Office for Nuclear Regulation

Operating Facilities

Hunterston B - Return to service safety case for Reactor 4 following core inspection results in 2018 - NP/SC 7785 - Civil engineering assessment

Assessment Report ONR-OFD-AR-18-085
Revision 0
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EXECUTIVE SUMMARY

This report presents my assessment findings for the civil engineering aspects of EDF Energy Nuclear Generation Limited's (NGL's) return to service safety case for the Hunterston B Reactor 4, NP/SC 7785, following core inspections in 2018.

In accordance with NGL's arrangements made under Licence Condition 22 (1), the safety case is Category 1 and therefore requires ONR's Agreement or Acknowledgement before it can be formally implemented.

The safety case presents the justification for the return to service of Reactor 4 from its graphite core inspections and for continued operation for a period of approximately 4 months. The updated case does not require any physical plant changes.

Keyway root cracking was first observed in the main population of graphite moderator fuel bricks at Hunterston B Reactor 3 in October 2015, and in September 2017 for Reactor 4. Since this time, the safety case for operation of the graphite cores at Hunterston B and Hinkley Point B has been based on determining an appropriate Justified Period of Safe Operation (JPSO) from core inspection results as set out in NP/SC 7716.

This safety case has proposed changes to both the Operational Allowance and the Currently Established Damage Tolerance Level for brick cracking and crack opening. These changes have been justified through developments in damage tolerance assessments. These developments include the use of a reduced seismic motion at the boundary between the core and its supporting structure, (the core boundary seismic motion)derived from revised modelling of the Pre-stressed Concrete Pressure Vessel (PCPV), which provides support to the graphite core.

The case seeks to demonstrate that core distortion under seismic faults will not prevent control rod insertion. The evidence presented describes a number of changes to the seismic modelling of the core, including an updated core boundary input motion.

The core boundary seismic motion used for previous assessments was based on a seismic analysis performed in support of the first Periodic Safety Review. NGL has recently identified unrealistic constraints in this legacy model and now considers that these cause unrealistic and excessive seismic motion in the PCPV. This safety case describes a new analysis model of the PCPV, which has been developed to update the core boundary input motion for the graphite core assessments.

From a civil engineering perspective, the most significant risks addressed by the case relate to the justification that core distortion will not prevent successful insertion of the control rods during and following a seismic event. This justification is based on the revised seismic modelling of the PCPV.

I have assessed the claims and supporting arguments with civil engineering content and sampled the supporting evidence. My assessment focused on the revised modelling of the PCPV. As part of my assessment, I also attended two meetings with the licensee and raised a significant number of assessment queries, which in general were adequately addressed.

I found that overall the safety case was valid, robust, integrated, balanced, and forward looking. I judge that there were certain areas within the case that lacked the intelligibility, completeness and evidential basis identified in ONR's guidance for assessment of safety cases. My key assessment findings are summarised below.

- I judge that the modelling approach was conventional and in general accordance with relevant good practice.
- The changes to the restraints in the existing model in order to de-couple the PCPV from the Reactor Building have been adequately justified.

- The seismic input motion is considered conservative within the frequency range of significance for the core.
- For frequency ranges of significance to the core response, there was a significant reduction in core seismic input motion for the best estimate model compared with the legacy best estimate model.
- The best estimate material properties for the concrete structure, bearings, rock and backfill are deemed adequate.
- A limited, though acceptable, sensitivity study has been undertaken that considered the effects of uncertainty due to variation in key material properties
- In order to address my queries, the licensee has supplied additional evidence taken from its updated modelling work for the PCPV and graphite core. I note that this material is preliminary in nature but judge it adequate as additional supporting evidence to the present safety case.
- The most onerous case for channel distortion margins was obtained from a combination of upper bound properties for the rock, backfill and bearings. However, the safety case claims in relation to the core are based on a best estimate analysis, which may be un-conservative.
- Insufficient evidence was presented that the bearings could fulfil their safety functional requirements or that the bearings complied with current codes and standards. .
- The walk-down to confirm the as-built details important to the analysis had not been reported in a manner that could be used as evidence in the safety case.
- The effect of the changes to the PCPV modelling on other Structures, Systems and Components (SSCs) and safety cases requires further investigation.
- I identified a number of areas where the intelligibility and evidential basis of the PCPV analysis could be improved. I judge that the risk associated with any changes resulting from these enhancements and additions is acceptably small.

I have captured my findings in three recommendations for the licensee, and I intend to raise an ONR Regulatory Issue so that I can track the licensee's progress in completing my recommendations in a timely manner.

I have raised a recommendation for ONR in relation to the graphite assessment of the safety case and my reservations regarding the use of a best estimate PCPV model to support the claims on graphite core margins.

I have raised a recommendation for ONR in relation to the assessment of future safety cases where additional sensitivity studies may be required if there are changes to the natural frequency of the graphite core.

To conclude, from a civil engineering perspective, and subject to my recommendations, I am satisfied with the claims, arguments and evidence laid down within the licensee's safety case. I judge the proposal adequate to justify the issue of a Licence Instrument to signify ONR's Agreement under arrangements made under Licence Condition 22 (1) and have recommended that ONR issue such an Agreement.

Based on the areas for improvement identified in my findings, overall I judge that the licensee's submission should be rated as Amber with respect to the ONR Assessment Rating Guide.

LIST OF ABBREVIATIONS

ABSC	ABS Consulting Ltd
ALARP	As Low As is Reasonably Practicable
ASCE	American Society of Civil Engineers
BE	Best Estimate
BS	British Standard
CEDTL	Currently Established Damage Tolerance Level
CM	Content Manager
CMG	Charge Machine Gantry
DCB	Doubly-axially Cracked Bricks
EC	Engineering Change
EDF	Electricite de France
GCORE	Graphite Core (finite element program) – see Glossary
HOW2	(ONR) Business Management System
HNB	Hunterston B Power Station
HPB	Hinkley Point B Power Station
HPC	Hinkley Point C Power Station
Hz	Hertz
IAEA	International Atomic Energy Agency
IJCO	Interim Justification for Continued Operation
INA	Independent Nuclear Assurance
INSA	Independent Nuclear Safety Assessment
JPSO	Justified Period of Safe Operation
LB	Lower Bound
LLB	Lower Lower Bound
LTG	Long Travel Girders
MCB	Multiply axially Cracked Bricks
NGL	EDF Energy Nuclear Generation Ltd
OA	Operational Allowance
OD	Ordnance Datum
ONR	Office for Nuclear Regulation
PCPV	Pre-stressed Concrete Pressure Vessel
PML	Principia Mechanica Limited
PSR1	The first Periodic Safety Review
R3/R4	Reactor 3/Reactor 4
RGP	Relevant Good Practice
RSI	Rock Structure Interaction

SAP	Safety Assessment Principle(s) (ONR)
SCAP	Safety Case Anomalies Process
SCB	Singly-axially Cracked Bricks
SRS	Secondary Response Spectra
SSC	Structures, Systems and Components
SS1/SS2	Stage Submission 1 or 2
TAG	Technical Assessment Guide(s) (ONR)
TWd	Terawatt days
UB	Upper Bound
UHS	Uniform Hazard Spectrum/Spectra

GLOSSARY

Term	Definition
CEDTL	Currently Established Damage Tolerance Level: The level of brick cracking and crack opening that has currently been assessed and demonstrated to be tolerable, i.e. that does not challenge the fundamental nuclear safety requirements of the core.
GCORE	A computer program used to generate ABAQUS finite element models of the graphite core for displacement and loading analysis for the seismic hazard.
Keyway Root Cracking	Cracking initiating from a keyway root of a fuel moderator brick, caused by a combination of internally generated shrinkage and thermal stresses and propagating the full height and full thickness of the brick.
LEWIS	Control rod entry margin is calculated by LEWIS and reported as the variable m3dsf (the maximum distortion scale factor on the given channel shape which just satisfies the geometrical no-overlap constraints between the assembly and the channel shape).
OA	Operational Allowance: The operating limit for the state of the core (in terms of brick cracking and crack opening) which has been demonstrated to be tolerable and provides margin to the CEDTL.
PML spectrum/input motion	A piecewise linear spectrum anchored at 0.14g. It is a generic UK wide design spectrum that does not contain any site-specific characterisation other than the general ground classification as “rock”. It was developed by Principia Mechanica Limited (PML) and was chosen as the 10^{-4} per annum seismic hazard spectrum in for assessments carried out in support of PSR1.
SRL	Specified Rod Length – a method of assessing the level of distortion of an interstitial channel profile by identification of the minimum distance between an imaginary sensor rod and the interstitial channel’s instantaneous profile. This is used to identify channel profiles that would challenge the entry of 6-section control (sensor) rods into the core.
UHS	Uniform Hazard response Spectrum/Spectra - Response spectra derived so that the annual probability of exceeding the spectral quantity (acceleration, displacement, etc.) is the same for any spectral frequency.
3BL	3 Brick Length – a method of assessing the level of distortion of an interstitial channel profile by identification of the minimum distance between an imaginary control rod three brick lengths long and the interstitial channel’s instantaneous profile. This is used to identify channel profiles that would challenge the entry of 8-section control rods into the core.

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1 INTRODUCTION

1.1 Background

1. As the reactor has aged, cracks have begun to form in the graphite moderator bricks that make up the reactor core. Since the control rods are deployed down vertical channels within these stacked bricks, their insertion could be prevented if the cracking leads to excessive displacement of the bricks during an earthquake. Because of this cracking, the operational safety case for the core depends on repeated inspections and assessments of the graphite bricks.

2. This report presents the findings of my civil engineering assessment of the Hunterston B (HNB) return to service safety case for Reactor 4 following core inspection results in 2018 (hereinafter the safety case), as presented in Ref. 6 and supporting documentation provided by EDF Energy Nuclear Generation Ltd (NGL).

3. NGL has requested (Ref. 7) that the Office for Nuclear Regulation (ONR) provide Agreement of the safety case in accordance with the licensee's arrangements made under Licence Condition 22 (1). ONR has decided to assess the case and, subject to a satisfactory assessment outcome, to issue an Agreement via a Licence Instrument. The updated safety case does not require any physical modifications to the plant.

4. I undertook the assessment in accordance with the requirements of the ONR HOW2 Business Management System guide NS-PER-GD-014 (Ref. 1). The ONR Safety Assessment Principles (SAPs) (Ref. 2), together with supporting Technical Assessment Guides (TAGs) (Ref. 3), have been used as the basis for this assessment.

1.2 Scope

5. The scope of this report covers only the civil engineering aspects of the safety case, in particular the assessment of the revised seismic modelling for the Pre-stressed Concrete Pressure Vessels (PCPVs). This seismic modelling has been carried out in order to revisit the previous seismic models for HNB Reactors 3 (R3) and 4 (R4) and Hinkley Point B (HPB) Reactors 3 and 4.

6. My assessment considers the adequacy of the seismic modelling for the PCPV structure, which provides seismic accelerations for use in the assessment of the graphite core using the GCORE finite element model (see Glossary). This assessment does not consider the derivation of the GCORE model or the adequacy of the results obtained from it, as these aspects are part of the graphite assessment (Ref. 44).

1.3 Methodology

7. The methodology for the assessment follows HOW2 guidance on mechanics of assessment within ONR (Ref. 4).

8. My assessment supports the graphite assessment of Claim 1, Argument 1.3 of Ref. 6, which argues that at the end of the proposed Justified Period of Safe Operation (JPSO), core distortion will not prevent successful insertion of the control rods during normal operation, plant faults or following a seismic event.

9. I have rated the licensee's submission in accordance with the ONR Assessment Rating Guide (Ref. 5).

2 ASSESSMENT STRATEGY

10. My strategy for the assessment of the safety case is set out in this section. This identifies the scope of the assessment and the standards and criteria that have been applied.

2.1 Standards and Criteria

11. The relevant standards and criteria adopted within this assessment are principally the Safety Assessment Principles (SAPs) (Ref. 2), internal ONR Technical Assessment Guides (TAGs) (Ref. 3), relevant national and international standards and relevant good practice informed from existing practices adopted on UK nuclear licensed sites. The key SAPs and any relevant TAGs are detailed within this section. National and international standards and guidance have been referenced where appropriate within the assessment report. Relevant Good Practice (RGP), where applicable, has also been cited within the body of the assessment.

2.2 Safety Assessment Principles

12. The key SAPs applied within the assessment are included within Table 1 of this report.

2.2.1 Technical Assessment Guides

13. The following TAGs have been used as part of this assessment (Ref. 3):

- NS-TAST-GD-005 Guidance on the Demonstration of ALARP
- NS-TAST-GD-013 External Hazards
- NS-TAST-GD-017 Civil Engineering
- NS-TAST-GD-051 The purpose, scope and content of Nuclear Safety Cases

2.2.2 National and International Standards and Guidance

14. The following principal standards and guidance have been used as part of this assessment (Refs 8, 9, 10 and 11):

- American Society of Civil Engineers (ASCE) Standard 4-16 – Seismic Analysis of Safety-Related Nuclear Structures
- International Atomic Energy Agency (IAEA) Safety Report Series No. 28 - Seismic Evaluation of Existing Nuclear Power Plants
- IAEA Safety Guide NS-G-2.13 – Evaluation of Seismic Safety for Existing Nuclear Installations
- National Institute of Standards and Technology (NIST) GCR 12-917-21 - Soil Structure Interaction for Building Structures

2.3 Use of Technical Support Contractors

15. A technical support contractor has been employed on this assessment. ABS Consulting (ABSC) has provided independent advice to ONR on the suitability of the updated PCPV model to provide adequately robust seismic input for use in the assessment of the graphite core. ABSC has produced a report (Ref. 12) which has been used in support of the assessment described in Section 4 of this report.

2.4 Integration with Other Assessment Topics

16. This assessment is part of a suite of similar assessments being carried out by other ONR specialist inspectors who cover other technical disciplines and components and which will inform the Project Assessment Report. The civil engineering assessment

has been carried out in support of the graphite assessment, as described in Section 1.2.

