure identifies whether the thicknesses of the wall and steel faceplates are sufficient to prevent wall perforation by engine components.

The global failure analysis investigates the structural integrity of the RB during and after the impact. The global stability analysis is performed using a High-Fidelity-Physics-Based Explicit computer simulation following the guidance of NEI 07-13. Specific requirements and approaches for aircraft impact explicit dynamic analyses are not in the scope of this report.

5.9 Design of Steel-Plate Composite Floors

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5.10 Design and Detailing Requirements Around Openings

Design and detailing of the RB floor and wall penetrations and openings is coordinated with the fabricator and meets the requirements in ANSI/AISC N690, Appendix N9, Section N9.1.7, to the extent they apply to the construction of DP-SC modules.

5.11 Design of Steel-Plate Composite Connections

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Figure 5-10: Illustration Showing Joint Shear Capacity of DP-SC Panel-to-Panel Connection

5.12 Effect of Curvature on Behavior of Steel-Plate Composite Structures

In curved wall applications, the most unique components of force demands are the out-of-plane moment and shear force caused by the curvature of a wall subjected to axial forces. These out-of-plane forces are not induced in straight (rectilinear) walls.

Wang et al (Reference 9-74) compared the results of flat walls and curved walls under constant compression load and cyclic in-plane and out-of-plane loading. The curvature effects were found to be negligible for a thickness-to-radius ratio no more than 0.5, i.e., radius-to-wall panel thickness of 2.0. The integrated RB curved walls are designed and detailed to have a radius-to-wall panel thickness greater than 2.0. Hence, the findings of Reference 9-74 are applicable to the integrated RB SC (including DP-SC) curved walls.

The curvatures of the integrated RB walls are included in the FE model. If the above thickness-to-radius ratio requirement is not met, the curvature effects can be addressed by performing a second-order analysis for the most critical elements.

Since the curvature effects are accounted for in the integrated RB analysis and because of the findings of Reference 9-74, Appendix N9 of ANSI/AISC N690 can be extended to curved walls.

5.13 Fire Rating and Capacity Under Fire Condition Evaluation

The design and evaluation criterion of structural steel components, DP-SC systems, and frames for fire conditions is based on the provisions provided in ANSI/AISC 360-22, Appendix 4 and ANSI/AISC N690, Appendix N4.

Structural members and components in steel buildings are qualified for the rating period in conformance with ASTM E119 (Reference 9-75) and ANSI/AISC N690. It is also permitted to demonstrate equivalency to such standard fire resistance ratings using the advanced analysis methods in Subsection 5.13.1.1 per ANSI/AISC 360-22, Appendix 4, Section 4.2 in combination with the fire exposure specified in ASTM E119 and ANSI/AISC N690 as the design-basis fire. Additionally, design by simple methods of analysis, per Subsection 5.13.1.2, is also permitted to be used where applicable per ANSI/AISC 360, Section 4.2 and ANSI/AISC N690, Appendix N4. The fire rating of BWRX-300 critical DP-SC components are identified per the following criteria:

- The exposure time required for the DP-SC component to increase the temperature levels on the unexposed side of the fire barrier to 139°C above the ambient temperature (per ASTM E119) (termed the thermal insulation requirement)
- The exposure time required for the DP-SC component to lose its load carrying capacity due to the degradation in the material strength at elevated temperature.
- The protected liner remains intact to prevent projection of water beyond the unexposed surface during the hose stream test, and additionally to prevent any smoke from passing through the barrier.

All BWRX-300 DP-SC panels are designed to have a fire resistance rating not less than three hours.

Requirements of Section 5.14 are met to prevent steam pressure build-up.

5.13.1 Design by Engineering Analysis

5.13.1.1 Design by Advanced Methods of Analysis

The advanced method of analysis includes both a thermal response and a mechanical response to the design-basis fire.

The design-basis fire exposure is as specified in ASTM E119 or Eurocode 1 (Reference 9-76). The exposure conditions need to be stipulated in terms of a time-temperature history, along with radiation and convection heat transfer parameters associated with the exposure, or as an incident heat flux as described in ASTM E119, or Eurocode 1.

The thermal response produces a temperature field in each structural element as a result of the design-basis fire and incorporates temperature-dependent thermal properties of the structural elements and fire-resistive materials, as defined per Section 5.2.

The mechanical response includes the forces and deformations in the structural system due to the thermal response calculated from the design-basis fire. The mechanical response considers explicitly the deterioration in strength and stiffness with increasing temperature, the effects of thermal expansions, inelastic behavior and load redistribution, large deformations, time-dependent effects, and uncertainties resulting from variability in material properties at elevated temperature. Support and restraint conditions (forces, moments, and boundary conditions) represent the behavior of the structure during a design-basis fire. Material properties are defined as per Section 5.2.

The resulting analysis addresses all relevant limit states, such as excessive deflections, connection ruptures, and global and local buckling, and demonstrates an adequate level of safety as required by the authority having jurisdiction.

5.13.1.2 Design by Simple Methods of Analysis

Where applicable, the nominal compressive strength for flexural-buckling in filled DP-SC walls, is computed in accordance with ANSI/AISC 360-22, Appendix 4, Section 4.2.4d.(d) and Equation A-4-12.

5.13.2 Design by Qualification Testing

This approach establishes standard fire resistance ratings of structural steel by calculations. Use of this approach is permitted in place of and/or as a supplement to published fire-resistive assemblies based on ASTM E119.

5.13.2.1 Fire Resistance Rating of Diaphragm Plate Steel-Plate Composite Walls

The fire resistance rating for unprotected DP-SC panels, meeting the requirements of ANSI/AISC N690, Appendix N9 and satisfying the following conditions adapted from ANSI/AISC 360-22, Appendix 4, Section 4.3, is determined in accordance with Equations [5-51] and [5-52].

(a) Wall slenderness ratio, L/t_{sc}, is less than or equal to 20

(b) Axial load ratio, P_u/P_n , is less than or equal to 0.2

(c) Wall thickness, t_{sc}, is greater than or equal to 8 in. (200 mm)

$$R = \left[-18.5\left(\frac{P_u}{P_n}\right)^{\left(0.24-\frac{L/t_{sc}}{230}\right)} + 15\right]\left(\frac{1.9t_{sc}}{8} - 1\right) \quad [5\text{-}51]$$

$$R = \left[-18.5\left(\frac{P_u}{P_n}\right)^{\left(0.24-\frac{L/t_{sc}}{230}\right)} + 15\right]\left(\frac{1.9t_{sc}}{200} - 1\right) \text{ (SI Units)} \quad [5\text{-}52]$$

where R is the fire rating in hours, L is the unsupported length of DP-SC panel and P_u is the required axial load in kips (N). P_n and t_{sc} are as defined in Chapter I of ANSI/AISC 360-22. The calculations of fire rating of DP-SC panels are based on ANSI/AISC 360-22, Appendix 4, Section 4.3.2g, for design by qualification testing.

5.14 Vent Holes Requirements

Vent holes are required for concrete-filled steel composite members, to relieve the build-up of steam or vapor pressure caused by water evaporation from heated concrete at elevated temperatures and fire incidents. The same requirement applies for DP-SC walls and slabs. The vent holes are designed per the methodology provided in Design Guide 38 (Reference 9-77). The vent hole size and spacing depend on the allowable pressure, concrete moisture content, vent hole spacing, and thermal gradient through the wall thickness.

The following are the minimum vent holes requirements to achieve for the BWRX-300 DP-SC structures:

- Vent holes are used to relieve the steam pressure.
- At least two vent holes are placed at top and bottom of the wall (story height) at each floor, with a maximum spacing of 12 ft (3.7m) on center in the orthogonal directions. Each set of vent holes are located on the alternative face relative to the adjacent set of holes, where possible.
- Maximum spacing between vent holes in floor modules is limited to 12 ft (3.7m) on center in the orthogonal directions. Each set of vent holes is located on the alternative face relative to the adjacent set of holes.
- Vent hole diameter is not to exceed the size of the concrete infill coarse aggregate or 13 mm, whichever is less.
- At the locations where vent holes are not possible, other mechanical methods of releasing the steam may be used to collect and transport the steam to vented locations.

5.14.1 Design of Vent Holes

Equation [5-53] is used to calculate the required vent hole size for a designated effective area. For effective area calculation purposes, vent holes are considered located in the middle of the effective area. The maximum allowable vapor pressure is equated to the maximum allowable hydrostatic pressure on the steel plates during concrete casting. This allowable hydrostatic pressure is calculated per Reference 9-78. The vapor generation rate, m, is determined based on the thickness of the dry concrete, T_{dc} and is calculated by dividing the amount of evaporated water content from the dry concrete thickness, T_{dc}, with the time duration in seconds associated with drying, t_{dc}. The discharge rate of every vent hole is conservatively taken equal to the vapor generation rate, m. The vapor generation rate and the allowable pressure based on the concrete pouring height are calculated using Equation [5-54] and Equation [5-55], respectively.

The following conditions were considered in developing the vent holes design equations:

- Temperature of vapor does not exceed (392°F) while traveling inside the wall until it reaches a vent hole (T = 392°F, γ = 1.315).
- Water content of concrete evaporates when the temperature exceeds 212°F.
- Flow of vapor through vent holes is reversible and isentropic.
- Vent holes have a square edge for calculation purposes.
- Generated vapor rate is equal to the vapor discharge.

Equation [5-56] is obtained after simplifying Equation [5-53] and taking into account all listed conditions.

$$A = \frac{m}{K_d P \sqrt{\frac{\gamma M_m}{\bar{R}T}\left(\frac{2}{\gamma+1}\right)^{\left(\frac{\gamma+1}{\gamma-1}\right)}}} \qquad [5\text{-}53]$$

$$m = \frac{s_1 s_2 T_{dc} \omega \rho_w}{t_{dc}} \qquad [5\text{-}54]$$

$$P = \rho_c g h_c \qquad [5\text{-}55]$$

$$A = 116 \frac{s_1 s_2 T_{dc} \omega \rho_w}{t_{dc} \rho_c h_c} \qquad [5\text{-}56]$$

Where,

A = vent hole area, ft^2

K_d = discharge coefficient (a square edge hole = 0.62)

M_m = molar weight of water, lb/mol

P = allowable pressure, lb/ft-s^2

$\bar{R}$ = ideal gas constant, lb-ft^2/s^2-K-mol

T = maximum vapor temperature, K

T_{dc} = dry concrete thickness, ft (m)

g = gravitational acceleration, ft/s^2 (m/s^2)

h_c = concrete pouring height, ft (m)

m = vapor generation rate, lb/s

s_1 = horizontal spacing of vent holes, ft (m)

s_2 = vertical spacing of vent holes, ft (m)

t_{dc} = heating duration associated with the selected dry concrete thickness, s

γ = specific heat ratio

ρ_w = water density, lb/ft^3 (N/m^3)

ρ_c = concrete density, lb/ft^3(N/m^3)

ω = concrete water content, % by volume.

5.15 Corrosion Protection

The corrosion protection of DP-SC modules is met by one or a combination of the following approaches to meet the design life and decommissioning time of the plant:

- Corrosion tolerance of adding a sacrificial thickness by increasing the faceplate thickness
  - The additional sacrificial thickness is not considered in strength or stiffness estimates.
- Protective paint system suitable to the surrounding environment
  - The protective paint system is per International Organization for Standardization (ISO)-12944-5 (Reference 9-79) and ANSI/AISC 303 (Reference 9-80) requirements. Surface preparation and touch up painting are to meet The Society for Protective Coatings (SSPC) Manuals volumes 1 and 2 provisions and requirements (Reference 9-81 and Reference 9-82). All painting system are to be tested in accordance with ASTM D1014 (Reference 9-83) procedures.
- Membrane coating system.
- Impressed Current Cathodic Protection. The cathodic protection system is to meet ISO-12473 (Reference 9-84).

ASTM MNL20-2nd Edition (Reference 9-85) is used for all corrosion Tests and standards.

The corrosion protection of DP-SC modules will also conform to U.S. NRC RG 1.54, including the requirements for aging management of coatings.

5.16 Fabrication and Construction Requirements

The fabrication and erection requirements for non-containment DP-SC modules are per ANSI/AISC N690, Chapter NM. The acceptable dimensional tolerances for DP-SC modules are similar to those of conventional SC panels presented in ANSI/AISC N690, Section NM2.7(d) and are as follows:

- At diaphragm plate locations, on the flat surface away from the corners, the acceptance criteria for the perpendicular distance between the opposite steel plates is within plus or minus $t_{sc}/200$, rounded upward to the nearest 1/16 in. (2 mm), where t_{sc} is the design thickness and t_p is the faceplate thickness.
- In between the diaphragm locations, the acceptance criteria for the perpendicular distance between the opposite steel plates is within plus or minus $t_{sc}/100$, rounded upward to the

nearest 1/16 in. (2 mm). This tolerance check is to be performed along the free edge of the empty steel module.

Additional requirement established for the concrete compressive strength testing are provided in Section 3.2.2.1 of NEDO-33914-A. These requirements address NUREG/CR-7193 for the effect of small volume of concrete placed for the BWRX-300.

ANSI/AISC N690 implicitly accounts for the effects of locked-in stresses from initial imperfections and hydrostatic pressure exerted by the concrete pour during construction. These are accounted for by having a minimum plate thickness as per Section 5.1, minimum yield stress of the steel plates as mentioned in Section 5.2.2, meeting the non-slenderness requirement for the steel faceplates mentioned in ANSI/AISC N690, Section N9.1.3, and the waviness requirement for the steel faceplates after concrete casting per ANSI/AISC N690 Equation NM2-1.

5.17 Quality Control and Quality Assurance

BWRX-300 non-containment Seismic Category I DP-SC structures follow the requirements of ANSI/AISC N690, Chapter NN and Section NA5. U.S. NRC RG 1.28 is used for QA/QC in design, construction, inspection, and testing of steel and composite structures as required by U.S. NRC RG 1.243.

