Office for Nuclear Regulation

ONR Assessment Report

Generic Design Assessment of the BWRX-300 – Step 2 Assessment - Civil Engineering

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Executive summary

In December 2024, the Office for Nuclear Regulation (ONR), together with the Environment Agency and Natural Resources Wales, began Step 2 of the Generic Design Assessment (GDA) of the BWRX-300 design on behalf of GE Verona Hitachi Nuclear Energy International LLC United Kingdom (UK) Branch, the Requesting Party (RP).

This report presents the outcomes of my civil engineering assessment of the BWRX-300 design as part of Step 2 of the ONR GDA. This assessment is based upon the information presented in the RP's safety, security, safeguards and environment cases (SSSE), the associated revision 3 of the Design Reference Report and supporting documentation.

ONR's GDA process calls for an assessment of the RP's submissions, which increases in detail as the project progresses. The focus of my assessment in this step was to support ONR's decision on the fundamental adequacy of the BWRX-300 design and safety, and the suitability of the methodologies, approaches, codes, standards and philosophies which form the building blocks for the design and generic safety, security and safeguards cases.

I targeted my assessment, in accordance with my assessment plan, at the areas that were fundamental to the acceptability of the design and methods for deployment in Great Britain (GB), benchmarking my regulatory judgements against the expectations of the ONR's Safety Assessment Principles (SAPs), Technical Assessment Guides (TAGs) and other guidance which ONR regards as relevant good practice, such as International Atomic Energy Agency (IAEA) safety, security and safeguards standards. Where appropriate, I have also considered how I could use relevant learning and regulatory conclusions from the UK ABWR GDA to inform my assessment of the BWRX-300.

I targeted the following aspects in my assessment of the BWRX-300 SSSE:

- The Reactor Building was the main facility of interest due to it contributing the most significant radiological risk of all the individual buildings. Furthermore, the Reactor Building utilises a relatively novel (in UK terms) construction approach using Diaphragm Plate Steel-Plate Composite (DP-SC) and the building is subject to deep embedment. The peripheral buildings that surround the Reactor Building comprise surface founded traditionally constructed reinforced concrete and steel structures. The design of these types of facilities is well established in the UK and elsewhere and therefore deemed not a significant area of focus for GDA assessment.

- The suite of design principles and methodologies proposed by the RP. Seismic and Malicious Aircraft Impact were two notable areas of focus due to the tendency of these hazards to impart structural demands that often govern the design of structural elements.

- The DP-SC structural system is used throughout the Reactor Building in the below grade foundation raft, ground retaining walls, containment vessel, RPV pedestal, and above ground for aircraft impact protection. The DP-SC structural system has less technical provenance for Nuclear Power Plant application than the use of traditional reinforced and post stressed concrete systems. Therefore, my assessment placed considerable emphasis on reviewing the proposed design principles and methods. For this part of my assessment, I have sought to draw insight and confidence from existing Canadian and US regulatory reviews.

Based upon my assessment, I have concluded the following:

- From my assessment of the RP's application of its integrated engineering design processes, I am satisfied that the processes are being followed with appropriate expertise and governance (SAP EMC.4). Furthermore, the extensive use of 3D modelling tools within the design process is in accordance with RGP, see ONR TAG 17 Annex 2 [1]. In summary, I judge that there are no fundamental shortfalls associated with the design development processes for civil engineering.

- From my assessment of the overall safety case framework for civil engineering, I consider that the safety case philosophy and construct aligns with RGP and the intent of SAP SC.1, and the process for defining and allocating safety functional requirements is systematic and logical inline with SAPs SC.4, 5. In summary, I judge that there are no fundamental shortfalls associated with the safety case framework for civil engineering.

- The RP has adequately demonstrated for civil engineering structures that: the layout, structural form, proposed geometries, and functional performance are adequately underpinned; areas of residual design risk and/or uncertainty are understood; and the risk of foreclosure of the design is acceptably low. Therefore, I judge that there are no fundamental shortfalls associated with 'proof of concept' for civil engineering.

- I am satisfied that the suite of predominantly US based design codes and standards applied by the RP accords with RGP. I am content that the modelling and analysis architecture and methodologies presented by the RP are robust. Therefore, I judge there that there are no fundamental shortfalls associated with the RP's design principles and methods.

- My assessment of the RP's proposed use of DP-SC has been detailed ranging from the analysis and design methodologies through to constructability considerations. Overall, I consider the design approach to be robust, and the RP has provided compelling arguments for the use of DP-SC in place of more traditional construction approaches. Therefore, I am satisfied that there are no fundamental shortfalls associated with the use of DP-SC & Steel-Plate Composite for this design of NPP. This conclusion was found to be consistent with the views of Nuclear Regulatory Commissioning and Canadian Nuclear Safety Commission.

- Regarding application of Construction, Design and Management (CDM) principles, the impact of UK specific requirements and challenges has not yet been fully developed. However, the RP has demonstrated an understanding of the CDM principles and this is evident in their design processes and specifically the early involvement of fabrication and construction contractors in the design development. Therefore, I am satisfied that there are no fundamental shortfalls associated with the application of CDM principles in the civil engineering design.

Overall, based on my civil engineering assessment, I have not identified any fundamental safety shortfalls and consider the RP’s submission adequate for GDA Step 2.

List of abbreviations

ALARP	As low as reasonably practicable
ABWR	Advanced Boiler Water Reactor
BIM	Building Information Management
BTC	Basic Technical Characteristics
BWR	Boiling Water Reactor
CAE	Claim, Argument and Evidence
CDM	Construction, Design and Management Regulations
CNSC	Canadian Nuclear Safety Commission
DAC	Design Acceptance Confirmation
DBE	Design Basis Earthquake
DCWG	Design Centre Working Group
DEC	Design Extension Conditions
DESNZ	Department of Energy Security and Net Zero
DL	Defence Line
DP-SC	Diaphragm Plate Steel-Plate Composite
DR	Design Reference
DRP	Design Reference Point
DRR	Design Reference Report
EIMT	Examination, Inspection, Maintenance and Testing
ELM	Engineering Lifecycle Management
ESBWR	Economic Simplified Boiling Water Reactor
FAP	Forward Action Plan
FE	Finite Element
FSF	Fundamental Safety Functions
FSP	Fundamental Safety Properties
GB	Great Britain
GDA	Generic Design Assessment
GSE	Generic Site Envelope
GSR	Generic Security Report
GVHA	GE Vernova Hitachi Nuclear Energy Americas LLC
IAEA	International Atomic Energy Agency
ICS	Isolation Condenser System
LOCA	Loss of Coolant Accident
LTR	Licensing Topical Report
MAI	Malicious Aircraft Impact
MCR	Main Control Room
MDSL	Master Document Submission List
NPP	Nuclear Power Plant
NRC	US Nuclear Regulatory Commission
NRW	Natural Resources Wales
NS	Non-Seismic
ONR	Office for Nuclear Regulation
OPEX	Operational Experience
PCSR	Pre-construction Safety Report
PID	Project Initiation Document

PSA	Probabilistic Safety Assessment
PSR	Preliminary Safety Report
RB	Reactor Building
R&D	Research & Development
RGP	Relevant Good Practice
RI	Regulatory Issue
RO	Regulatory Observation
RP	Requesting Party
RPV	Reactor Pressure Vessel
RQ	Regulatory Query
RW	Radiological Waste
SC	Steel-Plate Composite
SCR	Secondary Control Room
SCCV	Steel-Plate Composite Containment Vessel
SSSE	Safety, Security, Safeguards and Environment Cases
SMR	Small Modular Reactor
SSCs	Structures, Systems and Components
SAP	Safety Assessment Principle(s)
SFAIRP	So far as is reasonably practicable
SSC	Structure, System and Component
SSI	Soil-Structure Interaction
TAG	Technical Assessment Guide(s) (ONR)
TB	Turbine Building
TSC	Technical Support Contractor
UK	United Kingdom
US	United States of America
WENRA	Western European Nuclear Regulators' Association

Contents

1. Introduction

1. This report presents the outcome of my civil engineering assessment of the BWRX-300 design as part of Step 2 of the Office for Nuclear Regulation (ONR) Generic Design Assessment (GDA). My assessment is based upon the information presented in the Safety, security, safeguards and environment cases (SSSE) head document [2], specifically chapters 1, 2, 3, 9B, 14, 15, 15.7, 15.8, 21, 24 (refs. [3] [4] [5] [6] [7] [8] [9] [10] [11] [12]) the associated revision of the Design Reference Report (DRR) (ref. [13]) and supporting documentation.

2. Assessment was undertaken in accordance with the requirements of ONR's Management System and follows ONR's guidance on the mechanics of assessment, NS-TAST-GD-096 (ref. [14]) and ONR's risk informed, targeted engagements (RITE) guidance (ref. [15]). The ONR Safety Assessment Principles (SAPs) (ref. [16]), together with supporting Technical Assessment Guides (TAGs) (ref. [1]), have been used as the basis for this assessment.

3. This is a Major report as per ONR's guidance on production of reports (NS-PER-GD-015) (ref. [17])).

1.1. Background

4. The ONR's GDA process (ref. [18]) calls for an assessment of the Requesting Party's (RP) submissions with the assessments increasing in detail as the project progresses. This GDA will be finishing at Step 2 of the GDA process. For the purposes of the GDA, GE Vernova Hitachi Nuclear Energy International LLC, United Kingdom (UK) Branch, is the RP. GE Vernova Hitachi Nuclear Energy Americas LLC (GVHA) is a provider of advanced reactors and nuclear services and is the designer of the BWRX-300. GVHA is headquartered in Wilmington, North Carolina, United States of America (US).

5. In Step 1, and for the majority of Step 2, the RP was known as GE-Hitachi Nuclear Energy International LLC, UK Branch, and GVHA as GE-Hitachi Nuclear Energy Americas LLC. The entities formally changed names in October 2025 and July 2025 respectively. The majority of the submissions provided by the RP during GDA were produced prior to the name change, and thus the reference titles in Section 6 of this report reflects this.

6. In the UK, the RP has been supported by its supply chain partner, Amentum, who has assisted the RP in the development of the UK-specific chapters of the Safety, Security, Safeguards and Environment cases (SSSE), and other technical documents for the GDA.

7. In January 2024 ONR, together with the Environment Agency and Natural Resources Wales began Step 1 of this two-Step GDA for the generic BWRX-300 design.

8. Step 1 is the preparatory part of the design assessment process and is mainly associated with initiation of the project and preparation for technical assessment in Step 2. Step 1 completed in December 2024. Step 2 is the first substantive technical assessment step and began in December 2024 and will complete in December 2025.

9. The RP has stated that currently it has no plans to undertake Step 3 of GDA and obtain a Design Acceptance Confirmation (DAC). It anticipates that any further assessment by the UK regulators of the BWRX-300 design will be on site-specific basis and with a future licensee.

10. The focus of ONR's assessment in Step 2 was:

- The fundamental adequacy of the design and safety, security and safeguards cases; and
- The suitability of the methodologies, approaches, codes, standards and philosophies which form the building blocks for the design and cases.

11. The objective is to undertake an assessment of the design against regulatory expectations to identify any fundamental safety, security or safeguards shortfalls that could prevent ONR permissioning the construction of a power station based on the design.

12. Prior to the start of Step 2 I prepared a detailed Assessment Plan for civil engineering (ref. [19]). This has formed the basis of my assessment and was also shared with the RP to maximise openness and transparency.

13. This report is one of a series of assessments which support ONR's overall judgements at the end of Step 2 which are recorded in the Step 2 Summary Report (ref. [20]) and published on the regulators' website.

1.2. Scope

14. The assessment documented in this report is based upon the SSSE for the BWRX-300 (refs. [2], [3], [4], [5], [21], [22], [23], [24], [25], [26], [6], [27], [28], [29], [30], [7], [8], [31] [32], [33], [34], [35], [36], [9], [10], [37], [38], [39], [40], [41], [42], [11], [43], [44], [12], [45], [46], [47], [48]).

15. The RP's GDA scope has been agreed between the regulators and the RP during Step 1. This is documented in an overall Scope of Generic Design Assessment report (ref. [49]). This is further supported by its DRR (ref. [13]) and the Master Document Submission List (MDSL) (ref. [50]). The GDA scope report documents the submissions which were provided in each topic area during Step 2 and provides a brief overview of the physical and functional scope of the Nuclear Power Plant (NPP) that is proposed for consideration in the GDA. The DRR provides a list of the systems, structures and components (SSCs) which are included in the scope of the GDA, and their relevant GDA reference design documents.

16. The RP has stated it does not have any current plans to undertake GDA beyond Step 2. This has defined the boundaries of the GDA and therefore of my own assessment.

17. The GDA scope includes the Power Block (comprising the Reactor Building (RB), Turbine Building, Control Building, Radwaste Building, Service Building, Reactor Auxiliary Structures) and Protected Areas as well as the balance of plant. It includes all modes of operation.

18. The regulatory conclusions from GDA apply to everything that is within the GDA scope. However, ONR does not assess everything within it, or all matters to the same level of detail. This applies equally to my own assessment, and I have followed ONR's guidance on the mechanics of assessment, NS-TAST-GD-096 (ref. [14]) and ONR's guidance on Risk Informed, Targeted Engagements (ref. [15]).

19. As appropriate for Step 2 of the GDA, information has not been submitted for all aspects within the GDA Scope during Step 2. The following aspects of the SSSE are therefore out of scope of this assessment:

- buildings not listed in ref. [49]
- detailed design substantiation
- site-specific characteristics, such as geotechnical investigations and interpretations,
- detailed site-specific construction specifications

20. My assessment has considered the following aspects that are expanded further upon in Section 4:

- maturity of the safety case framework & design processes
- extent to which the SSSE demonstrates 'proof of concept'
- design principles and methods including areas of novelty
- application of Construction, Design and Management principles

2. Assessment standards and interfaces

21. The primary goal of the GDA Step 2 assessment is to reach an independent and informed judgment on the adequacy of the RP's SSSE for the reactor technology being assessed.

22. ONR has a range of internal guidance to enable Inspectors to undertake a proportionate and consistent assessment of such cases. This section identifies the standards which have been considered in this assessment. This section also identifies the key interfaces with other technical topic areas.

2.1. Standards

23. The ONR Safety Assessment Principles (SAPs) (ref. [16]) constitute the regulatory principles against which the RP's case is judged. Consequently, the SAPs are the basis for ONR's assessment and have therefore been used for the Step 2 assessment of the BWRX-300.

24. The International Atomic Energy Agency (IAEA) safety standards (ref. [51]) and nuclear security series (ref. [52]) are a cornerstone of the global nuclear safety and security regime. They provide a framework of fundamental principles, requirements and guidance. They are applicable, as relevant, throughout the entire lifetime of facilities and activities.

25. Furthermore, ONR is a member of the Western European Nuclear Regulators Association (WENRA). WENRA has developed Reference Levels (ref. [53]), which represent good practices for existing nuclear power plants, and Safety Objectives for new reactors (ref. [54]).

26. The relevant SAPs, IAEA standards and WENRA reference levels are embodied and expanded on in the TAGs (ref. [1]). The TAGs provide the principal means for assessing the civil engineering aspects in practice.

27. The key guidance is identified below and referenced where appropriate within Section 4 of this report. Relevant good practice, where applicable, has also been cited within the body of this report.

