ENCLOSURE 2

M230114

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

Non-Proprietary Information

IMPORTANT NOTICE

This is a non-proprietary version of Enclosure 1, from which the proprietary information has been removed. Portions of the enclosure that have been removed are indicated by an open and closed bracket as shown here [[ ]].

GE Hitachi Nuclear Energy

NEDO-33926
Revision 1
August 2023

Non-Proprietary Information

Licensing Topical Report

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

INFORMATION NOTICE

This is a non-proprietary version of the GE Hitachi Nuclear Energy (GEH) document NEDC-33926P Revision 1, which has the proprietary information removed. Portions of the document that have been removed are indicated by an open and closed bracket as shown here [[ ]].

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 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). 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.

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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.

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
CANDU	CANada Deuterium Uranium
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
DEC	Design Extension Condition
DP-SC	Diaphragm Plate Steel-Plate Composite
EPRI	Electric Power Research Institute
ESBWR	Economic Simplified Boiling Water Reactor
FE	Finite Element
GDC	General Design Criterion
GEH	GE Hitachi Nuclear Energy
HGNE	Hitachi-GE Nuclear Energy, Ltd.
ILRT	Integrated Leak Rate Test
IN	Information Notice

Term	Definition
IPV	In-Plane Shear
ISO	International Organization for Standardization
LOCA	Loss-Of-Coolant-Accident
MSLB	Main Steam Line Break
NDRC	National Defense Research Council
NEI	Nuclear Energy Institute
NRC	Nuclear Regulatory Commission
NRIC	National Reactor Innovation Center
OOPV	Out-Of-Plane Shear
PCCS	Passive Containment Cooling System
PJP	Partial Joint Penetration
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
SRP	Standard Review Plan
SSCs	Structures, Systems, and Components
SSE	Safe Shutdown Earthquake
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 SC structural elements for the GEH BWRX-300 Seismic Category I (Canadian Seismic Category A) containment and RB structures that demonstrates compliance with the safety and performance objectives of established regulatory requirements.
- U.S. NRC approval and CNSC acceptance is requested for the requirements for the fabrication, construction, testing, and examination of SC structural elements for the GEH BWRX-300 containment and RB structures that demonstrate compliance with the safety and performance objectives of established regulatory requirements.
- U.S. NRC design-specific approval and CNSC acceptance is requested for the use of:
  - Proposed criteria and requirements for materials, design, fabrication, construction, 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 design, analysis, fabrication, construction, examination, and testing of BWRX-300 non-containment Seismic Category I structural members, including slabs and curved walls, built using SC modules with diaphragm plates.

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, 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 structuresand a general overview of SC structural elements and technical justification for the proposed use of SC modules with diaphragm plates 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 SC modules with diaphragm plates for the BWRX-300 non-containment SC structures and a demonstration of how the proposed designapproach meets the intent of applicable codes, presented in Section 5.0
- Technical evaluation of the proposed design parameters and requirements applicable to the proposed use of SC modules with diaphragm plates for the BWRX-300 SCCV and a demonstration of how the proposed design approach meets the intent 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 containment structure is still considered an ASME BPVC, Section III, Division 2 containment and is designed per the methodology and requirements proposed in Section 6.0 of the report for which we are requesting NRC approval and CNSC acceptance. The proposed containment design and requirements ensure its structural integrity meeting the requirements of 10 CFR 50.34(f)(3)(v)(A)(1).

Therefore, the BWRX-300 design meets 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 (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 meets 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, examination, and testing of the BWRX-300 SCCV.

10 CFR 50.55a(f), "Pre-service and in-service testing requirements," systems and components of boiling and pressurized water-cooled nuclear power reactors must meet the requirements for pre-service and in-service testing (referred to in this paragraph (f) collectively as in-service testing) of the ASME BPVC and ASME OM Code as specified in this paragraph (f). In facilities whose CP under this part, or design certification, design approval, combined license, or manufacturing license under Part 52 of this chapter, issued on or after November 22, 1999, pumps and valves that are classified as ASME BPVC Class 1 must be designed and provided with access to enable the performance of in-service testing of the pumps and valves for assessing operational readiness set forth in editions and addenda of the ASME OM Code (or the optional ASME OM Code Cases listed in U.S. NRC RG 1.192 (Reference 9-5), as incorporated by reference in Paragraph (a)(3)(iii) of this section), incorporated by reference in Paragraph (a)(1)(iv) of this section at the time the CP, combined license, manufacturing license, design certification, or design approval is issued.

Regulatory Requirement: 10 CFR 50.55a(f) requires that the pre-service and in-service inspection of systems and components classified as Class 1 meet the pre-service examination requirements set forth in the editions and addenda of Section III or Section XI (Reference 9-6) of the ASME BPVC.

> Statement of Compliance: The BWRX-300 design includes provisions to perform examinations, inspections, and testing of installed containment systems and components to

support plant operation and best maintenance practices to meet the requirements of 10 CFR 50.55a(f) as discussed in Sections 6.17 and 6.22 of this report.

10 CFR 50.55a(g), "Pre-service and in-service inspection requirements," systems and components of boiling and pressurized water-cooled nuclear power reactors must meet the requirements of the ASME BPVC. For a boiling or pressurized water-cooled nuclear power facility, whose CP under this part, or design certification, design approval, combined license, or manufacturing license under Part 52 of this chapter, was issued on or after July 1, 1974, components that are classified as ASME BPVC Class 1, Class 2, and Class 3 and supports for components that are classified as ASME BPVC Class 1, Class 2, and Class 3 must meet the pre-service examination requirements set forth in the editions and addenda of Section III or Section XI of the ASME BPVC incorporated by reference in Paragraph (a)(1) of this section (or the optional ASME BPVC Code Cases listed in U.S. NRC RG 1.147 (Reference 9-7), as incorporated by reference in Paragraph (a)(3)(ii) of this section) applied to the construction of the particular component.

Regulatory Requirement: 10 CFR 50.55a(g) requires that the pre-service and in-service inspections of systems and components classified as Class 1, 2, and 3 meet the pre-service examination requirements set forth in the editions and addenda of Section III or Section XI of the ASME BPVC.

> Statement of Compliance: As discussed in Sections 6.17 and 6.22 of this report, the pre-service and in-service inspection requirements of the SCCV meet the requirements of ASME Section XI, Division 1, complying with the requirements of 10 CFR 50.55a(g).

10 CFR 50.55a(g)(4), "Pre-service and in-service inspection requirements" requires that in-service 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," 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 Sections 6.17 and 6.22 of this report, the pre-service and in-service 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 meets 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 in-service inspection and maintenance program is established for the BWRX-300 Seismic Category I integrated RB structures. Inspection methodology for the RB and SCCV SC modules with diaphragm plates are discussed in Sections 5.18 and 6.22 of this report.

The BWRX-300 design meets 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 considers the airports based on a site-specific parameter. Aircraft missile sources are characterized in terms of dimensions, mass, energy, velocity, trajectory, and energy density resulting from a large or commercial aircraft impact. The BWRX-300 design applies the Nuclear Energy Institute's (NEI's) methodology in NEI 07-13 (Reference 9-8) for aircraft crash evaluations with plant-specific input on a case-by-case basis 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 LTR. The beyond design basis evaluation will demonstrate that the containment remains intact, and the fuel pool structural integrity is maintained for safe operations.

Therefore, the BWRX-300 design meets 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, 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 meets 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 meets 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 and testing and accident pressure and reaction loads that may result from equipment or piping failures as discussed in Section 4.3 of this report.

Therefore, the BWRX-300 design meets 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 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 meets 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 meets 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. The 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 (Reference 9-9). 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 meets the requirements of 10 CFR 50 Appendix A, GDC 51.

2.1.1.12 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 meets the requirements of 10 CFR 50 Appendix A, GDC 53.

2.1.1.13 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 (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.

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

2.1.1.14 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 containment is designed so that periodic integrated leakage rate testing can be conducted at containment design pressure in order to comply with 10 CFR 50, Appendix J as discussed in NEDC-33911P-A and in Sections 4.3, 6.17, and 6.22 of this report.

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

2.1.1.15 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 conformance of the BWRX-300 seismic design to the requirements of 10 CFR 50, Appendix S is evaluated in NEDO-33914-A (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 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.

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

2.1.2 10 CFR 100.21

10 CFR 100.21, "Non-seismic siting criteria," must have an exclusion area and a low population zone. The physical characteristics of the site, including meteorology, geology, seismology, and hydrology, must be evaluated and site characteristics established such that potential threats from such physical characteristics will pose no undue risk to the type of facility proposed to be located at the site. Potential hazards associated with nearby transportation routes and industrial and military facilities must be evaluated.

Regulatory Requirement: Radiological effluent release limits associated with normal operation from the type of facility proposed to be located at the site can be met for any individual located off-site. Radiological dose consequences of postulated accidents shall meet the criteria set forth in §50.34(a)(1) of this chapter for the type of facility proposed to be located at the site.