Requirements for placement and installation of ties in conventional SC modules are applicable to the diaphragm plates of DP-SC modules.

5.18 Aging Management, Inservice Inspection, and Testing Requirements for the Integrated RB

An inservice inspection and testing program is established for the DP-SC integrated RB to ensure the structure can fulfill its intended functions throughout its design service life. The examination program may also include requirements for additional examination beyond the regulatory requirements for critical components such as the below-grade RB exterior wall and mat foundation. The scope of this program includes all structural components in the RB other than those covered by Section 6.0 of this report.

The inservice inspection and testing program for the DP-SC integrated RB is similar to that described in the NUREG-2191, Chapter XI.S6 (Reference 9-86). In particular, the program consists of periodic visual inspections of the accessible areas of the RB by qualified personnel for pertinent aging effects, such as those described in ACI 349.3R (Reference 9-87) and SEI/ASCE 11 (Reference 9-88).

Failure Mode Effect Analysis (FMEA) will be performed to identify aging and degradation mechanisms associated with the integrated RB DP-SC construction, inspection processes to detect the abnormalities and proposed repair methods. The condition assessment of accessible steel faceplates can be performed by means of visual inspection as well as using applicable nondestructive testing techniques such as ultrasonic pulse-echo thickness measurement (typically used for steel liners). However, the ultrasonic pulse-echo thickness measurement method is not applicable for testing inaccessible steel faceplates such as the below-grade exterior wall of the RB.

The use the ultrasonic guided wave phased-array method via access ports installed on the inaccessible faceplate allows for the nondestructive testing of the back faceplate (currently being evaluated by the NRIC project). This method utilizes guided wave pulser/receiver equipment and a circular piezoelectric phased-array sensor to detect section loss caused by general or pitting corrosion, cracks, ruptures, dents, and corrosion/crack in welds.

As discussed in Section 5.15, corrosion tolerance may be used as a method of corrosion protection by adding an additional thickness to the faceplate thickness. Alternatively, the inaccessible steel faceplates can also be coated and the gap around the exterior walls filled with waterproofing materials to provide corrosion protection. The integrity of the inaccessible steel faceplates can therefore be maintained throughout the service life of the structure by monitoring the integrity of protective coatings or waterproofing system to assess corrosion potential. Corrosion of inaccessible faceplates can also be estimated by measuring the flexural strain to detect changes in the elastic neutral axis of the composite section due to material loss. This technique is, however, limited to evaluating the material loss due to corrosion only at locations instrumented with strain gauges which provide local damage detection.

The inservice visual inspection of concrete infill in DP-SC modules is not feasible, thus other applicable methods such as nondestructive examination techniques described in ACI 349.3R, Section 3.6.2 can be used.

As part of the NRIC project, the Electric Power Research Institute (EPRI) demonstrated the effectiveness of some potential nondestructive examination techniques on mockups/prototypes fabricated with DP-SC modules to inspect concrete placed between the faceplates. The techniques used for this demonstration included high-energy X-ray and low-frequency ultrasound testing.

EPRI concluded that the high-energy X-ray method can detect the presence of defects and honeycombs in concrete when imaging from both sides of the structure is performed but that it does not provide depth information of the honeycomb. EPRI recommended that the use of this technique be limited to an as-needed basis in areas where defects/cracks are suspected.

The low-frequency ultrasound is performed with a low-frequency ultrasound shear wave array to detect contact between the concrete and steel interface and to detect defects within the concrete. The results of the demonstration tests performed by EPRI indicated that this method allows the inspection of the contact between the steel plate and the concrete, and detection of flaws within the concrete core. However, the effectiveness of this technique is limited to a faceplate thickness of 8 mm. Beyond that thickness, information regarding the concrete could not be obtained. To overcome this limitation, a recommendation was made to prepare inspection areas where a portion of the steel plate, slightly larger than the size of the test array, is replaced with a (8 mm) steel faceplate thickness. Alternatively, making windows of exposed concrete for examination would eliminate the limitation presented by the presence of thicker plates (more than 8 mm) steel faceplate. The windows also permit the use of other techniques such as impact echo, impulse response, surface sounding, and ultrasonic pulse velocity tests to inspect the concrete.

Another potential technique that may be used for the inspection of the concrete infill includes the use embedded ultrasonic sensors that enable determining the relative changes of ultrasonic wave velocity traveling between the two steel faceplates. A drop in the wave velocity indicates that a defect is present within the path of the ultrasonic waves in concrete.

As demonstrated by testing carried out as part of the NRIC project, techniques for inservice inspection and testing that may be deployed for the BWRX-300 DP-SC modules include:

- Ultrasonic guided wave phased-array (screening of defects within steel plates)

- High-energy X-ray (location of voids and foreign material within concrete)
- Low-frequency ultrasound (evaluation of steel plate contact and defects within the concrete)

Additional methods may be implemented after further evaluation during detailed design.

As per the structures monitoring program described in NUREG-2191, Section XI.S6, baseline preservice inspection data will be established by testing during original construction. Baseline inspections including non-destructive examination measurements for the methods identified as part of the aging management program need to be collected at the time of original construction to be used as part of data collection used for trending analysis with respect to subsequent inspections.

The material properties and other parameters to be measured as a baseline data for specific DP-SC modules (e.g., RPV pedestal) will be confirmed based on the outcomes of the FMEA that summarizes the pertinent aging effects, including irradiation embrittlement. A detailed neutron fluence analysis will be performed to identify the locations experiencing high levels of neutron irradiation. Baseline material testing results listed below will be required as part of Certified Material Test Report for DP-SC structures exposed to high levels of neutron irradiation exceeding the threshold level identified to potentially change the mechanical properties of carbon steels (i.e., $1x10^{17}$ neutrons/cm^2 as per NUREG-1509 (Reference 9-89)). By exceeding this threshold, these locations will potentially be prone to neutron irradiation embrittlement.

In addition to chemical analyses and tensile testing of the steel materials used in the faceplates of the DP-SC RPV pedestal, baseline data of the impact testing (either by the drop weight tests or Charpy V-notch impact test), need to be collected for future trending analysis. Impact testing shall conform to one of the following tests:

- The nil-ductility transition temperature in accordance with ASTM E208 (Reference 9-90)
- The Charpy V-notch impact test in accordance with ASTM A370/ASME SA-370 (Reference 9-91)

Based on the outcomes of the inservice inspections, any identified aging effects are evaluated by qualified personnel against predefined acceptance criteria. The acceptance criteria are derived from applicable codes and standards including ACI 349.3R, ACI 318, SEI/ASCE 11, and ANSI/AISC 360-16 specifications as well as the findings from ongoing testing programs. The program also includes periodic testing of ground water samples to assess the impact of any changes in the water chemistry on below-grade portions of the RB. If protective coatings are used, the program is to cover the protective coating monitoring and maintenance during plant operation.

The frequency of inspections of all structural components, protective coatings and ground water quality for the integrated RB is established according to U.S. NRC RG 1.160 with a maximum interval of 5 years as per ACI 349.3R and NUREG-2191. This program supports a plant-specific aging management plan for the DP-SC integrated RB (including items governed by section 6.0 of this report) to provide timely detection and mitigate aging effects. The aging management program begins with the plant commissioning followed by periodic inservice inspection and testing at predefined intervals up to the plant decommissioning.

6.0 PROPOSED DESIGN APPROACH FOR BWRX-300 STEEL-PLATE COMPOSITE CONTAINMENT VESSEL (SCCV)

6.1 Introduction

The general requirements and rules of ASME BPVC, 2021 Edition, Section III, Division 2, Subsection CC, Subsubarticles CC-1110 to CC-1130 are applicable to the BWRX-300 DP-SC containment (SCCV). The proposed design, fabrication, construction, examination and testing requirements presented in this section for the SCCV are adapted from the ASME BPVC, 2021 Edition, Section III, Division 2, Article CC-2000 to CC-6000. These proposed requirements meet the safety goals established by the NRC and CNSC for ensuring the protection of public health and safety and the environment.

The design code applicability is shown in Figure 4-1. As shown in Figure 4-1, the containment boundary includes the containment vessel, including the mat foundation inside the containment and the containment top slab, and all penetration assemblies or appurtenances attached to the containment vessel.

The SCCV DP-SC modules, including the inner and outer faceplates, diaphragm plates, steel headed stud anchors (see Section 5.3) and concrete infill, are part of the containment pressure boundary. In addition to being part of the containment pressure boundary, the modules inner faceplate (i.e., at the containment side) also serves as the leak-tight liner (i.e., containment leakage barrier). Requirements presented in this Section are applicable to the SCCV DP-SC modules, with the exception of leak tightness requirements. Leak tight requirements related to liners are only applicable to the inner faceplate of the DP-SC modules (i.e., containment side). For the SCCV DP-SC modules design parameters, refer to Section 5.1.

6.2 Materials

The requirements for the SCCV DP-SC modules materials follow ASME BPVC, Section III, Division 2, Subsection CC, Article CC-2000, as applicable, in addition to the NRC staff regulatory guidance reported in U.S. NRC RG 1.136. Applicable Subarticles, Subsubarticles, Paragraphs, Subparagraphs, or Subsubparagraphs referenced in Article CC-2000, are followed to the extent they apply to DP-SC modules without reinforcing steel or prestressing tendons. Reinforcing steel bars, where used in SCCV DP-SC connections regions, shall meet the material requirements in ASME BPVC, Section III, Division 2, Subsection CC, Subarticle CC-2300. The following subsections present the proposed requirements specific to the BWRX-300 SCCV.

6.2.1 Concrete Infill

The self-consolidating concrete infill of SCCV DP-SC modules meets the requirements of ASME BPVC, Section III, Division 2, Subsection CC, Subarticle CC-2200 with the following modifications:

- The requirement for the maximum size of coarse aggregate in the concrete infill (CC-2222.1(g)) is limited to maintain acceptable fresh properties of self-consolidating concrete. In particular, the self-consolidating concrete mixture is qualified using tests including static and dynamic segregation resistance and passing ability tests as per Subparagraph CC-2232.3.

Basis of selection of self-consolidating concrete: based on ASME BPVC, Section III, Division 2, Subsection CC, Subparagraph CC-2232.3, the use of self-consolidating concrete is permitted for areas where conditions make manual consolidation difficult. The basis of selection of self-consolidating concrete for the general use in the SCCV is to achieve the required workability and consistency of concrete through the diaphragm holes and around shear studs (particularly for horizontal modules) without segregation or excessive bleeding as per Subparagraph CC-2232.1. This is especially important since the visual inspection of the concrete infill is not feasible after the concrete placement in the DP-SC modules. The self-consolidated concrete mixture used in the integrated RB (including the SCCV) is designed according to the procedure described in ACI 237 (Reference 9-92) and qualified based on ASTM standard test methods specified in U.S. NRC RG 1.136, Section C.1.

- The water-soluble chloride content of the DP-SC modules concrete is limited to 0.06% by mass of total cementitious materials. This value is the maximum specified value for concrete placed in direct contact with prestressing steel as specified in ASME BPVC, Section III, Division 2, Subsection CC, Subparagraph CC-2231.2 and is selected to minimize the possibility of corrosion of the steel plates and shear studs.
- The exposure categories in Table CC-2231.7.1-1 are applicable to the BWRX-300 SCCV, where “concrete” is replaced with “DP-SC concrete infill”. The category for corrosion protection of steel materials in DP-SC modules follow those for reinforcement steel.

6.2.2 Steel Materials

All DP-SC steel faceplates and diaphragm plates used in the BWRX-300 SCCV meet ASME BPVC, Section III, Division 2, Subsection CC, Subarticle CC-2500 requirements in addition to the following:

- The design of the inner faceplate of DP-SC modules that serves as the leak barrier meets the material requirements of Subarticle CC-2500. Given the fabrication sequence of the DP-SC modules, the outer faceplate and the diaphragm plate also meet the same Subarticle CC-2500 requirements.
- The effect of elevated temperatures on the mechanical properties of steel materials of DP-SC modules is determined in accordance with ASME BPVC, Section II, Part D.

6.2.3 Welding Materials

All welding materials conform to the requirements of ASME BPVC, Section III, Division 2, Subsection CC, Subarticle CC-2600.

Additional welding requirements are discussed in Sections 6.13 through 6.15.

6.2.4 Material for Embedment Anchors

If used, steel materials classified as load bearing steel materials are to meet the requirements of ASME BPVC, Section III, Division 2, Subsection CC, Subarticle CC-2700. Examples of these materials may include embedded anchors used to support the attachments to the faceplates and ensure the proper load transfer as well as stiffeners used in the DP-SC connection areas.

6.3 Effective Stiffness, Geometric and Material Properties of Diaphragm Plate Steel-Plate Composite Modules for Finite Element Analysis

Based on Subsubarticle CC-3320 of ASME BPVC, Section III, Division 2, elastic behavior is the accepted basis for predicting internal forces, displacements, and stability of the containment shells.

The effective stiffnesses, geometric and material properties, for operational and accidental conditions, of SCCV elements are computed as shown in Section 5.5.

6.4 Damping Values

Damping values specified for SC walls in Tables 1 and 2 of U.S. NRC RG 1.61 are used to account for the dissipation of energy in the SCCV DP-SC elements. These values are consistent with the stiffness properties assigned to the SCCV developed following the approach in Section 5.5 of this report.

6.5 Design Loads and Load Combinations for Steel-Plate Composite Containment Vessel

The loading criteria provisions outlined in ASME BPVC, Section III, Division 2, Subarticle CC-3200 supplemented by U.S. NRC RG 1.136 are applicable to the SCCV and are followed in the analysis of the structure.