2.1.1. Safety Assessment Principles (SAPs)

28. The key SAPs applied within my assessment are the Civil Engineering (ECE) suite of SAPs, namely:

- Principles ECE.1-3
- Design ECE.6-8, 12-15
- Construction ECE.16-19, 25
- Examination, Inspection, Maintenance & Testing (EIMT) ECE.20,22
- Decommissioning ECE.26

29. The other relevant SAPs invoked within my assessment are the suites of SAPs associated with safety case (SC), safety classification and standards (ECS), key engineering principles (EKP), external and internal hazards (EHA), reliability (EDR and ERL), layout (ELO), ageing and degradation (EAD) and assurance of validity of data and models (AV).

30. A list of the SAPs used in this assessment is recorded in Appendix 1, and the principles themselves are referenced explicitly within the assessment narrative.

2.1.2. Technical Assessment Guides (TAGs)

31. The following TAGs (ref. [1]) have been used as part of this assessment:

- NS-TAST-GD-096, Guidance on Mechanics of Assessment.
- ONR-TAST-GD-017, Civil Engineering
- ONR-TAST-GD-020, Civil Engineering for Containments for reactor plant
- ONR-TAST-GD-013, External Hazards
- ONR-TAST-GD-014, Internal Hazards
- ONR-TAST-GD-094, Categorisation of safety functions and classification of SSCs
- NS-TAST-GD-051, The Purpose, Scope and Content of Nuclear Safety Cases
- NS-TAST-GD-005, ONR Guidance on the Demonstration of As Low as Reasonably Practicable (ALARP)

2.1.3. National and international standards and guidance

32. The following non exhaustive list of international standards and guidance have been used as part of this assessment:

- IAEA SSR-2/1 – Safety of Nuclear Power Plants: Design (ref. [55])
- IAEA SF-1 – Fundamental Safety Principles (ref. [56])
- IAEA SSG-30 – Safety Classification of Structures, Systems and Components in Nuclear Power Plants (ref. [57])
- IAEA SSG-53 – Design of the Reactor Containment and Associated Systems for Nuclear Power Plants (ref. [58])
- IAEA SSG-67 – Seismic Design for Nuclear Installations (ref. [59])
- IAEA SR86 – Safety Aspects of Nuclear Power Plants in Human Induced External Events: General Considerations (ref. [60])
- IAEA SR87 – Safety Aspects of Nuclear Power Plants in Human Induced External Events: Assessment of Structures (ref. [61])
- WENRA Safety Reference Levels (ref. [62])

- WENRA Safety of new NPP designs (ref. [63])
- INSAG-12 Basic Safety Principles for Nuclear Power Plants (ref. [64])
- ACI 349-23 Nuclear Safety-Related Concrete Structures Code Requirements and Commentary (ref. [65])
- ASCE4-16 Seismic Analysis of Safety Related Nuclear Structures (ref. [66])
- ASCE43-19 Seismic Design Criteria for Structures, Systems and Components in Nuclear Facilities (ref. [67])
- ASME Boiler and Pressure Vessel Code, Section III Rules for construction of Nuclear Facility Components (ref. [68])
- ANSI/AISC N690-18 Specification for Safety Related Steel Structures for Nuclear Facilities (ref. [69])
- ANSI/AISC N690-24 Specification for Safety Related Steel Structures for Nuclear Facilities (ref. [70])
- ANSI/AISC-360-16 Specification for Structural Steel Buildings (ref. [71])
- ANSI/AISC-360-22 Specification for Structural Steel Buildings (ref. [72])
- ANSI/AISC, Design Guide 32: Design of Modular Steel-Plate Composite Walls for Safety-Related Nuclear Facilities (ref. [73])
- AISC, Design Guide 38: SpeedCore Systems for Steel Structures (ref. [74])
- NEI 07-13 - Methodology for Performing Aircraft Impact Assessments for New Plant Designs (ref. [75])
- ASTM E119 − 20: Standard Test Methods for Fire Tests of Building Construction and Materials (ref. [76])
- NRC, Quality Assurance Program and Criteria (Design and Construction) (ref. [77])
- JEA, JEAC 4618-2009, Technical Code for Aseismic Design of Steel Plate Reinforced Concrete Structures (ref. [78])
- KEPIC-SNG, Nuclear Safety Related Structures – Steel-Plate Concrete Structures (ref. [79])

2.2. Integration with other assessment topics

33. To deliver the assessment scope described above I have worked closely with a number of other topics to inform my assessment. Similarly, other assessors sought input from my assessment. These interactions are key to the success of GDA to prevent or mitigate any gaps, duplications or inconsistencies in ONR's assessment.

34. The key interactions with other topic areas were:

- External Hazards (ref. [80]) to confirm the adequacy of the generic site envelope for use in civil engineering design basis definitions and the link into the civil engineering safety case.
- Internal Hazards (ref. [81]) to ensure that civil engineering barriers have been appropriately identified, the methodology for developing the civil engineering load functions is appropriate, and the links into the civil engineering safety case are clear and navigable.
- Fire Safety (ref. [82]) to ensure the RP's proposed layout can accommodate the UK specific requirements e.g., the provision of protected fire fighting shafts and other related requirements.
- Fault Studies (ref. [83]) to ensure the adequacy of the RP's approach to the categorisation of safety functions and classification of SSCs, and the containment thermal and pressure accident conditions that form inputs to civil engineering analyses for containment and pools.
- Mechanical & Electrical Engineering (refs. [84], [85]) to confirm the adequacy of spatial provision for EMIT purposes and the maturity of modelling of equipment and methodology for analysis and modelling purposes.
- Conventional Health and Safety (ref. [82]) for layout and constructability considerations and the application of the CDM regulations.

2.3. Use of technical support contractors

35. During Step 2, I engaged a Technical Support Contractor (TSC) to support the review of the following aspects of my assessment of civil engineering for the BWRX-300 GDA.

- Design codes and standards and good practice for more novel areas such as the use of Diaphragm-Plate Steel-Plate Composite (DP-SC);
- Modelling and analysis architecture and software application including use of Verification and Validation (V&V) and sensitivity analyses;
- Design principles and methodologies for topics such as: Geotechnics, Seismic analysis, Static and Dynamic Soil-Structure and Structure-Soil-Structure Interaction, Malicious Aircraft Impact (MAI), and Thermal effects under accident conditions;
- Modelling, analysis and design methods applied for DP-SC RB structures including the Steel-Plate Composite Containment Vessel (SCCV) and aircraft impact protection; and
- Broader construction and design management related matters and principles important to reducing risks ALARP in the conceptual and preliminary design phases.

36. The TSC provided me with technical advice (ref. [86]) and supported my assessment, working under my close direction and supervision. It should be noted that all regulatory judgements have been made exclusively by ONR.

3. Requesting Party's submission

37. The RP submitted the SSSE at the start of Step 2 in four volumes that integrate environmental protection, safety, security, and safeguards. This was accompanied by a head document (ref. [2]), which presents the integrated GDA environmental, safety, security, and safeguards case for the BWRX-300 design.

38. All four volumes were subsequently consolidated to incorporate any commitments and clarifications identified in regulatory engagements, regulatory queries and regulatory observations, and were resubmitted in July 2025. This consolidated revision is the basis of the regulatory judgements reached in Step 2.

39. This section presents a summary of the RP's safety case for civil engineering. It also identifies the documents submitted by the RP which have formed the basis of my Step 2 assessment of the BWRX-300 design.

3.1. Summary of the BWRX-300 Design

40. The BWRX-300 is a single unit, direct-cycle, natural circulation, boiling water reactor with a power of ~870 MW (thermal) and a generating capacity of ~ 300 MW (electrical) and is designed to have an operational life of 60 years. The RP claims the design is at an advanced concept stage of development and is being further developed during the GDA in parallel with the RP's SSSE.

41. The BWRX-300 is the tenth generation of the boiling water reactor (BWR) designed by GVHA and its predecessor organisations. The BWRX-300 design builds upon technology and methodologies used in its earlier designs, including the Advanced Boiling Water Reactor (ABWR), Simplified Boiling Water Reactor (SBWR) and the Economic Simplified Boiling Water Reactor (ESBWR). The ABWR has been licensed, constructed and is currently in operation in Japan, and a UK version of the design was assessed in a previous GDA with a view to potential deployment at the Wylfa Newydd site. Neither the SBWR or ESBWR have been built or operated.

42. The RB and the turbine building, along with the majority of the significant SSCs are housed with the 'power block'. The power block also includes the radwaste building, the control building and a plant services building.

43. The BWRX-300 reactor core houses 240 fuel assemblies and 57 control rods inside a steel reactor pressure vessel (RPV). It uses fuel assemblies (GNF2) that are already currently widely used globally (ref. [21]).

44. The reactor is equipped with several supporting systems for normal operations and a range of safety measures are present in the design to provide cooling, control criticality and contain radioactivity under fault

conditions. The BWRX-300 utilises natural circulation and passive cooling rather than active components, reflecting the RP's design philosophy.

45. A general description of the design is provided in (ref. [87]). It is notable that the civil structures are surface founding apart from the RB that is significantly embedded. The RP has provided general arrangement drawings that give a detailed overview of the layout and geometries, see (refs. [88], [89], [90]).

46. The RPV Containment, RPV support pedestal, and the RB itself are all formed from DP-SC construction. This is claimed to have many benefits for construction and through life performance.

47. All other power block structures are formed from conventional steel and reinforced concrete construction founded on foundations that will be specific to the site geology.

48. Protection from aircraft impact is provided by the RB outer shell itself noting that much of the RB is embedded and, although not claimed as providing any beneficial protective affect within the Aircraft Impact Assessment safety justification, the RB is also shielded via the adjoining power block buildings. This shell not only provides protection but also functions to support internal components such as the main RB crane.

3.2. BWRX-300 Case Approach and Structure

49. The RP has submitted information on its strategy and intentions regarding the development of the SSSE (refs [91], [92], [93], [94]). This was submitted to ONR during Step 1.

50. The RP has submitted a SSSE for the BWRX-300 that claims to demonstrate that the standard BWRX-300 can be constructed, operated, and decommissioned on a generic site in GB such that a future licensee will be able to fulfil its legal duties for activities to be safe, secure and will protect people and the environment. The SSSE comprises a Preliminary Safety Report (PSR) which also includes information on its approach to safeguards and security, a security assessment, and a Preliminary Environment Report (PER), and their supporting documents.

51. The format and structure of the PSR largely aligns with the IAEA guidance for safety cases, SSG-61 (ref. [95]), supplemented to include UK specific chapters such as Structural Integrity and Chemistry. The RP has also provided a chapter on ALARP, which is applicable to all safety chapters. The RP has stated that the design and analysis referenced in the PSR is consistent with the March 2024 Preliminary Safety Analysis Report submitted to the US Nuclear Regulatory Commission (NRC). The Security Assessment and PSR are for the same March 2024 design but have more limited links to any US or Canadian submissions.

3.3. Summary of the RP's case for Civil Engineering

52. The safety case adopts a Defence Line (DL) concept that is derived from the IAEA 5-layer model outlined in IAEA SSR 2/1 (ref. [55]). The definitions of each DL are provided in the BWRX Safety Strategy report (ref. [91]) and Figure 2-2 in (ref. [91]) illustrates the concept. The substantiation of civil structures in terms of analysis, quality, robustness, durability, through life performance all fall under DL1.

53. The full detailed set of SFRs has not yet been fully defined for civil structures. However, the process being applied for their development and a broad overview of the safety requirements developed thus far is provided in refs. [96], [91], [6]. This is described in the sections that follow.

3.3.1. Safety Classification and Categorisation

54. Civil structures are assigned a Safety Classification (SC) based on the highest SC of the components they house or support, excluding components for which failure of the supporting structure results in fail-safe performance of the component's safety category function. Four safety classes are defined in (ref. [97]), namely, SC1, SC2, SC3, and SCN. SC1 SSCs perform DL3 functions, which are the most reliable defense line functions as defined in (ref. [97]).

55. The Seismic Category of the Buildings & Structures reflects the SSC's performance requirements during and after a seismic event and governs how the SSC is designed and qualified. The seismic categorisations for civil structures are 1A, 2, Radiological Waste (RW) and Non-Seismic (NS), noting that Cat. 1B applies only to active SSCs and cannot apply to civil structures. These reflect the suite of US and Canadian requirements and are described in Section 3.4 and Table 3-2 of (ref. [98]). A brief summary is given below.

- Cat. 1A civil structures are designed to remain essentially elastic against the full design basis without any significant permanent deformation (Limit State D of ASCE43-19 [67]).
- Cat. 2 applies to NS civil structures that interact with Cat. 1A/1B SSCs. These civil structures are designed to local building codes but supplemented by an interaction evaluation which analyses and designs the structure to prevent its collapse under Design Basis Earthquake (DBE) or extreme wind events.
- Cat. RW Civil Structures are designed to remain essentially elastic without any significant permanent deformation to the half the DBE. This is also supplemented by an interaction evaluation which analyses and designs the structure to prevent its collapse under DBE or extreme wind events.
- Cat. NS civil structures are designed to the local building codes noting that interaction with Cat. 1A/1B SSCs during a DBE or extreme wind events must be ruled out.

3.3.2. Safety Requirements

56. The Fundamental Safety Functions are claimed to be consistent with IAEA in (ref. [56]) and given as control of reactivity, fuel cooling and confinement of radioactive materials. These FSFs are maintained by functions in DL2, DL3, DL4a, DL4b, or combinations thereof, depending on the Plant State / Event Sequence, and related acceptance criteria. The FSFs are always being performed, even during “normal” operation. If the FSFs are performed successfully, the physical barriers to radioactive release (such as the containment) maintain their integrity.

57. The safety case also uses Fundamental Safety Properties (FSPs) described in Section 2.3 of (ref. [91]). FSPs are claimed to provide assurance that the FSFs will be performed with the expected reliability as, when, and under the conditions required; and that their successful performance can be confirmed by operating staff. The FSPs are attributes of the design architecture and its SSCs (including their “quality”) required to achieve the assumed reliability of the DL functions. Examples of these are provided in Section 3.2 of (ref. [91]).

58. The Safety Strategy report (ref. [91]) describes the process for identifying hazards and faults, and how deterministic and probabilistic analysis are conducted to derive barriers and safety requirements on such barriers.

59. Safety requirements are the main source of input to the Integrated Design Process. Management of requirements is guided and informed by ISO/IEC/IEEE 15288 / 19248 / 29148 and defined in the BWRX-300 Requirements Management Plan (ref. [96]). Traceable relationships (links) are used to map the flow down of information.

60. During the design process, requirement validation is used to assess the extent to which the applicable requirements have been fulfilled. Feedback from the validation process informs revisions to requirements or creation of new requirements and design decisions through an iterative process.

61. The BWRX-300 requirements and decisions are organised into a hierarchy where artifacts classified as “Plant Level” (examples being refs. [99] [100] [101]), are decomposed into more detailed artifacts at the System and Component level of design. Each discrete artifact contains metadata, including a basis, maturity level, document ID, and safety category.

62. Links are created to establish relationships between requirements and design decisions. By using these links, the RP claims a requirement can be traced downward to find all the design features that have been established to fulfill it. Figure 3-1 of (ref. [96]) illustrates the above process.

3.3.3. Management and Allocation of Safety Requirements

63. The RP uses the Engineering Lifecycle Management (ELM) software tool to store, organise and manage requirements from the Safety Analysis and

implement them into the design process[1]. The ELM process consists of a hierarchical structure with relationships that demonstrate upward traceability to the source requirements and downward traceability to the design decisions that fulfill them. ELM also documents the basis for plant, system, and component design. Specifications are also being input to ELM so that all engineering requirements and decisions are traceable by the Requirements Management Plan process, see (ref. [96]).

64. For civil structures, a Safety Requirements Schedule is written to summarise the hazard requirements and present the ELM outputs, together with additional engineering assumptions around hazard and fault withstand requirements. Component specifications for the equipment vendor are not prepared in ELM, however the ELM provides inputs to the scope of these documents. Other processes (Procurement / QA) then take over to ensure the requirements specified in the Component-Level documents are fulfilled by external suppliers.