> Statement of Compliance: As discussed in Subsection 6.23.3, the calculated release for the more likely severe accident challenges, following the initial 24-hour period, meets the site-specific radiological dose consequences in accordance with the requirements of 10 CFR 100.21 and 10 CFR 50.34.

Therefore, the BWRX-300 design meets the requirements of 10 CFR 100.21 and 10 CFR 50.34.

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 9-13), 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, meeting 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 9-14), 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 in-service 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 in-service 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 in-service surveillance programs

Statement of Conformance: For code applicability, the BWRX-300 SCCV is designed in accordance with ASME BPVC, Section III requirements. The code jurisdictional boundary for application of Section III of ASME BPVC to the SCCV is shown in Figure 4-1. The proposed design approach for the BWRX-300 SCCV presented in Section 6.0 of this report meets the intent 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 9-15), 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 in-service 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 in-service surveillance programs
- Special testing and in-service surveillance requirements proposed for new or previously untried design approaches, and for new reactors, it is important to accommodate in-service inspection of critical areas.

Statement of Conformance: For code applicability, the BWRX-300 SCCV is designed in accordance with ASME BPVC, Section III requirements. The code jurisdictional boundary for application of Section III of ASME BPVC to the SCCV is shown in Figure 4-1. The proposed design approach for the BWRX-300 SCCV presented in Section 6.0 of this report meets the intent of the regulatory guidance of SRP 3.8.2. Design of Class MC components of the containment is not in the scope of this LTR 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 9-16), 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 in-service 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 in-service inspection of containment internal structures, and post-construction testing and in-service 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, 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 containment internal structures presented in Section 5.0 of this report meet the intent 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 9-17), 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 9-18), with supplemental guidance by U.S. NRC RG 1.142 (Reference 9-19) 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 in-service 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 in-service 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 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 intent 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 9-20), 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 ingradients, reinforcing bars, structural steel, and rock anchors
- Testing and in-service survelliance 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 in-service 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 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. These proposed approaches in Sections 5.0 and 6.0 meet the intent of the regulatory guidance of SRP 3.8.5.

2.2.7 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 9-21), 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 with plant-specific input on a case-by-case basis 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 LTR. The beyond design basis evaluation will demonstrate that the containment remains intact, and the fuel pool structural integrity is maintained for safe operations.

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 9-22), 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 meet the requirements specified in 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 9-23), 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 ASME Class 2, Quality Group B and its design complies with the requirements of 10 CFR 50 Appendix A, GDC 1. The BWRX-300 containment design is discussed in Section 6.0 of this report and meets the requirements 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.

2.3.4 Regulatory Guide 1.57

RG 1.57, "Design Limits and Loading Combinations for Metal Primary Reactor Containment System Components" (Reference 9-24), 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 is in compliance with 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.

2.3.5 Regulatory Guide 1.61

RG 1.61, "Damping Values for Seismic Design of Nuclear Power Plants" (Reference 9-25), 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: U.S. NRC RG 1.61 does not specify damping values for SC modules. As a result, damping values for the SCCV and the non-containment Seismic Category I SC elements are per Table 3-1 of American Society of Civil Engineers (ASCE)/Structural Engineering Institute (SEI) 43 (Reference 9-26) as discussed in Section 6.4. The regulatory guidance of U.S. NRC RG 1.61 is followed for the response level considered for the generation of in-structure response spectra.

2.3.6 Regulatory Guide 1.136

RG 1.136, “Materials, Construction, and Testing of Concrete Containments” (Reference 9-27), 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, 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 intent of the regulatory requirements 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.

2.3.7 Regulatory Guide 1.160

RG 1.160, “Monitoring the Effectiveness of Maintenance at Nuclear Power Plants” (Reference 9-28), 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: An in-service inspection and testing program is established to satisfy the general requirements for examination of the integrated RB to ensure it can fulfill its intended functions throughout the design service life of the BWRX-300, in compliance with 10 CFR 50.65 and the regulatory guidance of U.S. NRC RG. 1.160 as discussed in Section 5.18 of this report.

2.3.8 Regulatory Guide 1.199

RG 1.199, “Anchoring Components and Structural Supports in Concrete” (Reference 9-29), 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 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.

2.3.9 Regulatory Guide 1.216

RG 1.216, "Containment Structural Integrity Evaluation for Internal Pressure Loadings Above Design-Basis Pressure" (Reference 9-30), 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 of the containment structure, including the SCCV, containment closure head, and other Class MC components, under beyond design basis internal pressure loads meets the requirements of U.S. NRC RG 1.216 as discussed in Section 6.23.

2.3.10 Regulatory Guide 1.217

RG 1.217, "Guidance for the Assessment of Beyond-Design-Basis Aircraft Impacts for Aircraft Impact Assessment" (Reference 9-31), 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 LTR. The beyond design basis evaluation will demonstrate that the containment remains intact, and the fuel pool structural integrity is maintained for safe operations.

2.3.11 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, construction, testing, and evaluation of the non-containment Seismic Category I SC structures follow the regulatory guidance of U.S. NRC RG 1.243 and the provisions of ANSI/AISC N690, Appendix N9 supplemented by the additional criteria and requirements provided in Section 5.0 of this report.

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 complimentary 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 9-32) used in conjunction with REGDOC-1.1.2, “Licence Application Guide: Licence to Construct a Reactor Facility” (Reference 9-33).

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 9-34). 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 complimentary 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 9-35).

> 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 complimentary 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 complimentary 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 complimentary 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 SC modules for the construction of the integrated RB structures. Information in Sections 5.0 and 6.0 of this report is complimentary 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 complimentary 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 provide 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 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 complimentary 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 complimentary 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 complimentary 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 complimentary 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 SC modules with diaphragm plates fire protection. Information in Sections 5.13 and 6.20 of this report is complimentary 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 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 complimentary 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 alterntive design requirements presented in Sections 5.0 and 6.0. Information in Sections 5.0 and 6.0 of this report is complimentary 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 in-service inspection and testing of the integrated RB structures, including the SCCV. Information in Sections 5.18 and 6.22 of this report is complimentary 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 complimentary 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 9-36).

> 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 complimentary 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, 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 complimentary 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. Information in Sections 5.0 and 6.0 of this report is complimentary 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 complimentary 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 complimentary 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. Information in Sections 5.18 and 6.22 of this report is complimentary 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 safety-related 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 objectives of CSA N291 (Reference 9-37) standard following the regulatory guidance of REGDOC-2.5.2, Sections 7.15.1 and 8.6.8. 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 meets the intent of CSA N291, Section 10 provisions.

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 SC structures ensure a level of safety and performance commensurate with the requirements of CSA N291, CSA S16 (Reference 9-38) (for steel) and CSA A23.1/A23.2 (Reference 9-39) and CSA A23.3 (Reference 9-40) (for concrete) design standards.

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 objectives of the CSA N287 series of standards for CANada Deuterium Uranium (CANDU) concrete containments, including:

- General requirements of CSA N287.1 (Reference 9-41)
- Material requirements of CSA N287.2 (Reference 9-42)
- Design requirements of N287.3 (Reference 9-43)
- Construction, fabrication and installation requirements of CSA N287.4 (Reference 9-44)
- Construction examination and testing requirements of CSA N287.5 (Reference 9-45)

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 design, construction, fabrication, and installation requirements discussed in Section 6.0 of this report meet the intent and 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.

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 9-46)
- In-service examination and testing in Section 6.22 meet the applicable provisions of CSA N287.7 (Reference 9-47)

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 9-48). 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 287.3, Clause 11 for the seismic design of concrete containments.

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 9-49) 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 9-50) 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 9-51) 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 surfaces 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 SC modules is addressed in Sections 5.15 and 6.19 of this report. The in-service 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 safety-related systems and components 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 (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.