6.5.1 Structural Thermal Analysis

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6.6 Design Allowables and Acceptance Criteria for Steel-Plate Composite Containment Vessel

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Table 6-1: Acceptance Criteria for BWRX-300 Steel-Plate Composite Containment Vessel

(a) Allowable Stress/Strain Limits for Factored Loads

Material	Force Classification	Type of Force Action	Criteria for Factored Loads	
			Stress Limit	Strain Limit, if any
Concrete	Primary	Membrane	$0.60f_c'$	-
		Membrane + Bending (2)	$0.75f_c'$	-
	Primary + Secondary (1)	Membrane	$0.75f_c'$	-
		Membrane + Bending (2)	$0.85f_c'$ (3)	-
Steel Plates	Primary	Membrane or Membrane + Bending (2)	$0.90F_y$	-
	Primary + Secondary (1)	Membrane or Membrane + Bending (2)	-	$2\varepsilon_y$ (4)

(1) The primary portion of this calculated stress shall not exceed the allowable stress applicable when primary stress acts alone.
(2) The membrane portion of this calculated stress shall not exceed the allowable stress applicable when membrane stress acts alone.
(3) The maximum allowable primary-plus-secondary membrane and bending compressive stress of 0.85f'c corresponds to a limiting strain of 0.002 in./in (0.002 mm/mm). The concrete allowable stresses for factored compression loads shall be reduced, if necessary, to maintain structural stability per Subparagraph CC-3421.1 of ASME BPVC, Section III, Division 2.
(4) Limit for mechanical (net) strain due to primary forces, which is calculated by subtracting strain induced by secondary force (e.g., thermal strain) from the total strain as per Subsubparagraph CC-3422.1(e) of ASME BPVC, Section III, Division 2. For analysis purposes, ϵ_y is defined as the yield stress divided by Young's modulus.

(b) Allowable Stresses for Service Loads

Material	Force Classification	Type of Force Action	Criteria for Service Loads
			Stress Limit
Concrete	Primary	Membrane	$0.30f_c'$
		Membrane + Bending (2)	$0.45f_c'$
	Primary + Secondary (1)	Membrane	$0.45f_c'$
		Membrane + Bending (2)	$0.60f_c'$
Steel Plates	Primary	Membrane or Membrane + Bending (2)	$0.50F_y$ (3) (4)
	Primary + Secondary (1)	Membrane or Membrane + Bending (2)	$0.67F_y$ (3) (4

(1) The primary portion of this calculated stress shall not exceed the allowable stress applicable when primary stress acts alone.
(2) The membrane portion of this calculated stress shall not exceed the allowable stress applicable when membrane stress acts alone.
(3) Where the steel plates are under tension stress, the stress limit may be increased by 50%, with an upper limit of $0.9F_y$ when the temporary pressure loads during the test condition are combined with other loads in the load combination.
(4) Where the steel plates are under compression stress, the stress limit may be increased by 33%, with an upper limit of $0.9F_y$ when the temporary pressure loads during the test condition are combined with other loads in the load combination.

6.7 Required Strength (Demand) Calculations

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Figure 6-1: Element Member Force and Moment Demands

6.7.1 Principal Stresses

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6.7.2 Steel Plates

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6.7.3 Concrete Infill

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6.8 Section Capacities of Steel-Plate Composite Elements

Membrane forces (i.e., tensile axial, compressive axial, tangential shear), twisting moment, and out-of-plane flexural moments are evaluated using the methodology in Section 6.7 for the allowables in Section 6.6 for factored and service loads.

6.8.1 One-Way Out-of-Plane Shear Strength

6.8.1.1 Allowable Stresses for Factored Loads

The computation of one-way (out-of-plane) shear strength of the SCCV DP-SC panels is as shown in Subsections 5.7.5.1 and 5.7.5.2 for factored loads.

6.8.1.2 Allowable Stresses for Service Loads

Similar to the approach in ASME BPVC, Section III, Division 2, Subparagraph CC-3431.3, for one-way out-of-plane shear strength under service loads:

a) Use 50% of capacities computed as discussed in Subsections 5.7.5.1, and 5.7.5.2.

b) Use 67% of capacities computed as discussed in Subsections 5.7.5.1, and 5.7.5.2 where pressure loads due to testing exist.

c) Use 67% of capacities computed as discussed in Subsections 5.7.5.1, and 5.7.5.2 where secondary forces (e.g., thermal) are included. However, a separate check with no secondary forces induced demands is required using 50% of capacities computed per Subsections 5.7.5.1, and 5.7.5.2 only as in (a) above.

6.8.2 Two-Way (Punching) Shear Strength

6.8.2.1 Allowable Stresses for Factored Loads

The two-way (punching) shear strength of the SCCV DP-SC panels under localized concentrated loads is calculated as shown in Subsection 5.7.5.3 for factored loads.

6.8.2.2 Allowable Stresses for Service Loads

Similar to the approach in ASME BPVC, Section III, Division 2, Subparagraph CC-3431.3, for two-way (punching) shear strength under service loads:

a) Use 50% of capacities computed as discussed in Subsection 5.7.5.3.

b) Use 67% of capacities computed as discussed in Subsection 5.7.5.3 where pressure loads due to testing exist.

c) Use 67% of capacities computed as discussed in Subsection 5.7.5.3 where Secondary forces (e.g., thermal) are included. However, a separate check with no secondary forces induced demands is required using 50% of capacities computed per Subsection 5.7.5.3 as in (a) above.

6.8.3 Out-of-Plane Shear Interaction Checks

6.8.3.1 Out-of-Plane Shear Interaction for Factored Loads

The out-of-Plane (radial) shear interaction check for the SCCV DP-SC panels is calculated as shown in Subsection 5.7.6 for factored loads.

6.8.3.2 Out-of-Plane Shear Interaction for Service Loads

Similar to the approach in ASME BPVC, Section III, Division 2, Subparagraph CC-3431.3, for one-way shear interaction under service loads, for equation [5-32]:

a) Use 50% of V_c and $V_{c\,conc}$ as defined in Subsection 5.7.6.
b) Use 67% of V_c and $V_{c\,conc}$ as defined in Subsection 5.7.6 where pressure loads due to testing exist.
c) Use 67% of V_c and $V_{c\,conc}$ as defined in Subssection 5.7.6 where secondary forces (e.g., thermal) are included. However, a separate check with no secondary forces induced demands is required using 50% of V_c and $V_{c\,conc}$ as defined in Subsection 5.7.6 as in (a) above.

6.9 Allowable Bearing Stress of Containment Steel-Plate Composite elements

6.9.1.1 Allowable Stresses for Factored Loads

Under Factored loads, per ASME BPVC, Section III, Division 2, Subparagraph CC-3421.9, the maximum bearing stress in concrete shall not exceed $0.60\ f_c'$.

6.9.1.2 Allowable Stresses for Service Loads

Similar to the approach in ASME BPVC, Section III, Division 2, subparagraph CC-3431.3, under Service loads, the maximum bearing stress in concrete shall not exceed $0.30\ f_c'$.. Where pressure loads due to testing exist, the maximum bearing stress in concrete shall not exceed $0.40\ f_c'$.

Under Service loads, where Secondary forces (e.g., thermal) included, the maximum bearing stress in concrete shall not exceed $0.40\ f_c'$. However, a separate check with no secondary forces induced demands is required with a maximum bearing stress in concrete of $0.30\ f_c'$.

6.10 Impulsive and Impactive Design

The BWRX-300 SCCV is designed for impulsive and impactive loads per the regulatory guidelines of NUREG-0800 SRP 3.8.1, Appendix A.

ASME BPVC, Section III, Division 2 provisions are not fully applicable to DP-SC containment. Shear requirements and deformation limits for the containment design are determined as shown in Section 5.8.

6.11 Design of Brackets and Attachments

Similar to ASME BPVC, Section III, Division 2, Subsection CC, Subarticles CC-3125, CC-3650, and CC-3750 requirements, brackets and attachments connected to the SCCV structure are designed and analyzed using accepted techniques applicable to beams, columns, and weldments such as those illustrated in ANSI/AISC N690 and ANSI/AISC 360-16.

6.12 Design and Detailing of Penetrations and Openings

The design and detailing of the SCCV penetrations and openings is coordinated with the fabricator and meets the requirements of ASME BPVC, Section III, Division 2, Subsection CC, Subsubarticle CC-3740 to the extent applicable to DP-SC modules.

6.12.1 Design and Detailing Requirements of Large Openings

Design and detailing of large openings is in accordance with the provisions of ANSI/AISC N690, Section N9.1.7b.

6.12.2 Design and Detailing Requirements Around Bank of Small Penetrations and Openings

Design and detailing of bank of small openings is in accordance with the provisions of ANSI/AISC N690, Section N9.1.7c.

6.13 Welded Construction of Diaphragm Plate Steel-Plate Composite Containment

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Figure 6-2: Illustration of Typical Welded Joint Locations for all Joint Categories

Table 6-2: Weld Categories Applicability to Diaphragm Plate Steel-Plate Composite (DP-SC) Containment Vessel

Weld Category	Definition	Permissible Types of Welded Joints and Rules for Making Welded Joint(1)	Required Examination of Welds(3-6)
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Figure 6-3: DP-SC Typical Welded Joint Details

6.14 Design of Steel-Plate Composite Connections

ASME BPVC, 2021 Edition, Section III, Division 2, Subsection CC does not include requirements for the design of SC connections. The requirements of ANSI/AISC N690, Appendix N9, Section N9.4 are adapted as described in Section 5.11, to the design of the SCCV splices, slab-to-wall and wall-to-mat foundation connections.

6.15 Fabrication and Construction Requirements

The fabrication and construction requirements for the SCCV DP-SC modules follow ASME BPVC, Section III, Division 2, Subsection CC, Article CC-4000, as applicable, in addition to the Regulatory Guidance of Position 10 reported in RG 1.136 related to CC-4240 Concrete Curing. Applicable Subarticles, Subsubarticles, Paragraphs, Subparagraphs, or Subsubparagraphs referenced in Article CC-4000, are followed to the extent they apply to DP-SC modules without reinforcing steel or tendons. Leak tightness requirement related to liners are only applicable to the inner faceplate (i.e., containment side) of DP-SC modules.

The following sections of ASME BPVC, Section III, Division 2, Subsection CC, Article CC-4000 are not applicable to the construction and fabrication of DP-SC modules:

- CC-4122.3 Prestressing System Material and CC-4400 Fabrication and Installation of Prestressing Systems

  Reason for non-applicability: Prestressing systems are not used in the construction of the SCCV.

- CC-4230 Preplaced Aggregate Concrete and CC-4270 Repairs to Concrete

  Reason for non-applicability: Repairing concrete using preplaced aggregate concrete is not applicable to the construction of DP-SC modules.

  Concrete consolidation and filling are verified through mockups per CC-4226.3 requirements. Visual inspection of DP-SC modules is difficult. Detectors of concrete filling, vent holes, cameras, telltale tubes are used to ensure proper concrete filling of modules.

- CC-4250 Formwork and Construction Joints, except CC-4251.3

  Reason for non-applicability: Temporary formworks are not required for DP-SC modules construction. SC modules are used as permanent concrete forms. Therefore, only CC-4251.3 is applicable to SC construction.

  Concrete construction joints are not used in DP-SC modules construction. Only cold formed joints between concrete lifts exist that require no surface preparation. Faceplates and diaphragm plates ensure reinforcement continuity through the cold formed joints.

The requirements of the following CC-4000 subsections are amended to adapt them to the construction and fabrication of DP-SC modules:

- CC-4226.3 Placeability Tests

  Basis of amendment: Mock-up specimens for the placeability tests contain representatively complicated portions of SCCV configurations, such as special joints with surrounding structures, penetration sleeves, horizontal stiffener plate, and other embedment. Concrete mix, pumps, other equipment, and procedures used in the tests are as similar as practically possible to those used in the actual construction of the SCCV.

- Weld joints applicable to DP-SC construction are defined in Table 6-2. These categories shall be used in lieu of Paragraph CC-4542 rules for making welded joints including Subparagraphs CC-4542.1 and CC-4542.2 applicable to concrete liner.

The following additional requirements are established for the design of the BWRX-300 SCCV:

- Empty DP-SC modules are to be properly stiffened not to cause excessive deformations or distortions during the construction and concrete placement.
- Concrete filling procedures are demonstrated using construction mockups to secure filling and consolidation especially beneath the penetration sleeves and horizontal components (i.e., slabs and mat foundation).
- In addition to the tolerance requirements in Section 5.16, the Construction Specification shall delineate the tolerance requirements for fabrication and construction of DP-SC SCCV. The Designer shall ensure that the tolerances specified in the Construction Specification are compatible with the design assumptions. The SCCV analysis shall consider deviations in modules geometry due to the fabrication and erection tolerances, which are stated in ASME Section III, Division 2, Paragraph CC-4522, and any additional tolerances stated in the Construction Specification.
- Consideration shall be given to the limitations of interpass temperatures for quenched and tempered material to avoid detrimental effects on the mechanical properties.
- The requirement of ASME BPVC, Section III, Subsubparagraph CC-4532.2.1 (e) is revised as follows for the DP-SC SCCV: "The identification of welders or welding operators is not required for non-structural attachment welds provided that the Fabricator or Constructor maintains a system to permit the Inspector to verify that all such attachment welds were made by qualified welders or welding operators."
  Structural attachments will utilize the same practices for documentation provided in Subsubparagraph CC-4532.2.1(c).

6.16 Construction Testing and Examination Requirements, Including Weld Examination and Qualification for Diaphragm Plate Steel-Plate Composite Modules

This section discusses construction testing and examination requirements of DP-SC components, tests and examinations of materials including steel, concrete and welds, and qualifications of personnel performing the tests and examinations.