65. The RP recognises within its submissions that a fully UK context compliant Safety Case is not yet available. For example, the current safety case documentation does not currently include Bases of Safety Case or safety requirement schedules in the same way as is considered RGP in the UK. The RP claims that its current process does comprise all the required information to do this. During GDA the RP developed a safety requirements schedule for the RB (ref. [102]). This document outlines how safety requirements pertaining to the integrated RB structures are derived and how such requirements are translated into input parameters to a safe structural design.

3.3.4. Design Basis and BDB philosophy

66. The philosophy for design of civil structures for design basis loads and design extension condition is articulated in (ref. [98]) and follows standard US guidance in terms of methodology. For design extension conditions the methodologies are described although the work itself has not yet been completed.

3.3.5. Codes & Standards

67. The codes and standards basis are outlined in Section 4 of (ref. [103]). This comprises a comprehensive suite of US and Canadian codes, standards, regulations and regulatory guidance. The key design codes and standards pertinent to civil structures are captured in Table 5-1 of (ref. [98]).

[1] The IBM Engineering Lifecycle Management product provides a digital foundation (digital thread) to establish traceability across the development environment from requirements to delivery, see IBM Engineering Lifecycle Management

3.3.6. Modelling and Analysis architecture

68. The modelling and analysis architecture for civil structures is outlined in (refs. [104], [105], [106], [107]). This consists of four integrated analysis pathways for structural analysis of static loads, seismic soil-structure interaction (SSI) analysis, internal containment analysis, and aircraft impact analysis. The process is illustrated in Figure 1 of (ref. [108]). The main software used consists of ACS SASSI, ANSYS and LS DYNA.

3.3.7. ALARP by Design

69. A synopsis of the RP's claims regarding reducing risks ALARP is provided in (refs. [109], [110]) and (ref. [111]). The important factors of key conceptual design decisions relating to the BWRX-300 civil structures that are intrinsic to the ALARP methodology given in appendix A.2 of (ref. [6]) are:

- Use of internationally accepted codes, standards and guidance that constitute relevant good practice;
- Use of operational experience and learning from ABWR, AP1000 with respect to modular construction techniques, and the standard design optimisation for the Darlington New Nuclear Project in Canada and the Tennessee Valley Authority project in the US;
- Use of engineering judgement in modelling and analysis; and
- Identification and evaluation of options in optimising the design and layout.

3.4. Basis of assessment: RP's documentation

70. The principal documents that have formed the basis of my civil engineering assessment of the SSSE are defined in (ref. [49]):

- GDA PSR Chapter 9B: Civil Structures (ref. [6])
- NEDO-33914-A, BWRX-300 Advanced Civil Construction and Design Approach, Rev 2 (ref. [112])
- NEDC-33926P, Steel-Plate Composite Containment Vessel (SCCV) and RB Structural Design, Rev 2 (ref. [113])
- 005N9341, BWRX-300 General Civil Structural Design Criteria, Rev 2 (ref. [98])
- 006N8279, BWRX-300 Civil Structural Seismic Analysis and Design Criteria, Rev 3 (ref. [104])
- 006N8280, BWRX-300 Civil Structural Modelling Criteria for RB, Rev 3 (ref. [105])
- 006N8281, BWRX-300 Civil Structural Analysis Criteria for RB, Rev 1 (ref. [106])

71. These core documents have been supplemented by further submissions as recorded in the MSDL (ref. [50]), the suite of formal RQ responses, and

technical workshop presentations. These will be referenced as necessary in Section 4.

3.5. Design Maturity

72. My assessment is based on Revision 3 of the DRR (ref. [13]). The design reference report presents the baseline design for GDA Step 2, outlining the physical system descriptions and requirements that form the design at that point in time.

73. The reactor building and the turbine building, along with most of the significant SSCs are housed within the ‘power block.’ The power block also includes the radwaste building, the control building and a plant services building. For security, this also includes the protected area boundary and the protected area access building

74. The GDA Scope Report (ref. [49]) describes the RP’s iterative design engineering process that follows basic phases to accomplish the design objectives. This process is described further in the Design Plan (ref. [114]). To allow sequencing and development of requirements, the process is expressed via four design phases BL0, BL1, BL2, and BL3 that are defined in Tables 3-1, 3-2, 3-3, 3-4 and illustrated via Figures 3-1 and 3-2 in (ref. [114]). For context, BL0 represents the concept stages where functional requirements are defined whereas BL3 represents a fully mature design ready for construction.

75. In the March 2024 design reference, SSCs in the power block are stated to be at BL1. The balance of plant remains at BL0 for which only plant requirements have been established, and SSC design remains at a high concept level.

76. The RP provided additional responses for information, which stated that as of April 2025, for civil structures the RB is within the BL2 stage whereas the Turbine Building, Control Building and Radwaste Building are at BL1 (ref. [115]).

4. ONR assessment

4.1. Assessment strategy

77. The objective of my GDA Step 2 assessment was to reach an independent regulatory judgement on the fundamental aspects of the BWRX-300 design, relevant to civil engineering as described in sections 1 and 3 of this report. My assessment strategy is set out in this section and defines how I have chosen which matters to target for assessment. My assessment is consistent with the delivery strategy for the BWRX-300 GDA (ref. [116]).

78. GVHA is currently engaging with regulators internationally, including the Nuclear Regulatory Commission in the US (US NRC) and the Canadian Nuclear Safety Commission in Canada (CNSC). It is proposing a standard BWRX-300 design for global deployment with minimal design variations from country to country. My assessment takes cognisance of work undertaken by overseas regulators, where appropriate, notably on the use of DP-SC, and has involved engagement with US NRC / CNSC, see [117] & [118].

79. Whilst there is no operating BWR plant in the UK, ONR has previously performed a four-step GDA on the Hitachi-GE UK ABWR (ref. [119]). I have taken learning from this previous activity, targeting my assessment on those aspects of the BWRX-300 which are novel or specific to this design. I have not looked to reassess inherent aspects of BWR technology which were considered in significant detail for the UK ABWR and judged to be acceptable.

80. My assessment strategy developed from my assessment plan (ref. [19]) focussed on ascertaining whether the RP's submissions provide adequate assurance for the key areas below.

- Design Processes: The design development is being managed and controlled through explicit, robust gated processes, with appropriate QA oversight;
- Safety Case Framework: Evidence of a coherent safety case construct that is capable of comprehensively deriving and allocating safety functions and associated functional and design requirements to civil structures;
- Proof of Concept: Demonstration for civil engineering structures that the layout, structural form, proposed geometries and functional performance are adequately underpinned. Areas of residual design risk and/or uncertainty are understood, and the risk of foreclosure of the design is acceptably low;
- Design Principles & Methods: A suite of design principles and methods that accord with relevant good practice, and are integrated within a clear modelling, analysis, and design architecture. Limitations, uncertainties, and sensitivities are identified via an associated framework of V&V and sensitivity exploration.

- Novelty: Enhanced justification of novel / less proven design features and/or construction types/techniques, with more rigorous modelling analysis and design approaches, bespoke testing and validation, and conservatism that links to the uncertainty and significance of the SSC under consideration; and
- Application of CDM Principles: CDM principles are being appropriately considered within the design development.

81. The overall synthesis of my findings against these attributes formed the basis for my judgement regarding whether the RP's submission is adequate.

82. My assessment strategy included six technical workshops with the RP's technical specialists. These workshops were structured around objectives and expectations submitted to the RP in advance. The topics and dates for these workshops were as follows:

- Workshop 1, 15-16 Jan 2025 - Design Maturity (ref. [120])
- Workshop 2, 14 Feb 2025 - Safety Case (1) (ref. [121])
- Workshop 3, 20 Feb 2025 - Malicious Aircraft Impact (ref. [122])
- Workshop 4, 12 Mar 2025 - Modelling and analysis ((ref. [123])
- Workshop 5, 8-9 Apr 2025 - DP-SC (ref. [124])
- Workshop 6, 13 May 2025 - Safety Case (2) (ref. [125])

83. The technical queries arising from these workshops were formalised via suites of RQs.

84. Therefore, the overall body of evidence that formed the basis for my assessment comprised the RP's submissions, technical presentations and information provided at the 6 technical workshops, and RQ responses.

4.2. Assessment Scope

85. My assessment scope and the areas I have chosen to target for my assessment are set out in this section. This scope is consistent with the overall GDA scope agreed between the regulators and the RP during Step 1 as summarised in Section 1.2 of this report.

86. In line with the objectives for Step 2, I have undertaken a broad review of the highest level, fundamental claims and supporting arguments related to civil engineering and supplemented this with more detailed review of areas of significance.

87. My assessment focussed on the RB as the main facility of interest due to it contributing the most significant radiological risk profile of all the individual buildings. Furthermore, the RB utilises a relatively novel (in UK terms) construction approach that uses a deeply embedded layout geometry coupled with the use of a DP-SC structural system.

88. The peripheral buildings that surround the RB comprise surface founded traditionally constructed reinforced concrete and steel structures. The design of these types of facilities is well established in the UK and elsewhere and therefore deemed not a significant area of focus for GDA assessment.

89. My assessment scope included a review of the suite of design principles and methodologies that are proposed by the RP. Seismic and MAI were two notable areas of focus due to the tendency of these hazards to impart structural demands that often govern the design of structural elements. It is notable that US practice is invoked almost exclusively by the RP in these methodologies and my assessment seeks to ascertain the suitability of these approaches.

90. The DP-SC structural system is used throughout the RB in the below grade foundation raft, ground retaining walls, containment vessel, RPV pedestal, and above ground for aircraft impact protection. Coupled with this, the DP-SC structural system has less technical provenance for NPP application than the use of traditional reinforced and post stressed concrete systems. Therefore, my assessment scope places considerable emphasis on reviewing the proposed DP-SC design principles and methods. For this part of my assessment, I have sought to draw insight and confidence from existing Canadian and US regulatory reviews.

4.3. Assessment

91. The record of my assessment below is formatted into subsections that align with the attributes outlined in Section 4.1 above. The introduction to each subsection sets out my assessment objectives and expectations followed by the RP's evidence that forms the basis for the assessment. Sources of RGP that I invoke are referenced within the assessment commentary that follows. Comments and notes are provided to inform a future iteration of the BWRX-300 safety case. The end of each subsection includes an assessment summary that provides a regulatory judgement. The augmentation of these assessment summaries provides the basis for the conclusions presented in Section 5.

92. The technical advice provided to me through my TSC is recorded at (ref. [86]). Although this has informed my assessment it should be noted all regulatory judgements have been made exclusively by ONR.

4.3.1. Design Development Processes

93. My assessment objective was to gain assurance regarding the design management systems and processes used by the RP to manage the evolution of the civil engineering design. This was expected to comprise explicitly described, robust gated processes, with appropriate QA oversight that both informs and draws from the safety case development. It should be noted that my assessment targets those specific areas of the process significant to civil engineering.

94. The RP's evidence forming the basis for this assessment is contained within submissions (refs. [114], [96], [98]) the RQ responses (refs. [111], [110], [109], [115]), and workshop presentation materials (refs. [120], [121]). The integrated design process is illustrated by Figures 3-1 and 3-2 of (ref. [114]) and is described therein.

95. The RP's process includes the gathering of top-level product, owner and regulatory requirements, inputs from deterministic and probabilistic safety analysis to establish the set of safety requirements. These requirements and information flow into the design development process where engineering disciplines come together and execute design responsibilities in collaborative data-centric workspaces. The RP uses 3D modelling tools and system simulation tools to explore system design options and perform optimisations to evaluate feature and function choices, performance margins and cost. It is notable that this design process explicitly includes pathways for OPEX, past BWR designs and a Research and Development (R&D) program.

96. The 3D Building Information Model (BIM) is the principal design tool used by the RP for space control and design drawing production. It is the key source of information used to produce various 2D discipline drawings. The files in the BIM system contain the structural, architectural, and civil components that are individually drafted into different layers that can be reviewed by design teams as needed[2]. I note that this 3D modelling environment is also used to extract volumes of commodities including concrete, steel, and report such quantities in bills of materials. It is also how interference checking is accomplished to ensure an interference-free design to minimise rework during actual construction and at the end of the project. I note that a separate 3D model of the RB is maintained that includes detailed modelling of the DP-SC structural elements. This model is the source of information used to produce 2D drawings for DP-SC detailing for the fabrication and construction contractors.

97. Design reviews and design document generation are implemented by the RP at the end of each design phase. I note that in addition to a review of the system requirements and design, these reviews include all disciplines and considers topics such as constructability, reliability, maintainability, and human factors. Moreover, the process explicitly acknowledges that the results of these design reviews may change the requirements and/or the design necessitating iterative loops of design refinement.

98. Decisions that have a significant effect on cost or scope are reviewed by the Design Centre Working Group (DCWG). The DCWG function is to:

- Aid the development of appropriate mitigation strategies consistent with the complexity and level of risk involved; and

[2] . The files in the BIM system also contain information of the Mechanical, Electrical, Instrument and Control Systems.

- Promote safety and standardization of BWRX-300 design through harmonisation of regulatory and engineering practices where there may be a safety and design benefit.

99. The design process is further controlled through the four design phases: BL0 – BL3 described in para. 73 above. I note that the design process of Figure 3-2 of (ref. [114]) is repeated at each of the four design phases. Furthermore, the iterative nature of the RP's process, the use of optioneering, multidisciplinary evaluation, 3D modelling tools, OPEX and independent review provide assurance that the design produce will contribute significantly to the safety case process of demonstrating risks are reduced ALARP.

100. From my civil engineering assessment of the RP's integrated engineering design processes, I consider that the RP's arrangements are rigorous and robust and inline with examples of RGP such as the RIBA Plan of Work process[3].

101. As further validation of this conclusion, I tested the demonstration of the RP's design processes during technical workshops 1 and 2 where the layout development was one area of the design subject to interrogation, see (refs. [120], [121]). During these live sessions, the RP's experts were able to provide a convincing demonstration using 3D modelling tools that evidenced the effectiveness of its design configuration and control processes. The formal RQ responses at (refs. [111], [110], [109]) provide a record of this.

4.3.1.1. Assessment Summary:

102. From my assessment of the RP's application of its integrated engineering design processes, I am satisfied that the processes are being followed with appropriate expertise and governance (SAP EMC.4). Furthermore, the extensive use of 3D modelling tools within the design process is in accordance with RGP, see ONR TAG 17 Annex 2 (ref. [1]). In summary, I judge that there are no fundamental shortfalls associated with the design development processes for civil engineering.

4.3.2. Safety Case Framework

103. My assessment objective was to gain assurance that the safety case framework was appropriate, in line with international and UK RGP and cognisant of the UK context. My assessment expectations are based on IAEA SF-1, SSR-2/1 (refs. [56], [55]), INSAG-12 (ref. [64]), SAPs SC.1,2,4,5,6 (refs. [16], [126]). These call for a coherent safety case construct that is accurate, objective, and capable of deriving and allocating safety functions and associated functional and design requirements to civil structures.

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[3] The RIBA Plan of Work organises the process of briefing, designing, constructing and operating building projects into eight stages and explains the stage outcomes, core tasks and information exchanges required at each stage. See RIBA Plan of Work for further information.

Furthermore, it should be clear regarding why/how risks will be reduced ALARP see (ref. [127]).

104. My assessment consisted of reviewing:

- The proposed philosophy and construct of the safety case for civil structures;
- The processes for determining safety classification and defining safety requirements are rigorous and robust;
- The approaches applied to transfer requirements to SSCs;
- How Safety Functional Requirements (SFR) will be represented in the basis of design; and
- How the ALARP principle is considered.