2.5 Out of Scope Items

17. The Reactor Building seismic modelling, which remains unchanged from the previous safety case, is not reassessed.

18. The assessment of the effects of the revised seismic motions on the GCORE model are considered out of scope for this report and are addressed in the graphite assessment report.

19. This assessment does not consider any changes to the characterisation of the seismic input motion, which remains the same as that used in the extant safety case. Although the revised modelling report includes some examples of the effect of using a HPB Uniform Hazard Spectra (UHS) as seismic input motion, this is not claimed in the safety case and has not been assessed.

3 LICENSEE'S SAFETY CASE

3.1 Background

20. Hunterston B Reactor 4 was shut down in October 2018 in order to carry out inspections of the graphite core. NGL has presented a Category 1 return to service safety case, NP/SC 7785, for this reactor (Ref. 6).

21. Keyway root cracking (see Glossary) was first observed in the main population of graphite moderator fuel bricks at HNB Reactor 3 (R3) in October 2015 and in September 2017 for R4. Since this time, the safety cases for operation of the graphite cores at HNB and HPB have been based on appropriate JPSOs determined from the core inspection results. The basis for determining these JPSOs is set out in the existing safety case NP/SC 7716 (Ref. 13).

22. Inspections of the HNB R3 graphite core in March 2018 identified cracking in excess of the NP/SC 7716 Operational Allowance (OA) of 350 axially cracked bricks, leading to R3 being shut down. The extent of cracking identified within R3 raised the potential for R4 to exceed the OA within its JPSO and an Interim Justification for Continued Operation (IJCO) was produced. In October 2018 when the R4 core burn-up reached the limit justified by the IJCO, R4 was shut down and a graphite core inspection was performed.

23. Recent work for Doubly axially Cracked Bricks (DCB) has challenged whether the existing NP/SC 7716 OA and Currently Established Damage Tolerance Limit (CEDTL) for DCB remain valid due to control rod entry safety margins in several interstitial channels being less than one (a margin greater than or equal to one being deemed acceptable) in a sub-set of the runs. This issue has recently been considered under the licensee's Safety Case Anomalies Process (SCAP) (Ref. 16), primarily for HPB since those reactors remained on-load; however, the conclusions are also valid for HNB R4. The SCAP concluded that continued operation was justified pending further work to resolve the anomaly, and the OA and CEDTL from NP/SC 7716 were judged to remain valid.

24. The intent of the proposal is to provide a justification for the return to service and continued operation of HNB R4 to a core burn up of 16.025 Terawatt days (TWd) (a period of approximately 4 months) following completion of core inspections. The safety case is based upon the NP/SC 7716 approach but with changes made to both the OA and the CEDTL. The licensee claims that these changes are justified through developments in the Damage Tolerance Assessments (DTA) since NP/SC 7716, including the use of a significantly reduced core boundary seismic motion derived from revised modelling of the PCPV (Ref. 17). The tolerability of Multiply axially Cracked Bricks (MCB) is also incorporated into the OA, supported by an appropriate CEDTL for MCB.

25. The intention is that this case will be superseded by a new R4 operational safety case that will be produced during the 4-month JPSO to allow extension of the operating period.

26. Work is currently ongoing to develop a new approach to graphite safety cases for HPB and HNB. The principles for producing future graphite safety cases for seismic loading are set out in Paper of Principle NP/SC 7766 (Ref. 15), which has been presented to ONR but still requires station approval. As this paper is not yet approved, it is not part of this justification.

27. The updated case does not require any physical plant modifications. This proposal defines a JPSO in accordance with the principles of NP/SC 7716, whereby the predicted extent of cracking at the end of the JPSO (with a calculated confidence of

99.9%) is within the OA, which will be set with a margin to the CEDTL. As a further prudent measure, it is shown that the forecasted R4 core state remains broadly within the current R3 core state (i.e. is less cracked). Limiting Condition of Operation (LCO) 4.4.1 will be updated to specify the new core burn-up limit for R4.

3.2 Nuclear safety requirements

28. The fundamental nuclear safety requirements of the graphite core, in normal and fault conditions, are to:

- Allow unimpeded movement of control rods and fuel.
- Direct gas flows to ensure adequate cooling of the fuel and core.
- Provide neutron moderation and thermal inertia.

29. Damage to core components, for example, cracking of moderator fuel bricks, can affect the geometric response of the graphite core during normal operation, faults and seismic events, and can affect the calculated margins for control rod entry, thus affecting the first of the graphite core fundamental nuclear safety requirements.

30. If inadequately conceived or executed, this proposal could lead to a significant increase in the probability of failure of the reactor shutdown and hold down functions, or an increase in the risk of dropped fuel or flow blockage. Consequently, this could lead to a serious increase in radiological risk.

31. The proposal demonstrates that HNB R4 remains within the framework presented in NP/SC 7716 and its associated Addenda for the proposed JPSO. The introduction of a revised OA is not considered either novel or complex in nature. The proposal seeks to demonstrate that the assessment methodology employed includes significant margin and conservatism and that there is no ‘cliff-edge’ effect beyond the proposed JPSO.

3.3 Claims, arguments and evidence

32. The safety case is presented based on two claims. Each of the claims has a series of arguments and pieces of evidence that substantiate the claim. The claims are:

- Claim 1: Graphite core degradation over the proposed JPSO will not undermine the required reliability of the Primary Shutdown (PSD) system for shutdown and hold-down during normal operation and plant faults and the seismic hazard, nor adversely affect fuel integrity.
- Claim 2: All reasonably practicable measures have been taken in order to ensure that the risk associated with continued operation of HNB R4 is As Low As Reasonably Practicable (ALARP).

33. Claim 1 is supported by five arguments, the most relevant of which to the civil engineering assessment is:

- Argument 1.3: At the end of the proposed JPSO, core distortion will not prevent successful insertion of the control rods during normal operation, plant faults or following a seismic event.

34. The magnitude and extent of core distortion is considered by the licensee to be associated with the number of axially cracked bricks (SCB, DCB and MCB), the extent of crack opening and the graphite component strength and clearances, which are dependent upon core age. The established damage tolerance at the end of the JPSO, considering these parameters, is presented in Evidence 1.3.2 for the seismic hazard. Evidence 1.3.3 then provides demonstration that there is margin between the forecast core state and appropriately defined OA and CEDTL.

35. Evidence 1.3.2 is intended to demonstrate that predicted core distortion under seismic faults will not prevent control rod insertion. The evidence presented describes a number of improvements to the seismic modelling of the core, including an updated core boundary input motion, together with GCORE assessments for a range of distributions and configurations of SCB, DCB and MCB.

36. The core boundary input motion used for previous GCORE assessments, including those supporting the current graphite core safety case (NP/SC 7716), was based upon the PCPV response calculated by the 'legacy Reactor Building seismic assessment that was performed in the 1990's to support the first Periodic Safety Review (PSR1). Unrealistic constraints have since been identified in the legacy model and these have been found to cause excessive predicted PCPV seismic motion. A new finite element model of the PCPV has therefore been developed (Ref. 17) to update the input motion for the GCORE assessments. In addition to removing the unrealistic constraint, the new model incorporates improvements to methodology and to the definition of the structure.

37. Ref. 17 identifies itself as a preliminary assessment of the updated PCPV modelling, and acknowledged that refinements will be made to the model for the longer-term seismic safety case. Provided margin is demonstrated on control rod freedom of movement, the model is claimed to be appropriate and adequate to support the proposed return to service of HNB for a limited operating period.

38. Acceleration time histories for subsequent use in GCORE are extracted at the core boundary, which is taken to be the base of the Boiler Shield Wall (Ref. 17). To facilitate the assessment of multiple input motions, the preliminary PCPV model and the full core model have been combined to form a single model (the "Combined Model") using kinematic couplings to replace boundary conditions in the full core model. The base of the Circulator Outlet Gas Duct is also coupled in all six degrees of freedom to the floor of the PCPV chamber to account for rocking of the PCPV. Boundary conditions to constrain global torsional displacement within the full core model have been retained in the combined model. No other model properties or characteristics have been changed for the PCPV or full core model in the combined model.

39. The PCPV assessment applies the same ground motion for the bottom line seismic event that was used for the previous safety case. This is a single unidirectional synthetic time history developed from the 0.14g hard site Principia Mechanica Limited (PML) design spectra. The ground motion is considered synthetic, as it is not derived from the records of real earthquakes. The PML unidirectional synthetic time history is judged (Ref. 35) to provide a conservative and bounding surrogate for a $1E^{-4}$ per annum site-specific HNB hazard when developed as a UHS.

40. The assessment also considers the PCPV seismic response with ground motions that are more in accordance with current codified seismic guidance (i.e. Ref. 8). These motions use real-record seismic data and consider five time histories for each of the targeted spectra (both the PML hard site spectra and the HPB site specific UHS, which is being considered for potential future safety cases). It is shown that a similar PCPV seismic response is calculated when using either the synthetic time history or the real record data, when targeted at the same spectra.

41. The Best Estimate (BE) core boundary time history produced by the new PCPV model is greatly reduced in severity from the corresponding time history used in previous assessments. This is mainly attributed to the legacy model including connections between the top of the PCPV and the Reactor Building, which unrealistically tie the two structures together, leading to excessive excitation of the top of the PCPV. In the new model, the PCPV is effectively isolated from the Reactor Building, with its excitation (as would be expected) driven from its base. The inclusion of the improved representation

of the PCPV foundation embedment is also contributory to the reduced core boundary motion.

42. The results of the GCORE assessments in Ref. 14 are that a minimum margin of 2.69 (Distortion Utilisation of 0.37) is calculated against full insertion of a control rod (across all interstitial columns and at all times during the seismic event) using the conservative LEWIS method. This minimum margin occurs for a sensor rod during the seismic motion, for the case with 1,000 DCB. For this case, the minimum margin across the 10 core states assessed ranges from 2.69 to 3.21, with an average of 2.95. These margins compare with a minimum acceptable margin of 1.0.

43. Even with the substantially increased levels of cracking being modelled (e.g. the OA has been increased from 350 to 700 axially cracked bricks), the margins upon control rod entry from the current assessment are similar, if not better than, the margins presented in NP/SC 7716. This is attributed to the reduction in core boundary motion provided in the updated PCPV seismic model. This is demonstrated in Ref. 14, whereby the current GCORE model is used with the previous core boundary input motion, leading to results, which are broadly consistent with the previous cases.

44. The GCORE analysis intends to predict the expected response of the graphite core to the bottom line seismic event. This is achieved through performing the assessment, in general, on a BE basis. For the proposed operating period the uncertainties in the GCORE analysis, are judged to not significantly degrade the confidence in the GCORE assessment outputs and are minor compared to the large predicted margins. The most significant uncertainty for the seismic assessment remains with the forecast core state. The licensee claims however that the core states assessed by GCORE clearly bound those that could develop in the next operating period. For the current assessments, the uncertainty in the GCORE calculations will be a low contributor to the overall uncertainty associated with assessing confidence in the ability of the control rods to enter the core in a seismic event.

45. Claim 2 is an overall claim that the risk of continued operation of R4 is ALARP and is supported by three arguments. Of these arguments only Argument 2.2, which claims that all reasonably practicable measures have been taken to reduce the risk associated with return to service of HNB R4, is relevant to the civil engineering assessment.

3.4 Commitments

46. The safety case has not made any commitments.

3.5 Conclusion

47. In conclusion, NGL considers that this proposal justifies the return to service of R4 from its October 2018 graphite core inspection campaign, and for continued operation for approximately 4 months, to a core burn-up of 16.025 TWd.

48. The damage tolerance assessments show large margins for the key parameters for normal operation, fault loadings and the seismic hazard. There is high confidence that all control rods will successfully enter the core in all credible faults and hazards. There is further margin and no cliff-edge in reactivity control for larger core distortions due to the provision of control rods with additional articulation.

49. Overall, NGL considers that this proposal demonstrates that the nuclear safety risks associated with the graphite core for the proposed period of operation are acceptable and ALARP.

4 ONR ASSESSMENT

50. My assessment has been carried out in accordance with HOW2 guide NS-PER-GD-014, “Purpose and Scope of Permissioning” (Ref. 1). In accordance with its arrangements, the licensee has deemed the safety case a Category 1 submission. Based on the identified nuclear safety risks if inadequately conceived or executed, I agree with its categorisation.

51. In my assessment, I refer to the claims, arguments and evidence provided by NGL, and I make my own judgement on how the claims have been substantiated within the safety case and the supporting documentation.

4.1 INA assessment

52. In my assessment, I have taken note of the work completed and the conclusions presented by the licensee’s internal regulator, Independent Nuclear Assurance (INA). The Independent Nuclear Safety Assessment (INSA) approval statement (Ref. 18) notes that INA has reviewed the case and appropriate supporting evidence and agrees that the revised Operational Allowances are justified. INA further agrees that the case for return to service and operation of HNB R4 to the identified core burn up limit is acceptable on the basis that there is an appropriately high confidence that the core damage will remain within the OA.

53. As part of its assessment, INA has reviewed the changes that have been made to produce the preliminary revised buildings (i.e. PCPV) model. In my assessment, I took note of the INA comments on the modelling and the responses provided by NGL (Ref. 19). INA is content that the connectivity changes (between the PCPV and the building) more accurately model the Reactor Building structure and lead to a more appropriate structural response. INA notes that sensitivity studies were included in the preliminary revised buildings model that covered lower bound, best estimate and upper bound treatments of backfill stiffness and bearing pad stiffness, and combinations of these. INA has reviewed the sensitivity studies and considers that they are appropriately bounding and in all likelihood conservative.

4.2 Scope of Assessment Undertaken

54. The general scope of my assessment is described in Section 1.2. My assessment has focused on the changes made to the seismic assessment of the PCPVs, and in particular the way in which the PCPVs are connected to the rest of the Reactor Building structure.