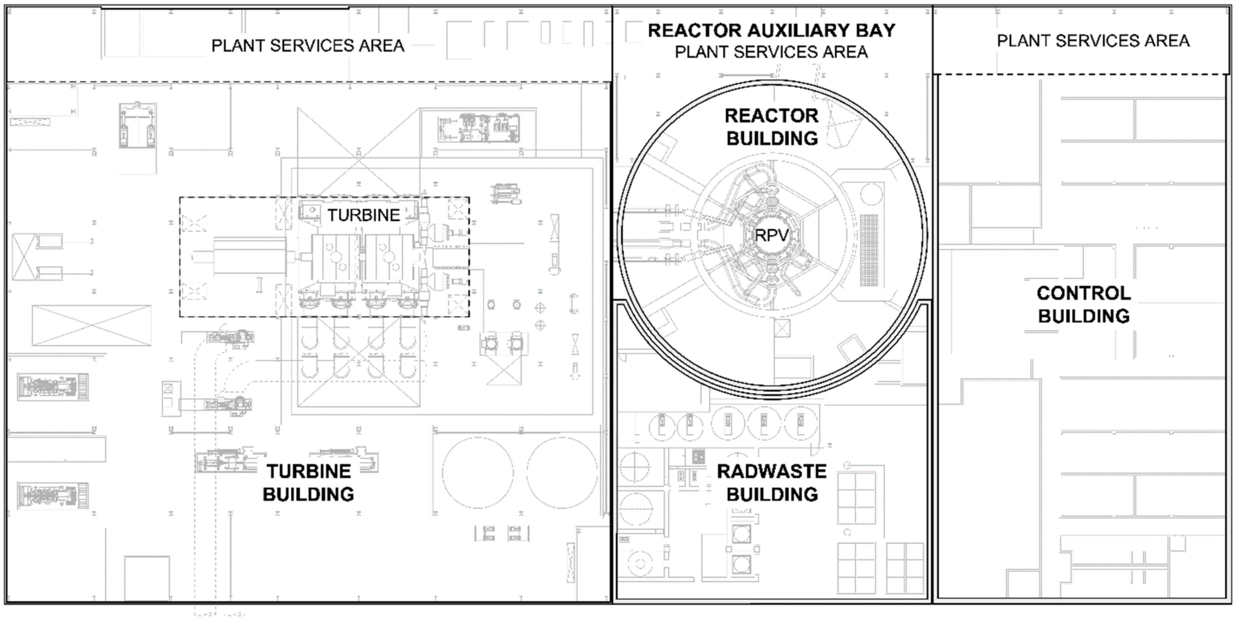

Figure 3-1: BWRX-300 Power Block Plan View

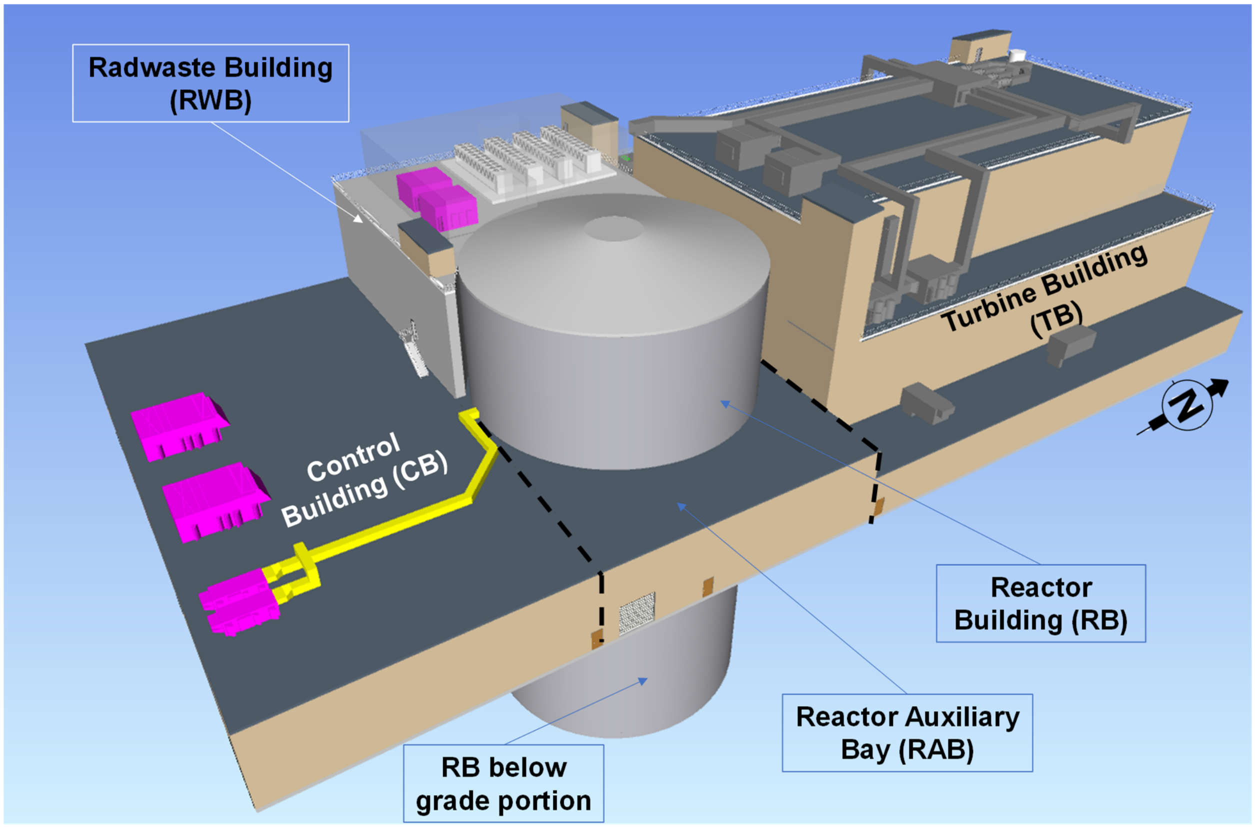

Figure 3-2: BWRX-300 Power Block Three-Dimensional View

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. Figures 3-3 and 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 SC modules with diaphragm plates. 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 safety-related 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 SC modules with diaphragm plates. 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 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 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 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 mat foundation, also constructed using SC modules with diaphragm plates. 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 or semi-rigid connections. Semi-rigid connections are used to help accommodate some of the SCCV thermal deformations and thus relieve thermal stresses in the RB structure. These semi-rigid connections are used mostly to connect the below-grade SC members as shown in Figure 3-5. 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.

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

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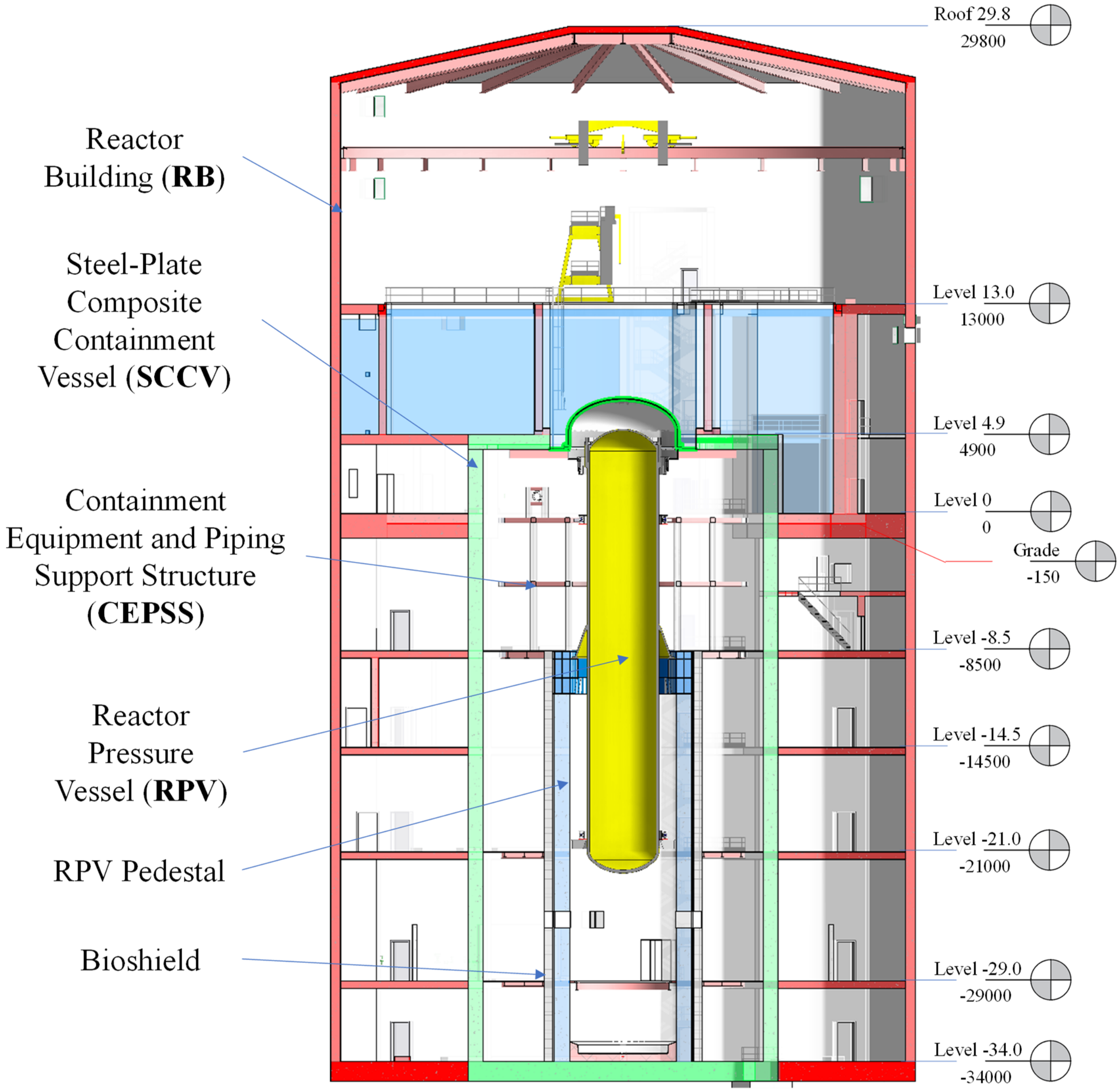

Figure 3-4: Section View of Integrated Reactor Building

*Elevations provided in m/mm

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Figure 3-5: Semi-Rigid Connection Locations

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 3-6. In the first group (Figure 3-6(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 delay 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 3-6(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 provide composite action between the steel faceplates and the concrete infill, and out-of-plane shear reinforcement for the composite section. Additional ties or shear stud anchors may be used to anchor the steel faceplates to the concrete infill and control faceplate local buckling.