The requirements for construction testing and inspection of materials and welds of ASME Section III, Division 2, Subsection CC, Article CC-5000 are followed, where applicable. Concrete and concrete constituents are examined and tested in accordance with Subarticle CC-5200 including the following modifications:

- Concrete used in DP-SC modules is exempted from visual inspection requirements and therefore can be inspected using nondestructive testing techniques as described in Section 5.18. The nondestructive tests can either be performed directly on the concrete surface (where possible) or through the faceplate depending on the technique being used to detect hidden defects, honeycombing, and voids.

- To monitor concrete during placement in highly congested areas (e.g., connections), cameras can be installed inside the fabricated steel modules to assess the concrete flow/consolidation. These cameras can remain embedded in the concrete infill after hardening. Alternatively, the demonstration of the filling and consolidation of concrete can be achieved on site through the testing of mock-up specimens as per ASME BPVC, Section III, Division 2, Subsection CC, Article CC-4000, Subparagraph CC-4226.3.
- Additional concrete sampling requirements (beyond those described in ASME BPVC, Section III, Division 2, Subsection CC, Article 5000, Subparagraph CC-5232.3 for the compressive strength testing program) provided in Section 3.2.2.1 of NEDO-33914-A are used to address NUREG/CR-7193 for the effect of small volume of concrete placed for the BWRX-300.

Welds examination is in accordance with Subarticle CC-5500, considering the following modifications:

- Where radiographic examination is required and the joint detail does not permit the examination to be performed (i.e., due to configuration of the SCCV, if backup bars are used per Subparagraph CC-4542.1, or obstruction of the headed studs), magnetic particle or ultrasonic examination method for the full length of the weld can be used as allowed by Paragraph CC-5521.
- Leak testing required by Subparagraph CC-5521(e) and described in Paragraph CC-5536 is limited to the inner steel faceplate welds (except attachment welds that do not penetrate the inner faceplate), and is to be completed prior to concrete infill placement.
- Required examination for different welding categories shall follow the requirements described in the Table 6-2 instead of Paragraph CC-5521 requirements.

6.17 Steel-Plate Composite Containment Vessel Pre-Service Inspection and Testing Requirements

The SCCV SIT follows the requirement of ASME BPVC, Section III, Division 2, Subsection CC, Article CC-6000 as applicable. Applicable Subarticles, Subsubarticles, Paragraphs, Subparagraphs, or Subsubparagraphs referenced in Article CC-6000, are followed to the extent they apply to DP-SC modules without reinforcing steel or tendons. Leak tightness requirement related to liners are only applicable to the inner faceplate (i.e., containment side) of DP-SC modules.

The following ASME BPVC, Section III, Division 2, Subsection CC, Article CC-6000 sections related to containment pre-service inspection and testing are not applicable to the SCCV:

- Concrete visual inspection as spalling or unusual cracking of the concrete required by CC-6210
- CC-6225: Crack Measurements
- CC-6350: Surface Cracking
- Concrete visual inspection for permanent damage to the concrete structure as required by CC-6410(b)
- CC-6420: Surface Cracks

- Reporting a summary and discussion of crack measurements as required by CC-6530(c)

Reason for non-applicability: DP-SC construction has an advantage of having the main reinforcement plates exposed and thus strain measurements and damage detection can be performed easily during the pressure test. However, concrete surface crack measurements and mapping, and concrete surface visual inspection are not applicable to DP-SC construction as the concrete is inaccessible and enclosed within the steel faceplates. This is similar to inaccessible concrete behind the liner in concrete containment. SCCV structural integrity is verified by comparing the displacement measurements to the analytical model predictions following ASME BPVC, Section III, Division 2, Subsection CC, Subsubarticles CC-6160 and CC-6510. Furthermore, faceplate strain measurements are compared to the analytical model predictions for the prototype containment (i.e., BWRX-300 first tested unit treated as a prototype containment as per ASME Section III, Subsubarticle CC-6150 definition).

Mock-up tests are performed per ASME BPVC, Section III, Division 2, Subsection CC, Article CC-4000, Subparagraph CC-4226.3 to confirm and demonstrate the filling and consolidation of concrete. The mock-up specimens contain representative portions of SCCV configurations, such as special joints with surrounding structures, penetration sleeves, horizontal stiffener plate, and other embedment. Concrete mix, pumps, other equipment, and procedures used in the tests are as similar as practically possible to those used in the actual construction of the SCCV.

6.18 Effect of Curvature on Behavior of Steel-Plate Composite Containment Vessel

As discussed in Section 5.12, the SCCV wall curvature is included in the integrated RB FE model.

Faceplates rolling and bending shall follow ASME BPVC, Section III, Division 2, Subsection CC, Paragraph CC-4521 requirements.

6.19 Corrosion Protection of Diaphragm Plate Steel-Plate Composite Modules

The corrosion protection approach discussed in Section 5.15 is applicable to the SCCV structure.

6.20 Fire Resistance of Diaphragm Plate Steel-Plate Composite Modules

The BWRX-300 SCCV is designed to have a 3-hour fire resistance rating. The design and evaluation criterion for fire protection of the SCCV are as described in Section 5.13.

6.21 Vent Hole Requirements

The SCCV vent hole requirements are the same as those for non-containment DP-SC structures discussed in Section 5.14 with the following exceptions:

- Vent holes are only used on the external faceplate of the containment walls and slabs.
- Vent holes are not used on the internal faceplates of the leak boundary.
- Vent holes are not used on the internal face of the water storage tanks and pools.
- Vent holes are not used on the external face plated facing the soil.

6.22 Steel-Plate Composite Containment Vessel Inservice Inspection and Testing Requirements

The inservice inspection and testing program supports the aging management plan for the integrated RB described in Section 5.18. The aging management plan includes the details of the inservice inspection and testing methodologies.

A pre-service and periodic inservice inspection and testing program is established for the SCCV to meet the requirements of ASME Section XI, Division 1, Subsections IWE and IWL, as per 10CFR50, 50.55a (b)(2)(viii) and (b)(2)(ix). The pre-service examinations are performed prior to plant startup following the completion of the SIT. The inservice inspections of the SCCV, including penetrations, are performed after the completion of SIT and following plant outages (such as refueling shutdowns or maintenance shutdowns) in accordance with ASME Section XI, Subsections IWE and IWL and before each periodic ILRT in accordance with Appendix J to 10 CFR 50. In accordance with 10 CFR 50.55a(g)(4) and ASME Section XI, Subsection IWE, the accessible inner and outer faceplates, welds and their integral attachments are subject to inservice inspection. The DP-SC diaphragm plates, headed stud anchors, embedments, and their welds are inaccessible after concrete infill placement, and, therefore, are exempted from the inservice inspection examination requirements of Article IWE-2000 as per IWE-1220(b), for embedded or inaccessible portions of containment vessels, parts, and appurtenances that meet the requirements of the original Construction Code. Subsequently, the requirements listed in IWE-1232 are not applicable to these components. All welds of the diaphragm plates and headed stud anchors will be examined before concrete infill placement in accordance with Section 6.16. As part of the inner and outer faceplates inservice inspection, any indication of separation of the DP-SC faceplates from its stud anchor to the concrete infill, or separation of the anchor from the concrete, the bulging (inward or outward curvature) of the faceplates shall require corrective action or engineering evaluation to meet the requirements of IWE-3122 prior to continued service.

For the purposes of inservice inspection, Subsections IWE and IWL of ASME Section XI are used where applicable to SCCV DP-SC modules. Metallic components of the SCCV DP-SC modules (inner and outer faceplates, diaphragm plates, headed stud anchors, and welds), that are pressure retaining components and their integral attachments, shall meet the inservice inspection, repair, and replacement requirements applicable to Class MC components as defined in ASME Section XI, Subsection IWE. DP-SC concrete infill shall meet the inservice inspection, repair, and replacement requirements applicable to Class CC concrete containment pressure retaining components as defined in ASME Section XI, Subsection IWL. Note that the SCCV DP-SC modules, including the inner and outer faceplates, diaphragm plates, headed stud anchors, and concrete infill are part of the containment pressure boundary, whereas the inner faceplate only act as a leak-tight barrier, as explained in Section 6.1.

The following are the considerations for the inservice inspection and testing of the SCCV concrete infill:

- According to ASME BPVC, Section XI, Division 1, Subsection IWL, Subsubarticle IWL-1220, portions of the concrete surface that are covered by the faceplates are exempted from visual examination. This exemption applies to all concrete infill used in the SCCV due to their inaccessibility for visual examination.

Critical locations within the SCCV, such as areas around penetrations and/or at stress concentrations, are also exempted from visual examination. Potential examination techniques at these areas include the use of acoustic emission monitoring during the SIT and subsequent ILRTs to detect and localize cracking activities of the concrete infill. The acoustic emission technique has been extensively used in the crack detection and quantification of concrete structures and its effectiveness was also extended to monitoring the health monitoring of SC shear walls (Reference 9-94). Recently, this approach was successfully implemented in pressure-induced damage monitoring in prestressed concrete of a 1:3 scale nuclear containment structure (VeRCoRs mock-up) in France (Reference 9-95).

- If conditions exist after visual examination in accessible areas of the faceplates that indicate the presence of or result in the degradation of the inaccessible concrete, other means of inspection, such as the nondestructive examination techniques described in Section 5.18, can be used to evaluate the condition of concrete.
- Testing mock-up specimens (used during construction) exposed to similar conditions as the SCCV can also provide a means for destructive testing (e.g., core testing) to evaluate the condition of the concrete infill over time as a result of aging degradation effects.

6.23 SCCV Beyond Design Basis Evaluation

This section provides guidance on the BWRX-300 approach for meeting the SCCV structural integrity requirements in:

- 10 CFR 50, Appendix A, GDC 50, “Containment Design Basis,” related to the containment structural capacity for design-basis internal pressures presented in Subsection 6.23.1
- 10 CFR 50.44(c)(5) related to the combustible gas control presented in Subsection 6.23.2

6.23.1 Ultimate Pressure Capacity of Steel-Plate Composite Containment Vessel

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6.23.2 Steel-Plate Composite Containment Vessel Robustness Against Combustible Gas Pressure Loads

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6.23.3 Steel-Plate Composite Containment Vessel Behavior Following a Severe Accident

Per U.S. NRC SECY-93-087 , the BWRX-300 containment under the more likely severe accident conditions shall:

- Maintain its role as a reliable leak-tight barrier for approximately 24 hours following the onset of core damage
- Continue to provide a barrier against the uncontrolled release of fission products following the initial 24-hour period

The containment robustness to meet these requirements is evaluated following the methods provided in Regulatory Position 3 of U.S. NRC RG 1.216.

The BWRX-300 design minimizes generation of combustible, non-condensable gases from corium-concrete interaction.

6.23.3.1 Evaluations for 24-Hour Period Following the Onset of Core Damage

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6.23.3.2 Evaluation for Period Following Initial 24 Hours After the Onset of Core Damage

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7.0 NATIONAL REACTOR INNOVATION CENTER (NRIC) DEMONSTRATION PROJECT OVERVIEW

NRIC demonstration project is a collaboration between various nuclear industry stakeholders, including GEH and Purdue University, for testing the DP-SC design, including application to containment, to be used with BWRX-300. The confirmatory prototype tests are performed on specimens made of Steel Bricks™ representing DP-SC modules manufactured using a proprietary and unique process.

Other types of DP-SC modules, such as the ones shown in Figure 3-5 and Figure 3-6, have the same overall performance characteristics as Steel Bricks^{TM}. As a result, the confirmatory test results obtained for Steel Bricks^{TM} discussed in Section 7.3 are applicable to other types of DP-SC modules.

7.1 Objective of the NRIC Project

The NRIC ACT Demonstration Project is comprised of two phases. NRIC Phase 1 (Detailed Design and Structural Performance Testing) and NRIC Phase 2 (Construction, Testing, Decommissioning Activity and Quality Control).

The main objectives of the NRIC Demonstration Project (NRIC Project) include:

- Demonstration of the structural performance of DP-SC modules,
- Development and demonstration of the efficient fabrication, installation, and construction processes for use of DP-SC and in particular Steel Bricks^{TM} for nuclear applications, and
- Advancing the technical readiness level of the DP-SC technology and establishing regulatory process development.

The objectives of the confirmatory prototype tests (NRIC Phase 1) are to evaluate the performance of DP-SC modules for various loading conditions applicable for containment (i.e., pressure-retaining) and non-containment applications. A total of 14 Steel Bricks™ scaled prototype specimens are constructed and tested. The scaled prototypes are designed to be representative of the following components:

1. Mat foundation
2. Inner cylindrical shaft (i.e., SCCV wall)
3. Inside cylindrical shaft (i.e., SCCV wall)-to-mat foundation connection
4. Outer cylindrical shaft (i.e., RB exterior wall)-to-mat foundation connection
5. RB exterior wall

The confirmatory test results are to support:

- Applicability of ANSI/AISC N690, Appendix N9 with modifications in Section 5.0 for the design and construction of SC structures made of DP-SC modules
- Applicability of the proposed design approach presented in Section 6.0 for the design and construction of containment structures DP-SC modules

7.2 NRIC Phase 1 Test Plan

7.2.1.1 NRIC Phase 1 Prototype Testing

Table 7-1 summarizes the prototype testing for NRIC Phase 1 selected to support the technical evaluation of the modified ANSI/AISC requirements provided in Section 5.0 of this report. Further details of the Prototype Test Plan for each test are presented in subsequent sections. Full details including loading, specimen geometry and materials are presented in the NRIC Prototype Test Plan.

Figure 7-1 and Figure 7-2 show the test specimens for out-of-plane shear for mat foundation, Figure 7-3 shows bi-axial tension test specimens for SCCV, Figure 7-4 shows in-plane shear test specimens for SCCV-to-mat foundation connection, Figure 7-5 shows in-plane shear + out-of-plane shear test specimen for RB-to-mat foundation connection and Figure 7-6 shows missile impact test specimens for the RB.