55. Due to the legacy connection between the PCPV and the Reactor Building Central Block, the revised finite element model is often referred to as the “buildings model” in the safety case and supporting documentation. In this report, the model will be consistently referred to as the PCPV model as that is a more accurate description.

56. NGL reports on a preliminary analysis (Ref. 17) intended to demonstrate that the way in which the PCPV was modelled in the existing safety case was incorrect and that the PCPVs are more accurately modelled as isolated structures. This preliminary analysis forms the basis for my assessment.

57. The modelling has been described by NGL as preliminary as it was recognised that there was further work to do to address comments raised during technical review, by both NGL (whose review comments were included in Ref. 17) and by an Independent Peer Review (IPR), (Ref. 20). NGL considers that the modelling is adequately conservative and fit for purpose but wishes to update it to provide the evidence for future safety cases. My assessment has focused on the preliminary model presented in Ref. 17, but where appropriate has sought additional evidence from the licensee that

subsequent sensitivity studies demonstrate that the preliminary model is adequately conservative.

58. My sampling strategy has been to rely on the licensee's own INA and IPR processes for overall coverage, and to concentrate my assessment effort on those aspects of the PCPV model that have changed since the previous safety case, and to consider whether these changes have been appropriately justified.

59. Whilst I have noted the challenges raised by others regarding the PCPV modelling, I have carried out my own assessment, supported by the work of my technical support contractor, and have formed my own judgements as to the adequacy of the model.

60. The preliminary modelling includes consideration of potential changes to the legacy ground motion defined in the extant safety case. I noted that changes to the ground motion are proposed for a future long-term seismic safety case for the HNB and HPB PCPVs but these changes have not been assessed in this report, as they are not claimed in the safety case.

61. My focus in this assessment has been on those aspects of Claims 1 and 2 that I consider relevant to the civil engineering aspects sampled. Claim 2 is an overall claim that the risk of continued operation of R4 is ALARP. This assessment will consider the extent to which the PCPV modelling aspects of the proposal demonstrate that risks are reduced ALARP.

62. I have assessed the claims (Sections 4.3 and 4.4) against the SAPs and the following safety case qualities described in ONR TAG NS-TAST-GD-051 (Ref. 3):

- Intelligible
- Valid
- Complete
- Evidential
- Robust
- Integrated
- Balanced
- Forward Looking

63. The structure and content of the safety case has been assessed against ONR's safety case TAG (NS-TAST-GD-051, Ref.3). In assessing whether risks have been reduced ALARP, I have used the ONR ALARP TAG (NS-TAST-GD-005, Ref. 3).

64. During the course of my assessment, I have raised a number of queries with NGL, to which they have subsequently provided responses. The queries are shown in Appendix 1 and responses are included in References 21 and 22. My technical support contractor (ABSC) also raised a number of queries as listed in Appendix 2. Responses from NGL to the ABSC comments are found in References 23 and 24. In general, the responses provided were adequate, though some required follow up queries to resolve. Where appropriate I have discussed these questions and responses within this report.

65. Level 4 meetings were held with NGL to discuss the preliminary PCPV model. An initial meeting (Ref. 25) was held so that NGL could introduce the revised model and explain its effect on the GCORE analysis. Following preliminary assessment of the safety case and the raising of a number of ONR and ABSC queries, a further Level 4 meeting was held (Ref. 26) so that NGL could explain its responses in more detail

4.3 Assessment of Claim 1

66. Claim 1 states that “Graphite core degradation over the proposed JPSO will not undermine the required reliability of the Primary Shutdown (PSD) system for shutdown and hold-down during normal operation and plant faults and the seismic hazard nor adversely affect fuel integrity.”

67. The licensee presents five arguments in support of Claim 1. I have carried out a high-level review of the arguments and their supporting evidence and chose to sample Argument 1.3, which I consider the most relevant to the preliminary PCPV model. I consider that other ONR assessors will adequately cover the evidence presented in support of the other arguments.

4.3.1 Assessment of Argument 1.3: At the end of the proposed JPSO, core distortion will not prevent successful insertion of the control rods during normal operation, plant faults or following a seismic event.

68. This argument is supported by five pieces of evidence. The evidence relevant to civil engineering is:

- Evidence 1.3.2: Predicted core distortion under seismic faults will not prevent control rod insertion.

69. Evidence 1.3.2 presents a number of improvements to the seismic modelling of the core, including an updated core input motion, together with GCORE assessments. The preliminary PCPV model, from which the updated core boundary input motion was derived, is presented in Ref.17, which I have chosen to assess. Revised GCORE modelling, based on output from the preliminary PCPV model, is described in Ref. 14. ONR graphite structural integrity inspectors have assessed (Ref. 44) the updated GCORE modelling, which is not within the scope of this report.

70. The following sections present my assessment of the preliminary PCPV model as described in Ref. 17. In summarising my assessment findings, I have considered the adequacy of the model against the following key aspects:

- PCPV model description and general modelling assumptions (4.3.1.1)
- Seismic input motion (4.3.1.2)
- Rock properties and Rock Structure Interaction (RSI) (4.3.1.3)
- Structural material properties (4.3.1.4)
- Backfill properties (4.3.1.5)
- Bearing functional requirements and properties (4.3.1.6)
- Restraint to PCPVs by other Structures, Systems and Components (SSCs) (4.3.1.7)
- Validation and verification (4.3.1.8)
- Sensitivity studies and modelling enhancements (4.3.1.9)
- Conservatisms and areas of uncertainty (4.3.1.10)
- Analysis results and conclusions (4.3.1.11)

4.3.1.1 PCPV model description and general modelling assumptions

71. The preliminary PCPV model is idealised in Figure 2. It is a development of the first seismic “buildings model” produced in support of PSR1. This “legacy” model (see Figure 1) was developed to perform a BE seismic assessment of the structural members of the Reactor Building and Turbine Hall. It included representations of the PCPVs, Central Block, Circulator Hall and ancillary buildings. The legacy model was used to derive acceleration time histories, which were used as the basis for seismic assessments of the graphite cores.

72. One of the key features of the PCPV design is the presence of neoprene bearing pads between the underside of the vessel and the top of the foundation disk. These

bearings were installed to accommodate thermal movement and to prevent transfer of pre-stressing forces into the foundation. Although not designed for that purpose, the bearings also provide a degree of seismic isolation for the PCPVs.

73. The principal changes from the legacy model to the preliminary PCPV model are:

- The horizontal restraint of the PCPVs at the charge face level is removed.
- Compacted backfill has been modelled around the lower 4.5 m height of the PCPV walls. This backfill depth has been assumed to extend from the underside of adjacent cable and pipe tunnels to the base of the walls.
- The bearing pad stiffness and damping values have been amended
- The Rock Structure Interaction (RSI) properties have been amended based on revised rock parameters derived from work done at Hinkley Point C (HPC). In addition, when calculating rock stiffness, the width of the pre-stressing gallery has been added to that of the foundation disk.
- Restraint provided by the bearings, backfill and RSI have been analysed based on BE properties, in order to provide direct comparison with the results of the legacy model. Limited studies were carried out to investigate the sensitivity of the analytical results to Lower Bound (LB) and Upper Bound (UB) material properties, but this work has not been used to demonstrate graphite core margins.

74. Variations on the basic model have been used to investigate sensitivity to various secondary effects such as the possible restraint to movement of the PCPV by the Long Travel Girders (LTG), which support the Charge Machine Gantry (CMG). The LTG are supported on concrete columns, which are in turn supported by the PCPV via built-in concrete corbels. The report concludes that other SSCs do not significantly restrain the PCPV, which behaves similarly to an isolated structure. I have assessed this aspect of the modelling in Section 4.3.1.7.

75. In assessing the modelling work as reported in Ref. 17, I have taken into account the requirements of SAP AV.5, which requires that documentation be provided to facilitate review of the adequacy of the analytical models and data. Examples of documentation include input description, information showing that models and data are not employed outside their range of application and a description of the uncertainties in the model.

76. I consider that the model is conventional for use in soil-structure interaction (SSI) analysis and is based on established software widely used in the nuclear industry. The model uses methods that are in general accordance with ASCE 4-16 (Ref. 8), which I consider meets the requirements of SAP ECS.3 and represents RGP for seismic modelling of nuclear safety significant structures. This code of practice defines analytical methods that provide reasonable levels of conservatism to account for uncertainties. Notwithstanding a number of approximations (as detailed in Ref. 12), I consider that overall the modelling meets the requirements of SAP AV.2 in that calculation methods adequately represent the physical processes taking place.

77. NGL has highlighted a number of areas where it has used a more conservative approach than required by Ref. 8. During my assessment, however, I have identified a number of areas where the preliminary PCPV model and its output motions are not fully compliant with Ref. 8 and hence may not meet the requirements of SAP ECE.13 (for the data used to be selected or applied so that the analysis is demonstrably conservative). In my assessment, I have considered both these aspects in order to form a view on the overall adequacy of the basic assumptions in the preliminary model.

78. NGL acknowledges that for the preliminary model, the approach to seismic input motions is not fully in accordance with Chapter 2 of Ref. 8, but considers its approach conservative; this is discussed further in Section 4.3.1.2. NGL's intent is that the final

PCPV modelling in support of the future long-term safety case will be in full compliance with the requirements of Chapter 2 of Ref. 8.

79. In considering the allowances made for uncertainty in the modelling, I have considered SAP ECE.14, which requires that studies be carried out to determine the sensitivity of analytical results to the assumptions made, the data used, and the methods of calculation. Although the focus of NGL's preliminary PCPV modelling has been on the use of BE properties, NGL has studied the effects of variation in RSI, backfill and bearing properties to create LB and UB model variants. As shown in Table 7 of Ref. 17, the legacy input motion (known as the synthetic PML input motion) has been applied to the LB, BE and UB model variants. However, for the preliminary model, no detailed study was undertaken of the effect of varying RSI, bearing and backfill material properties individually. For example, in the LB case all the properties were combined at their LB level. In this respect, I consider that the preliminary modelling has only partially satisfied SAP ECE.14.

80. I consider that the relationship between soil or rock stiffness properties and corresponding damping has not been investigated in detail. For example, a case consisting of high rock or backfill stiffness in combination with a low percentage of critical damping has not been studied. Similarly, for the bearings, the effect of varying damping independently of stiffness has not been investigated (Ref. 12).

81. NGL acknowledged that further work is being done for the final PCPV model to consider a wider range of combinations of material properties. In order to provide confidence that both the maximum PCPV displacement and core damaging accelerations have been determined, NGL has presented to ONR selected results from its updated analysis (see Ref. 24). These results are discussed further in Sections 4.3.1.6, 4.3.1.9 and 4.3.1.11.

82. Although LB and UB sensitivity cases have been studied to the limited degree described above, the safety case claims for the graphite core are based on the use of the BE PCPV model at this stage. An updated PML input motion and a HPB geometric mean input motion have been studied using a BE PCPV model only and are included in Ref. 17 for comparison only. The implications of relying on a BE analysis are discussed further in Section 4.3.1.10.

83. In response to ONR Query 3, NGL claims (Ref. 21) that the modelling is fully compliant with the stick modelling techniques in Chapters 3 and 4 of Ref. 8. Based on the sampling undertaken, I concur that the stick modelling technique is compliant with RGP. Compliance with Chapter 2 (Seismic Input) and Chapter 5 (Soil-Structure Interaction Modelling and Analysis) of Ref. 8 are considered further in Sections 4.3.1.2 and 4.2.1.3 respectively.

84. The stick model of the PCPV does not include additional inertia elements, which will have omitted some of the rotational inertia (see ABSC Query 3). The rotational inertia will influence the tendency for the lateral translational mode of the PCPV on its bearing pads to combine with or to be separated from the rocking mode. NGL acknowledged (Ref. 24) that there was a small amount of coupling between the rocking and translational modes and that the rotational inertia of each beam element is affected by the lumping of mass at the nodes. NGL provided further information to substantiate its claim that the modelling was insensitive to this effect, including providing supplementary calculations to compare with finite element analysis results (Ref. 24). Based on sampling this information I considered there was good agreement between the hand calculations and finite element analysis and on this basis, I considered the modelling to be an adequate representation of the PCPV.

85. I found that the modelling report (Ref. 17) provided a basic summary of the masses included in the model but did not clarify that some of these had changed since the

legacy model nor explain the reasons for such changes. I did not find this approach to be fully in accordance with SAP ECE.6 with respect to the scheduling of design loads.

86. I have summarised the discrepancies between the masses included in the legacy (Ref. 40) and preliminary models (Ref. 17) in Table 2. In response to my queries ONR 19 and 20 (Ref. 22), NGL confirmed that, as part of the preliminary PCPV model a recalculation of loads was undertaken. The revised calculations corrected errors in the previous calculations (e.g. the underestimate of the mass of the pile cap) and now excluded the mass of reactor internals not supported on the diagrid, such as the boilers. Relatively minor loads (e.g. the charge face floor beams) were also excluded. I consider that the omission of these masses from the model was not justified in Ref. 17 and is not in accordance with Section 3.4.2 of Ref. 8, which requires that the model "shall include all mass expected to be present at the time of the earthquake." I accept however, NGL's argument that such secondary system masses have a negligible overall effect on the analysis results due to the substantial mass of the PCPV (approximately 50,000 Tonnes).

4.3.1.2 Seismic input motion

87. The preliminary PCPV model has been used to analyse the effects of a number of input ground motions as described in Ref. 17. These include:

- The legacy synthetic PML ground motion as used in the PSR1 assessment (Ref. 29) and in the analyses supporting the current graphite core safety case NP/SC 7716. This ground motion was used as it is referenced in the current Reactor Building safety case and because it allowed direct comparison between the legacy and preliminary PCPV models.
- Modified PML ground motion based on real records with the duration of the strong motion targeted to be between 3.5 and 11.5 seconds, to be compliant with current codified guidance for seismic hazard assessment. For each target spectrum, five independent sets of three orthogonal component input motions have been derived.
- HPB mean UHS, which comprise horizontal and vertical spectra considering the geometric mean for the definition of the horizontal component and for an annual frequency of exceedance of 10^{-4}. This UHS is being considered for future safety cases.