105. The RP's evidence forming the basis for this assessment is contained within RP submissions (refs. [6], [5], [32], [13], [91], [96], [47], [113], [128], [102]), the RQ responses (refs. [111], [110], [109], [108], [115], [129] [130], [131], [132]), and Workshop 2 and 6 presentation materials (refs. [121], [125]).

106. The RP's safety case philosophy is for a design with a high level of intended and inherent safety and applies design requirements from IAEA principles in SSR-2/1 (ref. [55]). Moreover, the basis of safety case adopts the safety objectives established from IAEA in SF-1 (ref. [56]) and INSAG-12 (ref. [64]). This overarching approach accords with International and UK RGP for safety case construct and meets the intent of SAP SC.1.

107. The safety case structure is clarified generally in (ref. [6]) where the SFRs and the breakdown of these into the discrete engineering and design requirements is presented for three general categories of structures; 'Foundations and buried structures'; 'Integrated RB', and 'Other Structures'. Further information in (ref. [91]), clarifies the safety case logic from the DL's, Safety Classifications, FSPs and safety requirements. Although a full basis of safety case for civil structures is not yet available the RP provided a full demonstration for the RB via (refs. [129], [102]). From my review, this provided assurance that the safety case framework and construct proposed was coherent, the golden thread was navigable, and the future intentions were in line with SAPs SC.1,2,4 and IAEA SSR 2/1.

108. The RP's safety classification of civil structures is based on the highest safety classification of the SSCs that they house or support. I note this excludes components for which failure of the supporting structure results in fail-safe performance of the component's safety category function. The Seismic Category reflects structure and component requirements during and after a seismic event and governs how structures and components are designed and qualified. The RB is the only Seismic Category 1A civil structure and is expected to remain essentially elastic without any significant permanent deformation against the full design basis earthquake (i.e., Limit State D in (ref.

[67])). I note that the interaction of the RB with adjacent Seismic Category 2 facilities is expected to be evaluated for seismic interaction and extreme wind interaction. I am content this captures the interaction issues appropriately.

109. The Main Control Room (MCR) is in the Control Building which is seismic category 2 and not protected from MAI. I note that the IAEA SSR-2/1 Requirement 65 expects the control room to be operable in all operational states. Furthermore, paragraph 6.40A highlights: *"The design of the control room shall provide an adequate margin against levels of natural hazards more severe than those considered for design…".* Therefore, the RP's philosophy for seismic classification for the MCR is not consistent with IAEA SSR-2/1 (refs. [55], [59]). Further commentary is provided in the Human Factors assessment regarding the evacuation of MCR operators to the RB (ref. [133]).

110. I note from my review of the seismic categorisation that the Radwaste Building represents an anomaly whereby half of the DBE value is specified as the design input. I consider that given the robustness of the structures against the seismic inputs outlined in Section 4.3.3.4, half of the DBE (corresponding to 0.15g PGA) may still be sufficient for some UK sites. Nonetheless, as part of a future iteration of the BWRX-300 safety case this will need to be justified more rigorously against the expectations of the ONR SAPs [16]. Further commentary on this is provided by the External Hazards inspector in (ref. [80]).

111. Overall, from my assessment I judge that the RP's approach for safety classification is adequate for GDA Step 2. I consider that the observations made regarding the seismic categorisation of the Radwaste building and the protection afforded to the MCR within the Control Building require further consideration within future safety case iterations in order to satisfy SAPs ECS.1,2.

112. Civil structural SSCs either directly support the FSFs, for example confinement of radioactivity, or they protect or support SSCs housed within them that perform DL functions which in turn contribute to the FSFs, or they are assigned FSPs that are aligned to DL requirements. These FSPs ensure that the DL functions can be performed for the range of conditions they are subject to.

113. The FSFs are broken down into primary functions that are complimentary to the FSPs, see (refs. [128], [134], [135], [136]). Detailed safety requirements, design behavioural requirements and performance criteria for civil structures are then developed as shown in Section 5 and 6 of (ref. [102]). Appendix A of [102] provides a demonstration of how these requirements are allocated to SSCs. The RP has clarified that the information in Appendix A of (ref. [102]) will be captured within the design specifications that form the basis of design.

114. From my assessment of the RB, I note that the SFRs are not fully developed (at this Step 2 GDA stage) and are, in some cases, based on OPEX and high-level inputs from early standard design safety studies. Furthermore, both the

deterministic and probabilistic safety analyses are not yet fully mature. Consequently, the RB primary safety functions used in (ref. [102]) have been developed largely from engineering judgement and OPEX. I note that the RP intends to iterate further as the safety analysis matures as part of its declared design process, see para. 98. Nonetheless, the demonstration provides a clear summary of the basis of safety case principles being applied to the integrated RB. It shows a systematic flow of the SFRs definition for the SCCV, RPV pedestal structures, RB internals, pool structures and outer wall - leading logically to their detailed design behaviours and performance criteria requirements. In turn this process will identify the requirements for the integrated design process and building design / hazard specific reports as part of a suite of inter-related design documents.

115. I am content that the RB demonstration for deriving SFRs and transferring these requirements to civil structures provides sufficient confidence that the expectations of SAPs EKP.4, ECE.1 can be met as the design and safety case develops. As highlighted by forward action plan item PSR 9B-312 in (ref. [6]), further development of this area will be required as additional safety case inputs become available and the ELM tool becomes more integrated within the production of design specifications.

116. From my assessment of how the safety case demonstrates that risks are likely to be ALARP presented in (refs. [6], [47]), supplemented by the further information in (ref. [109]), I consider that the RP has provided sufficient information for GDA Step 2 and has demonstrated an appreciation of the UK context and expectations for this area. The long and rigorous design development and evolution history of this design provides assurance that the fundamental ALARP principles have been accounted for, see SAP SC.4.

4.3.2.1. Assessment Summary

117. From my assessment of the overall safety case framework for civil engineering, I consider that the safety case philosophy and construct aligns with RGP and the intent of SAP SC.1, and the process for defining and allocating SFRs is systematic and logical inline with SAPs SC.4, 5, EKP.4. In summary, I judge that there are no fundamental shortfalls associated with the safety case framework for civil engineering.

4.3.3. Proof of Concept

118. My assessment objective was to gain assurance that the design is sufficiently developed and mature for GDA Step 2. My assessment expectations were that the layout, structural form, proposed geometries, indicative ultimate capacities and functional performance for civil engineering structures are adequately underpinned and follow well established civil engineering design principles, see ONR TAG 17 (ref. [1]) and IAEA SSR-2/1, SSG-53, SSG-67 (refs. [58], [59], [55]). Areas of residual design risk and/or uncertainty are understood, and the risk of foreclosure of the design is acceptably low.

119. My assessment consisted of reviewing:

- The evolution and optimisation of the building layout, structural form, and configuration;
- The demonstration that the spatial design provided by the civil structures meets the requirements of the housed equipment and that the risk of foreclosure of the design is shown to be acceptably low;
- Whether the proposed construction approaches incorporate OPEX, CDM and ALARP principles and have considered the broad range of UK geologies; and
- The extent to which the proposed structural form, geometries, and details are underpinned by design.

120. The RP's evidence forming the basis for this assessment is contained within RP submissions (ref. [137]), methodology documents (refs. [6], [13], [113], [128], [112], [98], [104], [105], [106]), design specification (ref. [128]), general arrangements (refs. [100], [88], [89], [90]), RQ responses (ref. [111], [110], [109]) and technical workshop presentations (refs. [120], [121], [122], [123], [124], [125]).

4.3.3.1. Layout & Structural Design Evolution

121. The BWRX-300 evolution has predominantly been driven by improvements in reactor safety performance and OPEX on the reactor plant and evolution of the reactor technology to accommodate Small Modular Reactor principles. The design evolution includes features that the RP claims simplify the overall design layout. These include integral RPV isolation valves that rapidly isolate a ruptured pipe to help mitigate the effects of a LOCA. All large fluid pipes with RPV penetrations are equipped with double isolation valves that are integral to the RPV. Safety Relief Valves have been eliminated as the large capacity Isolation Condenser System (ICS) in conjunction with the large steam volume in the RPV provides overpressure protection. The dry containment (SCCV) is designed to contain the releases of steam, water, and fission products after a LOCA. This all contributes to a simplified compact system layout that requires fewer safety systems and safety-related pools of water.

122. The civil structure layout (by default) follows/services the required plant layout. In the case of the BWRX-300 the civil structural layout is a logical arrangement that supports and segregates the essential safety systems. There is clear structural delineation between the primary containment zone that comprises the RPV, RPV pedestal support structure and the containment structure. The above reactor cavity operating zone is defined as operating decks with clear access for RPV operations, cranage activities and fuel movements. The ICS is segregated and located within its own protected pool to support natural circulation claims. Outer cooling pools are provided in the upper area of the RB outer annulus to provide back-up capability to ensure water shielding and coverage of fuel components. The fuel pools are logically positioned to allow clear and defined fuel handling activities with appropriate

segregation and discrete pool cavities with leak monitoring and detection capability.

123. The Fine Motion Control Rod Drive systems are located and protected in the basement zones of the RB annulus to provide reactor control. The essential safety systems are generally located around the annular disposition of the RB with appropriate location and segregation of electrical systems, mechanical plant and supporting back-up and injection systems allowing a logical interaction of safety circuits and optimal use of the available RB building space.

124. It is noteworthy that the height of the RPV to accommodate passive safety measures including the ICS is such that the RB civil structure has been modified to a partially embedded structure buried in the ground to accommodate this overall geometry. Accordingly, the civil structure layout is dissimilar to the previously proven and operational BWR designs (ESBWR apart). Consequently, this effectively leads to a first-of-a-kind civil layout for the RB. The ESBWR design concept is noted to have a similar embedded reactor building structure – this design was certified by NRC in the US (2014), but to date no ESBWR has been either taken to final design or constructed. A future BWRX-300 safety case would benefit from inclusion of commentary regarding this earlier design proposal, and how this has contributed to the progression of the BWRX-300 optimised civil and structural layout.

125. The Secondary Control Room (SCR) is located within the RB (with associated hazard protection) and a protected access route from the MCR (in the Control Building) is proposed. The comments noted in para. 108 are relevant here. In line with SAP ELO.4, a future BWRX-300 safety case would need to provide further substantiation of this aspect of the layout philosophy.

126. The deep embedment of the RB (see [88], [89] for depths) provides safety benefits due to greater protection of SSCs against MAI. The limitation is the location of the steam lines on the RPV, these are required to be at grade elevation for two reasons. Firstly, so that the steam condensate could be routed to the condenser in the Turbine Building (TB) to preclude water hammer from slugs of water. Secondly, by avoiding steam lines below grade, the flooding risk and maintenance problems arising from penetrations through the outer RB wall are reduced. These constraints fix the RPV bottom head at about 22m below grade.

127. Furthermore, to remove and replace the 4.3-meter-long control rod drives, space must be provided under the RPV bottom head. Adding allowances for through-life maintenance of these items places the basemat at approximately 35 meters below grade. It is noteworthy that the RP has explored embedment depths of 30.5, 45.7 and 61m and these studies support the proposed arrangements as optimal. This use of optioneering meets the intent of SAPs SC.4 & 5.

128. Regarding the structural characteristics of the layout, I note the following points that are all consistent with minimising seismic effects as highlighted in IAEA SSG-67 (ref. [59]):

- The fuel pools are located between 5 and 13m above grade level. The overall geometry / deep embedment of the RB leads to the centre of mass located below grade level;
- Due to the overall symmetry of the RB structure the centre of rigidity is judged to be close to the centre of mass thus minimising torsional effects;
- Floor plans are simple and regular with clear load paths for the transmission of seismic forces to the foundations;
- Seismic gaps are provided between the RB and adjacent buildings to mitigate the risk of pounding and hammering; and
- The deeply embedded RB benefits from reduced seismic demands (less amplification or even attenuation of demands at deeper elevations, especially in rock), and the inherent stability of an embedded structure (centre of gravity below grade) to address traditional seismic stability concerns associated with sliding and overturning.

129. Further to the above, the cylindrical geometry of the RB selected by the RP is the most defendable structure both for external threats and for seismic construction below ground. This shape allows hoop stress to assist the defence of items in contact with the exterior of the above-ground surfaces. Below ground the cylinder distributes the soil pressures and other interactions from other buildings. Internally the RB cylinder is reinforced with integral partition walls and floors connecting the containment to the outer wall, thus acting like spokes on a wheel.

130. The use of DP-SC as structural elements as illustrated in Figures 3-3, 3-5(b), 3-6 of (ref. [113]), gives rise to noteworthy structural performance characteristics. The DP-SC modules include continuous reinforcing diaphragm elements as the ties that prevent de-lamination of the plain concrete core and serve as out-of-plane shear reinforcement. The reinforcing diaphragm plates significantly increase the structural stiffness and strength, as compared to traditional reinforced concrete and conventional steel composite (SC) structures. The presence of faceplates together with diaphragm plates naturally leads to increased missile and blast resistance. Rather than a separate liner, the DP-SC faceplates are welded to achieve a leak-tight containment barrier on the inside of the SCCV. DP-SC also offers increased shielding capability and enables a reduction in wall thickness when compared to traditional reinforced concrete designs.

131. I note that although most of the RB including the foundation is formed from DP-SC, the RP highlights that some elements, where DP-SC is judged overly conservative for structural demand (such as the SCCV radial wing walls), have been modified to conventional SC to aid/simplify construction.

132. Issues such as corrosion protection, in-service inspection and testing programs, and ageing management have been considered to ensure the structure can fulfill its intended functions throughout its design service life and decommissioning period (SAPs EAD.1,2). It is noteworthy that the Containment design maintains a nitrogen-inerted atmosphere during most operating modes. This inert atmosphere design minimises long-term corrosion and degradation of the SCCV and the contained components by limiting oxygen exposure during plant operating service life.

133. Less mature areas of the containment design, such as, the use of mock ups and testing, substantiation against thermal excursions, design of openings, and design of the containment closure head have been sampled and reviewed via Workshop 5 and RQ's, see (ref. [86]). The RP's response to these topics all give assurance regarding the proposed containment geometry.

134. I note that the other buildings comprising the power block that surround the RB are proposed to be founded on individual rafts and follow conventional design practices for reinforced concrete structures.

135. From my assessment, I am satisfied that the civil engineering aspects of the layout apply sound design concepts and a robust structural form in line with the principles of SAPs EKP.1,3, ECE.2. I judge that the structural characteristics will contribute significantly to substantiating the functional performance necessary (as per SAP ECE.1).

136. As part of a future iteration of the BWRX-300 safety case, I consider that the substantiation of the layout could be enhanced inline with SAPs ELO1 & 4. The following areas are highlighted for consideration:

- Further substantiation of the MCR location and degree of protection provided;
- Further commentary regarding the ESBWR and its contribution to the optimisation of the BWRX-300 layout;
- The development and optimisation of the deep shaft and below grade RB construction;
- The absence of common raft foundation for the extended structures & power block buildings; and
- The location of fuel pools at elevated building levels in the RB layout.

137. From my assessment, I judge that there are no fundamental shortfalls associated with the evolution and optimisation of the building layout, structural form and configuration from the civil engineering perspective.

4.3.3.2. Spatial Provision

138. From my assessment, I note that the design footprint and layout consider both 50Hz and 60Hz variations of plant and equipment with spatial margins explicitly included. This was demonstrated via the 3D models during

Workshop 1 (ref. [120]), and information in (ref. [110]). Climate change affects are accounted for conservatively via the generic external hazard inputs and spatial allowances that enable future adaptability e.g., chillers for cooling rooms are located on the roof of the control building so that larger units can be installed if needed.