The prototype test specimens are scaled to facilitate testing using the existing loading assemblies available at the testing laboratory. All test specimen geometric properties are scaled based on SC section sizes and steel plate thicknesses comparable to the conceptual design section properties of the BWRX-300 full-scale structure. Self-consolidating concrete was used as concrete infill in the NRIC Phase 1 testing specimens. Hence the NRIC confirmatory test conclusions are directly applicable to the BWRX-300 integrated RB design.

The specimens are approximately 1:2, 1:3, or 1:6 scale depending on the loading and estimated capacity. The scaling refers to the geometric size of the test specimen.

Pre-test calculations and numerical simulations using FE analysis were performed to calculate the capacities of the specimens and ensure they were within the limits of the testing apparatus. These calculations were based on ANSI/AISC N690 code provisions, with modifications as applicable. Material properties taken directly from material test reports, which are usually higher than the specified minimum code/standard properties, were used in the pre-test calculations to provide predictions of the expected specimen capacities. However, the acceptance criteria are based on the nominal capacities calculated based on specific minimum steel and concrete material strengths without the resistance factor ϕ and compared with experimental results.

NEDO-11209-A, GEH quality assurance program, was implemented during the testing program which was performed using a graded approach to fabrication and testing activities. GEH inspection reports demonstrating procurement and manufacturing traceability, and GEH witness test reports were documented. Testing plan and results were reviewed and accepted per NEDO-11209-A.

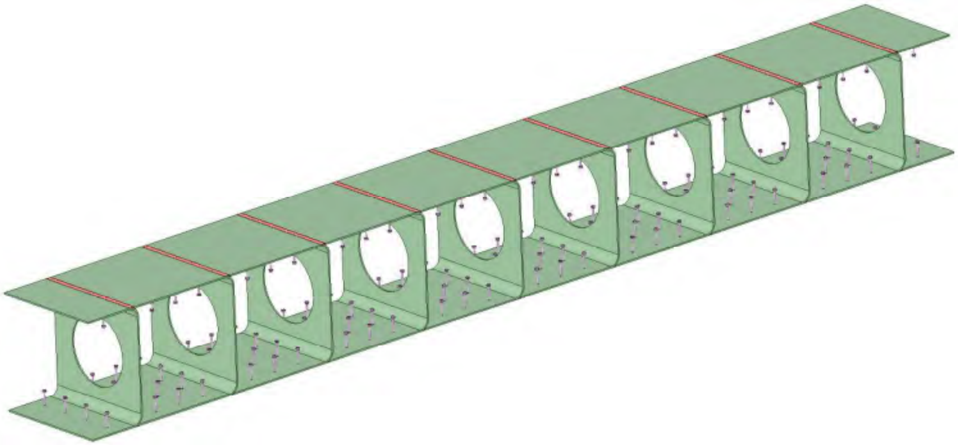

Figure 7-1: Out-of-Plane Shear Test Specimen -
Diaphragm Plate Orientation Parallel to Loading (OOPV-1)

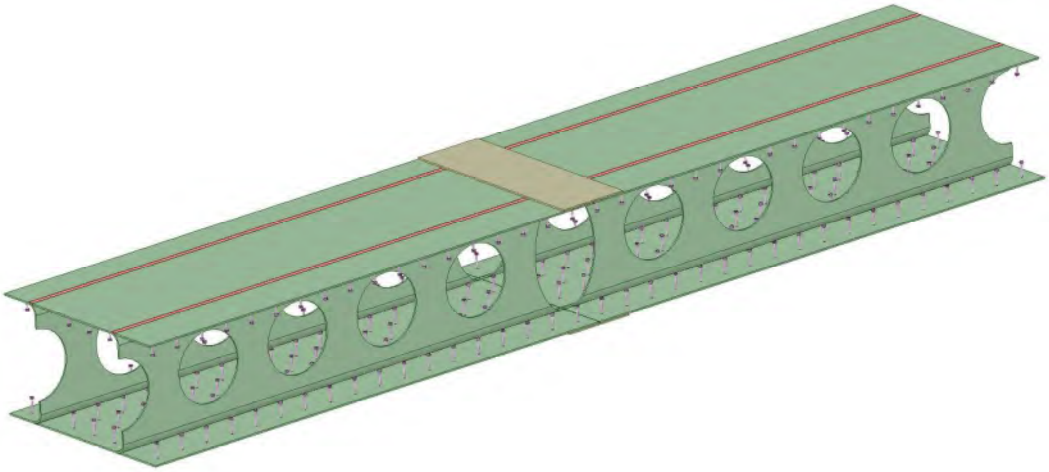

Figure 7-2: Out-of-Plane Shear Test Specimen -
Diaphragm Plate Orientation Perpendicular to Loading (OOPV-2)

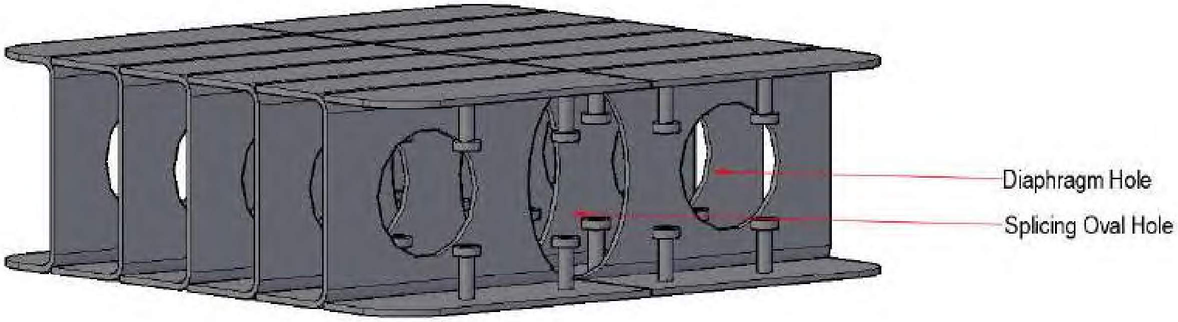

Figure 7-3: Bi-Axial Tension Test Specimen

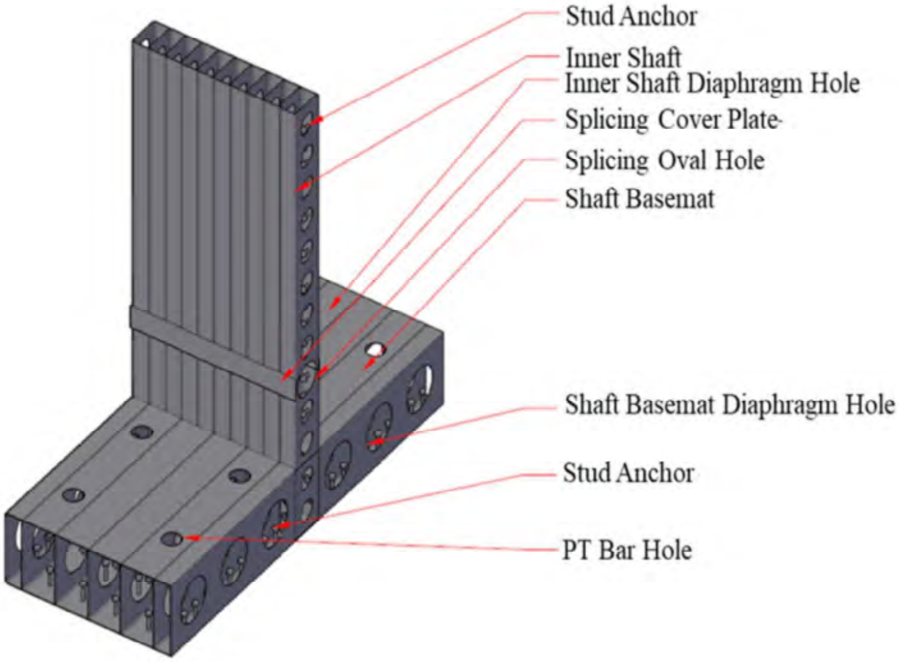

Figure 7-4: In-Plane Shear Test Specimen

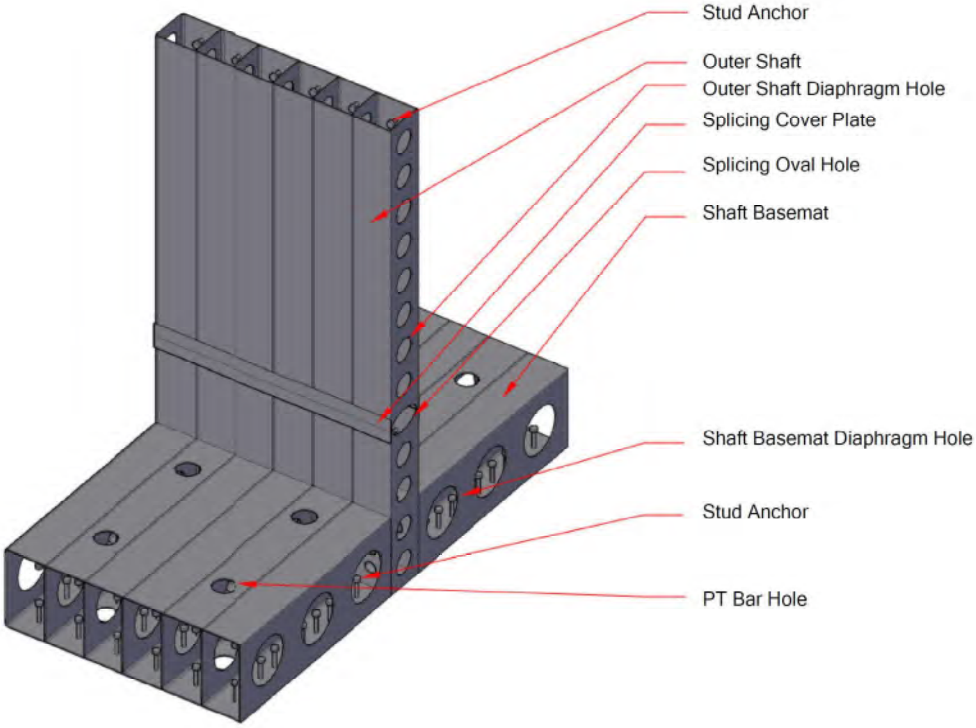

Figure 7-5: In-Plane Shear + Out-Of-Plane Shear Test Specimens

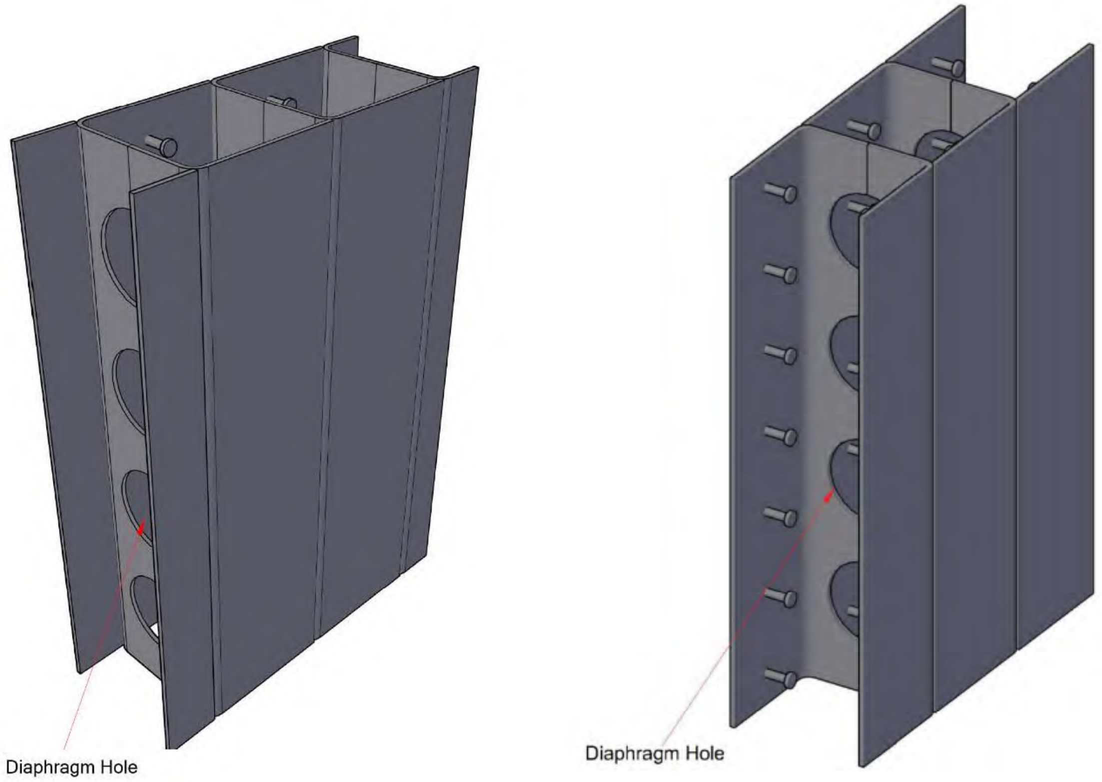

**Figure 7-6: Missile Impact Test Specimens –
Impact Location at Center Diaphragm Plate (IMP-D) (left) -
Impact Location Between Two Adjacent Diaphragm Plates (IMP-C) (right)**

Table 7-1: Summary of Steel-Plate Composite Modules with Diaphragm Plates NRIC Phase 1 Prototype Loading Tests