As shown in Figure 3-6(b), DP-SC modules can be built by welding a series of components:

(A) Double web bi-shape components: straight or curved faceplates are connected by two 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 3-7.

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Figure 3-6: Different Configurations of Steel-Plate Composite Structural Modules

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Figure 3-7: 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 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 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.

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 Finite Element (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 ASCE/SEI 4 (Reference 9-52) 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.

The integrated RB model captures the semi-rigid connections with 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 RB DP-SC members. 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 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 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 for the RB steel structures including ANSI/AISC N690, Appendix N9 for the RB 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. 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 Main Steam Line Break (MSLB) is considered. Quasi-static pressures resulting from this event is applied on the containment structure. Although the DBA pressures (P_a) resulting from MSLB 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.

- Seismic Loads (E)

  The design of RB integrated structure considers the following seismic load (E) 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) 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.

- 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 MSLBs and heat-up of fuel pool

  The MSLB 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 MSLB 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 (R_r, R_b)

  The design considers local load effects on the containment due to high-energy line breaks during a DBA, including the reaction, jet impingement, and impact of ruptured high-energy pipe, and blast loads, as applicable. 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.

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, 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 and Section IWE are followed considering the inner face faceplates are serving as leak-tight containment liner.

Computer programs, such as ANSYS and SASSI, used to analyze the BWRX-300 integrated RB structures are verified in accordance with NEDO-11209-A that complies with ASME NQA-1 and CSA N286.7 (Reference 9-53).

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Figure 4-1: BWRX-30 Integrated Reactor Building Design Codes Jurisdictions

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

The design of the BWRX-300 non-containment DP-SC structures meets the intent of the requirements of ANSI/AISC N690 as endorsed by the regulatory guidance of U.S. NRC RG 1.243.

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 DP-SC walls, and the applicability of the ANSI/AISC N690 modified rules to 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 a DP-SC modules are:

(i) spacing between diaphragm plates W_{sc}, in (mm)
(ii) depth t_{sc}, in (mm)
(iii) plate thickness t_p, in (mm)
(iv) steel plate yielding strength grade F_y, ksi (MPa)
(v) diaphragm hole diameter D, in (mm)
(vi) diaphragm hole spacing S, in (mm)
(vii) stud anchor tensile strength F_{uta}, ksi (MPa)
(viii) stud anchor diameter d_{st}, in (mm)
(ix) stud length l_{st}, in (mm)
(x) stud anchor spacing s, in (mm)
(xi) concrete compressive strength f_c', ksi (MPa)

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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, Section N9.1.1a provisions. The minimum steel plate thickness, t_p, is 0.25 in (6.4 mm). These limits are based on practical fabrication considerations, and do not suggest any deviations in the fundamental behavior or mechanics.

The maximum reinforcement ratio for the non-containment DP-SC walls is taken as 0.10 following the requirements of ANSI/AISC 360 (Reference 9-54), Section I1.6.

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

5.2 Materials

5.2.1 Concrete Infill

The compressive strength, f_c', of the concrete infill of DP-SC modules ranges from 4 ksi (28 MPa) to 8 ksi (55 MPa) per the requirements of ANSI/AISC N690, Section N9.1.1.

Aggregates used in high-density concrete for radiation shielding purposes conform to American Society for Testing and Materials (ASTM) C637 (Reference 9-55), per ACI 349.

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.

5.3 Composite Action

The faceplates of DP-SC modules are anchored using a combination of diaphragm plates and steel headed stud anchors, if needed, with the webs of the modules (i.e., diaphragms plates), acting as ties preventing splitting of sections and serving as out-of-plane shear reinforcement.

The BWRX-300 construction uses yielding steel headed stud anchors in all composite construction. Steel headed stud anchors are designed and detailed per ANSI/AISC 360, Section I8.3 requirements.

As the diaphragm plates are quite substantial, and do not need additional contributions from the stud anchors to develop the yield strength of the steel faceplates or to provide interfacial shear strength for the panels, headed studs of DP-SC panels are designed to meet the requirements of ANSI/AISC N690, Section N9.1.3 for faceplate slenderness requirements only, in order to improve the stability of the steel faceplates after concrete casting. Requirements of ANSI/AISC N690, Section N9.1.4b for interfacial shear prevention are not applicable to DP-SC modules as confirmed by NRIC specimens (Out-Of-Plane-Shear (OOPV)-1 and OOPV-2) testing (see Section 7.0).

5.4 Diaphragm Requirements

The maximum requirements for tie spacing in Equation I1-5 of ANSI/AISC 360 specifications do not apply to DP-SC panels due to their large steel panel shear stiffness contributed by the diaphragm plates.

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. Tie plates or bars may be added for additional stiffness and strength.

5.5 Determination of Effective Stiffness of Steel-Plate Composite Elements

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5.6 Effective Stiffness of Semi-Rigid Connections

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5.7 Section Capacities of Steel-Plate Composite Elements

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Figure 5-2: Unit Width Design Strip Along the Direction of Diaphragm Plates

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Figure 5-3: Unit Width Design Strip Perpendicular to the Direction of Diaphragm Plates

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Figure 5-4: 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

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5.7.3.2 Parallel to Diaphragm Span

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Figure 5-5: Stress and Force Distribution Across Diaphragm Plate Steel-Plate Composite Panel Section to Compute Out-of-Plane Flexural Capacity (Adopted from Reference 9-59)

5.7.4 In-Plane Shear Strength

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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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5.7.5.3 Two-Way (Punching) Shear

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Figure 5-6: Punching Shear Effective Perimeter

5.7.6 Out-of-Plane Shear Force Interaction

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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, CSA N291, Clause A.5 and CSA N287, Clause B.4, 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
Reinforcing steel		
Grade 40	1.20	1.05
Grade 60	1.10	1.05
Concrete compressive strength	—	1.25
Concrete shear strength	—	1.10

5.8.1.3 Allowable Limits

- Damage criteria for DP-SC structures subjected to impulsive loads are presented in Table 5-2 and Table 5-3, conservatively adapted from ACI 349.4R (Reference 9-63) and meet the general criteria discussed in Subsection 5.8.1.1.
- 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	Superficial Damage	Limited, Moderate, Severe Damage	Limited Damage	Moderate Damage	Severe Damage
		Shear and Flexure	Shear and Compression	Flexure		
		-	Ductility μd	Support Rotation r_θ (2) (8) (deg)	Support Rotation r_θ (2) (3) (4) (7) (9) (deg)	Support Rotation r_θ (3) (4) (7) (9) (deg)
Beams	Flexure Shear: (1) (6)	Essentially Elastic Behavior (5)	-	1	2	4
	Concrete + Ties		1.6			
	Ties Only		3.0			
	Compression		1.3			
Slabs	Flexure Shear: (1) (6)	Essentially Elastic Behavior (5)	-	1	4	6
	Concrete + Ties		1.6			
	Ties Only		3.0			
	Compression		1.3			
Beam-Columns, Walls and Slabs in Compression	Flexure	Essentially Elastic Behavior (5)	1.3	-	2	4
	Compression		1.3			
Shear Walls, Diaphragms	Flexure	Essentially Elastic Behavior (5)	3.0	-	1.2	2
	Shear, in-plane		1.5			

Notes:

(1) Shear controls when the nominal shear capacity of the member is less than the shear corresponding to 120% of flexural resistance.

(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) Ties are always required in SC panels design. For DP-SC panels, the diaphragm plates act as ties.

(4) These rotation criteria (in degrees) are in general consistent with those in the ASCE/SEI 59-11 (Reference 9-64), which does not specify allowable inelastic deformation in terms of ductility ratio-criteria for flexure.

(5) Essentially elastic behavior means elastic structural analysis using design strain acceptance criteria of 1%, which corresponds to superficial damage of elements.

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

(7) For beams and columns, the minimum ties requirements are governed by other applicable codes.