88. As described in Ref. 35, the legacy synthetic PML response spectrum is a piecewise linear spectrum anchored at 0.14g and is a generic UK wide spectrum. TAG 13 (Ref. 3) acknowledges the synthetic PML spectrum as the default spectrum that has traditionally been used as a minimum requirement in the UK. It does not contain any site-specific characterisation other than that the ground classification is "rock". It is demonstrated in Ref. 35 that the synthetic PML spectrum bounds a site specific UHS developed in 1991 up to frequencies of around 18 Hertz (Hz). The vertical response spectrum is taken as 2/3 of the horizontal response spectrum. Three statistically independent synthetic acceleration time histories were developed (in East-West, North-South and vertical directions) of duration 10.24 seconds and targeted at the 5% damping spectra.

89. The ground motions for the HPB mean UHS and the modified PML were considered as preliminary at the time of writing Ref. 17 and were presented to allow comparison with the legacy modelling. It is noted that the GCORE modelling reported in the safety case and detailed in Ref. 14 is based upon the synthetic PML hard-site synthetic input motion. The input motion used is horizontal only and unidirectional.

90. Relevant good practice as described in Ref. 8 is to develop compatible ground motion histories through modification of recorded ground motion histories according to procedures defined in ASCE/SEI 43-05 (Ref. 36). Five ground motion histories fitted to

the target design response spectrum are required in the analysis for each direction of input, where the mean response due to the five input ground motion histories is used to develop in-structure response. Resulting ground motion histories should have characteristics that reasonably represent the input motion expected for the location, such as an appropriate duration.

91. This preliminary PCPV model uses the synthetic PML motions to allow direct comparison with the legacy model. The legacy motions are not real records but the structural response has been compared against real record effects from the modified PML and HPB mean UHS input spectra. Figures 34 and 35 from Ref. 17 indicate that core boundary accelerations are less than those from the synthetic PML input spectrum across the range of frequencies of relevance to core damage (2 to 8 Hz according to Ref. 17).

92. I consider that, as noted in Ref. 3 (NS-TAST-GD-013), RGP (such as References 8 and 36) is progressively moving away from the use of artificially generated records such as the synthetic PML ground motions. Their use is not precluded for linear analysis provided the responses are consistent with those developed using modified real recorded motions for the responses of interest. I have considered the revised preliminary spectra presented in Ref. 17 and agree that the synthetic PML spectrum is conservative for use in the essentially linear analysis of the preliminary PCPV model in the frequency range of interest to core response and hence is fit for purpose. The GCORE modelling, derived from the PCPV model, is non-linear and for this work, the synthetic PML ground motions are inconsistent with the requirements of RGP.

93. NGL has not addressed the topic of Beyond Design Basis (BDB) earthquakes in Ref. 17, which would be expected to be considered in accordance with SAP EHA.18. No analysis has been undertaken for earthquakes greater than the design basis. NGL has stated in its response to ABSC Query 21 that the core analysis and substantiation will address the topics of BDB and absence of cliff edge effects (SAP EHA.7). NGL further state that the changes from the legacy model have reduced the accelerations in the PCPV by a factor of around two and that this demonstrates an adequate BDB margin. I note that the safety case does claim the absence of cliff-edge effects with respect to the core and the assessment of these claims will be considered as part of ONR's graphite assessment.

94. From a civil engineering perspective, I consider that one potential cliff edge effect of a BDB seismic input would be to challenge the continued validity of the PCPV model as an isolated structure (see ABSC 21) due to the closing of movement joints. I was satisfied with NGL's response (Ref. 24) that there is adequate margin against restraint of the PCPV by other structures for an earthquake significantly larger than the design basis earthquake.

95. As displacements increase in a BDB event, the performance of the bearings and the assumption of a linear response could become increasingly challenged. I was satisfied that even if the maximum shear strain in the bearings (31.2% as reported in Ref. 17) was doubled, there would still be a significant margin with respect to the maximum codified shear strain limit of 100% (Ref. 39). The review undertaken in Ref. 37 concluded that in moving from a shear strain of 100% to one of 50% there was a change in dynamic shear modulus of 20%, indicating only a small degree of non-linearity in this property in the strain range of interest. I was satisfied that any such non-linear effects had been bounded by the sensitivity analyses undertaken.

96. I was satisfied that a sufficiently wide range of soil properties had been considered in the sensitivity analyses to capture any BDB effects of soil non-linearity.

97. NGL agreed (Ref. 26) that the reporting of BDB effects would be enhanced in its final modelling report and this expectation has been captured in my Recommendation 5.

4.3.1.3 Rock properties and Rock Structure Interaction

98. The adopted methodology is based on the assumption that the soil–structure system behaviour is a rigid foundation in uniform ground. The layered ground properties at the HPB site have been converted to equivalent uniform properties. No allowance has been made for the sloping nature of the rock layers. The rock material properties have been derived based on recent work done in support of the design for HPC, which has similar geology to HPB.

99. Ref. 17 makes no mention of the differing ground conditions on the HNB site and makes the inherent assumption that the ground conditions at HPB are bounding for the seismic assessment of the PCPV. The legacy building analysis (Ref. 29) notes that both sites are considered as “hard sites” which normally results in the effects of SSI being relatively small. HNB is considered by NGL to be a harder site than HPB; hence, only one analysis has been undertaken based on properties applicable to HPB.

100. I asked NGL to provide evidence to support its judgement that HPB was the bounding site regarding RSI properties. This evidence was necessary to demonstrate that the modelling was based on sufficient geotechnical site investigation in accordance with SAP ECE.5. I was satisfied based on the additional information provided (Ref. 30) that HNB is a harder site than HPB and that based on previous sensitivity studies the displacement of the PCPV at the first mode of vibration (the most important mode for core distortion margins) is greatest based on HPB ground conditions. Although it is not clear in Ref. 17, NGL has confirmed (Ref. 21) that when considering its LB and UB rock and soil properties the chosen values have taken into account the conditions at both HPB and HNB. I therefore consider that NGL’s use of a ground model based on HPB, (with consideration given to the soil properties at HNB when selecting UB parameters), is appropriately bounding for the HNB site in terms of secondary response spectra at the base of the PCPV.

101. Structure Soil Structure Interaction (SSSI) is the phenomenon of coupling of the dynamic response of adjacent structures through the soil. SSSI was not mentioned in the preliminary model report but was justified as not significant in the legacy analysis due to the hard nature of the site and the limited expected foundation displacements. In response to ABSC Query 24, NGL provided additional justification for the omission of SSSI effects (Ref. 24). I accept that due to the hard nature of the rock strata, the massive nature of the PCPV and the effect of the bearings to isolate the PCPV from the foundation disk that any SSSI effects are likely to be insignificant. The omission of SSSI effects is further supported by Section 5.1.5 of Ref. 8, as the PCPV is a massive structure in comparison to other adjacent foundations and not therefore likely to be affected by interaction effects. NGL has agreed to provide further information on its reasoning for omitting consideration of SSSI effects in its final model report and this commitment will be tracked using my Recommendation 5.

102. According to Ref. 8, Section 1.3.1, for SSI (or RSI) a minimum of three soil cases should be analysed using a range of soil properties and the results are enveloped. As acknowledged in Section 1.1.1 of Ref. 8, this is considered a conservative approach. In the preliminary model reported in Ref. 17, sensitivity studies have considered the effect of LB, BE and UB RSI properties which I consider meets the intent of Ref.8 so far as structural modelling is concerned. I note that as regards the seismic input into the core, the GCORE modelling reported in Ref. 14 has only considered the seismic input based on the BE preliminary model. The acceptability of this approach is further discussed in Section 4.3.1.10.

103. Allowance for uncertainty of soil or rock properties is covered in Section 5.1.7 of Ref.8, which permits both deterministic and probabilistic methods. In lieu of a probabilistic analysis, an acceptable method to account for uncertainties in SSI analysis is to vary

the soil shear modulus based on the application of a coefficient of variation C_v. The minimum value of C_v is 0.5 based on adequate site investigation, however if insufficient data are available to address uncertainties in soil properties, C_v shall be taken as no less than 1.0.

104. NGL has adopted a deterministic approach based on BE properties and has considered the sensitivity to variations in rock properties on the basis that there is confidence in the site investigation data and that using the minimum C_v of 0.5 identified in Ref. 8 is appropriate. There is no additional justification given to support the use of this minimum value. As the rock properties have been based on the results of site investigations, and the response of the PCPV is relatively insensitive to the RSI properties (response being dominated by translation at the bearings), I accept the approach adopted.

105. Compared with the legacy analysis, the preliminary model assumes a significant increase in the rotational stiffness of the foundation slab. This change is largely due to the inclusion of the pre-stressing gallery in the foundation width calculation, even though this structure is isolated from the foundation using flexible joints. As was noted in the IPR (Ref. 20), the pre-stressing gallery is a separate structure from the foundation slab and PCPV and does not support the PCPV hence the use of the additional width for the effective foundation was questioned.

106. ABSC also questioned the inclusion of the pre-stressing gallery when calculating RSI properties (ABSC Query 7). NGL confirmed that this aspect has been restudied as part of the work for the final PCPV model and that softer rock rotational springs have now been analysed based on the width of the foundation disk alone. NGL considers that this change is not critical, as dominant modes are translational and not rocking. The translational RSI properties have not been modified in the final model as NGL considers that the whole supporting medium is mobilised. ABSC did not agree with the NGL approach to deriving the translational RSI springs, but recognising that the translational response of the PCPV is dominated by the properties of the bearings, the disagreement is considered not to significantly affect the model output.

107. The spring and damper values have been calculated as frequency-dependent impedance functions using established solutions described in Ref. 11. This approach assumes an elastic response for a rigid foundation at the ground surface, with correction factors applied to account for depth of embedment. The ground is assumed to be an elastic half-space and corrections have been made to account for the soil layering by the application of influence factors.

108. The RSI properties were derived by converting the circular foundation into an equivalent rectangle. The use of an equivalent rectangular base was queried (ABSC Query 18), on the basis that ASCE 7-16 (Ref. 41) provides explicit equations for circular bases. ABSC considered that the calculation might not provide rock damping properties within the 5% tolerance expected by Ref. 8. ABSC did not accept NGL's view that bearing stiffness dominated the rocking response, as the vertical stiffness of the bearings and rock are considered similar, and the rock stiffness will further reduce in the final model when the width of the pre-stressing gallery is omitted from the calculation (see ABSC Query 7). In response to ABSC Queries 5, 6 and 7, NGL carried out a sensitivity analysis, which halved the rock damping coefficients in conjunction with other modelling changes. I have assessed the sensitivity results in Section 4.3.1.6 and considered that the effect on the core was small.

109. According to the shear wave velocities listed in Table 3 of Appendix B to Ref. 17, the site class of HPB is Class B therefore requiring a check on the reduction of soil shear modulus in accordance with Ref. 11. It was identified in Query ABSC 19 that no such reduction has been carried out. NGL responded that the rock is expected to be subject

to low levels of degradation and that the reduction factors for a Class B material would be in the range of 5 to 10%. It is noted in Appendix B of Ref. 17 that for the expected rock strain the maximum degradation level would range from 0% to 7%. NGL considers the degradation insignificant compared to the variation applied for the LB and UB analyses. I accept NGL's judgement, based on the PCPV response being dominated by the lateral bearing stiffness, which is significantly greater than the lateral rock stiffness.

110. I consider that the RSI properties have been derived based on established methods that give a reasonable approximation of rock response. I have identified a number of areas where potentially un-conservative assumptions have been made, but I am satisfied that due to the isolating effect of the bearings that the response of the PCPV is relatively insensitive to the RSI properties. To address uncertainty, NGL has studied the effect of varying the RSI properties using LB and UB values. Based on the evidence seen I consider the RSI properties to be adequate.

4.3.1.4 Structural material properties

111. The concrete elements of the PCPV have been modelled using only BE properties as required in Section 3.3.2 of Ref. 8. I note that the approach in Section 3.3.2 is justified on the basis that for the generation of input motion to subsystems, uncertainties in the stiffness properties of the concrete elements are accounted for by the broadening of the Secondary Response Spectra (SRS), or the equivalent modification in the time domain. As these adjustments have not been adopted in deriving the input motion for GCORE, the sensitivity to changes in concrete stiffness has not been considered in Ref.17. The acceptability of the overall approach taken by the licensee to modelling uncertainty is discussed in Section 4.3.1.10.

112. In the legacy analysis (Ref. 29), Section 5.3 gives the value assumed for concrete elastic modulus as 42 GPa, which was said to include for ageing and dynamic enhancement. The same properties have been used in the new analysis. The value of elastic modulus was challenged by the IPR (Ref. 20) as being potentially too high.

113. I agree with the IPR challenge regarding the elastic modulus however I consider that the PCPV is very stiff in relation to the stiffness of the bearings on which it is supported and that the response of the PCPV is relatively unaffected by varying this parameter. My judgement is supported by the sensitivity analysis undertaken on the legacy buildings model by NGL (Ref. 31), which examined a LB elastic modulus of 26.7 GPa and found the dynamic response of the buildings to be insensitive to the variation in this parameter. In terms of the effect on accelerations at the base of the PCPV, the use of a relatively high concrete stiffness is conservative.

114. I therefore consider that the concrete properties used in the model are adequate, whilst noting my reservations regarding the absence of a sensitivity study into these properties.

4.3.1.5 Backfill properties

115. The backfill material around the base of the PCPV was not included in the legacy model, which in conjunction with the assumed restraint at the charge face led to conservative core boundary accelerations. The current model has included the effect of soil backfill below the level of the underside of the cable and pipe tunnels (see Figure 2), the effect of which is to provide additional damping to the model, resulting in a lesser lateral displacement at the charge face compared with omitting this material. The assumed properties for the backfill are important because they have a significant effect on model behaviour. A fill material stiffer than BE tends to increase the core boundary accelerations and a material less stiff than BE will increase PCPV

displacement, which may lead to interaction with other structures and challenge the assumption that the PCPV behaves as an isolated structure.