Test	Prototype	Test Objective	Number of Tests	Scale	Specimen	Loading Type* - Orientation	Thermal Effect
Out-Of-Plane Shear (OOPV)	Mat foundation	Confirm that the out-of-plane strength of DP-SC modules can be calculated conservatively using ANSI/AISC N690 or ACI 349 code provisions before undergoing failure due to out-of-plane shear / bending loading.	2	1:2	OOPV-1	M – Diaphragm plate parallel to loading	Ambient
					OOPV-2	M – Diaphragm plate perpendicular to loading	
Bi-Axial Tension	SCCV	Confirm that the DP-SC constructed SCCV wall and the corresponding splice detail can develop yield strength before undergoing failure due to bi-axial tension simulating effects of accident pressure and concurrent thermal loading conditions.	3	1:3	BA-1-AMB	T – Orientation 1	Ambient
					BA-1-TH	T – Orientation 1	Thermal
					BA-2-TH	T – Orientation 2	Thermal
In-Plane Shear (IPV)	SCCV-to-mat foundation connection	Confirm that the DP-SC constructed SCCV-to-mat foundation connection detail and the nearby SCCV wall-to-wall splice can develop the in-plane flexural capacity of the DP-SC constructed SCCV wall before undergoing failure due to cyclic loading simulating the effects of earthquakes along with concurrent accident thermal loading.	2	1:3	IPV-1	C	Ambient
					IPV-2	C	Thermal
In-Plane Shear + Out-Of-Plane Shear (IPV+OOPV)	RB-to-mat foundation connection	Confirm that the DP-SC constructed RB exterior wall-to-mat foundation connection detail and the nearby DP-SC constructed RB wall-to-wall splice can develop their in-plane flexural capacity, in accordance with the interaction between in-plane strength and out-of-plane strength, before undergoing failure from sustained out-of-plane loading.	2	1:3	IPV+ OOPV-1	C 40% OOPV	Ambient
					IPV+ OOPV-2	C 54% OOPV	
Missile Impact	RB	Confirm that the modified three step design method can conservatively estimate the projectile / missile impact resistance of DP-SC walls.	5	1:6	IMP-D-1 IMP-D-2	I – on center diaphragm plate	Ambient
					IMP-C-3 IMP-C-4 IMP-C-5	I – between two adjacent diaphragm plates	

*Loading Type Key: M – Monotonic Shear C – Cyclic Shear T – Tension I – Missile Impact

7.2.2 Out-Of-Plane Shear (OOPV)

7.2.2.1 Test Objective

The out-of-plane shear (OOPV) tests aim to confirm that the out-of-plane strength of DP-SC modules can be calculated conservatively using ANSI/AISC N690 or ACI 349 code provisions, as applicable, before undergoing failure due to out-of-plane shear / bending loading.

7.2.2.2 Acceptance Criteria

The acceptance criteria for the out-of-plane shear tests are as follows:

1. The specimens will develop flexural yielding before shear failure. That is, yielding of the tension faceplate will occur prior to shear failure.
2. The load carrying capacity of the specimens will be equal to or greater than the load associated with the nominal flexural capacity (M_n) calculated using ANSI/AISC N690 or ACI 349 code equations, whichever applies to the configuration. Nominal capacity is computed using specified minimum steel and concrete material strengths,
3. The specimens exhibit some ductility before failure achieving a minimum ductility ratio of 3.0.

7.2.2.3 Specimen Details

The specimens are illustrated schematically in Figure 7-1 and Figure 7-2. There are two 1:2 scaled specimens (OOPV-1 and OOPV-2) representing two different orientations of diaphragm plate.

Orientation OOPV-1 (Figure 7-1) is used to represent diaphragm plates oriented parallel to the loading (transverse to the longitudinal direction of the specimen). Orientation OOPV-2 (Figure 7-2) is used for diaphragm plates oriented perpendicular to the loading (parallel to the longitudinal direction of the specimen). Specimen OOPV-2 includes a horizontal (longitudinal) splice with cover plates and an oval-shaped splicing hole to represent the actual construction of the mat foundation in the BWRX-300.

7.2.2.4 Test Set-Up

The test subjects the specimens to monotonic loading in a four-point bending test at ambient temperature with a shear span-to-section thickness ratio of 2.5 designed to develop flexural yielding before shear failure. The loading simulates the effects of reactions from the soil foundation support on the mat foundation.

Yielding is established using strain gauges attached to the tension faceplate at locations near the midspan subjected to maximum bending moment. The specimens are loaded until the specified load carrying capacity and displacement per the acceptance criteria are achieved.

7.2.2.5 Calculated Capacities

For the out-of-plane shear test OOPV-1, diaphragm plates oriented parallel to the loading, nominal shear capacity is based on ANSI/AISC N690 code provisions, as presented in Subsection 5.7.5.1, Equation [5-26]. The nominal flexural capacity is calculated based on ANSI/AISC N690 code provisions, as presented in Subsection 5.7.3.1, Equation [5-19].

For the out-of-plane shear test OOPV-2 with diaphragm plates oriented perpendicular to the loading, the nominal shear capacity is calculated based on modified ANSI/AISC N690 code provisions as provided in Reference 9-66 (refer to Subsection 5.7.5.2, Equations [5-28] to [5-31]). The nominal flexural capacity is calculated based on ACI 349 code provisions as developed and verified by Reference 9-64 (refer to Subsection 5.7.3.2, Equation [5-20]).

The governing failure mode for both tests is expected to be flexural yielding of the steel faceplates. The calculated nominal capacities are compared with the experimental strengths.

7.2.3 Bi-Axial Tension

7.2.3.1 Test Objective

The bi-axial tension tests aim to confirm that the DP-SC constructed SCCV wall and corresponding splice detail can develop yield strength before undergoing failure due to bi-axial tension, simulating the effects of accident pressure and concurrent thermal loading conditions.

7.2.3.2 Acceptance Criteria

The acceptance criteria for the bi-axial tests are as follows:

1. The bi-axial specimen under the ambient condition shall reach the yield strength of the steel faceplates accounting for the bi-axial stress state.
2. The bi-axial specimen under the accidental thermal condition shall reach the yield strength of the steel faceplates for the bi-axial stress state and the elevated temperature.

7.2.3.3 Specimen Details

The specimen is illustrated schematically in Figure 7-3. There are three 1:3 scale specimens and all are identical in the geometry and material properties.

The specimen design includes a central splice with a CJP and oval-shaped hole to simulate the joint between different DP-SC units.

7.2.3.4 Test Set-up

Differences in the three tests are primarily the loading orientations and the existence of thermal effects (refer to Table 7-1). For Orientation 1, the applied tension along the brick width will be twice compared to that along the brick length. For Orientation 2, the applied tension along the brick length will be twice compared to that along the brick width.

The applied tension force magnitudes follow a 2:1 ratio to reproduce the membrane stress of a cylindrical shell structure under internal pressure. The load is increased monotonically in stages up to load representative of the BWRX-300 accidental design pressure. The specimens are loaded until the steel plates undergo yielding per the acceptance criteria.

For the tests with thermal loading, one-sided heating is applied to the prototype specimens. The elevated temperature is representative of BWRX-300 accident thermal loading. As the specimens are 1:3 scaled structures compared to the full-scale inner shaft, the heating time is modified so the scaled specimens have a similar through-thickness temperature profile to the full-scale structure.

7.2.3.5 Calculated Capacities

For the bi-axial tension test, the nominal strength is calculated according to the von Mises yield criteria, which is typically used and referenced in ASME BPVC. The calculated nominal capacity is compared with the experimental strengths.

7.2.4 In-Plane Shear (IPV)

7.2.4.1 Test Objective

The In-Plane Shear (IPV) tests aim to confirm that the DP-SC constructed SCCV-to-mat foundation connection detail and the nearby SCCV wall-to-wall splice can develop the in-plane flexural capacity of the DP-SC constructed SCCV wall before undergoing failure due to cyclic loading, simulating the effects of earthquakes along with concurrent accident thermal loading.

7.2.4.2 Acceptance Criteria

The acceptance criterion for the in-plane shear tests is as follows:

1. Develop the in-plane flexural capacity, defined as the plastic moment capacity, M_P, of the DP-SC constructed SCCV wall segment simplified as a concrete-filled composite member.

7.2.4.3 Specimen Details

The specimen is illustrated schematically in Figure 7-4. There are two 1:3 scale specimens and all are identical in the geometry and material properties. The wall of the specimen includes a splice with cover plates and an oval-shaped splicing hole representative of the joint between units.

7.2.4.4 Test Set-up

The specimens are subjected to increasing cyclic in-plane shear simulating the effects of seismic loading; one at ambient temperature (IPV-1) and the other at an elevated temperature simulating accidental thermal loading conditions (IPV-2).

Force-controlled cycles are applied to measure the elastic response and displacement-controlled cycles are applied in the inelastic range as illustrated in Figure 7-7. Testing continues until the specimen fails due to concrete crushing or fracture of the steel plates/connections, or until the lateral load resistance reduces below 80% of the lateral load capacity.

For the test with thermal loading (IPV-2), one-sided heating is applied to the prototype specimen as per the bi-axial tension test as discussed in Subsection 7.2.3.4. The thermal loads are then maintained, and the specimen is subjected to lateral loading in the same manner as specimen IPV-1.

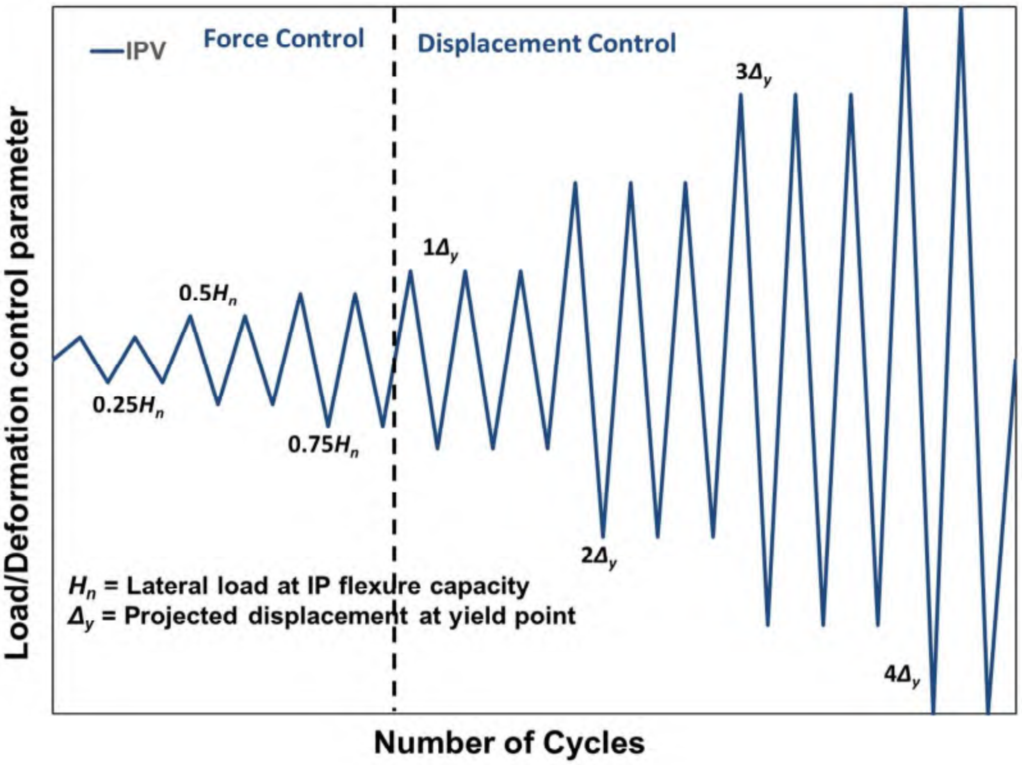

Figure 7-7: Lateral Loading Protocol for In-Plane Shear Tests

7.2.4.5 Pre-Test Calculated Capacities

For the in-plane shear test (IPV), the nominal in-plane shear capacity is calculated based on ANSI/AISC N690 code provisions. The nominal in-plane flexural capacity is calculated based on the plastic moment capacity (M_P) of the simplified concrete-filled composite wall using the plastic stress distribution method referenced in ANSI/AISC 360-16. The governing failure mode is expected to be in-plane flexural failure. The calculated nominal capacities are compared with the experimental strengths.

7.2.5 In-Plane Shear + Out-Of-Plane Shear (IPV+OOPV)

7.2.5.1 Test Objective

The in-plane shear + out-of-place shear (IPV+OOPV) tests aim to confirm that the DP-SC constructed RB exterior wall-to-mat foundation connection detail and the nearby RB wall-to-wall splice can develop their in-plane flexural capacity, in accordance with the interaction between in-plane strength and out-of-plane strength, before undergoing failure due to sustained out-of-plane loading. This test simulates lateral earth pressure and cyclic in-plane loading simulating earthquake effects.

7.2.5.2 Acceptance Criteria

The acceptance criterion for the in-plane shear + out-of-plane shear tests is as follows:

1. Develop the in-plane flexural capacity calculated based on the linear interaction between in-plane and out-of-plane flexure capacities.

7.2.5.3 Specimen Details

The specimen is illustrated schematically in Figure 7-5. The two 1:3 scale specimens are identical in the geometry and material properties. The wall of the specimen includes a splice with cover plates and an oval-shaped splicing hole representative of the joint between different units.

7.2.5.4 Test Set-up

The out-of-plane loading is monotonically applied in force-control mode until the desired out-of-plane force is achieved. The out-of-plane loading is then held constant while the specimen is subjected to incremental cyclic loading in the in-plane direction as illustrated in Figure 7-8. The in-plane load is applied under force-control for elastic cycles and displacement-control for post-yield cycles. Testing continues until the specimen fails due to concrete crushing or fracture of the steel plates/ connections, or until the lateral load resistance reduces below 80% of the lateral load capacity.