(8) 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.

(9) 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.

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	0.140 / TF
304 Stainless Steel Plate	Membrane principal strain (tension)	0.010	0.033	0.067
	Local ductile tearing effective strain	N/A	0.138/TF	0.275 / TF
Grade 60 Reinforcing Steel	Tensile Strain	0.010	0.025	0.050

Note:

Conservatively, 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 effective or equivalent stress. Conservatively, the tri-axiality factor, TF, value is taken as 2 for DP-SC panels. The values in Table 5-2 and Table 5-3 are maximum values under the loading condition. It should be noted that the acceptance criteria presented in Table 5-2 and Table 5-3 are applicable to large structural portions 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 SC module system. The components of 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. Local areas for missile impact are defined as having a maximum diameter equal to 10 times the effective diameter of the impacting missiles, or $5\sqrt{t_{SC}}\left(2.76\sqrt{t_{SC}}\right)$ plus the effective diameter of the impacting missile, whichever is smaller.

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 Reference 9-65.

(a) Concrete Infill Penetration Depth of DP-SC structures:
The penetration depth $x_{c.sc}$ for the concrete infill is calculated as follows:

$$x_{c.sc} = K_{sc} x_c \qquad [5\text{-}33]$$

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

$$K_{sc} = 2.073 - 0.661K + 0.688\left(\frac{\alpha_p d}{t_c}\right) + 0.835\left(\frac{x_c}{t_c}\right) \qquad [5\text{-}34]$$

K = concrete penetrability factor defined as $\frac{180}{\sqrt{f_c'}}$ (f_c' in psi)

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

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

$$x_c = \sqrt{4KNW_p d\left(\frac{V_{imp}}{1000d}\right)^{1.80}} \qquad \text{for } \frac{x_c}{d} \leq 2.0 \qquad [5\text{-}35]$$

$$x_c = KNW_p\left(\frac{V_{imp}}{1000d}\right)^{1.80} + d \qquad \text{for } \frac{x_c}{d} > 2.0 \qquad [5\text{-}36]$$

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:

$$V_{p.conc} = 1000d\left(\frac{d}{1.44KW_pNK_{sc}{}^2}\left(2.2 \pm \sqrt{4.84 - 1.2\left(\frac{t_c}{\alpha_p d}\right)}\right)^2\right)^{\frac{5}{9}} \qquad \text{for } \frac{t_c}{\alpha_p d} \leq 2.65 \qquad [5\text{-}37]$$

$$V_{p.conc} = 1000d\left(\frac{d}{4KW_pNK_{sc}{}^2}\left(\frac{t_c}{1.29\alpha_p d} - 0.53\right)^2\right)^{\frac{5}{9}} \qquad \text{for } 2.65 < \frac{t_c}{\alpha_p d} < 3.27 \qquad [5\text{-}38]$$

$$V_{p.conc} = 1000d\left(\frac{d}{KW_pNK_{sc}}\left(\frac{t_c}{1.29\alpha_p d} - (0.53 + K_{sc})\right)\right)^{\frac{5}{9}} \qquad \text{for } \frac{t_c}{\alpha_p d} \geq 3.27 \qquad [5\text{-}39]$$

(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:

$$V_r = \sqrt{\left(\frac{W_p}{W_p + W_{cf}}\right)\left({V_{imp}}^2 - {V_{p.conc}}^2\right)} \qquad [5\text{-}40]$$

Where,

W_p = missile weight in lbs

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

$$W_{cf} = \frac{1}{3}\pi\rho_c(t_c - x_{c.sc})(r_2^2 + r_1r_1 + r_1^2) \qquad \text{for } x_{c.sc} < t_c \qquad [5\text{-}41]$$

$$W_{cf} = 0 \qquad \text{for } x_{c.sc} \geq t_c \qquad [5\text{-}42]$$

ρ_c= concrete density, lbs/ft^3

r_1= $d/2$

$$r_2 = r_1 + (t_c - x_{c.sc})\tan\theta \qquad \text{for } x_{c.sc} < t_c \qquad [5\text{-}43]$$

$$r_2 = \text{N/A} \qquad \text{for } x_{c.sc} \geq t_c \qquad [5\text{-}44]$$

$$\theta = \frac{45^0}{\left(\frac{t_c}{d}\right)^{\frac{1}{3}}} \qquad [5\text{-}45]$$

(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:

$$t_{p.min} = 0.72\left(\frac{(12V_r)^2 + m_t}{\frac{\pi}{2}d^2\sigma_s}\right) \qquad [5\text{-}46]$$

Where,

m_t= total mass of missile and concrete frustum defined as $(W_p{+}W_{cf})/\ (386\ \text{in/sec}^2)$

σ_s= the von Mises yield criterion defined as

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

$3.9F_y + 64000$ for $t_p < 0.25$ in.

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.

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 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 LTR.

5.9 Design of Steel-Plate Composite Floors

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5.10 Design and Detailing Requirements Around Openings

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5.11 Design of Steel-Plate Composite Connections

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

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5.13 Fire Rating and Capacity Under Fire Condition Evaluation

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

Structural members and components in steel buildings are qualified for the rating period in conformance with ASTM E119 (Reference 9-69) or ANSI/UL 263 (Reference 9-70). 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, Section 4.2 in combination with the fire exposure specified in ASTM E119 or ANSI/UL 263 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.

Three limit states exist for elements serving as fire barriers (compartment walls and floors):

(i) Heat transmission leading to unacceptable rise of temperature on the unexposed surface; unacceptable rise of temperature is identified using applicable RG

(ii) Breach of barrier due to cracking or loss of integrity

(iii) Loss of load bearing capacity

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, ANSI/UL 263, or Eurocode 1 (Reference 9-71). 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, ANSI/UL 263, 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 per ANSI/AISC 360, Section 4.2.

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 ANSI/AISC 360, Section 4.2.

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, 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 or ANSI/UL 263.

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

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, Appendix 4.3, is determined in accordance with Equations [5-48] and [5-49].

(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)

$$R = \left[-18.5\left(\frac{P_u}{P_n}\right)^{\left(0.24-\frac{L/t_{sc}}{230}\right)} + 15\right]\left(\frac{1.9t_{sc}}{8} - 1\right) \qquad [5\text{-}48]$$

$$R = \left[-18.5\left(\frac{P_u}{P_n}\right)^{\left(0.24-\frac{L/t_{sc}}{230}\right)} + 15\right]\left(\frac{1.9t_{sc}}{200} - 1\right) \text{ (SI Units)} \qquad [5\text{-}49]$$

where R is the fire rating in hours, P_u is the required axial load in kips (N), and P_u, P_n, and t_{sc} are as defined in Chapter I of ANSI/AISC 360. The calculations of fire rating of DP-SC panels are based on ANSI/AISC 360, Appendix 4, Clause 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 9-72). 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 [5-50] 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 9-73. 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 [5-51] and Equation [5-52], 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 [5-53] is obtained after simplifying Equation [5-50] and taking into account all listed conditions.

$$A = \frac{m}{K_d P \sqrt{\frac{\gamma M_m}{RT}\left(\frac{2}{\gamma+1}\right)^{\left(\frac{\gamma+1}{\gamma-1}\right)}}} \qquad [5\text{-}50]$$

$$m = \frac{s_1 s_2 T_{dc} \omega \rho_w}{t_{dc}} \qquad [5\text{-}51]$$

$$P = \rho_c g h_c \qquad [5\text{-}52]$$

$$A = 116\frac{s_1 s_2 T_{dc} \omega \rho_w}{t_{dc} \rho_c h_c} \qquad [5\text{-}53]$$

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

ρ_c = water 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 9-74) and ANSI/AISC 303 (Reference 9-75) 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 9-76 and Reference 9-77). All painting system are to be tested in accordance with ASTM D1014 (Reference 9-78) procedures.
- Membrane coating system.
- Impressed Current Cathodic Protection. The cathodic protection system is to meet ISO-12473 (Reference 9-79).

ASTM MNL20-2nd Edition (Reference 9-80) is used for all corrosion Tests and standards.

5.16 Fabrication and Construction Requirements

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5.17 Quality Control and Quality Assurance

BWRX-300 non-containment Seismic Category I SC structures follow the requirements of ANSI/AISC N690, Chapter NN. U.S. NRC RG 1.28 is used for 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, In-Service Inspection, and Testing Requirements for the Integrated RB

An in-service inspection and testing program is established for the DP-SC integrated RB to ensure it can fulfill its intended functions throughout its design service life in compliance with 10 CFR 50.65 and the regulatory guidance of U.S. NRC RG. 1.160. 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 in-service inspection and testing program for the DP-SC integrated RB is similar to that described in the NUREG-1801, Chapter XI.S6 (Reference 9-81). 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 9-82) and SEI/ASCE 11 (Reference 9-83).