139. With respect to dropped loads, I note that the basic design of the RB floors has been thickened. The refuel floor is 1.5m (5ft) thick, as is the truck bay where the spent fuel cask is lowered down to. The shielded spent fuel cask loaded with spent fuel, is sealed, and is removed from the spent fuel pool (which also has a 1.5m (5ft) thick floor), lifted to the refueling floor and set down for cleaning, sealing, and dewatering. Once the shielded cask is ready for transport to the interim storage location it is lifted again and lowered from the refuel floor down to the truck bay in the RB at near grade elevation. The significant thickness of these floor elements and the ability to locally increase capacity of the DP-SC structural elements as necessary provides assurance that dropped load hazards can be substantiated (SAP ECE.12) as the design develops.

140. UK conventional fire safety regulatory expectations can influence the civil structural layout and spatial provision, a notable example being the need for protected fire shafts. This topic has been assessed by the ONR fire safety inspector, see ref. [82]. I note that ref. [82] highlights potential deficiencies with the proposed layout that require resolution as part of a future BWRX-300 safety case. From my review of these areas, and further assurance provided in (ref. [110]), I judge that they do not undermine the proposed layout of the primary DP-SC structures.

141. I note that UK regulatory requirements for the pipe rupture hazard may require relocation of vulnerable plant/equipment or diverting of pipelines but would not have a significant effect on the structural layout and spatial provision from the civil engineering perspective. At the present time, the areas where there are known risks for the potential for high energy piping ruptures have limited SC 1 equipment or have protective walls. For example, the steam tunnel from the RB to the TB has blowout panels to divert steam from the RB into a protected area of the TB. The steam tunnel also incorporates pressure and watertight doors to protect other rooms in the RB from the steam or water. Although further work is needed in this area to substantiate the layout, the RP has provided confidence that the main issues are being considered and managed appropriately – see the ONR assessment of Internal Hazards (ref. [81]).

142. The layout has provided flexibility and space for structural design changes. An example being the SCCV wall that has progressively been thickened from 0.6m to 0.9m to 1.2m. This change was based on radiation shielding analysis and optioneering studies that considered construction, maintenance, installation, cost and schedule. The RP provided an overview of these changes via its 3D BIM model during Workshop 1 (ref. [120]). This change resulted in the relocation of mechanical equipment and rerouting of piping

systems to accommodate the thickened SCCV wall. A sensitivity study was then performed demonstrating no significant change in dynamic behaviour and predicted seismic demands. I note that the increase in thickness of the SCCV wall from 0.9m to 1.2m and the use of high-density concrete for the SCCV are design changes made beyond the GDA Design Reference Point.

143. From my assessment, I note the following strengths associated with spatial provision that give confidence the design is considering SAPs ELO.1 & 4, ECE.8, 20, 25 & 26:

- Travel paths for operation, maintenance, inspections, testing, construction, and decommissioning including haul paths for large equipment have been planned and provided for using the 3D BIM tools;
- Each type of equipment has been reviewed considering open top construction (i.e., installation of large equipment that will not fit through hatchways prior to construction of higher-level floors and roof) and life of plant expected maintenance evolutions;
- Heat exchangers have excess tube allotments for potential tube plugging if it cannot be easily removed from a location.;
- Motors are placed such that they can be removed and replaced without disassembly of surrounding equipment from other systems;
- Shielding hatches are designed into the floor/ceilings of vaults to facilitate filter exchanges or equipment refurbishment;
- Most equipment is replaceable except for very large items that are expected to exceed the 60-year lifetime of the facility;
- At each elevation, in all the power block buildings, oversized travel paths are incorporated for people in normal operation and lifesaving evacuations. These same paths are designated for equipment installation during construction and repair or replacement including end of life decommissioning; and
- In places where the normal pathways are not large enough, there are hatches for maintenance and replacement for most large equipment.

144. I consider that the above spatial allowances and features of the RB plant layout will facilitate the access necessary for decommissioning or dismantling activities as per the intent of SAP ECE.26.

145. Therefore, from my civil engineering assessment, I judge that there are no fundamental shortfalls associated with the spatial design, and I am satisfied that the spatial design is sufficiently mature such that the risk of foreclosure is acceptable for this stage of GDA.

4.3.3.3. Constructability

146. The declared goal of BWRX-300 construction is to avoid costly and time-consuming placement of engineered backfill, including elimination of incurred costs associated with testing and inspection of this safety-related backfill

material. The surface founded buildings surrounding the RB utilise traditional structural types for which construction methods are well established. Therefore, the main focus of my assessment here has been the RB.

147. The below-grade portion of the RB is constructed using traditional vertical shaft construction techniques to excavate an oversized shaft full depth. This approach uses good practice from the tunneling industry for shaft excavation. I note that the RP's approach has been underpinned via optioneering studies (ref. [111]) that have evaluated:

- traditional excavation and wall placement
- top-down wall placement using jack strand suspension
- bottom-up wall placement using slurry wall as outer form
- steel side wall shoring with bottom-up wall placement using the shoring as outer form

148. The RB will be constructed inside of the shaft by lowering prefabricated DP-SC assemblies into position. These are then filled with Self-Consolidating Concrete that flows easily, fills congested areas without the need for vibration and minimises the risk of voids.

149. The DP-SC system will be used to form the RB structural basemat, cylindrical exterior wall, SCCV, RPV Pedestal, fuel and cooling pools, and refuel floor of the RB. I note that the DP-SC diaphragm plates provide element stiffness during erection and help to resist pressures from the infill concrete placement.

150. The RP's application of DP-SC to the RB basemat foundation arises from lessons learnt from the Westinghouse AP1000 units and ensures better integration with the overall structure and improved structural reliability and robustness. The proposed foundation arrangement includes a concrete mat to found and protect the outer steel plate of the DP-SC basemat. Furthermore, I note that the integration of the RPV pedestal support structure into the basemat DP-SC modules results in a very robust pedestal structure and supports early RPV placement as part of the RB structure erection sequence.

151. The RP claims the DP-SC system provides advantages (ref. [111]), notably:

- The added stiffness of the modules provides benefits during rigging, transportation, and resisting load due to concrete placement plus the elimination of formwork and rebar installation. This is claimed to reduce labour demands and shorter construction schedules.
- The DP-SC modularisation techniques, including Prefabrication, Pre-Assembly, Modularization and Off-Site Fabrication will improve quality, reduce site man-hours, reduce weather-related delays, improve schedule duration and margin, and increase overall safety. The RP proposes that individual DP-SC modules will be fabricated and formed into pre-engineered segments forming walls, cylinders, and floors in the controlled environment of a certified fabrication shop.

152. The RP has indicated that early identification of potential constructability challenges may be facilitated by the construction of mockups. A combination of tight dimensional control and fabrication fixtures/jigs will be employed to ensure the segments will fit together and form complete structural elements of the RB structure. Segments forming critical structural elements may be trial assembled into full or partial modules at the fabrication facility prior to transport to the project site. This will ensure the component can be assembled on site within the dimensional tolerance allowed by the site construction procedure, thus reducing site rework and lowering the risk of construction delays. The RP notes that all modules leaving remote fabrication facilities will be sized to ship on over the road trucks as non permit loads or on barges/ships as applicable.

153. As mentioned in para. 96 above and evidenced in Workshop 1 & 5 (refs. [120], [124]), I note that the RP has already integrated constructability reviews involving its design team and the constructor and fabricators within its design development process. The design is clearly benefiting from this early engagement and expertise, and I consider the RP's approach offers significant benefit in early identification of potential challenges and aligns with the CDM principles.

154. From my assessment I am satisfied that the generic construction approaches proposed incorporate OPEX, CDM and ALARP principles and meet the intent of SAP ECE.25. Therefore, I judge that there are no fundamental shortfalls associated with the constructability of the design.

4.3.3.4. Extent of design development

155. From my assessment informed by information outlined in para. 119 and specifically in (refs. [111], [120], [123]), I note that the RP has made substantial progress to underpin its proposed civil structural configuration and section geometries. The modelling and analysis work is ongoing but has already reached a relatively advanced stage as summarised below.

- The integrated RB structural Finite Element (FE) model represents the structural configuration for all main RB, containment, and containment internal structural members. It meets the RP's declared mesh refinement and quality attributes required for calculation of structural stress demands;
- Large mechanical and electrical piping penetrations are modelled explicitly in the integrated RB model with finer meshes used around section penetrations larger than half the DP-SC wall or slab thickness to enable accurate computations of the stress demands for design of the opening/penetration locations;
- Simplifying modelling assumptions are made to facilitate the development of the model without having a significant impact on the ability of the model to represent the analysed loading conditions. A summary of these are:
    - Use of a lumped mass stick (or beam) model to represent the RPV, reactor internals, and fuel that is validated in terms of its dynamic

characteristics against results from the stand-alone RPV model used for analysis and design of the RPV (see Figure 4-32 of (ref. [107])).

- Use of a containment equipment and piping support structure beam element model (see Figure 4-33 of (ref. [107])).
- The openings not explicitly modelled are judged not to significantly affect results and will be included as the model develops.
- Slab centrelines are approximations of the weighted average centreline for levels with slabs with varying thickness.
- Loads are currently distributed (rigid) mass to the slab centreline and dynamic coupling is deemed negligible. Note that actual equipment weights and centres of gravity and more refined load modelling and dynamic coupling considerations will be included in a later revision of the model.
- Platforms/doors/hatches are not included structurally but represented with lumped masses.
- Shear connectors and diaphragms contributions to flexural stiffness of DP-SC elements are ignored.

- The same FE model of the integrated RB is used for both structural and seismic analyses of the integrated RB structures. SSI analyses models are developed by coupling the detailed integrated RB model with simplified coarse mesh FE models of the adjacent Power Block structures which capture the dynamic characteristics of the buildings, as illustrated in Figure 5-1 of (ref. [107]), I note this also captures Structure-Soil-Structure Interaction effects. The surrounding subgrade is represented by a layered half-space continuum with equivalent linear elastic stiffness properties and complex damping. Detailed FE models of the adjacent Power Block structures with a more refined mesh and loads are used for structural design of those buildings;
- Generic seismic input parameters were developed following the approach outlined in (ref. [112]) and the dynamic geotechnical assumptions (in the form of shear wave velocity profiles) have been confirmed by ONR External Hazards to be representative of the UK site conditions, see (ref. [80]);
- Of note is that the generic seismic input spectra used for analyses (shown in Section 4.1 of (ref. [138])), are representative of a range of Soft, Medium and Hard site conditions, these spectral shapes are anchored to 0.3g. The RP has acknowledged that for very hard sites, an example being Wylfa Newydd in UK, the Hard spectral shape associated with rock sites capable of delivering a high-frequency content may not be sufficiently conservative. Therefore, this spectrum is scaled to a PGA of 0.5g for both the horizontal and vertical GDRS. These four spectral inputs are more conservative than any other UK GDA presented to date;
- Seismic analysis cases, as presented in Section 4.4 of (ref. [138]), pair the four seismic input spectra with the eight generic soil/rock profiles

presented in Section 4.2 of (ref. [138]) to form the individual SSI analysis cases; and

- Load combinations for the analyses are developed by the RP based on NUREG 0800 and SRP 3.8.1 and are outlined in Tables 4-2. 4-3 and 5-2. 5-3 of (ref. [139]). From my review I note that this considers both normal operation, fault, and extreme environmental conditions, along with combinations of these. Notably this includes seismic acting in combination with the pressure and temperature conditions arising from a LOCA (SAP ECE.6).

156. Outputs from the integrated RB FE model inform governing load design checks of the critical elements of the Standard Plant design as described in Sections 5 and 6 of (ref. [113]). From the conclusions in Section 7.0 of (ref. [139]), I note that the Demand-to-Capacity Ratios (DCRs) for the primary DP-SC members indicate design margins of 15% for most of the BWRX-300 structural components for abnormal and abnormal/extreme environmental load conditions, except for small local areas where high stresses could potentially be averaged. In view of the variety of load combinations analysed, I consider this provides confidence that the section sizes, characteristics and geometries that underpin the layout are likely to be sufficient.

157. The RP noted that the exterior RB wall below grade, basemat outside containment and lower wing wall were found not to have acceptable design margins for the assumed section sizes. For these structural elements the RP confirmed that the section properties of these elements have all been modified as part of the continual design evolution via combinations of increases in section thickness and steel plate thickness and reduced diaphragm plate spacing. The result of further analysis runs confirmed acceptable design margins and incorporation of these changes via the 3D BIM model verify continued adequacy of the spatial layout.

158. The RP notes that redesign in the next iteration of the integrated RB FE model will address local reinforcement at openings where there is predicted overutilisation.

159. With respect to protection against MAI the RP has justified the proposed section thicknesses using a generic envelope of the US based threat definition. Although explicit detail on the threat definition could not be made available due to security considerations, it is apparent that the engine size considered in the capacity evaluation is less onerous than the UK threat definition. Although the local capacity evaluation for the UK threat definition has not yet been completed, expert review outlined in (ref. [86]) indicates that there is a high likelihood that the proposed thickness of the RB protective shell will not be sufficient to satisfy the acceptance criteria. Nonetheless, the RP has provided assurance (ref. [140]) that the capacity of the RB exterior wall can be enhanced to satisfy the demands from the UK threat definition without unduly impacting the layout and configuration. This area will need to be assessed further as part of a future BWRX-300 safety case.

160. From my assessment of these analysis results along with the conservative seismic inputs used and broad range of generic site geologies, I consider that the RP has robustly demonstrated that the proposed structural form and section sizes are likely to provide sufficient capacity (as per SAP ECE.12). More detailed consideration of the Hazard Shields local capacity to protect against the UK MAI threat definition is needed as part of a future iteration of the BWRX-300 safety case.

161. Therefore, I judge that there are no fundamental shortfalls associated with the extent of design development.

4.3.3.5. Assessment Summary

162. I am satisfied that the RP has adequately demonstrated for GDA Step 2 the following:

- For civil engineering structures the layout, structural form, proposed geometries, and functional performance are adequately underpinned; and
- Areas of residual design risk and/or uncertainty are understood, and the risk of foreclosure of the design is acceptably low.

163. Therefore, I judge that there are no fundamental shortfalls associated with ‘proof of concept’ for civil engineering.

4.3.4. Design Principles & Methods

164. My assessment objective was to determine whether the RP’s proposed design principles and methodologies meet RGP. My assessment expectations are founded on ONR TAG17 (ref. [1]), IAEA SSR-2/1 Requirement 9 (ref. [55]), and ONR SAPs ERL.1,4, ECE.2,12-15 and AV.1-6 and can be broadly summarised as follows:

- Use of a suite of design codes and standards that accord with relevant good practice and are compatible with one another;
- Use of appropriate and reasoned engineering knowledge and judgement where codes are non-specific or ambiguous;
- Application of a coherent, integrated, modelling, analysis, and design architecture;
- Being aware of, and working within, the limitations of analysis methods and design software;
- Taking due account of limitations, uncertainties, and sensitivities via an associated framework of V&V and sensitivity exploration; and
- Adopting appropriate and rigorous quality assurance (QA) procedures.

165. My assessment consisted of reviewing:

- The RP’s proposed codes and standards that form the basis of the design principles;

- The overarching modelling and analysis architecture and the integration of analysis streams; and
- The analysis methodologies for seismic and MAI.