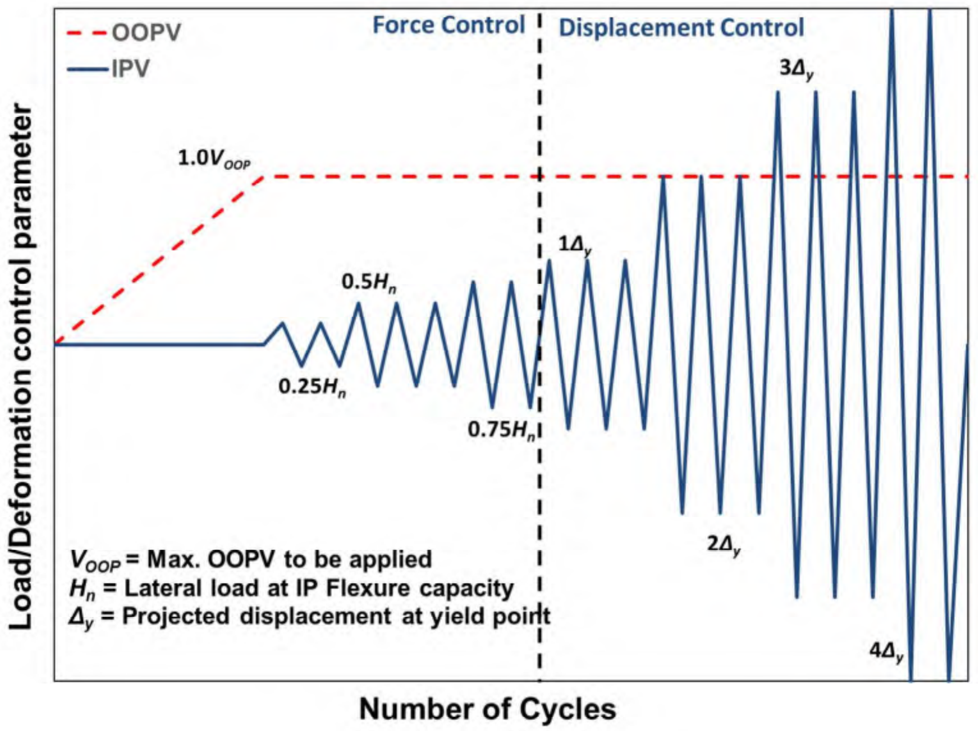

Figure 7-8: Loading Protocol for In-Plane Shear+ Out-of-Plane Shear Tests

7.2.5.5 Calculated Capacities

For the in-plane shear + out-of-plane shear test (IPV+OOPV), the various capacities are calculated as follows:

- Nominal in-plane shear capacity is calculated based on ANSI/AISC N690 code provisions
- Nominal out-of-plane shear capacity is calculated based on modified ANSI/AISC N690 code provisions provided in Reference 9-66 (refer to Subsection 5.7.5.2, Equations [5-28] to [5-31])

- Nominal in-plane flexural capacity is calculated based on the plastic moment capacity (M_P) of the simplified concrete-filled composite wall using the plastic stress distribution method referenced in ANSI/AISC 360-16
- Nominal out-of-plane flexural capacity is calculated based on ACI 349 code provisions as developed and verified by Reference 9-64 (refer to Subsection 5.7.3.2, Equation [5-20])

The calculated nominal capacities are compared with the experimental strengths. Flexural yielding is expected to be the governing failure mode in both in-plane and out-of-plane directions for both specimens; that is the specimens are expected to develop the flexural capacity at the base before the shear capacity is achieved. It is expected that the application of out-of-plane forces will reduce the in-plane capacity of the specimens. The actual reduction in capacity is ascertained from the experimental results and plotted on the interaction diagram as illustrated in Figure 7-9. In Figure 7-9 the linear interaction (yellow) between the in-plane and out-of-plane flexure is a conservative estimation while the parabolic interaction (purple) is expected to be closer to the actual experimental response. The data points for the two experiments are expected to lie above the linear interaction curve for the tests to satisfy the acceptance criteria.

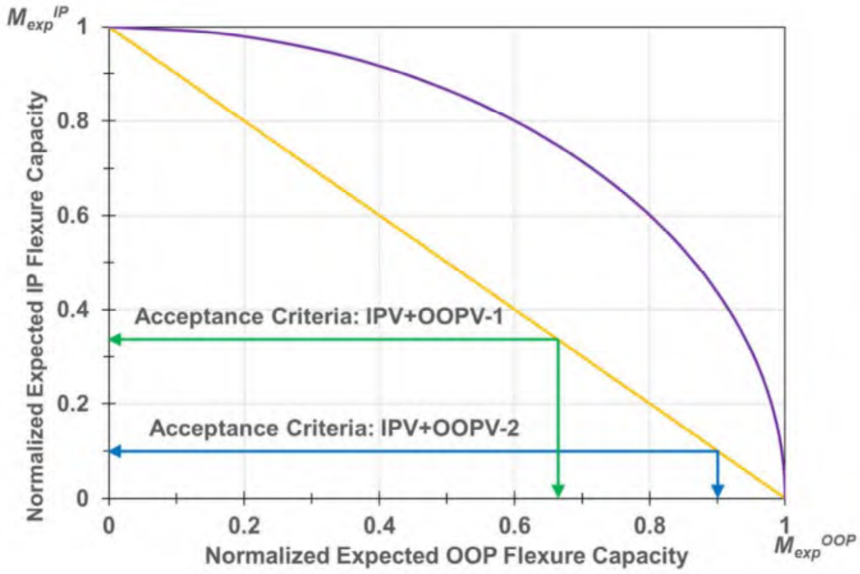

Figure 7-9: Illustration of Interaction between In-Plane and Out-of-Plane Flexural Capacities

7.2.6 Missile Impact

7.2.6.1 Test Objective

The missile impact tests aim to confirm that the modified three step design method (Reference 9-69) can conservatively estimate the projectile/missile impact resistance of DP-SC walls.

7.2.6.2 Acceptance Criteria

The acceptance criterion for the missile impact tests is as follows:

1. Experimental results for missile perforation resistance of small-scale DP-SC specimens are conservative with respect to the estimated missile perforation resistance calculated by the Modified Design Method for DP-SC walls (Reference 9-69).

7.2.6.3 Specimen Details

The specimens are illustrated schematically in Figure 7-6 and are representative of a BWRX-300 RB wall. There are five 1:6 scale specimens that are designed with two different orientations to enable impact loading to be applied from a missile impacting at different locations on the DP-SC specimen. Missile impact is on the center diaphragm plate (two specimen tests designated IMP-D) or between two adjacent diaphragm plates (three specimen tests designated IMP-C). The specimens have identical material properties.

7.2.6.4 Test Set-up

The test subjects the specimens to impact loading from a nondeformable flat-nosed missile with a projectile diameter of 1 inch (25.4 mm) and a weight of 2 lbs (0.9 Kg). The main test parameters in the testing program are impact location and impact velocity.

A high-speed camera is used to capture the instance of the projectile impact on the prototype wall specimens and to measure the actual projectile impact velocity. Damage to the front and rear of the specimens is quantitatively and qualitatively recorded and analyzed upon completion of each test. Qualitative measures include the nature of the damage (e.g., bulging or tearing of rear faceplate). Quantitative measures include the projectile penetration depth and the rear steel faceplate bulging depth.

7.2.6.5 Calculated Capacities

Figure 7-10 shows typical stages in local failure mechanisms of SC walls due to missile impact to illustrate the range of damage modes from bulging to full perforation of the back faceplate. The actual test specimens are expected to exhibit increasing damage with increasing missile velocity.

For the missile impact tests, the perforation resistance curve generated by the Modified Design Method (Reference 9-69) for a 1-inch (25.4 mm) diameter missile is used to determine the expected velocity required to perforate the specimens for the missile weight of 2 lbs (0.9 Kg). For the Modified Design Method, refer to Subsection 5.8.2.2.1, Equations [5-33] to [5-36]. Expected damage modes are compared with the experimental results.

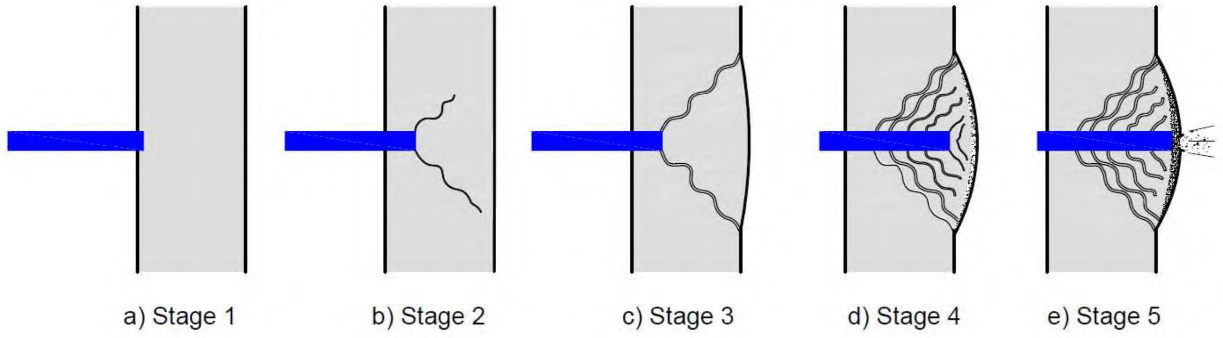

Figure 7-10: Stages in Local Failure Mechanisms of SC walls subject to Missile Impact (Adopted from Reference 9-69)

7.3 NRIC Confirmatory Prototype Phase 1 Test Results

Summaries of the NRIC Phase 1 Prototype Test results are presented in Table 7-2 and in the following subsections. Full details are presented in the NRIC Prototype Test Report (Reference 9-96). As shown in Table 7-2, all specimens met both the acceptance criteria (A) and (B).

Table 7-2: NRIC Prototype Summary Test Results

Test	Specimen	Behavior	Acceptance Criterion (A)	Acceptance Criterion (B)
			$R_{exp}/\phi R_{n\text{-}meas}$	$R_{exp}/R_{n\text{-}nom}$
OOPV	**OOPV-1**	Out-of-Plane flexure	1.61	1.93
	OOPV-2	Out-of-Plane flexure	1.45	1.74
Bi-Axial	**BA-1-AMB**	Bi-axial tension	1.11	1.24
	BA-1-TH	Bi-axial tension + thermal	1.11	1.24
	BA-2-TH	Bi-axial tension + thermal	1.11	1.24
IPV	**IPV-1**	In-plane flexural capacity	1.58	1.82
	IPV-2	In-plane flexural capacity + thermal	1.54	1.74
IPV+OOPV	**IPV+OOPV-1**	In-plane + out-of-plane shear	1.24	1.41
	IPV+OOPV-2	In-plane + out-of-plane shear	1.44	1.67
Missile Impact	**IMP-D-1,** **IMP-D-2** **IMP-C-3** **IMP-C-4** **IMP-C-5**	Missile impact resistance	See Section 7.3.5	N/A

Notes:

(A) Evaluation for original Acceptance Criterion (A) per NRIC Prototype Test Report (Reference 9-96)

$R_{exp}/ \phi R_{n\text{-}meas} \geq 1$

(B) Evaluation for alternative Acceptance Criterion (B)

$R_{exp}/R_{n\text{-}nom} \geq 1$

Where:

- R_{exp} is the experimental strength obtained from the test.
- $R_{n\text{-}meas}$ is the calculated experimental strength, calculated per the code-based/proposed equations developed in Section 5.7 using 'measured' material properties obtained from the Certified Material Test Report (and properties derived from the measured material properties).
- ϕ is the resistance factor, also termed capacity or strength reduction factor.
- $R_{n\text{-}nom}$ is the nominal strength, i.e., M_n (flexure), or V_n (shear), calculated per the code-based/proposed equations developed in Section 5.7 using nominal or specified material properties (and properties derived from nominal).

7.3.1 Out-of-Plane Shear (OOPV)

7.3.1.1 OOPV-1 Test Results

The OOPV-1 specimen was subjected to a maximum load that exceeded the calculated nominal flexural capacity. The test was terminated at this point although the specimen had not failed or lost its load carrying capacity. Steel yielding at the bottom faceplate and diaphragm plate occurred close to the flexural capacity. The specimen developed flexural yielding without undergoing any shear failure or fracture failure.

Thus, the acceptance criteria described in Subsection 7.2.2.2 were met for the OOPV-1 test.

7.3.1.2 OOPV-2 Test Results

The OOPV-2 specimen was subjected to a maximum load that exceeded the calculated nominal flexural capacity. The test was terminated at this point although the specimen had not failed or lost its load carrying capacity. Steel yielding at the bottom faceplate and diaphragm plate occurred close to the flexural capacity. The specimen developed flexural yielding without undergoing any shear failure or fracture failure.

Thus, the acceptance criteria described in Subsection 7.2.2.2 were met for the OOPV-2 test.

7.3.2 Bi-Axial Tension

7.3.2.1 BA-1 AMB Test Results

For bi-axial test BA-1-AMB at ambient temperature, the applied tension along the brick width is twice compared to that along the brick length (designated Orientation 1). The maximum tensile force from the experiment exceeded the nominal strength. The results show that the specimen can reach the yield strength of the steel faceplates accounting for the bi-axial stress state.

Thus, the acceptance criteria described in Subsection 7.2.3.2 were met for the BA-1-AMB test.

7.3.2.2 BA-1-TH Test Results

For bi-axial test BA-1-TH under the heated condition, the applied tension along the brick width is twice compared to that along the brick length (designated Orientation 1). The maximum tensile force from the experiment exceeded the nominal strength. The results show that the specimen can reach the yield strength of the steel faceplates accounting for the bi-axial stress state and elevated temperature.

Through-thickness temperature measurements were taken during the test at various thermocouple locations. Mechanical loading was initiated after the through-thickness thermal gradient was achieved. All temperatures exceeded the minimum through-thickness temperature requirement.

Due to safety concerns, the experiment was stopped when the specimen reached the expected strength.

Thus, the acceptance criteria described in Subsection 7.2.3.2 were met for the BA-1-TH test.