The loss of material due to corrosion of the steel faceplates has been identified as the primary aging and degradation mechanism associated with SC construction. 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 in-service 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.

Based on the outcomes of the in-service 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 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-1801. 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 according to REGDOC-2.6.3. The aging management program begins with the plant commissioning followed by periodic in-service 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 BWRX-300 SCCV is considered an ASME BPVC, Section III, Division 2 containment. The code jurisdictional boundary for application of Section III of ASME BPVC to the BWRX-300 containment 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, if needed, 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).

6.2 Materials

The properties of concrete fill and structural steel are in accordance with the guidelines of ASME BPVC, Section III, Division 2, Subsection CC, Article CC-2000, endorsed by U.S. NRC RG 1.136, as applicable. The following subsections present the proposed requirements specific to the BWRX-300 SCCV.

6.2.1 Concrete Infill

The concrete infill of 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 9-84) 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. The category for corrosion protection of steel materials in DP-SC modules follow those for reinforcement steel.

6.2.2 Steel Materials

All 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 hollow 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 Load Bearing Steel

If used, load bearing steel materials are to meet the requirements of ASME BPVC, Section III, Division 2, Subsection CC, Subarticle CC-2700.

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

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6.4 Damping Values

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

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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	Membrane or Membrane + Bending (2)	-	$2\varepsilon_y$ (4)

(1) The primary portion of this calculated stress does exceed the allowable stress applicable when primary stress acts alone.
(2) The membrane portion of this calculated stress does 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).
(4) Limit for mechanical (net) strain, which is calculated by subtracting strain induced by secondary force (i.e., thermal strain) from the total strain.

(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	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

6.8.1 Uniaxial Tensile Strength

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6.8.2 Compressive Strength

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6.8.3 Flexural Strength

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6.8.4 One-Way Out-of-Plane Shear Strength

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6.8.5 Tangential Shear Strength

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6.8.6 Two-Way (Punching) Shear Strength

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6.9 Out-of-Plane Shear Interaction Checks

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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 and the requirements of Sections 7.15.1 and 7.15.3 of REGDOC-2.5.2.

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.

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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Table 6-2: Weld Categories Applicability to Steel-Plate Composite Containment Vessel

Weld Category	Definition per CC-3841	Applicability to SCCV
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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 360 and Design Guide 32 are adapted, as applicable 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

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6.16 Construction Testing and Examination Requirements, Including Weld Examination and Qualification for SC Modules with Diaphragm Plates

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6.17 Steel-Plate Composite Containment Vessel Pre-Service Inspection and Testing Requirements

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6.18 Effect of Curvature on Behavior of Steel-Plate Composite Containment Vessel

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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 In-Service Inspection and Testing Requirements

The in-service 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 in-service inspection and testing methodologies.

A pre-service and periodic in-service 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), and REGDOC-2.5.2. The pre-service examinations are performed prior to plant startup following the completion of the SIT. The in-service 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.

The following are the SCCV in-service inspection and testing requirements:

- 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 9-85). 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 9-86).

- 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.
- If used during construction, mock-up specimens 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

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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

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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 Steel Bricks™ 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 3-6 and Figure 3-7, 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 safety-related 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. 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. After the testing was completed, design capacities were calculated based on measured steel and concrete material strengths multiplied by the recommended resistance factor ϕ and compared with experimental results.