166. The RP's evidence forming the basis for this assessment is contained within methodology documents (refs. [6], [103], [113], [112], [98], [104], [105], [106], [107], [141], [142], [143], [138], [139], [144], [145], [146]), design specifications (refs. [128], [134], [147], [148]), RQ responses (refs. [149], [108], [150], [151], [152], [153], [154], [155], [156], [157], [158], [159], [160], [161], [162]) and technical workshop presentations (refs. [122], [123], [124]).

4.3.4.1. Codes & Standards

167. My assessment of the proposed codes and standards has considered whether they are clearly identified, up-to-date, mutually compatible, appropriate to the functional reliability requirements and SSC safety classification, representative of RGP and compatible with UK material codes and standards.

168. The RP's philosophy and full specification of regulations, codes, standards and technical specifications applicable to the civil structures is articulated in (refs. [103], [98]). The full list is not replicated herein but is noted to include reference to:

- US Regulatory Requirements (e.g. CFR Code of Federal Requirements)
- US NRC Regulatory Guidelines – Nuclear Regulatory Reports (e.g. NUREGs, RGs)
- US Industry Codes and Standards (e.g. ACI, ANSI/AISC, ASCE/SEI, ASME, EPRI)
- International Guides (e.g. IAEA NS-G, SSG, SSR)

169. The RP's primary codes used to develop the civil structural design specifications for the RB are noted to comprise ACI 349-13 (ref. [163]), ACI 318-19 (ref. [164]), ANSI/AISC N690-18 (ref. [69]), ASCE/SEI 4-16 (ref. [66]), ASCE/SEI 43-19 (ref. [67]), and ASME BPVC Section III (ref. [68]).

170. From my assessment, I note that two of the important codes and standards have been updated, including issue of ACI 349-23 (ref. [65]) and AISC N690-24 (ref. [70]).

171. The RP has used ANSI/AISC-N690-18 as the basis for the modelling and structural design of the DP-SC structures. This is supplemented by reference to ANSI/AISC-360-16 (ref. [71]) (which is the previous revision ANSI/AISC-360-22 (ref. [41])), to published design guides (ref. [73]) and literature (ref. [165]) and by reference to a series of tests (ref. [166]) to arrive at the methodology and modified design criteria set out in (ref. [113]). In addition, for the containment, requirements referenced in ASME BPVC, Section III (ref. [68]) are also applied, and the proposed design, fabrication, construction, examination and testing requirements (Section 6 of (ref. [113])) are adapted from ASME BPVC Section III 2021 (ref. [68]) Division 2, Article CC2000 –

CC6000, which is the previous version of the ASME BPVC Section III 2023 (ref. [167]).

172. A future iteration of the BWRX-300 safety case should incorporate these updates to codes and standards. The RP has provided assurance via (ref. [168]) and Workshops 4 and 5 (refs. [123], [124]) that this will be reviewed as the design develops beyond the design reference point.

173. From my assessment, I am content that the proposed choice of codes and standards codes meet international and UK RGP and the intent of SAP ECS.3. I note that the design information provided is heavily biased towards US and Canadian codes for seismic analysis, ultimate strength, and serviceability requirements. Further consideration of British Standards / Eurocodes will be needed as part of a future iteration of the BWRX-300 safety case to support UK deployment. Example areas being ultimate design strength, material specification & strengths, fire performance, reinforcement detailing and serviceability checks.

174. In summary, I judge that there are no fundamental shortfalls associated with the RP's approach for codes and standards.

4.3.4.2. Modelling & Analysis Architecture

175. My assessment of the modelling and analysis architecture for the RB has considered whether there is a coherent and integrated overall approach that uses appropriate software and that accounts for limitations, uncertainties, and sensitivities via a framework of V&V and sensitivity exploration.

176. I note that the four analysis streams are clearly articulated in Figure 1 of (ref. [108]) for Structural, Seismic SSI, Internal Containment and Aircraft Impact Assessment and the interconnections between them are clearly highlighted. The architecture presented represents a sophisticated analysis process that provides confidence in the overall design concept.

177. The response in ref. [108] does not provide explicit references to the validation of the analysis models or the associated sensitivity evaluations, some of which are described in Section 7 of [106]. Furthermore, certain critical elements of the analytical scope—such as the treatment of localised modelling approaches and the internal containment analysis used to assess LOCA-induced pressure and temperature transients, as well as the evaluation of containment ultimate pressure capacity—are not incorporated.

178. As part of a future iteration of the BWRX-300 safety case, I consider that further development is needed to:

- Further integrate V&V and sensitivity exploration into the architecture (SAPs AV.6, ECE.14,15); and
- Expand the architecture illustrated in Figure 1 of (ref. [108]) to fully capture all analyses that support the civil engineering safety case.

179. The RB structure has been modelled in ANSYS. The ANSYS model is developed for all structural elements, with inclusion for non-structural mass, then translated into ACS SASSI format to allow integration with the layered far field model representing the dynamic properties of the subgrade materials. The ANSYS and SASSI model are used to complete the analysis of the RB structure, including Seismic SSI, to allow for design. Structure-soil-structure interaction is also considered through the inclusion of coarse FE models of surrounding structures and their foundations, including the Turbine Building, Rad Waste Building and Control Building. For the analysis of MAI, the models for assessing global impact use LS-DYNA.

180. I am content that both ANSYS, ACS SASSI and LS-DYNA are well-recognised software capable of completing advanced analysis that are widely used for analysis of nuclear facilities.

181. The validation methods outlined in (refs. [105], [106], [107]) for both the ANSYS and SASSI models includes comparison of structural response from a fixed based analysis in ANSYS and a “1-g” analysis in SASSI with ground conditions effectively simulating a fixed base. However, as the SASSI model is developed using a translation from the ANSYS model, I judge that further validation is required to meet the intent of SAP ECE.15.

182. I note that the different types of analyses are performed on RB structural models that have the same node and element type configurations taken from a Global Structural Model. I consider this good practice as it allows the demands from different load cases to be compared and combined on an element-by-element basis, depending on the applicable load combinations.

183. The approach for local models is yet to be fully developed by the RP. Furthermore, the RP has confirmed that the work to evaluate the ultimate capacity of the containment is still to be progressed. Although the details are not yet available, the RP highlighted in Workshop 5 (ref. [124]) that this will use a fully non-linear FE representation (using LS-DYNA) of the containment. I note that this additional model is independent of the ANSYS model used for design basis analysis. In addition to predicting ultimate capacity this independent model could enhance the validation of the design basis response predicted by the ANSYS model (SAP ECE.14,15, paras. 682, 683).

184. In summary, from my assessment there are aspects of the general modelling & analysis architecture where further discussion and development is needed as part of a future iteration of the BWRX-300 safety case. However, from my review I judge there are no fundamental shortfalls.

4.3.4.3. Seismic & Geotechnics

185. The RP’s methodology for Seismic analysis is based upon US practice and draws from ASCE4-16 (ref. [66]), ASCE43-19 (ref. [67]), which I consider RGP.

186. The RP's SSI analyses of the RB structure are based on Best Estimate, Lower Bound and Upper Bound ground profiles as per guidance in ASCE 4-16. This accounts for uncertainties and variations of dynamic properties of the subgrade materials. The shear wave velocity, compression wave velocity and damping ratios for eight different soil and rock types have been presented by the RP. Similarly, horizontal and vertical generic design response spectra (ref. [161]) are presented for four ground profiles ranging from firm to increased hard ground conditions. I note that these ground profiles and resulting ground parameters all reflect North American geology and seismic spectra. However, this is judged acceptable for GDA purposes, see the External Hazards assessment (ref. [80]).

187. The RP has demonstrated via Workshop 4 (ref. [123]) and further information in (refs. [151], [169]) that the finite element models of the RB are sufficiently refined to transmit the entire frequency range of interest for the seismic design of the RB SSCs. The RP has provided sensitivity analyses for the proposed FE mesh and various levels of more refined mesh configurations to validate the proposed models used. I note that there is evidence, within these mesh sensitivity plots of differences associated with in-plane shear forces between the original mesh and more refined mesh. Confidence in the suitability of the mesh size would be increased if the approach for extracting design forces/stresses from the model and translating these into a suitable format for design code compliance checks was presented as this could inform a better comparison. It is recommended that the mesh validation studies are enhanced and that the approach is included in a future iteration of the BWRX-300 safety case.

188. With respect to the FE modelling of the embedment of the RB within the ground and associated backfill, further information was provided by the RP at (ref. [169]). From my assessment, I note that the range of UB and LB subgrade properties used in the various structural analyses has been selected to ensure the modelling approach results in a bounding design demand on the below-ground RB structure under various loading types. I record the following points that will require further consideration in a future iteration of the BWRX-300 safety case:

- The modelling stiffness of the spring elements used at the interface of the RB and the subgrade is claimed to not influence the static and seismic stability of the RB. I consider that this claim requires further justification;
- Further discussion should be presented regarding the dynamic Poisson's ratio which is used for the dynamic analysis;
- It is noted in (ref. [169]) that no static bearing stress checks were undertaken. I consider that the bearing pressures should be calculated for the static and dynamic conditions to understand the suitability of the soil conditions. Furthermore, the construction challenges and associated deterioration of ground properties in both static and dynamic conditions should be further evaluated during the design stages;

- I note from Section 5.1 of (ref. [112]) that the construction sequence is not modelled and in Section 5.3.8 the excavation support e.g., the slurry wall and infill concrete are excluded from the models used for the static and dynamic SSI. For the site-specific design, I note that the pre-existing stress state in the ground and the effects of the construction sequence will require consideration. Moreover, whilst the slurry wall may be regarded as temporary works, it remains in the ground (effectively a permanent structure), and its mass and stiffness will influence the seismic response of the RB. Therefore, in line with SAPs ECE.13,14,15 further clarification is required regarding how the influence of these aspects will be captured in the analysis methodology and how bounding load cases are established and justified; and
- Considering the importance of the uncertainties related to the modelling of friction at the RB shaft interfaces, further sensitivity SSI analyses should be performed to ensure that there are no cliff-edge effects in the assessments (SAP ECE.7,14).

189. The RP's current approach for the modelling of plant and equipment assumes that the equipment is both rigid and connected rigidly to the supporting structure. The actual stiffness of the equipment or its connection to the structure is not estimated or modelled explicitly. Thus, the dynamic response of the equipment and the potential dynamic feedback into the supporting structure is not captured. The information provided in (ref. [150]) provides assurance that the modelling of plant and equipment will be accounted for as more detailed vendor equipment information becomes available during design development. I am content with this for GDA Step 2.

190. In summary for seismic and geotechnics, I am content with the methodologies adopted by the RP. There are areas highlighted where further work is needed as part of a future iteration of the BWRX-300 safety case. However, I judge there are no fundamental shortfalls.

4.3.4.4. Malicious Aircraft Impact

191. The RB is designed to maintain structural integrity during and after MAI with no perforation of the protective walls and roof. The RP's protection strategy aims to: protect the spent fuel in the pool by maintaining pool's minimum water level; prevent any RB damage which could allow pressurised or propagated fire and burning jet fuel inside the RB; prevent any post-impact debris of concrete and steel components from falling into the reactor and fuel pool; prevent any crane components from falling into the reactor and fuel pool. The acceptance criteria and justifications presented in (ref. [155]) align with IAEA SR87 (ref. [61]) DEE-1 and DEE-2, and NEI 07-13 (ref. [75]) and I am content this represents RGP.

192. The protection strategy is limited to the RB only, surrounding buildings such as the Turbine Building, Rad Waste facility and Control Building are not claimed as protected. The radiological consequences arising from MAI to these adjacent buildings will need to be evaluated to fully substantiate the

position. Of specific note is that the MCR within the Control Building is not claimed as protected, see para.108 above. From review of the information provided, I consider that further underpinning of the protection strategy is needed by both engineering and safety analysis as the design develops.

193. The benefits of the DP-SC system include reducing or removing the risks of perforation, penetration and through thickness cracking and the removal of the scabbing failure mechanism due to the inner plate on the non-impact face. These characteristics are beneficial for protection against impacts such as MAI. I note that although the construction of the roof is not intended to be DP-SC, the RP has confirmed at (ref. [122]) the presence of an inner steel liner that serves the same function. For local capacity evaluation of the RB, based on expert advice received at ref. [86], I judge that the Bruhl method proposed by the RP is suitable for the local impact assessment of the DP-SC structures. The RP's intent to validate the results using non-linear analysis provides further confidence in the proposed methodology inline with SAPs AV.2, ECE.15.

194. From my assessment of the global response based on information presented in (ref. [122]), the RP appears to have used different models for the global response analysis. I note that although the so called "Partial Model: Ground Level to Roof" looks adequate in terms of level of modelling detail, the geometry of the impact force application appears oversimplified. The other FE models appear unsuitable, and it is not clear why there is a separation between models and why different models have been used for the global response analysis. Based on expert advice at ref. [86], I consider that use of a single model of the entire RB but with different levels of detail in modelling would be more appropriate. Further justification for the modelling approach for evaluating global response is recommended as part of a future iteration of the BWRX-300 safety case.

195. From my assessment of the RP's methodology for assessing the response of internal SSCs, I consider the approaches adopted align with RGP at (ref. [75]), but specific comment is warranted regarding the polar crane. The support structure of the polar crane is attached directly to the external protective structure and hence can be subjected to direct impact loads. NEI 07-13 (ref. [75]) highlights that any components attached to the impacted face are assumed to fail during impact and specifically outlines that polar cranes supported from the outer containment wall in a hittable region represents a large internal missile and should be considered susceptible to falling. This would have significant safety consequences associated with the cranes located above the fuel pools and would threaten the RP's protection strategy. The RP has confirmed in (ref. [157]) that an analytical approach will be used to ascertain the structural response parameters (accelerations, spectral accelerations and displacements) at polar crane support locations to demonstrate the response is acceptable. Assurance was also provided by the RP that this approach has technical provenance and has been applied for ESBWR and NuScale NPP designs in the US and Canada. I consider that

further justification for this modelling approach for substantiating the polar crane is required as part of a future iteration of the BWRX-300 safety case.

196. In summary for MAI I have noted areas of the analysis methodology and design substantiation that do require further justification as part of a future iteration of the BWRX-300 safety case. However, I judge that these do not represent a fundamental shortfall.

4.3.4.5. Assessment Summary

197. In summary, I am satisfied that the suite of design codes and standards applied by the RP accord with RGP. I am content that the modelling and analysis architecture and methodologies presented by the RP are robust and that the areas highlighted for further development can be assessed further as part of a future iteration of the BWRX-300 safety case. Therefore, I judge there that there are no fundamental shortfalls associated with the RP’s design principles and methods.

4.3.5. Areas of Novelty – DP-SC

198. The BWRX-300 is the first proposed use of DP-SC modules in any nuclear safety related structure in the UK and the first proposed use of SC (including DP-SC) for a containment structure. DP-SC is a bespoke form of SC with diaphragm plates running in one direction between the steel faceplates. Furthermore, BWRX-300 makes extensive use of curved DP-SC walls in the RB, SCCV and reactor pedestal.

199. There are, at present, only three design codes that cover the structural design of SC structures in nuclear facilities. These are published by the Japan Electric Association (ref. [78]), the Korea Electric Association (ref. [79]) and American Institute of Steel Construction (ref. [70]). These represent what is currently considered RGP for the design of SC structures and form the basis for my assessment along with principles in the ONR SAPs ERL.1, ECE.2,12-15,17,18,19,25, AV.1-6 (ref. [16]) and TAG 17 (ref. [1]). My assessment has also been cognisant of the work undertaken by US NRC and CNSC summarised in [118] and [117].