116. The PCPV analysis (Ref. 17) acknowledges that there is little information available with which to characterise the backfill material. Based on the original construction specification, construction photographs from HPB, engineering judgement as to the construction methodology and the limited information on drawings, NGL has determined that re-compacted site won material was used for backfill. Although it is not clear from Ref. 17, NGL has confirmed (via ONR Query 5) that the LB, BE and UB properties assumed for the fill are relevant to both HPB and HNB sites. For instance, the LB values were derived from the soil properties at HPB, which mainly comprise mudstones and which are considered more susceptible to degradation than those soils likely to have been used at HNB. NGL has made a commitment (see response to ABSC Query 8) to provide further justification that the LB and UB backfill properties also bound the HNB site in the final model report.

117. Based on a review by an ONR specialist inspector with geological experience (Ref. 45), I judge that the LB, BE and UB backfill stiffness properties are adequate based on the assumption that compacted site-won material was used. For the UB case, stiffer soil properties could be envisaged using a higher quality well compacted imported fill, but given the quantity of site-won material available, and the absence of differing fill zones shown on the drawings, I consider its use unlikely. As Ref, 17 bases its assessment on HPB and it is conceivable that a higher quality fill was used at HNB, I have included within Recommendation 5 a requirement that NGL provides further evidence to support its judgement that the backfill properties for HNB are bounded by those at HPB.

118. I challenged the assumption (ONR Query 14) that the UB backfill properties were based on well-compacted fill rather than on mass concrete. In its response, NGL referred to the original drawings, which show joint and blinding details that would be unnecessary if mass concrete fill had been used (see Figure 3). I agree that the availability of suitable fill material, combined with the relative cost and difficulty of using mass concrete, mean that the use of concrete was unlikely. Taking into account the additional evidence provided by the construction photographs, I agree with NGL's judgement that the backfill material is likely to be compacted site-won soil.

119. Drawings HIN/R/3004 and 3008 included in Ref. 17 show there are substantial concrete pads used beneath four double column locations. At these locations, there is limited horizontal width of compacted backfill between the side of the PCPV and the column bases founded on rock, with local pinch points near the corners of the bases. In its response to ABSC Query 9, NGL did not agree that these pinch points would restrain the PCPV by more than the UB backfill properties, as well compacted soil may be more difficult to achieve in narrow gaps. I agree with ABSC's judgement, based on the relatively small estimated displacement of 3 mm, that the UB case is sufficient to bound any potential increase in stiffness arising from this detail.

120. Due to the limited surcharge acting on the backfill there is a possibility that a gap between the soil and the side wall of the PCPV will open up during a seismic event. This "gapping" effect would tend to reduce the damping effect of the backfill and increase the displacement at the charge face. In Ref. 17, the potential for gapping is acknowledged and has been modelled by restricting the soil spring force to a maximum of the adjacent soil pressure. NGL has commented that this non-linear spring method was not included in the modelling design basis (Ref. 32) and was challenged in the IPR (Ref. 20). ABSC considered in Query 10 that this approach to gapping was not in accordance with RGP, and that the backfill may be acting as an unrepresentative damper that may be having a significant but unrealistic effect in reducing the motion of the PCPV. NGL has confirmed that further work has been done

for the final modelling report to modify its approach and bring it in line with the methodology described in Section 5.1.9 of Ref. 8. NGL has stated that its final modelling report is substantially complete at the time of writing this report.

121. The methods used to calculate the damping properties of the backfill included a number of assumptions and approximations (see ABSC Query 20). To account for uncertainty, I agree with ABSC that some consideration of the sensitivity of the results to stiffness and damping values would be expected. Although the backfill stiffness has been varied, the damping values (as a percentage of critical damping) have not been varied and the response of the PCPV to changes in damping has not been investigated. NGL confirmed that it has now modelled a Lower-Lower Bound (LLB) backfill with the intent of demonstrating that softer backfill will not invalidate the modelling assumptions. As evidence for this view, NGL has issued (Ref. 24) to ONR the preliminary results of a sensitivity study (see Figure 8) that considers the effects on core distortion of using a LLB backfill applied to the final PCPV model. It can be seen that the LLB soil model gives similar results to that for BE soil properties and the UB soil model remains the most onerous case for core distortion, with the lowest margins. These results are reviewed in more detail in Section 4.3.1.11.

122. The modelling change to remove the non-linear spring and replace it with a LLB soil will be justified in the future final PCPV model report. In order to gain confidence that the modelling changes do not lead to more onerous effects on the core, I was provided with sensitivity results undertaken for the final model (Ref. 24). Having reviewed this further material, I judge that the backfill properties adopted in the preliminary model are adequately conservative.

4.3.1.6 Bearing functional requirements and properties

123. The PCPV is supported on 274 neoprene bearings, which transfer the vessel loads into the structurally separate foundation disk. The properties of the bearings are such that they are significantly stiffer in the vertical direction than they are in the horizontal direction. The safety function of the bearings is not defined in the present safety case and there is no assessment carried out as to the adequacy of the bearings when subjected to the imposed loads and displacements. I consider that SAP ECE.1 requires that the safety function and structural performance requirements for the bearings should be defined. SAP ECE.12 requires confirmation that the bearings can fulfil their safety functional requirements over the full range of loading for the lifetime of the facility. In response to Query ONR 21, NGL provided values for maximum shear strain in the bearings and made a commitment to incorporate a more detailed design substantiation into the final modelling report. I consider that this omission will require addressing (see my Recommendation 4), but given the relatively low reported strains, I am reasonably confident that the bearings can be adequately substantiated.

124. Reference to NGL's Bearing Pad Review (Ref. 33) confirms that the intent of the bearings was to allow movement of the vessel and to ensure that the pre-stress loads went into the bottom slab of the vessel and not the foundation. An additional function of the bearings, which is to isolate the PCPV from the ground motions applied through the rock into the foundation slab, was not considered in the original design but was an important factor in the legacy PSR1 model and in the present modelling.

125. In the current model, the top of the foundation slab is connected to the PCPV beam elements via six spring-damper pairs representing the bearing group. The properties of the springs were assumed linear, which I consider an acceptable approximation.

126. In my assessment of the bearing properties, I have taken into account SAP AV.3, which requires that the data used in the analysis should be shown to be valid by reference to established physical data or experiment. The stiffness of the bearings has been determined based on the originally specified hardness value and limited

hardness tests undertaken in 1995 and 2017. NGL has used the BE stiffness value adopted in the legacy model as a LB value in the current analysis on the basis that the legacy model did not account for loading rate or strain dependency. Further substantiation was requested via ABSC Query 5 in relation to this assumption. In response, NGL provided a copy of an expert report (Ref. 37) that reviewed the assumed bearing properties. The recommended properties in this report are based on a range of test data. As the LB and UB stiffness values adopted by NGL bound the values suggested by Ref. 37, I was content with the approach taken by NGL.

127. The damping value for the bearings (as a percentage of critical damping) was taken as 10% in the legacy model. This was considered too high by NGL, and as a lower damping level was likely to lead to a higher core input motion, the damping level was reduced to 5% for all the modelling in Ref. 17. The assumptions on damping were reviewed in Ref. 37, which suggested damping values of 2.5% (LB), 3% (BE) and 7.5% (UB). NGL has decided to adopt a single value of 3% damping for the final PCPV model, justified on the basis that the overall damping is dominated by the backfill and the effect of further variation in the bearing damping is small. I was provided (Ref. 24) with Figure 6, that illustrates the changes in SRS between the preliminary and final PCPV models, the final model incorporating the change in bearing damping to 3%, amongst other refinements. The results illustrate that in moving from the preliminary to final PCPV model, the peak spectral acceleration at the base of the PCPV increases. This suggests that the use of 5% damping in the preliminary model is non-conservative with respect to core input motion compared with the 3% BE value proposed for future models. The impact of this effect on core margins is discussed in Section 4.3.1.11.

128. Regarding the vertical damping properties of the bearings, Section 6.3.3.3 of Ref. 37 states that the damping factor is unpredictable and can only be determined from tests. The report also states that for higher shape factors than the PCPV bearings, the vertical damping factor is usually smaller than the horizontal one. Given the uncertainty over the vertical properties of the bearings, ABSC considered that further substantiation was required to bound the effects of variation in the rocking stiffness and damping on the SRS (ABSC Query 6). In response (Ref. 24) NGL reported that it had examined the sensitivity of the modelling by re-running the UB final PCPV model with the following changes: (i) vertical bearing damping reduced to 0.5%; (ii) vertical bearing stiffness doubled; and (iii) rock damping halved. NGL concluded that the peak vertical SRS is increased in amplitude but shifted to a higher frequency above that where significant core response is obtained. The change in horizontal SRS is small and the plots for core distortion margin suggest that varying the vertical stiffness and damping has a negligible effect on core margins. I am therefore content that the assumptions made for vertical damping properties are adequate.

129. The bearings are not routinely inspected as part of the Maintenance Schedule requirements. This absence of inspection does not comply with SAP ECE.3, which requires that the existence of defects that could compromise safety functions should be established. The absence of inspections is also not in accordance with SAP ECE.20, which requires that provision is made for inspection to demonstrate that the structure continues to meet its safety functional requirements. NGL's Bearing Pad Review (Ref. 33) outlines the difficulties with inspecting the bearings, and I agree that the narrow bearing gap and difficult to access location beneath the base of the PCPV make meaningful inspection very difficult.

130. NGL has placed reliance that the bearings have no significant defect on the results of tests in 1995 on a sample from one bearing (Ref. 28) and a similar test carried out from a sample presumed to be from a different bearing carried out in 2017 (Ref. 27). I have reviewed the test results and agree that they indicate that the bearing hardness has been essentially unaffected by ageing degradation and therefore the tests have provided evidence in support of compliance with SAP EAD.2. This testing has been

based on a very limited sample size (1 bearing out of 274) however I agree that it indicates that the main degradation mechanism likely to affect the bearings (ultraviolet or ozone related ageing) does not appear to have had a significant effect on hardness.

131. Given the lack of visual inspection evidence for the bearings or quality records of their original installation, I asked NGL (Query ONR 12) to confirm the reasons why the chosen BE and UB bearing properties were appropriately conservative. I considered that construction debris, such as over-spilled concrete could be present in the gaps between the bearings that might affect the stiffness assumed in the analysis. In its response, NGL justified why it considered the presence of concrete debris unlikely, and demonstrated that even if it were present it would provide minimal resistance to the seismic loads imposed on the vessel. I accept NGL's argument that even in the unlikely event that concrete had inadvertently seeped between the bearings during construction, its effects on the analysis would be small.

132. In summary, I consider that the properties assumed for the bearings are in general adequately conservative. I note that the degree of damping used is un-conservative with respect to core seismic input and the impact of this is addressed as part of my overall review of the analysis in Section 4.3.1.11. Although I accept that the structural demand on the bearings during a seismic event is likely to be within the structural capacity of the bearings, this has not been demonstrated within the current safety case. I have raised Recommendation 4 in order to track NGL's progress in resolving this shortfall.

4.3.1.7 Restraint to PCPVs by other SSCs

133. In the legacy model, the PCPV was assumed to be rigidly restrained in the horizontal direction by precast concrete beams that span between the PCPV and the Central Block. At each end of the precast beams, drawings indicate a 12.5 mm wide joint containing a proprietary compressible joint filling material. Assuming the joint filler has negligible stiffness and the joints have been constructed in accordance with the drawings there is theoretically up to 25 mm available to accommodate movement of the PCPV and Central Block before any significant lateral restraint force would be generated. A number of factors will influence the actual available movement range before significant lateral restraint occurs, such as construction tolerances and thermal movements that have occurred since the joint gaps were set. In addition, any movement of the Central Block during a seismic event may not necessarily be in phase with the PCPV movement, thus reducing the available joint gap.

134. I raised a number of queries with NGL in order to obtain more evidence to support the claim that the PCPV behaves as an isolated structure, with no significant lateral restraint above the backfill level. I was satisfied with the evidence presented in response to my Query ONR 18 that supports the judgement that the concrete beams were precast, with flexible joints of at least the expected width at both ends. I also noted NGL's statements that a site walk-down at HNB, attended by its independent peer reviewers, had confirmed the presence of flexible joints at the beam ends. I accept that NGL has checked that the expected construction detail is present, but I would have expected that, given their importance to the safety case, the inspections would have been formalised into a report. As part of its response to Query ONR 6, NGL has made a commitment to strengthen the reporting of its walk-downs in the final PVPV modelling report and I am content with that approach.

135. I queried the level of restraint provided by the joint filler and accept NGL's response to my Query ONR 18 that the restraint is small and does not alter the response of the PCPV. In terms of allowance for joint gap variation, NGL has estimated a thermal movement of 3 mm and a maximum Central Block displacement of approximately 3

mm (see ABSC Query 12). I conclude that there is approximately 19 mm of movement available for the PCPV in a seismic event before rigid lateral restraint is encountered.

136. The Charge Machine is supported by the CMG, which is in turn supported on fixed steel girders known as the Long Travel Girders (LTG). The LTG are supported on concrete corbels attached to the PCPV and the Central Block, thus some of the loads from the gantry are transferred into the PCPV. In the legacy buildings model, allowance was made for vertical load transfer between the LTG and PCPV, but the LTG provided no effective lateral restraint to the PCPV. The model assumed that the PCPV was laterally restrained at the Charge Face level by the concrete beams spanning between the PCPV and the Central Block. In the preliminary PCPV model, no lateral restraint by the LTG has been assumed, but the effect has been examined during sensitivity studies using a non-linear friction-limited restraint. Although further sensitivity studies were ongoing at the time of writing, the results of NGL's preliminary analysis are that the LTG do not provide any significant restraint to the PCPV.