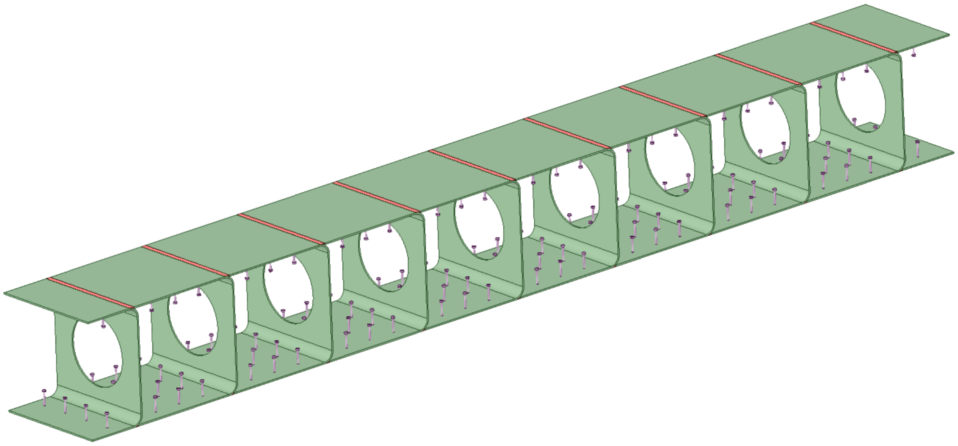

**Figure 7-1: Out-of-Plane Shear Test Specimen -
Diaphragm Plate Orientation Parallel to Loading (OOPV-1)**

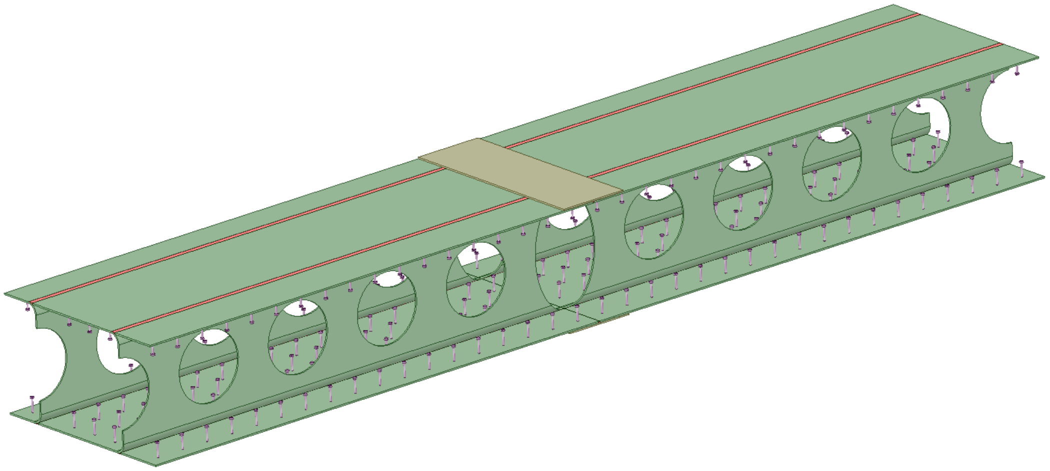

**Figure 7-2: Out-of-Plane Shear Test Specimen -
Diaphragm Plate Orientation Perpendicular to Loading (OOPV-2)**

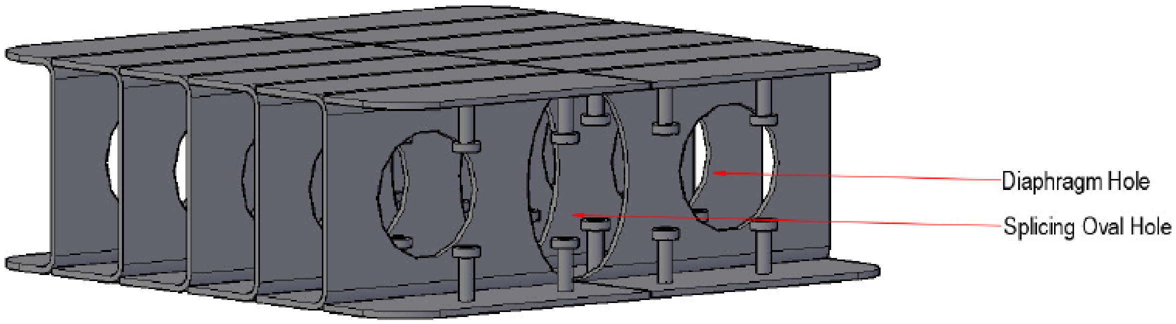

Figure 7-3: Bi-Axial Tension Test Specimen

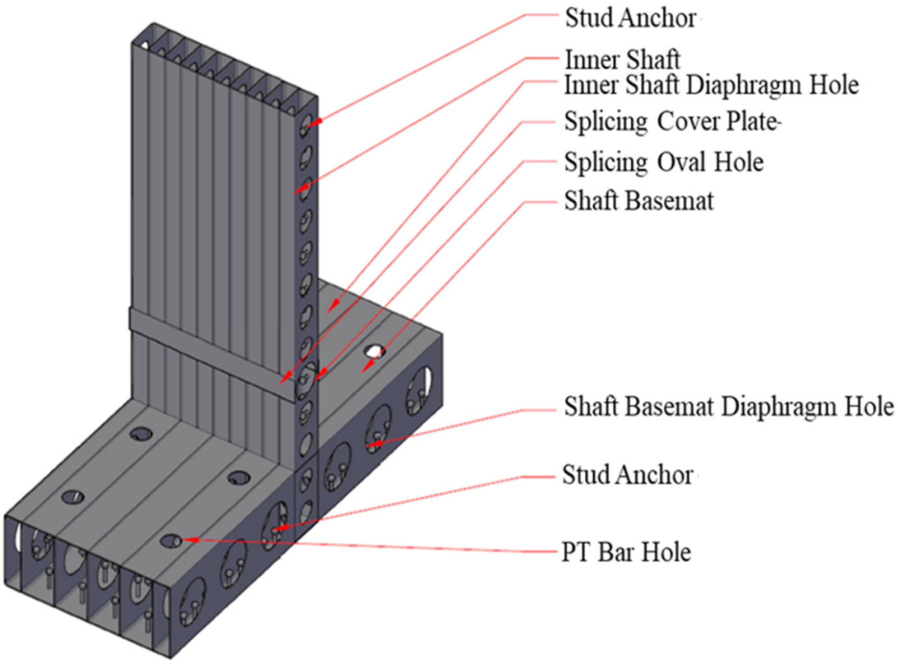

Figure 7-4: In-Plane Shear Test Specimen

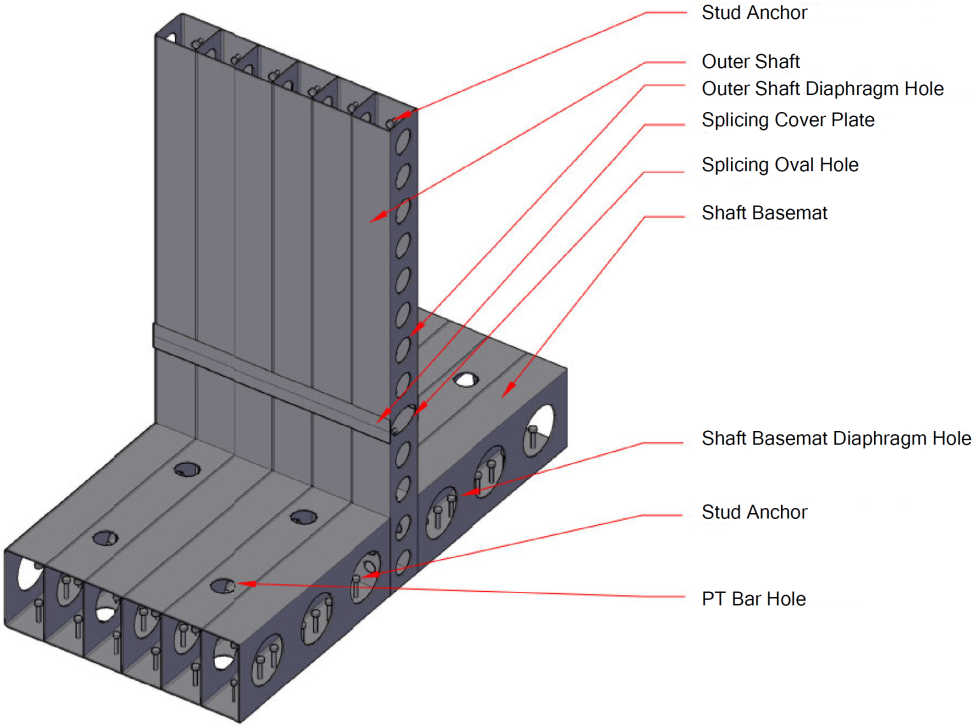

Figure 7-5: In-Plane Shear + Out-Of-Plane Shear Test Specimens

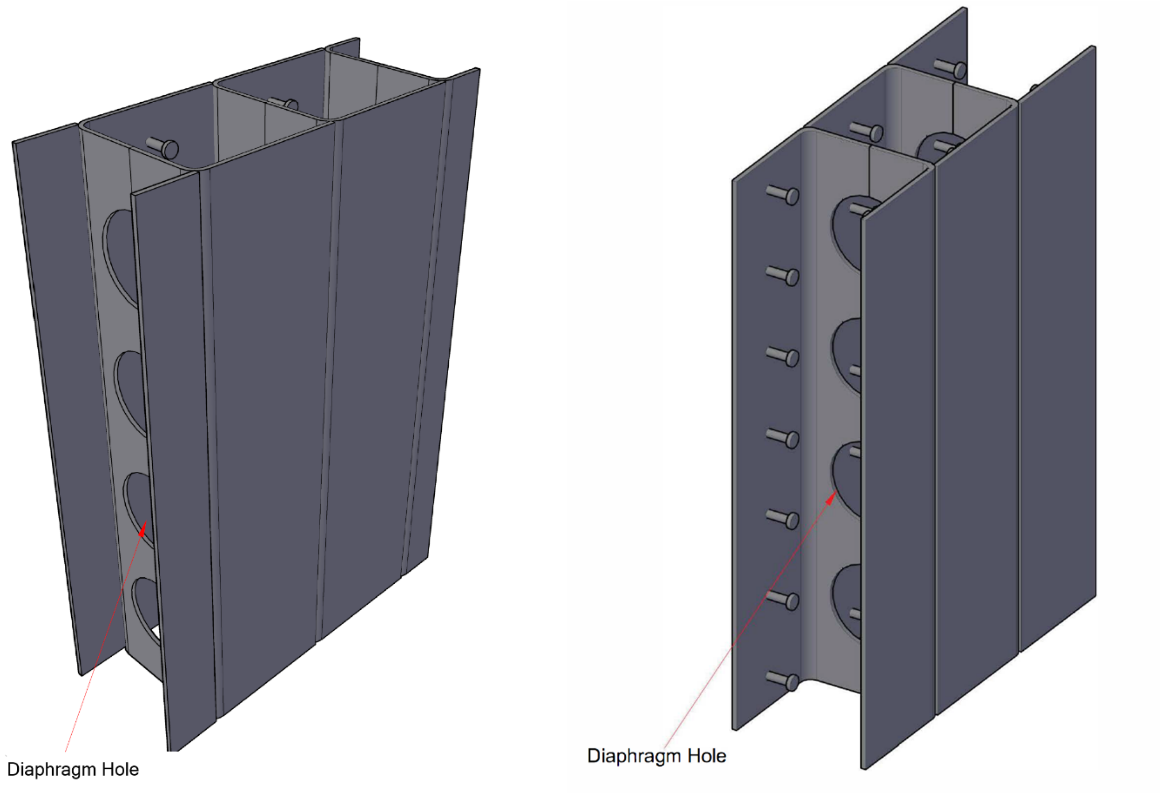

**Figure 7-6: Missile Impact Test Specimens –
Impact Location at Center Diaphragm Plate (IMP-D) (left) -
Impact Location Between Two Adjacent Diaphragm Plates (IMP-C) (right)**

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 design 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 design flexural capacity (ϕM_n) calculated using ANSI/AISC N690 or ACI 349 code equations, whichever applies to the configuration.
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, design shear capacity is based on ANSI/AISC N690 code provisions, as presented in Subsection 5.7.5.1, Equation [5-26]. The design 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 design shear capacity is calculated based on modified ANSI/AISC N690 code provisions as provided in Reference 9-61 (refer to Subsection 5.7.5.2, Equations [5-28] to [5-31]). The design flexural capacity is calculated based on ACI 349 code provisions as developed and verified by Reference 9-59 (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 design 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 design strength is calculated according to the von Mises yield criteria, which is typically used and referenced in ASME BPVC. The calculated design capacities are 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.