7.3.2.3 BA-2-TH Test Results

For bi-axial test BA-2-TH under the heated condition, the applied tension along the brick length is twice compared to that along the brick width (designated Orientation 2). The maximum tensile force from the experiment exceeded the nominal strength. The results show that the specimen can reach the yield strength of the steel faceplates accounting for the bi-axial stress state and elevated temperature.

Through-thickness temperature measurements were taken during the test at various thermocouple locations. Mechanical loading was initiated after the through-thickness thermal gradient was achieved. All temperatures exceeded the minimum through-thickness temperature requirement.

Due to safety concerns, the experiment was stopped when the specimen reached the expected strength.

Thus, the acceptance criteria described in Subsection 7.2.3.2 were met for the BA-2-TH test.

7.3.3 In-Plane Shear (IPV)

7.3.3.1 IPV-1 Test Results

The IPV-1 specimen was subjected to a maximum load that exceeded the nominal in-plane flexural capacity.

Steel yielding of the first flange (end) plate occurred during the force-controlled loading phase, and later at the web (face) plate during the displacement-controlled loading phase (refer to Figure 7-7 for illustration of loading cycles). The governing failure mode was in-plane flexural failure. There was no sign of shear failure prior to flexural failure.

The results confirm that the plastic stress distribution method can conservatively estimate the in-plane flexural capacity.

Thus, the acceptance criterion described in Subsection 7.2.4.2 was met for the IPV-1 test.

7.3.3.2 IPV-2 Test Results

The IPV-2 specimen was subjected to a maximum load that exceeded the nominal in-plane flexural capacity.

Steel yielding of the flange (end) plate occurred during the force-controlled loading phase, and later at the web (face) plate during the displacement-controlled loading phase (refer to Figure 7-7 for illustration of loading cycles).

Through-thickness temperature measurements were taken during the test at various thermocouple locations. Mechanical loading was initiated after the through-thickness thermal gradient was achieved. All temperatures exceeded the minimum through-thickness temperature requirement.

The IPV-2 results show that the application of the through-thickness thermal gradient reduces the experimental strength compared to the IPV-1 results. The in-plane capacity from the IPV-2 test still exceeds the nominal in-plane flexural capacity.

The governing failure mode was in-plane flexural failure. There was no sign of shear failure prior to flexural failure. The results confirm that the plastic stress distribution method can conservatively estimate the in-plane flexural capacity.

Thus, the acceptance criterion described in Subsection 7.2.4.2 was met for the IPV-2 test.

7.3.4 In-Plane Shear + Out-of-Plane Shear (IPV+OOPV)

7.3.4.1 IPV+OOPV-1 Test Results

The initial out-of-plane shear force was applied and maintained throughout the duration of the test.

The IPV+OOPV-1 specimen was subjected to a maximum in-plane load which exceeded the nominal in-plane flexural capacity. Steel yielding of the flange (end) plate followed by the web (face) plate during the force-controlled out-of-plane loading phase (refer to Figure 7-8 for illustration of loading cycles).

The results confirm that the plastic stress distribution method can conservatively estimate the in-plane flexural capacity.

When the experimental data points are plotted on the in-plane – out-of-plane interaction diagram (as illustrated in Figure 7-9), points lie above the linear interaction line.

Thus, the acceptance criterion described in Subsection 7.2.5.2 was met for the IPV+OOPV-1 test.

7.3.4.2 IPV+OOPV-2 Test Results

The initial out-of-plane shear force was applied and maintained throughout the duration of the test.

The IPV+OOPV-2 specimen was subjected to a maximum in-plane load which exceeded the nominal in-plane flexural capacity. Steel yielding of the flange (end) plate followed by the web (face) plate during the force-controlled out-of-plane loading phase (refer to Figure 7-8 for illustration of loading cycles).

The results confirm that the plastic stress distribution method can conservatively estimate the in-plane flexural capacity.

When the experimental data points are plotted on the in-plane – out-of-plane interaction diagram (as illustrated in Figure 7-9), points lie above the linear interaction line.

Thus, the acceptance criterion described in Subsection 7.2.5.2 was met for the IPV+OOPV-2 test.

7.3.5 Missile Impact

The test specimens exhibited increasing damage with increasing missile velocity. The expected and actual test results are summarized in Table 7-3. Four of the test specimens stopped the missile while only specimen IMP-C-4 was perforated as expected. Specimen IMP-C-3 stopped the missile as expected. Perforation by the missile was expected for tests IMP-D-1, IMP-D-2 and IMP-C-5 based on the perforation resistance curve. However, the resistance of the specimens to impact was stronger and the missile was stopped with bulging damage mode. Comparison of test results for

IMP-C-4 (perforated) and IMP-D-2 (stopped), which were both conducted at the same missile velocity, demonstrate the additional missile impact resistance provided by the diaphragm plate.

Thus, the test results confirm the impact resistance of DP-SC modules and demonstrate that the Modified Design Method (Reference 9-69) is conservative.

Thus, the acceptance criterion described in Subsection 7.2.6.2 was met for the missile impact test.

Table 7-3: Missile Impact Summary Tests Results

Specimen	Calculated Expected Result(1)	Simulated Expected Result(2)	Test Result	Damage Mode
IMP-D-1	Perforation	Stop	Stopped	Bulging
IMP-D-2	Perforation	Perforation	Stopped	Bulging
IMP-C-3	Stop	Stop	Stopped	Bulging
IMP-C-4	Perforation	Perforation	Perforated	Perforation
IMP-C-5	Perforation	Perforation	Stopped	Bulging

(1) Modified Design Method (Reference 9-69)

(2) Numerical Simulation

7.4 NRIC Phase 2

NRIC Phase 2 tests are not under the purview of this report.

8.0 CONCLUSION

GEH is seeking approval from the NRC and acceptance from the CNSC for the proposed design method of DP-SC modules of the BWRX-300 Seismic Category I (Canadian Seismic Category A) RB and containment structures, including the proposed codes and standards and requirements provided in Sections 5.0 and 6.0 of this report.

The design of the BWRX-300 RB and other non-containment Seismic Category I structures is governed by ANSI/AISC N690 as modified per U.S. NRC RG 1.243 and the modified rules discussed in Section 5.0. As stated in Section 5.0 of the report, the ANSI/AISC N690, Appendix N9 requirements can extend to the design, analysis, fabrication, construction, inspection, examination and testing of DP-SC constructed floors since their structural behavior and failure mechanisms are identical to those of walls when constructed to meet the general provisions of Section N9.1.1 of ANSI/AISC N690.

The provisions of ANSI/AISC N690, Appendix N9 as modified per U.S. NRC RG 1.243 and the proposed design rules discussed in Section 5.0, are extended to the design of BWRX-300 curved DP-SC walls. This is based on results of experimental and analytical evaluations that show the curvature effects are negligible for SC walls with radius-to-wall panel thickness ratios similar to those of the integrated RB walls.

The BWRX-300 containment is still considered a ASME BPVC, Section III, Division 2 containment and is designed per the rules in Section 6.0 adapted from ASME BPVC, 2021 Edition, Section III, Division 2, Subsection CC, Articles CC-1000 through CC-6000, for materials, design, fabrication, construction, inspection, examination, and testing, including Division 2 Appendices, to the extent they apply to an SC containment without reinforcing steel or tendons. The SCCV pre-service inspections, including inservice inspections throughout the life of the plant follow ASME BPVC, Section XI. Leak tests are performed in accordance with 10 CFR 50 Appendix J. Section 6.0 provides the proposed design rules for the SCCV that address the particularities of DP-SC elements and are in compliance with the safety and performance objectives of the regulatory requirements.

As discussed in Section 7.0, the design approaches provided in Sections 5.0 and 6.0 of this report are supported by the conclusions of the NRIC Demonstration Project Prototype tests, which confirm that the load carrying capacities of DP-SC modules are equal to or exceed the loads associated with the nominal capacity.

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ENCLOSURE 3

M240080

Affidavit

GE-Hitachi Nuclear Energy Americas, LLC

AFFIDAVIT

I, **Suzanne Karkour,** state as follows:

(1) I am Manager, Canadian Product Regulatory Affairs, GE-Hitachi Nuclear Energy Americas, LLC (GEH), and have been delegated the function of reviewing the information described in paragraph (2) which is sought to be withheld and have been authorized to apply for its withholding.

(2) The information sought to be withheld is contained in GEH Letter M240080, "NEDC-33926P/NEDO-33926, Revision 2, BWRX-300 Steel-Plate Composite Containment Vessel (SCCV) and Reactor Building (RB) Structural Design," April 18, 2024. GEH proprietary text is identified by dotted underline within double square brackets. [[This sentence is an example.{3}]] Figures and large objects containing GEH proprietary information are identified with double square brackets before and after the object. In all cases, the superscript notation {3} refers to Paragraph (3) of this affidavit, which provides the basis for the proprietary determination.

(3) In making this application for withholding of proprietary information of which it is the owner or licensee:

(a) GEH affirms that the information qualifies for an exemption or exclusion under the Access to Information Act (R.S.C., 1985, C. A-1), and includes proprietary information that is treated consistently as confidential.

(4) As defined in R.S.C., 1985, C. A-1, 20 (1) regarding third party information which fits into the definition of proprietary information in (3)(a) above subject to this section, the head of a government institution shall refuse to disclose any record requested under this Part that contains:

(a) trade secrets of a third party;

(b) financial, commercial, scientific or technical information that is confidential information supplied to a government institution by a third party and is treated consistently in a confidential manner by the third party;

(b.1) information that is supplied in confidence to a government institution by a third party for the preparation, maintenance, testing or implementation by the government institution of emergency management plans within the meaning of section 2 of the Emergency Management Act and that concerns the vulnerability of the third party's buildings or other structures, its networks or systems, including its computer or communications networks or systems, or the methods used to protect any of those buildings, structures, networks or systems;

(c) information the disclosure of which could reasonably be expected to result in material financial loss or gain to, or could reasonably be expected to prejudice the competitive position of, a third party; or

(d) information the disclosure of which could reasonably be expected to interfere with contractual or other negotiations of a third party.

The information sought to be withheld is considered to be proprietary for the reasons set forth in paragraphs (4)(a) through (4)(d) above.

(5) To address Canadian requirements, the information sought to be withheld is being submitted to the Canadian Nuclear Safety Commission (CNSC) in confidence. The information is of a sort customarily held in confidence by GEH and is in fact so held. The information sought to be withheld has, to the best of my knowledge and belief, consistently been held in confidence by GEH, no public disclosure has been made, and it is not available in public sources. All disclosures to third parties including any required transmittals to the CNSC, have been made, or must be made, pursuant to regulatory provisions or proprietary agreements which provide for maintenance of the information in confidence. Its initial designation as proprietary information, and the subsequent steps taken to prevent its unauthorized disclosure, are as set forth in paragraphs (6) and (7) following.

(6) Initial approval of proprietary treatment of a document is made by the manager of the originating component, the person most likely to be acquainted with the value and sensitivity of the information in relation to industry knowledge, or subject to the terms under which it was licensed to GEH.

(7) The procedure for approval of external release of such a document typically requires review by the staff manager, project manager, principal scientist or other equivalent authority, by the manager of the cognizant marketing function (or his delegate), and by the Legal Operation, for technical content, competitive effect, and determination of the accuracy of the proprietary designation. Disclosures outside GEH are limited to regulatory bodies, customers, and potential customers, and their agents, suppliers, and licensees, and others with a legitimate need for the information, and then only in accordance with appropriate regulatory provisions or proprietary agreements.

(8) The information identified in paragraph (2) is classified as proprietary because it contains preliminary proprietary design information for BWRX-300 systems and components, and regulatory acceptance criteria intended to be used for the safety analysis of the BWRX-300. The development of the preliminary proprietary design information for systems and components and proposed regulatory acceptance criteria for this new reactor technology was achieved at a significant cost to GEH.

The development of the evaluation process for this new reactor technology design, along with the interpretation and application of the regulatory acceptance criteria, is derived from the extensive experience database that constitutes a major GEH asset.

(9) Public disclosure of the information sought to be withheld is likely to cause substantial harm to GEH's competitive position and foreclose or reduce the availability of profit–making opportunities. The development of this new reactor technology is part of GEH's comprehensive BWR safety and technology base, and its commercial value extends beyond the original development cost. The value of the technology base goes beyond the extensive physical database and analytical methodology and includes development of the expertise to determine and apply the appropriate evaluation process. In addition, the technology base includes the value derived from providing analyses done with and CNSC-approved methods.

The research, development, engineering, analytical, and CNSC review costs for this reactor technology comprise a substantial investment of time and money by GEH.

The precise value of the expertise to devise an evaluation process and apply the correct analytical methodology to a new reactor technology is difficult to quantify, but it clearly is substantial.

GEH's competitive advantage will be lost if its competitors are able to use the results of the GEH experience to normalize or verify their own process or if they are able to claim an equivalent understanding by demonstrating that they can arrive at the same or similar conclusions.

The value of this information to GEH would be lost if the information were disclosed to the public. Making such information available to competitors without these competitors having been required to undertake a similar expenditure of resources would unfairly provide competitors with a windfall and deprive GEH of the opportunity to exercise its competitive advantage to seek an adequate return on its large investment in developing this very valuable reactor technology.

(10) The proprietary information provided is subject to the export control laws and regulations of the United States, including United States Regulations Title 10 Code of Federal Regulations (CFR) Part 810. In addition, GEH affirms compliance with the regulatory requirements of the Canadian Nuclear Non-proliferation Import and Export Control Regulations (SOR/2000-210). GEH understands that under these regulations the CNSC is obligated to not disclose, transfer, or export any Sensitive/Confidential Information it receives hereunder, or any product containing such Sensitive/Confidential Information, without the prior written permission of GEH.

I declare under penalty of perjury that the foregoing is true and correct.

Executed on this 18th day of April 2024.

Suzanne Karkour

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