137. NGL acknowledges that further work will be done to underwrite the assumption that any restraint provided to the PCPV by the LTG has an insignificant effect on core seismic input. This further work will be presented as part of the final PCPV modelling report.

138. In terms of the current case, I am satisfied based on the results of the sensitivity studies undertaken that the conservatively assessed restraining effect of the LTG on the PCPV will have only a small effect on the core seismic input.

139. The LTG do provide a lateral load path in a seismic event that will tend to increase the axial load in the LTG. NGL has confirmed that it will investigate whether the axial force in the LTG remains within the limits defined in the current safety case for the CMG (Ref. 42). NGL has raised a Condition Report (Ref. 38) to identify that the effects of the changes to the PCPV modelling on other SSCs (including the LTG) and safety cases require further investigation. This work is needed to demonstrate, in accordance with SAP ECE.12, that the SSCs can fulfil their safety functional requirements over the full range of loading. In response to Query ABSC 17, NGL has noted that in general the legacy model resulted in more onerous load effects on the other affected SSCs than result from the preliminary PCPV model. I am satisfied that this matter is being followed up by NGL but will track progress as recorded in my Recommendation 6 to confirm that the work has been completed in a timely manner.

4.3.1.8 Validation and verification

140. My assessment of the preliminary PCPV modelling has taken account of SAP ECE.15, which requires that where analyses have been carried out, the methods used should be adequately validated and the data verified.

141. The modelling has used proprietary software, ABAQUS. In order to validate the results, NGL has carried out simple hand calculations for comparison with selected analysis results. In addition, the analysis results have been compared with key results from the legacy building model. Comparison of modal frequencies and peak displacements from the PCPV model against hand calculations show good agreement. Differences between analysis results for the PCPV and legacy models are explained by reference to the changes made in the current model, particularly the removal of the lateral restraint provided by the floor beams at the charge face level.

142. The derivation of backfill spring properties and the use of superposition were challenged during the IPR (Ref. 20), To confirm the validity of the assumptions made, NGL has undertaken further analysis using the alternative software FLAC 3D (see response to ABSC Query 18). I consider the use of diverse software in the validation process to be compliant with RGP. Based on the preliminary results shared with ONR

(Ref. 24), the FLAC analysis tends to confirm the validity of the superposition assumption in the preliminary model.

143. I am satisfied that the analysis method has been verified by using alternative diverse methods which have provided good agreement with the chosen method and am therefore satisfied that the analysis method has been validated.

144. With respect to the verification of the data used in the analysis, I found that this was not described in any detail in Ref. 17. In accordance with SAP AV.4, computer models and datasets should be developed, maintained and applied in accordance with quality management procedures. I therefore requested and sampled the verification plan for the PCPV model (Ref. 43). I found this to identify the various tasks together with their verifiers, the models created, detailed verification check sheets and evidence of competency checks for authors and verifiers, which I sampled. I also sampled detailed check comments and responses for modelling of the PCPV and for bearing property calculations. I was satisfied that the data used in the analysis had been appropriately verified by the originators of the PCPV model, and based on the areas sampled, broadly met the requirements of Ref. 8, Section 1.2.1.

145. In addition to the validation and verification activities, an independent peer review was carried out for the seismic analysis (Ref. 20). I considered that the review was carried out by appropriately qualified and experienced external specialists and satisfied the requirements of Ref. 8, Section 1.2.3.

146. In summary, I am satisfied that adequate analysis validation and verification has been undertaken. For its final PCPV modelling report, NGL has agreed to enhance the description of the activities undertaken (see Recommendation 5),

4.3.1.9 Sensitivity studies and modelling enhancements

147. As part of its work to substantiate the planned long-term seismic safety case for HPB and HNB (NP/SC 7766, referred to as Stage Submission 2 or SS2), NGL is undertaking a number of refinements to the modelling reported in Ref. 17. The refinements will be reported in a final PCPV modelling report, which is currently in preparation. The refinements are summarised below:

- An improvement to the modelling and geotechnical justification of the backfill springs in order to address challenges to the use of bi-linear springs
- Use of LLB backfill spring stiffness by following ASCE 4-16 methodology for the modelling of gapping
- Revisions to the rock rotational springs to address challenges relating to the inclusion of the additional base width due to the pre-stressing gallery
- Following a review, the original LB, BE and UB bearing stiffness properties have been retained but the damping has been lowered from 5% to 3%.
- A more extensive check on the effects of modelling friction at the connections between the PCPV and the LTG and charge face floor beams
- A new analysis using FLAC software, to provide additional validation and verification for the backfill spring stiffness

148. NGL states that the purpose of the further work is to improve the robustness and substantiation of Ref. 17 and considers that the modifications have not fundamentally changed the seismic response. I consider the approach taken to further sensitivity studies meets the requirements of SAP ECE.14.

149. At a Level 4 meeting (Ref. 26) with the licensee I sought additional evidence to demonstrate that the modelling refinements taken as a whole do not have a significant adverse effect on the core. Following the meeting, NGL presented additional evidence

(Ref. 24) which I have assessed in conjunction with ABSC. My assessment conclusions for this material are contained in Section 4.3.1.11.

4.3.1.10 Conservatisms and areas of uncertainty

150. In accordance with SAP SC.5, safety cases should identify areas of optimism and uncertainty, together with their significance, in addition to strengths and any claimed conservatisms.

151. I consider that the modelling needed to address the following principal areas of uncertainty:

- It is not considered reasonably practicable to inspect or test the backfill material to confirm its composition and engineering properties.
- Only a very limited surface area of the bearings can be inspected in order to confirm they were installed correctly and have not been subject to degradation.
- The engineering properties of the bearings cannot be fully established without extracting and testing a complete bearing, which is considered not reasonably practicable,
- The degree of restraint provided to the movement of the PCPV by existing structures.

152. Consideration of defence in depth (SAP EKP.3) requires a conservative design and operation in accordance with appropriate safety margins, engineering practices and quality levels. In addition, SAP ECE.13 requires conservative assumptions to be made in analysis.

153. In assessing conservatism, I have had regard to the definition in the SAPs which states: “In analysis, an approach where the use of models, data and assumptions would be expected to lead to a result that bounds the best estimate (where known) on the safe side. The degree of conservatism should be proportionate to both the level of uncertainty and the overall significance of the estimate to the safety case.”

154. In order to consider the effects of varying modelling assumptions and to demonstrate that small changes in assumptions did not have disproportionate effects on model output, NGL undertook a number of sensitivity studies, based on deriving LB and UB properties for the rock, backfill and bearings. I am content that in general the values adopted for the variables considered are suitably conservative. However, I consider that the following value may be un-conservative with respect to its effects on the core:

- The bearing damping value of 5% of critical damping (adopted for all analyses) is higher than the LB and BE values recommended by an expert review.

155. In terms of considering the combination of LB, BE and UB properties into the model, NGL has considered three basic combinations in which all the variables are set at their LB, BE and UB values. Whilst NGL has considered this a conservative approach, this is not necessarily the case as the variables are independent of each other. I consider that further sensitivity analyses are required to confirm that other combinations of variables do not lead to more onerous effects on the core. The approach taken was challenged in ABSC Query 25, in particular the lack of consideration given to a credible case consisting of UB bearing stiffness and damping, combined with LLB backfill stiffness. Further evidence was obtained from NGL as a result of this query (Ref. 24), which is assessed in Section 4.3.1.11.

156. The approach taken in the subsequent GCORE analysis (Ref. 14) is based on seismic input motions from the BE preliminary PCPV model only. I considered that additional evidence was required to confirm that the most onerous seismic effects on the core have been captured by an analysis based on appropriately conservative assumptions.

This further evidence, extracted from preliminary work on the final PCPV model, is presented in Ref. 24. The information presented comprises a series of plots of core distortion margin for the LLB, LB, BE and UB cases and indicates that the UB properties case for the rock, backfill and bearings has a more onerous effect on the core than the BE case. The implications of using only the BE case for the core analysis are discussed in Section 4.3.1.11.

157. Chapter 6 of Ref. 8 provides requirements for the generation of seismic input for all subsystems that are analysed decoupled from the main building dynamic model. I consider this chapter relevant to the modelling undertaken, as the GCORE model is a subsystem to the PCPV model, which has been used to generate time histories for input into GCORE. In order to address overall uncertainty in the SSI, Section 6.2.3 of Ref. 8 requires that SRS are broadened to ensure they envelope all possible permutations in the analysis, or the equivalent to broadening is undertaken in the time domain by adjusting the time step (Section 6.3.2 of Ref. 8). NGL confirmed (Ref. 26) that the motion taken forward into the subsequent GCORE analysis is always the output time history corresponding to the analysis being run. There is no process undertaken by NGL in which the output SRS are broadened or the time step adjusted as required by Ref. 8. The absence of these adjustments was highlighted in ABSC’s report (Ref. 12) as an interface issue with the graphite assessment and their implications are further discussed below.

158. The licensee disagrees (Ref. 46) that the adjustments to the seismic input motion for subsystems, as described in Section 6 of Ref. 8, are appropriate to the non-linear modelling used in GCORE. I consider that the applicability of some aspects of Ref. 8 to the GCORE analysis is unclear and that the licensee has proposed an alternative approach to allow for uncertainty. I recognise that the licensee has undertaken some sensitivity studies to consider the effects of variation in modelling properties, and more studies are being undertaken in support of the final modelling report. The approach taken in Ref. 17 is potentially un-conservative with respect to the subsequent GCORE analysis, because it does not account for the possibility that credible combinations of modelling variables that have not been analysed may shift the response frequency of the PCPV to align with a peak response from the core.

159. I consider this topic to be a key interface area with the graphite assessment (Ref. 44). In order to gain confidence regarding the effects of variation in SSI parameters, I requested the output from further model runs beyond those reported in Ref. 17 and these are described in Sections 4.3.1.6, 4.3.1.9 and 4.3.1.11. In addition, Technical Query G35 (Ref. 47) was raised so that the licensee could confirm the frequency of spectral peaks for the UB sensitivity case so that this could be compared with the natural frequency of the core. In its response, and with reference to Figure 6, NGL confirmed that the first peak of the spectral response occurs for the UB case at a frequency of 2.5 Hz for the preliminary model and 2.4 Hz for the final model, which is very close to the core natural frequency (2.44 Hz). Noting that the UB case is currently the most onerous for seismic input to the core, I therefore consider that the effect on PCPV base accelerations of further modelling variants is likely to be small.

160. I have raised Recommendation 2 so that ONR graphite structural integrity inspectors can take into account when assessing core distortion margins the non-conservatisms identified in the seismic input to the GCORE model resulting from the use of the BE PCPV model. Although I am content that the sensitivity studies have identified the most onerous case for core distortion, future safety cases based on other core analysis models may result in changes to the predicted natural frequency of the core. I have therefore raised Recommendation 3 to highlight that further sensitivity studies may be required when changes in core frequency are predicted.

161. I have used SAP ECE.2 to assess whether multiple, independent and diverse arguments provide a robust, multi-layered justification, in which weaknesses in individual layers of the argument are offset by strengths in others. I consider that the strengths of the basic modelling methodology using nuclear specific codes combined with sensitivity studies to address known areas of uncertainty has provided an acceptable overall balance between conservatism and uncertainty so far as the PCPV model is concerned. As some of the information presented in support of this judgement has been of a preliminary nature, my Recommendation 5 captures my requirement for this information to be formalised in the final modelling report, which is currently in preparation.

4.3.1.11 Analysis results/conclusions

162. NGL has concluded that modelling the PCPV as an isolated structure significantly reduces the accelerations at the internal floor of the PCPV cavity, resulting in a large reduction in core boundary accelerations compared with the legacy analysis on which the extant safety case is based.

163. I consider it is apparent from Figure 4 that for the BE case, using the synthetic PML seismic input motion, that the spectral acceleration at the core boundary for the preliminary model is less than that for the legacy model at all frequencies above about 1.5 Hz. At lower frequencies, the two models gave similar core boundary accelerations.

164. Figure 4 also shows results for LB and UB sensitivity cases (i.e. in which RSI, bearing and backfill properties are all set to their individual LB or UB values simultaneously). These plots show that the core boundary accelerations are greater in the 2 to 5 Hz region for the UB case compared with the BE case, but remain lower than for the legacy model. For the LB case, the spectral acceleration exceeds that for the legacy model below 1.5 Hz. As part of its response to ABSC Query 2 (Ref. 24), NGL provided further evidence in the form of core distortion scores (an example of which is given in Figure 7) that confirmed that the UB sensitivity case was the most onerous for core distortion. Based on the evidence presented, I am satisfied that the core response is not critical at frequencies below 1.5 Hz.

165. Ref. 17 identifies that the natural frequency of the columns of graphite bricks is approximately 2.5 Hz. Given that the peak in spectral acceleration for the UB case occurs in the 2.5 to 3 Hz region, I consider that the sensitivity to UB properties is important for core response. Despite this sensitivity, the maximum PCPV base acceleration for the UB case is 5.5 m/s^2 at around 2.8 Hz, compared to a core boundary acceleration of 10.5 m/s^2 at a similar frequency in the legacy model. Whilst noting that the seismic input has been reported at slightly different locations, I consider that these results demonstrate a significant reduction (approximately 50%) in horizontal seismic response of the PCPV compared to the legacy model in the frequency range important for the response of the core.

166. NGL claims that the core boundary accelerations calculated from the modified PML input motions are consistent with the synthetic PML input motion. For the modified PML input motion the response spectra at the core boundary for the BE case in all three directions are shown in Figure 5. The horizontal response spectra are generally similar, with accelerations of up to 4 m/s^2 at approximately 2 Hz for the first peak and 3 m/s^2 at around 8 Hz for the second peak. In the vertical direction, all the input motions give a similar magnitude response of approximately 5 m/s^2 in the 7 to 10 Hz frequency range. I noted that the peak horizontal spectral acceleration in the important 2 to 3 Hz frequency range is similar between the BE synthetic PML input motion and the modified PML input motion. Some of the spectral accelerations for the modified PML exceed those for the synthetic PML at frequencies below about 2 Hz. I consider that

the results show that as regards accelerations of significance to core response, the legacy synthetic PML input motion is conservatively bounding and the licensee's claim has therefore been substantiated.