200. Due to its recent inception, the DP-SC structural system has less technical provenance for NPP application than the use of traditional reinforced and post stressed concrete systems. Therefore, my assessment has focused on determining whether the RPs approach to analysis and design is appropriate and within the stated limitations of the RP’s declared design codes. Of particular focus are the areas of the design methodology where the application of the code is outside these limits. For these areas, I expect the RP to adequately justify its methodology via an appropriate combination of further analysis, physical testing and the judicious application of conservatism and expert judgement.

201. My assessment basis draws from RP methodology documents (refs. [6], [113], [104], [105], [106]), design specifications (refs. [128], [134]), RQ responses

(refs. [170], [130], [131], [132], [171], [172], [173], [174], [175], [176], [177], [178]), and technical workshop presentations (refs. [123], [124]).

4.3.5.1. Analysis of Horizontal elements

202. Section 5.9 of (ref. [113]) states that the design rules in AISC N690-18 (ref. [69]) for SC walls can be extended to SC and DP-SC slabs as they are considered to behave in a similar manner. From my assessment, I note that the new revision of AISC N690-24 (ref. [70]) now includes SC slabs as a structural form covered by the specification. Therefore, the RP's review of this revised standard (see paras.170-171) will ensure the approaches are appropriate for DP-SC horizontal elements.

203. I note from Workshop 5 (ref. [124]) that post DRP the RB roof had been changed from DP-SC due to lift capacity limits. The new design was referred to as "RC with scabbing plate (termed half steel composite or Q-decking)". From my assessment, it is unclear whether this will be designed as reinforced concrete (with the plate treated as permanent formwork) or whether the plate will be designed to act compositely with the concrete (e.g. using headed shear studs or similar) and, if so, what design method will be used. I do note that half steel composite design is not covered in AISC N690 (ref. [70]); it is, however, covered in KEPIC-SNG (ref. [79]). This aspect of the design and the associated methodology will need to be clarified as part of a future iteration of the BWRX-300 safety case.

4.3.5.2. Concrete properties / shrinkage

204. Concrete shrinkage is an important consideration for the design of the DP-SC elements. I note that shrinkage will be of greater significance in thick panels and panels filled horizontally where the combination of shrinkage and trapped air could result in voids and/or loss of bond occurring between the steel faceplate and the concrete.

205. The effects of shrinkage should also be considered in the analysis and design of the DP-SC elements (e.g. use of effective concrete modulus that accounts for shrinkage and creep) and appropriate assumptions made about concrete cracking in the determination of section properties used in the analysis and design.

206. I note that concrete mix design is also critical to achieve the characteristics that are desirable for concreting DP-SC elements (e.g. high workability, good pumpability, low water content, high resistance to bleed and segregation, low shrinkage, prolonged plasticity and low heat of hydration). The RP's methodology will need to demonstrate that satisfactory concrete quality is achieved in horizontal as well as vertical DP-SC elements.

207. The RP's formal submissions do not address this topic in detail. Therefore this was discussed with the RP during Workshop 5 (ref. [124]) and further assurance provided via (ref. [175]). From my assessment, I consider that the

concrete mix design and its installation are indeed critical, and the following areas should be included in a future iteration of the BWRX-300 safety case.

- The design and testing of the proposed concrete mix should demonstrate that it achieves the desired concrete qualities such as, balancing flowability, pumpability, heat of hydration, strength requirements and shrinkage cracking (SAP ECE.16); and
- The RP should provide a methodology demonstrating how concrete installation and quality within the DP-SC modules is confirmed to meet the design intent. This is important to validate analysis assumptions (SAP AV.3, ECE.17,19).
- The methodology should include OPEX and is also expected to include associated repair methodologies (SAP ECE.3).

208. For GDA Step 2, I am content with the level of information provided and judge there are no fundamental shortfalls.

4.3.5.3. SC analysis methods for DP-SC

209. Appendix N9 of AISC N690-18 (ref. [69]) was developed for SC structures comprising two steel plates joined by discrete ties (which may be round bars or any other shape). It does not explicitly cover DP-SC structures wherein the plates are joined continuously by diaphragms running in one direction. The RP in (ref. [113]) has sought to modify/extend the design rules in AISC N690-18 (ref. [69]) to DP-SC elements with faceplates joined by continuous diaphragms spanning in one direction of the DP-SC element.

210. The resistance equations developed in (ref. [113]) have been subject to expert review at (ref. [86]) and I judge them to be acceptable when considering planar (flat) DP-SC elements at normal temperature. However, the properties calculated for use in the FE modelling of the structure and calculation of the demands ignore the presence of the diaphragm and treat the elements as being isotropic. This simplification is not justified appropriately by the RP and was therefore discussed during Workshop 5 (ref. [124]). Following this the RP provided further information in (ref. [172]) including test data in (refs. [179], [166]).

211. From my assessment, I recommended that the RP determine quantitatively whether the treatment of the DP-SC elements as isotropic (with equal flexural stiffness in the two orthogonal directions) in the FE models can be justified. In accord with SAPs ECE.14, AV.6, this can be demonstrated via sensitivity analyses using the FE model to determine the effect of orthotropy on the global stress distribution. The RP in ref. [172] has agreed to incorporate this into its analysis methodology, and I am content that this can be assessed further as part of a future iteration of the BWRX-300 safety case.

212. For GDA Step 2, I am content with the level of information provided and judge there are no fundamental shortfalls.

4.3.5.4. Curvature effects

213. The structural form of the RB uses cylindrical DP-SC structures for the RB, SCCV and RPV support pedestal. The curvature of these structural shapes expressed by the ratios of radius to section thickness is given in (ref. [88]). The RPV pedestal, SCCV and RB have values of 3.9, 10.0 and 29.3.

214. From my assessment, I note that AISC-N690-18 (ref. [69]) Appendix N9 and the recent update AISC-N690-24 (ref. [70]) are developed for straight SC walls but state that, where the ratio of radius to section thickness is greater than 20, the effects of curvature may turn out to be negligible, and the provisions of the appendix will be adequate. For smaller ratios, project specific design and detailing requirements for SC walls are warranted.

215. The RP have argued that the effect of curvature can be neglected when the ratio of radius to section thickness is larger than 2 citing (ref. [165]) as evidence. However, from my review of the work on curved steel composite panels at ref. [180], and noting that all the testing performed (see Section 4.3.5.11) has been on flat rather than curved specimens, I consider that further evidence to support this claim is warranted. Further discussion on this topic was held during Workshop 5 (ref. [124]), following which information was requested and provided by (ref. [171]) to clarify to what extent curvature has been considered in the analysis methodology. From my assessment, augmented by expert review recorded at (ref. [86]), I recommend that the following areas are given further consideration in the RPs analysis and design methodology as part of a future iteration of the BWRX-300 safety case (SAPs ECS.4,5, ECE.13, AV.2,3).

- The RP should quantify and account for the effect of curvature at ambient temperature on: global behaviour due to second order effects; plate buckling; tension forces in headed shear studs and diaphragms;
- The RP is expected to quantify the effects of curvature in the presence of thermal loads and thermal gradients through the walls; and
- It is recommended that the RP conduct a gap analysis of the applicability of the published technical references and scope of testing undertaken to date regarding the effects of curvature on the structural behaviour of DP-SC elements.

216. For GDA Step 2, I am content with the level of information provided and judge there are no fundamental shortfalls.

4.3.5.5. Equipment anchorage

217. The RP's design methodology articulated in (ref. [113]) classifies attachments as light or heavy. The methodology claims that light attachments can be attached directly to the faceplates (with local strengthening if needed) and that the design of DP-SC modules accounts for additional loadings of smaller attachments. It further claims that faceplates are to be locally strengthened as required. Reference was made during Workshop 5 (ref. [124]) to direct

attachments using baseplates. From my review I note that no information is provided regarding how attachments are classified, or the methodology regarding how the local stresses from such attachments are considered in the design of DP-SC elements.

218. For heavy attachments, it was stated in Section 5.11 of (ref. [113]) that these are supported using pre-installed cast-in place anchors, welded, or bolted, to the steel module bottom (for slabs) or far-side faceplate (for walls). From my review, I note that no indication was given as to what constitutes a heavy attachment necessitating a cast-in place anchor, or the form and detail of such anchors. Furthermore, no design methodology was provided for the design of the anchors or how the local stresses from heavy attachments are accounted for in the overall design of the DP-SC elements that support them.

219. Further to Workshop 5, the RP provided further information in (ref. [178]). From my review, I note that the RP has developed a standard catalogue of attachments for the initial layout of piping and equipment which no longer classifies attachments as light or heavy. Rather, it provides the capacities of various baseplate and direct weld sizes to support different applications. For loads exceeding the capacities outlined in the standard attachment catalogue, attachments will be treated as non-standard and analysed individually. Baseplates for these cases will be designed on a case-by-case basis to meet specific requirements.

220. From my assessment, I am content that this approach is reasonable, and I recommend the following areas are addressed as part of a future iteration of the BWRX-300 safety case.

- Provide further details of the attachments covered by the “standard catalogue”, the capacity tables used for sizing for these attachments, and the basis for the derivation of the values in these tables would need to be provided; and
- Provide a methodology for how the local stresses due to attachments (of each category/type) will be calculated and accounted for in the overall design of the supporting SC or DP-SC elements. This should include the approach where the need for strengthening is identified post construction and post concreting.

221. For GDA Step 2, I am content with the level of information provided and judge there are no fundamental shortfalls.

4.3.5.6. Fire analysis and design

222. The RP’s design and evaluation criterion for fire analyses is based on Appendix 4 of AISC360-22 (ref. [72]) and Appendix N4 of AISC N690-18 (ref. [69]). I note that Section 4.2 of AISC360-22 provides a simple method of analysis and also permits the use of advanced analysis in combination with the fire exposure curve specified in ASTM E119 (ref. [76]). From my review of the application of this approach to RB DP-SC structures I note the following:

- The simple method in AISC360-22 covers the fire design of composite plate shear walls which satisfy certain geometric and loading criteria, in particular, slenderness and axial load ratio. Appendix N4 of AISC N690-18 refers to ANSI/AISC 360-22 for fire design. Appendix N9 of AISC N690-18 gives recommendations for analysis and design for temperatures associated with accidental loads but does not extend to fire conditions;
- The fire exposure curve in ASTM E119 is a cellulosic fire curve typically used for qualification of building materials, and I consider it unlikely to be representative of the fire load arising within a NPP; and
- There was no reference found (either in (ref. [113]) or at Workshop 5 (ref. [124])) to the fire design of SC or DP-SC slabs. I note that for the design of slabs under fire conditions, failure criteria are defined in terms of rate of deflection and maximum deflection/strain, as well as elevated temperature load carrying capacity.

223. The RP presented the modelling and analysis methodology during Workshop 5 (ref. [124]). From my review of this information, I noted the following.

- The FE modelling approach using LS-DYNA was claimed to be validated against experimental results, but no details of the experiments or validation was presented or reported;
- Curvature of the structure can accentuate the stresses caused by the fire loading and would need assessing;
- The fire load used in the analysis was ISO 834 (similar to ASTM E119) which may not be representative / bounding of the fire load for the RB; and
- Sections 5.14 and 6.21 of (ref. [113]) refer to the need for vent holes to relieve the pressure caused by steam generation between the faceplates due to evaporation of concrete water content in the event of fire. It adopts the recommendations given in AISC Design Guide 38 (ref. [74]) for the design of vent holes. In the case of SCCV, vent holes are only to be introduced on the external faces of DP-SC elements and on the dry faces of water retaining structures. Below grade, vent holes are not to be used on the faceplates in contact with the soil. The RP's position on vent holes is still evolving with emphasis placed on the flexibility offered by AISC N690-18 (ref. [69]) on the basis that the faceplates may be capable of resisting the internal pressure generated.

224. In view of the above comments, further information was requested from the RP at (ref. [173]). From my assessment, I recommend the following areas are addressed as part of a future iteration of the BWRX-300 safety case:

- Explain where each fire design methodology (simplified approach, advanced analysis or qualification by testing) is being adopted;
- Provide detail of the LS-DYNA advanced analysis model, its mechanical and thermal properties, loading and boundary conditions and provide evidence of its validation against physical test results;

- Investigate the effects of realistic boundary conditions on structures and/or sub-structures (e.g. resulting from constraining structure from free thermal expansion);
- Explain how the effect of curvature is dealt with under fire loading; and
- Justify the final approach to the use (or otherwise) of vent holes and provide detailed justification where they are deemed unnecessary.

225. For GDA Step 2, I am content with the level of information provided and judge there are no fundamental shortfalls.

4.3.5.7. DP-SC Connection design

226. Section 5.11 of (ref. [113]) states that the RB connections are designed to meet the requirements of Section N9.4 of AISC N690 (ref. [69]), AISC 360-16 (ref. [71]) and guidance in AISC Design Guide 32 (ref. [73]). It further states that all DP-SC element splices meet the requirements for full strength as per N9.4.2 of AISC N690. It was also stated that other connections between elements may be rigid or semi-rigid.

227. During the Workshop 5 (ref. [124]), it was noted that in some cases, overstrength design may be adopted for splices at certain locations (e.g. where member sizes are governed by non-structural criteria and for floor to wall connections) and that all connections will be continuous and rigid. Section 6.14 of (ref. [113]) states that the same design approach is adopted for the SCCV.

228. From my review, I note that this information provides design principles rather than detailed design methodologies. While several connection concepts were presented during Workshop 5, no detailed design methodologies were presented other than for the shear strength of a L joint between two DP-SC elements.

229. To provide assurance regarding the RP's methodologies for connection design, information regarding the SCCV wall to basemat connection was requested and received from the RP (ref. [176]). This connection provides a continuous circular support to transfer the SCCV load actions to the lower and adjacent foundation. It is analogous to the "gusset" connection on a traditional PWR containment structure where combinations of flexure and shear are concentrated under accident conditions.

230. From my assessment, I noted that this connection design had reached quite an advanced stage and is in the process of being considered by the construction and fabrication contractors. Based on the design details, illustrations and overall maturity demonstrated by (ref. [176]), I am satisfied that there are no fundamental shortfalls for this area of the RPs' design methodology.

231. However, I recommend as part of a future iteration of the BWRX-300 safety case that the RP formalise its methodologies for connection design.

4.3.5.8. Leak tightness of liquid retaining structures

232. From my review of (ref. [113]) and information presented in Workshop 5 (ref. [124]), further clarity was deemed necessary regarding the incorporation of stainless steel liners for pools formed by the DP-SC structures and the design philosophy adopted by the RP.

233. Further information on the preliminary design was requested and provided along with illustrations at (ref. [174]). This confirmed that a non-structural stainless-steel liner will be used in “wet” areas and that issues such as bimetallic corrosion, leak detection are being considered.

234. From my assessment, it is evident that the design of this area is at a low level of design maturity and will need to be addressed as part of a future iteration of the BWRX-300 safety case (SAP ECE.22).

235. For GDA Step 2, I am content with the level of information provided and judge there are no fundamental shortfalls.

4.3.5.9. Fabrication & Construction Tolerances

236. The RP’s documents refer to AISC N690-18 (ref. [69]) for tolerance specification. However, I note that it only covers planar elements and therefore should be supplemented by additional tolerance specifications for curved elements. Quality control and quality assurance is by reference to Chapter NN of AISC N690-18 and US NRC RG1.28 (ref. [77]).

237. Given the predominantly welded nature of the DP-SC structures, I consider that both manufacturing and construction tolerances[4], will be critical to successful execution. From my review, I note that information on the management of tolerances is not provided by the RP (e.g. out-of-specification tolerances that may be rectified rather than rejected and acceptable methods of rectification). Therefore, further information was requested from the RP and received at (ref. [174]).

238. From my assessment, I note that the RP is clear that the approach for management of fabrication and construction tolerances is yet to be fully developed. This will form part of the ongoing design and construction work being carried out between the RP and the construction contractors.