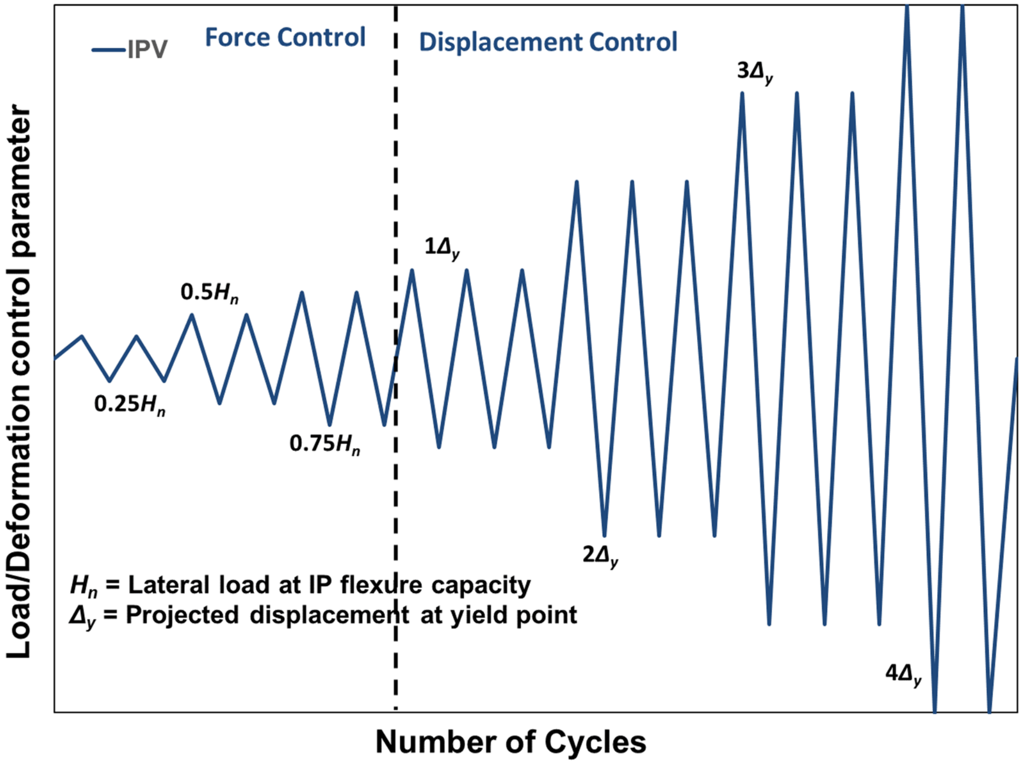

Figure 7-7: Lateral Loading Protocol for In-Plane Shear Tests

7.2.4.5 Pre-Test Calculated Capacities

For the in-plane shear test (IPV), the design in-plane shear capacity is calculated based on ANSI/AISC N690 code provisions. The design 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. The governing failure mode is expected to be in-plane flexural failure. The calculated design 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 design 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 expected 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.

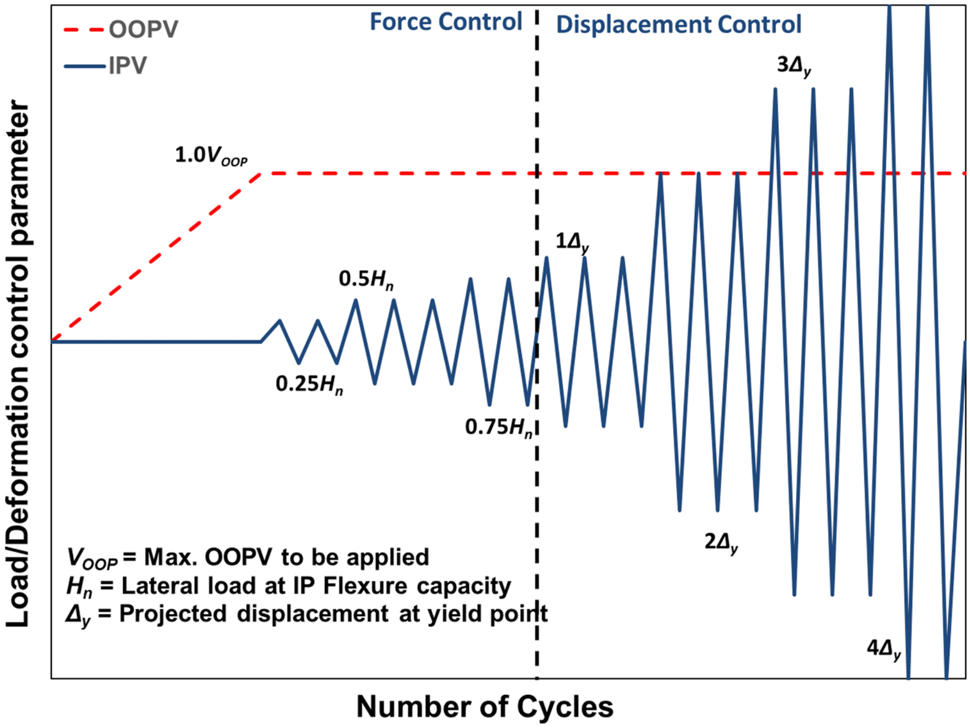

Figure 7-8: Loading Protocol for In-Plane Shear+ Out-of-Plane Shear Tests

7.2.5.5 Calculated Capacities

For the in-plane shear + out-of-plane shear test (IPV+OOPV), the various design capacities are calculated as follows:

- Design in-plane shear capacity is calculated based on ANSI/AISC N690 code provisions
- Design out-of-plane shear capacity is calculated based on modified ANSI/AISC N690 code provisions provided in Reference 9-61 (refer to Subsection 5.7.5.2, Equations [5-28] to [5-31])

- Design 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
- Design out-of-plane flexural capacity is calculated based on ACI 349 code provisions as developed and verified by Reference 9-59 (refer to Subsection 5.7.3.2, Equation [5-20])

The calculated design 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.

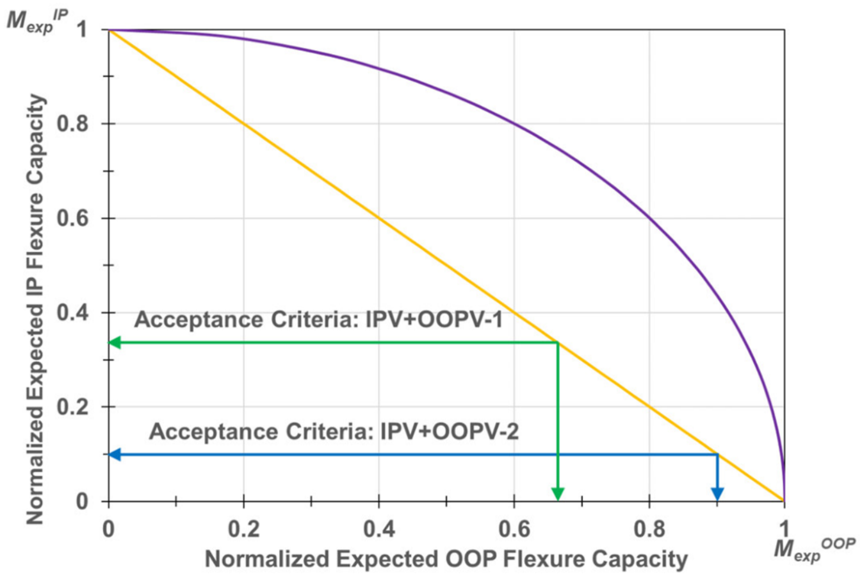

Figure 7-9: Illustration of Interaction between In-Plane and Out-of-Plane Flexural Capacities

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 9-65) 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 9-65).

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 9-65) 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.

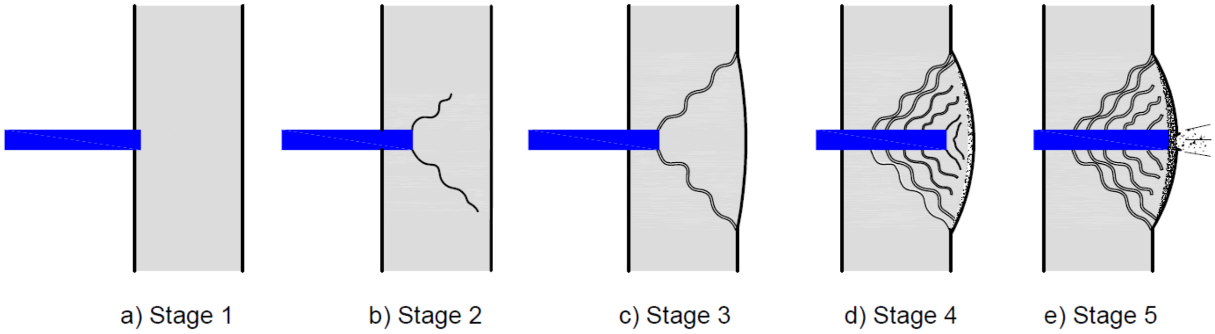

Figure 7-10: Stages in Local Failure Mechanisms of SC walls subject to Missile Impact (Adopted from Reference 9-65)

7.3 NRIC Confirmatory Prototype Phase 1 Test Results

Summaries of the NRIC Phase 1 Prototype Test results are presented in the following subsections.

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 both the calculated design flexural capacity and design shear 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 both the calculated design flexural capacity and design shear 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 design 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 design 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 design 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 design 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 design 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 design 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 both the design and expected in-plane flexural capacities. 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 both the design and expected in-plane flexural capacities. 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 7-2. 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 9-65) is conservative.

Thus, the acceptance criterion described in Subsection 7.2.6.2 was met for the missile impact test.

Table 7-2: 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 9-65)

(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 demonstrated in Section 5.0 of the report, the ANSI/AISC N690, Appendix N9 requirements can extend to the design, analysis, fabrication, construction, examination and testing of DP-SC constructed floors since their structural behavior and failure mechanisms, for a given shear span ratio, 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 considered a ASME BPVC, Section III, Division 2 containment and is designed per ASME BPVC, 2021 Edition, Section III, Division 2, Subsection CC, Articles CC-1000 through CC-6000, for materials, design, fabrication, construction, 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 in-service 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 intent 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 design capacity.

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