167. NGL claims that modelling the PCPV as an isolated structure is appropriate, as the maximum PCPV charge face displacements, relative to ground, are significantly smaller than the total gap between the ends of the charge face floor beams and the PCPV or Central Block.

168. Based on the LB, BE and UB analyses using the legacy PML input motion, the maximum absolute displacement, in the principal horizontal directions relative to the ground at the charge face level is 13 mm as shown in Table 9 of Ref. 17. It can be seen that for the modified PML input motion one of the cases considered (No. 7, Chuetsu) gave a maximum displacement of 10.5 mm based on BE properties, which suggests that had a LB case been analysed for this input motion, the displacement may have exceeded 13 mm. Nonetheless, I consider that there is an adequate margin between the maximum reported displacement of 13 mm, and the minimum available clearance at the charge face level (approximately 19 mm, as discussed in Section 4.3.1.7). I judge that the displacement of the PCPV at the charge face will not lead to significant restraint from the floor beams and this confirms the validity of modelling the PCPV as an isolated structure.

169. NGL concludes that the backfill embedment at the base of the PCPV reduces the PCPV displacements and accelerations. In order to test the sensitivity to reduced backfill stiffness, NGL has modelled a LB case, which includes a combination of LB RSI, backfill and bearing properties. The results of the analysis (Figure 6) show a significant reduction in PCPV base acceleration compared with the UB case, with the spectral peak in the UB case also being much closer to the maximum core response frequency. Examination of Table 9 of Ref. 17 demonstrates that it is the LB model that results in the greatest charge face displacements. I therefore agree with NGL that the addition of the backfill reduces both core damaging accelerations and PCPV displacement at the charge face.

170. The results presented in Ref. 17 do not include a comparison of vertical SRS. This was raised as Query ABSC 14, to which NGL responded that the vertical input motion was not critical to graphite core damage. I note NGL's response and whilst I do not have an immediate concern regarding this omission, I agree with ABSC that such information should be presented in the final modelling report and this requirement is included in my Recommendation 5.

171. In summary, I make the following conclusions from the results presented in Ref. 17::

- The legacy PML synthetic input motion is conservative with respect to core boundary accelerations of significance to the graphite core when compared with the updated PML input motion.
- The core input motion has reduced significantly compared with that derived from the legacy model, in the frequency range of importance to core response.
- The maximum displacement at the charge face level is consistent with the assumption that the PCPV behaves as an isolated structure.
- Of those cases analysed in Ref. 17, the most onerous case for PCPV base acceleration is the UB sensitivity case, which combined UB properties for the rock, backfill and bearings.

172. I considered it difficult to extract the analysis results of most significance to the core from the information presented in Ref. 17. This was raised as Query ABSC 2. Although SRS are presented for various LB, BE and UB combinations of properties the frequencies of significance to the core are not clearly presented and no information is given that identifies the margins for core distortion for the various cases analysed.

Further details supplied in response to this query (Ref. 24) have elicited information in the form of SRS comparisons for the preliminary and final models (e.g. Figure 6) and preliminary GCORE runs based on the final PCPV model output. These runs include graphs showing margins in relation to interstitial channel distortion (for examples see Figures 7 and 8). As it is not stated on the information provided, NGL has clarified (Ref. 34) that the core state assumed in these analyses was 931 SCB (in layers 3 to 8) and 400 DCB (in layers 4 to 6). It is understood that other core states have been analysed (including the inclusion of MCBs) and these gave similar results, but I consider this a matter for ONR's graphite assessment and outside the scope of this report.

173. The horizontal SRS presented in Figure 6 can be used to assess whether the modelling changes made by NGL to the preliminary model (described in Section 4.3.1.9) in order to create a final model are likely to have a more onerous effect on the core. For the BE case, the low frequency peak increased by around 17%, with the second peak increasing by around 50%. For the UB case, stated by NGL to be governing in GCORE, the low frequency peak is not significantly changed, but the second peak is increased by around 40%. The second peak is associated with the rocking mode, which NGL considers is not critical for core distortion. Although it appears that the effects of the changes to the model may be more onerous for the core, this can only be confirmed by sampling GCORE analysis results, samples of which I obtained as a result of raising queries with the licensee as described below.

174. A key measure of the effect of a seismic event on the GCORE modelling is provided by plots of the "3BL" and "SRL" scores (see Glossary). These scores are a measure of interstitial channel distortion and are a method of assessing the minimum distance between a control rod and distorted channel (3BL) and between a sensor rod and distorted channel (SRL). The 3BL or SRL score is plotted against the percentage of channels where the score is below a particular threshold value. NGL considers that a 3BL or SRL score above unity provides an acceptable margin so that all control and sensor rods have unimpeded access throughout a seismic event. It can be seen from the graphs in response to ABSC Query 2 (Ref. 24), samples of which are presented as Figures 7 and 8, that:

- The BE scores for the preliminary and final model are very similar, indicating that the modelling changes made have had little effect on core distortion.
- The UB model properties lead to an increased core distortion, although the minimum 3BL and SRL scores recorded were in excess of two, which is deemed an acceptable margin by NGL as it indicates that no control, or sensor rods are potentially obstructed as a result of channel distortion.
- The LB model was either similar to or less onerous in its effect on core distortion than the BE model.

175. As discussed in Section 4.3.1.10, the extent of NGL's sensitivity study was questioned, (ABSC Query 25), in particular whether credible combinations of rock, backfill and bearing properties other than those analysed could have a more onerous effect on core distortion. In response to this query, NGL analysed a case using its final model and comprising UB bearing stiffness and damping combined with a LLB backfill, which included for the effect of gapping (Ref. 24). Figure 9 shows the SRS comparison between this additional sensitivity case and the other cases analysed and Figure 10 shows the 3BL scores for channel core distortion taken from a GCORE run using input from the sensitivity study. From Figure 9, I note that for the sensitivity case, the primary and secondary spectral peaks are more severe, albeit at slightly lower frequencies, than the UB case, and the zero period acceleration value is higher. This indicates that the sensitivity case could credibly have a more onerous effect on core distortion than the UB case. After considering the 3BL scores (Figure 10), I judge that this is not the case and the UB model remains the sensitivity case with the lowest margins.

176. In summary, I consider that the evidence submitted demonstrates that the enhancements made to convert the model from preliminary to final status have had only a small effect on PCPV base accelerations of importance to core response and an insignificant effect on core distortion margins. There may be other credible combinations of variables that require further consideration, but I am content that this is being addressed as part of the production of the final modelling report (see Recommendation 5) and that based on the evidence presented the UB case (rock, bearing and backfill all at UB) is the most onerous for core distortion.

177. I consider that from a civil engineering perspective, and subject to my recommendations, that Claim 1 has been adequately substantiated. My judgement was supported by a significant amount of additional evidence obtained from the licensee by means of technical queries.

4.4 Assessment of Claim 2

178. Claim 2 states that “All reasonably practicable measures have been taken in order to ensure that the risk associated with continued operation of HNB R4 is ALARP.

179. The licensee presents three arguments in support of Claim 2. I have carried out a high-level review of the arguments and their supporting evidence and have decided to sample Argument 2.2, which I consider the most relevant to the preliminary PCPV model. I am aware that other ONR inspectors will adequately cover the evidence presented in support of the other arguments.

180. Argument 2.2 states, “all reasonably practicable measures have been taken to reduce the risk associated with return to service of HNB R4.” This argument is supported by Evidence 2.2.1, which states: “There are no reasonably practicable measures to reduce the risk associated with core distortion preventing control rod insertion.” This evidence states that the ALARP position is on the basis that Claim 1 has demonstrated that the likelihood of core distortion impeding control rod insertion over the JPSO remains very low.

181. In assessing this argument, I have confined my consideration to whether the preliminary PCPV model is adequate to support return to service and whether there is anything further that could be done from a seismic modelling perspective to reduce risks ALARP.

182. With reference to the ONR ALARP TAG (Ref. 3), I have based my assessment on the following criteria:

- Extent of compliance with RGP
- Where a different approach to controlling risks is used, that the risks are no greater than that which would have been achieved through adoption of RGP
- The extent to which other measures to reduce risk have been considered and whether the other measures are reasonably practicable.

Considering each of these points in turn:

183. My assessment has found that the preliminary model was broadly complaint with RGP. Where the modelling has departed from RGP, this has in some cases been to adopt a more conservative approach (such as the use of the legacy synthetic PML spectra rather than the more modern approach of Ref. 8 with regard to seismic input). In other cases, the departure from RGP may have resulted in non-conservative results (such as the modelling of soil gapping).

184. Where a different approach has been adopted, I obtained further justification from the licensee that the methods used had identified the most onerous PCPV modelling

configuration with respect to effects on the core and hence I consider that risks were ALARP for the alternative approach.

185. Other measures to reduce risk relate to more analysis being done using a range of different combinations of model properties. For example, Ref. 17 presents only 3 sensitivity cases based on rock, backfill and bearing properties, with all parameters being set at their LB, BE or UB properties simultaneously. I have noted that these properties are not dependent and hence other combinations are credible. To address all combinations of LB, BE and UB properties would require 27 separate analyses which I consider is reasonably practical for linear analysis of the PCPV model but significantly more onerous in terms of post-processing in the non-linear GCORE model. I sought further evidence in support of this assessment that certain credible additional model configurations did not lead to more onerous effects on the core and was satisfied that they did not. I consider that this further work to justify the identification of the chosen model configurations as bounding cases should be formally presented and I have included this requirement in my Recommendation 5.

186. I consider that from a civil engineering perspective, and subject to my recommendations, that Claim 2 has been adequately substantiated. My judgement was supported by a significant amount of additional evidence obtained from the licensee by means of technical queries

4.5 Comparison with Standards, Guidance and Relevant Good Practice

187. In carrying out my assessment, I have considered the guidance in SAP ECS.3. Although this is an existing plant not designed to modern standards, the guidance in the ALARP TAG (Ref.3, Section 6.2) is that for an existing facility relevant good practice is established by using the standards that would be applied to a new design as a benchmark and subjecting any shortfalls to an ALARP test.

188. In terms of the SSI analysis, I consider that ASCE 4-16 (Ref. 8) represents RGP, as referenced in TAG 13 (Ref. 3). Compliance with Ref. 8 has been considered throughout Sections 4.3 and 4.4 and is not discussed further here.

189. IAEA Safety Report Series No. 28 - Seismic Evaluation of Existing Nuclear Power Plants (Ref 9) provides general principles for undertaking seismic assessments and is therefore relevant to the PCPV seismic modelling. I consider that the work undertaken is broadly in accordance with the principles in Ref. 9. One aspect where there appears to be a shortfall is the rigour of the walk-down undertaken, which did not appear to be formally recorded. The standard emphasises the importance of using walk-downs to confirm the extent to which as-built conditions correspond to the design drawings. This shortfall is further discussed below.

190. Allowance for uncertainty is taken into account by parametric studies. For SRS, Ref. 9 does not require the variation of soil properties and of structural properties to be cumulated. For example, the parametric study of structural variability should be associated with the BE value of other variables. I consider that the licensee has undertaken an alternative approach based on Ref. 8 that is equally valid.

191. I consider that IAEA Safety Guide NS-G 2.13 “Evaluation of Seismic Safety for Existing nuclear Installations” (Ref. 10) contains guidance that is relevant to the revised seismic modelling and is complementary to the requirements of Ref. 9. I consider that the licensee’s assessment has broadly complied with this guidance.

192. Ref. 10 also emphasises the importance of walk-downs. No comprehensive survey is described in Ref. 17 that verifies that the assumptions made in the modelling are soundly based. In its response to ONR Query 6 (Ref. 21), the licensee confirmed that although no report was prepared, a walk-down was carried out at HNB. At a Level 4

meeting (Ref. 26), the licensee confirmed that no similar inspection appeared to have been carried out at HPB and accepted an action to undertaken one. My expectation is that a survey would be undertaken at both stations to verify assumptions relating to structural arrangement, dimensions, condition and joint widths. I consider that the absence of such information shows a shortfall when measured against RGP. This shortfall has been captured in my Recommendation 5.

193. I consider that an appropriate modern standard for the design of the PCPV bearing pads is British Standard BS EN 1337 (Ref. 39). Although no original calculations for the bearings have been found, NGL has not prepared any retrospective calculations that substantiate that the bearings can perform their required safety function. I raised this matter as ONR Query 21 and it was further discussed at a Level 4 meeting (Ref. 26). NGL accepted an action to include relevant substantiation in accordance with this code in its final modelling report and this commitment is captured in my Recommendation 6.

194. In summary, I have considered the licensee's compliance with the requirements of SAP ECE.3. With the exception of the requirements for carrying out and reporting of walk-downs and the substantiation of the PCPV bearings, I was satisfied that the licensee had met the requirements of the SAP. I was satisfied that on both these matters NGL had agreed to address these shortfalls by incorporating improvements into its final modelling report.

4.6 ONR Assessment Rating

195. In accordance with ONR's guidance (Ref. 4), the safety case has been rated based on the original submission without taking into account regulatory interventions undertaken by ONR.

196. I considered that the technical quality and detail in the safety case were generally adequate when judged in terms of being valid, robust, integrated, balanced, and forward looking. The safety case was based on complex methods of assessment and I considered it to have identified the most significant risks arising from the seismic hazard.

197. Regarding completeness and evidential basis, I considered that the sensitivity studies had not been completed and that not all the challenges raised during independent peer review had been addressed. I also found that the effects of the modelling changes on other safety cases had not been addressed.