239. I note that the RP plans to use a National Reactor Innovation Centre’s (NRIC) Advanced Construction Demonstration Project to check both the design and construction approach. These prototypes will allow the physically constructed assembly to be tested, checked and installed to confirm suitability prior to construction. The RP has confirmed that learning from the constructability of

[4] This includes the deformation that may result from the site welding of the panels.

the NRIC Advanced Construction Demonstration Project and from the DNNP-1 site will be incorporated into future stages of design development.

240. Although the design consideration of this area is at a low level of maturity, I consider that the proposed use of mock-ups and OPEX approach is in line with SAPs ECE.25,17,19. This will certainly help build the required confidence that tolerances can be achieved during fabrication and construction.

241. For GDA Step 2, I am content with the level of information provided and judge there are no fundamental shortfalls.

4.3.5.10. Corrosion Protection & EMIT

242. From my review of Sections 5.15 and 6.19 of (ref. [113]), I note that the RP lists the different methods of providing corrosion protection (e.g. sacrificial layer, cathodic protection, membranes, protective coatings). The RP also makes reference to US NRC RG1.54 (ref. [181]), which provides detailed guidance on the application and use of coatings. However, no indication is given as to which method will be used for the DP-SC structures based on the different internal and external exposure conditions. It is also unclear whether the steel would receive its final corrosion protection treatment at the fabrication shop, in the near-site fabrication shop or in its final installed position.

243. During Workshop 5 (ref. [124]) the RP confirmed that DP-SC and SC elements will be manufactured in a factory as transportable sub-assemblies or segments, assembled into modules near site and installed in-pit one level at a time (e.g. basemat, wall sections comprising complete ‘rings’). This gives rise to corrosion protection management issues at weld locations – any areas that are to be welded near site or in-pit may only be protected with a pre-fabrication primer but those areas may need additional protection if left in the open for any length of time (otherwise a grinding operation may be necessary to remove any rust that develops at nominally protected areas prior to welding). Following welding, corrosion protection may also need to be applied to those areas.

244. Further information was requested from the RP on these topics and the longer term EMIT programmes for DP-SC & SC structures and received at (ref. [170]). From my assessment of this information, I consider that the RP should address the following areas as part of a future iteration of the BWRX-300 safety case:

- Clarify the generic corrosion protection strategy to be used for site welded joints, and the construction measures and arrangements that will ensure the continued protection and material integrity of the installed DP-SC and SC modules; and
- Benchmark the Structures Monitoring and Aging Management Programme in (ref. [113]) against the IAEA IGALL principles.

245. For GDA Step 2, I am content with the level of information provided and judge there are no fundamental shortfalls.

4.3.5.11. Use of Physical Testing

246. The validation of the RP's design methodologies with a programme of physical testing is outlined in Section 7 of (ref. [113]), for a set of 14 tests performed on Steel-bricks specimens representing DP-SC modules and in (ref. [166]) for a set of 9 tests performed on DP-SC modules. From my review I note that the 9 tests performed on DP-SC modules (ref. [166]) comprise:

- Two out-of-plane bending tests and two out-of-plane shear tests. In each pair, one specimen spanned in the direction of the diaphragms and one orthogonally to the diaphragms. All four tests were at ambient temperature;
- Two biaxial tension tests; one at ambient and one at elevated temperature; and
- Two cyclic in-plane shear tests on a T-specimen (representing a wall to foundation connection); one at ambient and one at elevated temperature. A third test on a similar specimen was carried out with out-of-plane monotonic loading at elevated temperature.

247. The tests were modelled in ABAQUS with detailed FE models having geometric and material nonlinearity. For the elevated temperature tests, a thermal analysis was performed first and the nodal temperature profile exported to the mechanical model and included in the analysis under mechanical loading.

248. From my review, coupled with expert advice at (ref. [86]), I note the following key findings below.

- In the case of the out-of-plane bending and out-of-plane shear tests, the results demonstrated that the equations developed in (ref. [113]) (based on (ref. [69])) conservatively predicted the capacity of the specimens in all four cases. However, it was noted that the out-of-plane bending tests on specimens OOPM-1 and OOPM-2 (which had the diaphragm parallel to the loading in OOPM-1 and perpendicular to the loading in OOPM-2) showed that the initial stiffnesses of OOPM-1 was 20% smaller than calculated using equations in (ref. [113]) whereas OOPM-2 had an initial stiffness 21% greater than calculated using the equations in ref. [113]). However, no further comment was made about this difference or about the out-of-plane shear tests (OOPV-1 and OOPV-2) in which the initial stiffness can also be derived from the measurements;
- The descriptions of load application and orientation are not entirely clear in the reports (refs. [113], [166]. Furthermore, it would be helpful if the descriptions also related the orientation of the test set up to the actual configuration in the SCCV. The method used to calculate the biaxial capacity is not given, and so it is unclear how the diaphragm contribution was accounted for. Equation 5-15 in (ref. [113]) includes a contribution to

the uniaxial tensile resistance from the diaphragms in the direction of the diaphragms. However, it is not clear how this can be justified if the diaphragms are not joined at a splice between modules. If the loss of diaphragm connection at a splice is compensated for by cover plates, this is not stated, and no relationship is given for determining the minimum size of the cover plates for Equation 5-15 to be valid; and

- In the case of the in-plane shear test specimens (IPV-1-AMB, IPV-2-TH and IPV-3-OOPV), it is noted that the steel of all three specimens does not satisfy the ductility requirements of (ref. [69]), N9.1.1(d), with $F_u/F_y = 1.13 < 1.2$.

249. Further clarification on the above was provided by the RP at (ref. [172]). From my assessment, I am content the RP has acknowledged these gaps and has developed strategies to resolve them. Therefore, for GDA Step 2, I am content with the level of information provided and judge there are no fundamental shortfalls.

250. In line with SAPs ECS.4,5, ECE.2, and SSR-2/1 Requirement 9: Proven engineering practices [55], the residual areas below will require further consideration by the RP as part of a future iteration of the BWRX-300 safety case:

- Provide further explanation regarding how the detailed nonlinear numerical finite element models that were validated against the tests compare with the linear elastic models in terms of out-of-plane stiffness, bi-axial in-plane stiffness and connection stiffness.
- Provide commentary on whether the low ductility of the plates used in test specimens (which fall outside the limits of ANSI/AISC-690 N9) impacts the interpretation of the test results.
- The extent of physical testing to underwrite the proof of design concept may require to be expanded as the design develops especially to verify structural understanding of the containment performance and behaviour.

251. For GDA Step 2, I am content with the level of information provided and judge there are no fundamental shortfalls.

4.3.5.12. Assessment Summary

252. My assessment of the RP's proposed use of DP-SC has been detailed ranging from the analysis and design methodologies through to constructability considerations. Overall, I consider the design approach to be robust, and the RP has provided compelling arguments for the use of DP-SC in place of more traditional construction approaches. There are areas highlighted that will require further consideration and development of the design methodologies as part of a future iteration of the BWRX-300 safety case. Of particular importance are the areas not covered by existing design codes where the principles of SAPs ECS.4,5 and SSR-2/1 apply. Notwithstanding these, I am satisfied that there are no fundamental shortfalls associated with the use of DP-SC & SC for this design of NPP.

253. The above conclusion was discussed at a meeting with US NRC and CNSC on 7th April 2025 (ref. [117]). The meeting agenda centred upon the use of DP-SC and SC for the RB. From the discussions, assurance was gained that the assessment outcome above is consistent with the views of US NRC and CNSC (ref. [118]) and that there was alignment on the areas deemed important as the design continues to develop. It also served to validate the claims made by the RP regarding the degree of regulatory acceptance / approval for the US and Canadian sites under development.

4.3.6. Application of CDM Principles

254. My assessment basis draws from the RP documentation at (refs. [6], [7], [112], [12]), RQ response at (ref. [177]), and technical workshop presentations (refs. [120], [124]).

255. For this area my expectations are that assumptions regarding the construction and durability within the design are achievable. To align with CDM Regulations, consideration of whole-life health and safety risk reduction should be considered at GDA. It is expected that the RP has postulated viable (economical, reliable and low risk) construction and maintenance methodologies for the civil structures that underpin, inform and/or are consistent with the design assumptions. These methodologies are expected to be cognisant of the CDM Regulations, which aims at considering the site safety risks earlier in the design process and mitigate/reduce those risks.

256. From my assessment, I am satisfied that the RP’s design processes are explicitly seeking early involvement from construction and fabrication contractors to develop optimal design and construction approaches and mitigate risks.

257. Further information on this topic was provided by the RP at (ref. [177]). From my assessment of this, I note that the governance arrangements and information related to constructability are under development. However, the RP has shown intent in ref. [177] to implement suitable processes and has demonstrated an understanding of the CDM regulations and principles.

258. The RP’s response at (ref. [177]) provides a list of documents proposed to provide whole life-cycle records of the design and build arrangements. This is considered acceptable assurance for this stage of GDA. Furthermore the RP’s response at (ref. [177]) also provides a list of activities related to governance arrangements for which the principal designer will be involved.

4.3.6.1. Assessment Summary

259. The RP’s documentation suite focuses on US and Canadian requirements and does not link explicitly to UK requirements such as CDM regulations. The impact of UK specific requirements and challenges has not been yet been fully developed but the RP has demonstrated an understanding of the CDM principles and this is evident in their design processes and specifically the early involvement of fabrication and construction contractors in the design

development. Therefore, I am satisfied that there are no fundamental shortfalls associated with the application of CDM principles in the civil engineering design.

5. Conclusions

260. This report presents the Step 2 civil engineering assessment for the GDA of the BWRX-300 design. The focus of my assessment in this step was towards the fundamental adequacy of the design and safety case. I have assessed the SSSE chapters and relevant supporting documentation provided by the RP to form my judgements. I targeted my assessment, in accordance with my assessment plan (ref. [19]), at the content of most relevance to civil engineering against the expectations of ONR's SAPs, TAGs and other guidance which ONR regards as relevant good practice.

261. Based upon my assessment, I have concluded the following:

- From my assessment of the RP's application of its integrated engineering design processes, I am satisfied that the processes are being followed with appropriate expertise and governance (SAP EMC.4). Furthermore, the extensive use of 3D modelling tools within the design process is in accordance with RGP, see ONR TAG 17 Annex 2 (ref. [1]). In summary, I judge that there are no fundamental shortfalls associated with the design development processes for civil engineering;
- From my assessment of the overall safety case framework for civil engineering, I consider that the safety case philosophy and construct aligns with RGP and the intent of SAP SC.1, and the process for defining and allocating SFRs is systematic and logical inline with SAPs SC.4, 5. In summary, I judge that there are no fundamental shortfalls associated with the safety case framework for civil engineering;
- The RP has adequately demonstrated for civil engineering structures that: the layout, structural form, proposed geometries, and functional performance are adequately underpinned; areas of residual design risk and/or uncertainty are understood; and the risk of foreclosure of the design is acceptably low. Therefore, I judge that there are no fundamental shortfalls associated with 'proof of concept' for civil engineering;
- I am satisfied that the suite of design codes and standards applied by the RP accord with RGP. I am content that the civil engineering modelling and analysis architecture and methodologies presented by the RP are robust. Therefore, I judge there that there are no fundamental shortfalls associated with the RP's design principles and methods;
- My assessment of the RP's proposed use of DP-SC has been detailed ranging from the analysis and design methodologies through to constructability considerations. Overall, I consider the design approach to be robust, and the RP has provided compelling arguments for the use of DP-SC in place of more traditional construction approaches. Therefore, I am satisfied that there are no fundamental shortfalls associated with the use of DP-SC & SC for this design of NPP. This conclusion was found to be consistent with the views of US NRC and CNSC; and
- Regarding application of CDM principles, the impact of UK specific requirements and challenges has not yet been fully developed. However,

the RP has demonstrated an understanding of the CDM principles and this is evident in their design processes and specifically the early involvement of fabrication and construction contractors in the design development. Therefore, I am satisfied that there are no fundamental shortfalls associated with the application of CDM principles in the civil engineering design.

262. Overall, based on my civil engineering assessment, I have not identified any fundamental safety shortfalls and consider the RP’s submission adequate for GDA Step 2.

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Appendix 1 – Relevant SAPs considered during the assessment

SAP reference	SAP title
SC.1	The regulatory assessment of safety cases: Safety case production process
SC.2	The regulatory assessment of safety cases: Safety case process outputs
SC.4	The regulatory assessment of safety cases: Safety case characteristics
SC.5	The regulatory assessment of safety cases: Optimism, uncertainty and conservatism
SC.6	The regulatory assessment of safety cases: Safety case content and implementation
EKP.1	Engineering principles: key principles, (Inherent safety)
EKP.3	Engineering principles: key principles, (Defence in depth)
EKP.4	Engineering principles: key principles, (Safety function)
ECS.1	Engineering principles: safety classification and standards, (Safety categorisation)
ECS.2	Engineering principles: safety classification and standards, (Safety classification of structures, systems and components)
ECS.3	Engineering principles: safety classification and standards, (Codes and standards)
ECS.4	Engineering principles: safety classification and standards, (Absence of established codes and standards)
ECS.5	Engineering principles: safety classification and standards, (Use of experience, tests or analysis)
ERL.1	Engineering principles: Form of claims
ERL.4	Engineering principles: Reliability claims (Margins of conservatism)
ELO.1	Engineering principles: layout, (Access)
ELO.4	Engineering principles: layout, (Minimisation of the effects of incidents)
AV.1	Fault Analysis: assurance of validity of data and models, (Theoretical Models)
AV.2	Fault Analysis: assurance of validity of data and models, (Calculation Methods)
AV.4	Fault Analysis: assurance of validity of data and models, (Computer Models)
AV.5	Fault Analysis: assurance of validity of data and models, (Documentation)
AV.6	Fault Analysis: assurance of validity of data and models, (Sensitivity Studies)
EMC.4	Engineering principles: integrity of metal components and structures: general, (Procedural control)
EAD.1	Engineering principles: ageing and degradation, (Safe working life)

EAD.2	Engineering principles: ageing and degradation, (Lifetime margins)
ECE.1	Engineering principles: civil engineering, (Functional Performance)
ECE.2	Engineering principles: civil engineering, (Independent Arguments)
ECE.3	Engineering principles: civil engineering, (Defects)
ECE.6	Engineering principles: civil engineering: design, (Loadings)
ECE.7	Engineering principles: civil engineering: design, (Foundations)
ECE.8	Engineering principles: civil engineering: design, (Inspectability)
ECE.12	Engineering principles: civil engineering: structural Analysis and Model Testing, (Structural Analysis and Model Testing)
ECE.13	Engineering principles: civil engineering: structural Analysis and Model Testing, (Use of Data)
ECE.14	Engineering principles: civil engineering: structural Analysis and Model Testing, (Sensitivity studies)
ECE.15	Engineering principles: civil engineering: structural Analysis and Model Testing, (Validation of Methods)
ECE.16	Engineering principles: civil engineering: construction, (Materials)
ECE.17	Engineering principles: civil engineering: construction, (Prevention of Defects)
ECE.18	Engineering principles: civil engineering: construction, (Inspection during construction)
ECE.19	Engineering principles: civil engineering: construction, (Non conformities)
ECE.20	Engineering principles: civil engineering: in-service inspection and testing, (Inspection, testing and monitoring)
ECE.22	Engineering principles: civil engineering: in-service inspection and testing, (Leak tightness)
ECE.25	Engineering principles: civil engineering: design, (Provision for Construction)
ECE.26	Engineering principles: civil engineering: design, (Provision for Decomissioning)