198. In terms of intelligibility, I raised a significant number of regulatory queries (identified in Tables 2 and 3) in order to clarify the licensee's approach. I considered that the number of queries was relatively high and reflected the interim nature of the analysis report, which did not describe and justify the work undertaken to the level of rigour expected. In general, the responses received to my queries and those of my TSC were adequate and promptly delivered. Some responses confirmed my judgement regarding the weakness of evidence cited in the safety case.

199. I identified a number of shortfalls against RGP, mainly associated with the completeness and quality of presentation of the evidence.

200. I have raised three recommendations for the licensee to address. Based on discussions with the licensee, I was content that the majority of the identified work is already in progress and is expected to be completed in a timely manner.

201. Based on my findings, overall I judge that the licensee's submission should be rated as Amber with respect to the ONR Assessment Rating Guide (Ref. 5).

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

202. This report presents the findings of the ONR assessment of the Hunterston B return to service safety case for Reactor 4 following core inspection results in 2018 (Ref. 6) and supporting documentation provided by the licensee.

203. The intent of the proposal is to provide a justification for the return to service and continued operation of Hunterston B Reactor 4 to a core burn up of 16.025 TWd (a period of approximately 4 months) following completion of core inspections. The safety case has proposed changes to both the Operational Allowance and the Currently Established Damage Tolerance Level. These changes have been justified through developments in the damage tolerance assessments, including the use of a significantly reduced core boundary seismic motion derived from revised modelling of the PCPV. The safety case does not require any physical plant changes.

204. The safety case is structured around two claims. I have assessed the claims and supporting arguments with civil engineering content and sampled the supporting evidence. My assessment focused on the revised modelling of the PCPV, which provides seismic input into the core modelling and hence is important to the demonstration of adequate core margins during a design basis seismic event.

205. I found that overall the safety case was valid, robust, integrated, balanced, and forward looking. However, I judge that there were certain areas within the case that lacked the intelligibility, completeness and evidential basis identified in ONR's guidance for assessment of safety cases. My key assessment findings are described below.

206. I judge that the modelling approach was conventional and in general accordance with relevant good practice. The changes to the restraints in the existing model in order to de-couple the PCPV from the Reactor Building at the charge face level have been adequately justified.

207. The seismic input motion was the same as that used in the current graphite core safety case. The input motion is based on synthetic records and does not fully comply with relevant good practice, which adopts real ground motion records. Based on the studies presented, which compared the seismic input with real records, I considered the input motion to be conservative within the frequency range of significance for the core.

208. The results presented confirm that for frequency ranges of significance to the core response, there was a significant reduction in core boundary acceleration for the best estimate model compared with the legacy best estimate model.

209. In my opinion, the best estimate material properties for the concrete structure, bearings, rock and backfill are adequate. An acceptable sensitivity study has been undertaken that considered the effects of uncertainty due to variation in the properties of the rock, backfill and bearings. In order to make this judgement, I have relied on supplementary information provided as a result of my queries, which was not provided in the evidence referenced in the safety case. A key aspect of this additional information related to selected output from the GCORE finite element analysis, which provided comparative margins for interstitial channel distortion. Although the assessment of the GCORE results was not within the scope of this assessment, the results provided evidence as to which sensitivity cases in the PCPV model were the most important for the core assessment.

210. The most onerous case for channel distortion margins was obtained from a combination of upper bound properties for the rock, backfill and bearings. I observe that the safety case claims in relation to the core are based on a best estimate

GCORE analysis, which is not the most onerous case for channel distortion. I have raised Recommendation 2 so that this aspect can be considered further in the ONR graphite assessment (Ref. 44).

211. The licensee has been undertaking a range of further analysis in order to update the preliminary PCPV model referenced in the safety case. This further work is intended to address challenges raised in relation to the preliminary model and to report the results of further sensitivity studies. The final modelling report is not yet available but will be issued in due course in support of future safety cases. In order to address a number of my queries, the licensee has supplied additional evidence taken from its final modelling work. I note that this material is preliminary in nature but judge it adequate as additional supporting evidence to the present safety case.

212. Given the importance of the bearings to the revised modelling, I considered that insufficient evidence was presented that the bearings could fulfil their safety functional requirements or that the bearings complied with current codes and standards. Although I accept that the structural demand on the bearings during a seismic event is likely to be within their structural capacity, this has not been adequately demonstrated within the safety case. I have raised Recommendation 4 in order to track the licensee's progress in resolving this shortfall, which I judge is not required prior to return to service of Reactor 4.

213. The simplification of treating the PCPV as isolated from the frictional effects resulting from its connections with other structures such as the Long Travel Girders is slightly non-conservative. I am content that this effect is small and the reporting of further sensitivity studies will be included in the final modelling report, the progress of which I will track using my Recommendation 5.

214. There are aspects of the preliminary model which are being changed for the final model and which are expected to increase the input motion into the core. These changes include a reduction to the critical damping values for shear distortion of the bearings and a reduction in the foundation width assumed when calculating rocking parameters arising from rock structure interaction. Based on additional evidence presented from the final modelling, I was satisfied that these modelling changes have only a small adverse effect on the seismic input to the core and a negligible effect on core distortion margins.

215. Whilst I was content that a walk-down had been carried out at Hunterston B to confirm the as-built details important to the analysis, I found that this had not been reported in a manner that could be used as evidence in the safety case. The PCPV modelling is also intended to cover the Hinkley Pont B station, but I found no evidence that a similar walk-down had been conducted at that station. I have included a requirement to provide this additional evidence as part of my Recommendation 5.

216. I consider that the effect of the changes to the PCPV modelling on other SSCs and safety cases requires further investigation. This work is needed to demonstrate that the SSCs can fulfil their safety functional requirements over the full range of seismic loading. I am content that the licensee intends to carry out this work but have included it within my Recommendation 6 so that I can monitor progress,

217. I found that the number of sensitivity cases considered in the preliminary model was relatively low and was based on the assumption that combining material properties such that they all assume lower bound, best estimate or upper bound properties simultaneously will provide the most onerous case for seismic input to the core. I was satisfied based on the supplementary information provided in response to queries that additional work as part of the final modelling report has been done to demonstrate that the most onerous sensitivity case for the seismic input to the core has been identified.

218. The seismic input to the core has not been broadened to allow for uncertainty, which does not meet the intent of relevant good practice. I noted that the licensee disagreed that this was required and judge that an acceptable alternative would be to investigate a wider range of sensitivity cases focused around the critical upper bound case, to ensure that the peak spectral response was aligned with that of the core's natural frequency. I obtained confirmation from the licensee that the frequency of the spectral peak for the horizontal input motion for the upper bound sensitivity case coincides closely with the natural frequency of the current core model. Although this provided me with confidence that the most onerous case had been identified for the current models, I observe that future safety cases with differing core damage models may need to consider whether additional sensitivity studies using the PCPV model are needed to confirm the minimum core distortion margins. This requirement has been captured in my Recommendation 3.

219. I found a number of areas where the intelligibility and evidential basis of the preliminary analysis could be improved and the substantiation enhanced. The licensee has agreed to address these aspects in its final modelling report, which was being progressed at the time of writing. Whilst I consider that these areas are important, I have seen sufficient evidence from the licensee's final modelling work to judge that the risk associated with any changes to the safety case claims resulting from these enhancements and additions is acceptably small. I have captured my expectations regarding these matters in my Recommendation 5.

220. To conclude, from a civil engineering perspective I am satisfied with the claims, arguments and evidence laid down within the licensee's safety case. A number of aspects of the PCPV analysis and its reporting require further work and I have captured these in Recommendations 4, 5 and 6. Overall, I judge the proposal adequate to justify the issue of a Licence Instrument to signify ONR's Agreement under arrangements made under Licence Condition 22 (1).

5.2 Recommendations

221. My recommendations for ONR are:

- Recommendation 1 – From a civil engineering perspective, I recommend that ONR should issue a Licence Instrument granting Agreement to the safety case under Licence Condition 22 (1).
- Recommendation 2 – The ONR graphite assessment should take into account when assessing core margins for seismic events that the GCORE analysis reported in the safety case is based on the use of the best estimate PCPV model only. Sensitivity studies have indicated that the upper bound PCPV model is bounding for PCPV accelerations of significance to the core and for core distortion margins.
- Recommendation 3 – When assessing future safety cases, the ONR graphite and civil engineering assessments should take into account that further changes to core damage models may lead to alterations in the natural frequency of the core. Such changes may require the licensee to carry out additional sensitivity studies to demonstrate that the most onerous combination of PCPV model variables has been considered.

222. My recommendations for the licensee are given below. I intend to agree mutually acceptable deadlines with the licensee for completion of the recommendations. I then intend to raise an ONR Regulatory Issue in order to track the licensee's progress in addressing the recommendations in a timely manner.

- Recommendation 4 – The licensee should demonstrate to ONR that the bearings supporting the PCPV have adequate capacity under seismic loading.

- Recommendation 5 – In its final modelling report the licensee should provide evidence that the following matters arising from ONR's assessment of the preliminary PCPV modelling have been adequately addressed:

  - Uncertainty and bias when using theoretical formulae for compression stiffness of the bearings
  - Uncertainties in the damping properties for compression of the bearings
  - Justification that the HPC site-won backfill properties are relevant to HNB
  - Evidence that confirms that the bi-linear backfill soil springs used in the preliminary model have been replaced and that a LLB backfill case to address gapping has been included in the sensitivity studies
  - Detailed reporting of site walk-downs at both HNB and HPB that confirm the physical and geometric assumptions made in the analysis
  - Numerical quantification of the Central Block displacements
  - Expanded reporting of verification and validation of the final model compared with that provided for the preliminary model
  - Comparisons of the vertical motion into the core for the legacy model, preliminary model and final models
  - Consideration of the effects of a BDB seismic event, including increased displacements and possible closure of joints that may challenge the modelling assumptions of an isolated structure
  - Reporting of enhanced sensitivity studies reflecting the further work done since the preliminary analysis was completed
  - Justification that a UB case with LLB backfill is bounded by the UB case regarding its effects on the graphite core
  - Justification that Structure-Soil-Structure Interaction (SSSI) is not significant

- Recommendation 6 – The licensee should review all relevant safety cases that may be affected by the changes to the PCPV seismic modelling and confirm to ONR that any adverse effects on other SSCs have been adequately justified.

6 REFERENCES

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Table 1: Relevant Safety Assessment Principles considered during the assessment

SAP No	SAP Title	Description
AV.2	Fault analysis: assurance of validity of data and models: Calculation methods	Calculation methods used for the analyses should adequately represent the physical and chemical processes taking place.
AV.3	Fault analysis: assurance of validity of data and models: Use of data	The data used in the analysis of aspects of plant performance with safety significance should be shown to be valid for the circumstances by reference to established physical data, experiment or other appropriate means
AV.4	Fault analysis: assurance of validity of data and models: Computer models	Computer models and datasets used in support of the safety analysis should be developed, maintained and applied in accordance with quality management procedures.
AV.5	Fault analysis: assurance of validity of data and models: Documentation	Documentation should be provided to facilitate review of the adequacy of the analytical models and data.
EAD.2	Engineering principles: ageing and degradation: Lifetime margins	Adequate margins should exist throughout the life of a facility to allow for the effects of materials ageing and degradation processes on structures, systems and components
ECE.1	Civil engineering: Functional performance	The required safety functions and structural performance of the civil engineering structures under normal operating, fault and accident conditions should be specified.
ECE.2	Civil engineering: Independent arguments	For structures requiring the highest levels of reliability, multiple independent and diverse arguments should be provided in the safety case.
ECE.5	Engineering principles: civil engineering: investigations: Geotechnical investigation	The design of foundations and sub-surface structures should utilise information derived from geotechnical site investigation.
ECE.6	Civil engineering: design: Loadings	Load development and a schedule of load combinations, together with their frequencies, should be used as the basis for structural design. Loadings during normal operating, testing, design basis fault and accident conditions should be included.
ECE.12	Civil engineering: structural analysis and model testing	Structural analysis and/or model testing should be carried out to support the design and should demonstrate that the structure can fulfil its safety functional requirements over the full range of loading for the lifetime of the facility.

SAP No	SAP Title	Description
ECE.13	Civil engineering: structural analysis and model testing: Use of data	The data used in structural analysis should be selected or applied so that the analysis is demonstrably conservative.
ECE.14	Civil engineering: structural analysis and model testing: Sensitivity studies	Studies should be carried out to determine the sensitivity of analytical results to the assumptions made, the data used, and the methods of calculation.
ECE.15	Civil engineering: structural analysis and model testing: Validation of methods	Where analyses have been carried out on civil structures to derive static and dynamic structural loadings for the design, the methods used should be adequately validated and the data verified.
ECE.20	Civil engineering: in-service inspection and testing	Provision should be made for inspection, testing and monitoring during normal operations aimed at demonstrating that the structure continues to meet its safety functional requirements. Due account should be taken of the periodicity of the activities.
ECS.3	Codes and Standards	Structures, systems and components that are important to safety should be designed, manufactured, constructed, installed, commissioned, quality assured, maintained, tested and inspected to the appropriate codes and standards.
EHA.7	Engineering principles: external and internal hazards: ‘Cliff-edge’ effects	A small change in design basis fault or event assumptions should not lead to a disproportionate increase in radiological consequences.
EHA.18	Engineering principles: external and internal hazards: Beyond design basis events	Fault sequences initiated by internal and external hazards beyond the design basis should be analysed applying an appropriate combination of engineering, deterministic and probabilistic assessments.
EKP.2	Engineering principles: key principles: fault tolerance	The sensitivity of the facility to potential faults should be minimised.
SC.5	The regulatory assessment of safety cases: Optimism, uncertainty and conservatism	Safety cases should identify areas of optimism and uncertainty, together with their significance, in addition to strengths and any claimed conservatism.

Table 2: Loads included within the legacy and preliminary PCPV models

Item	Legacy model mass (Te)	Preliminary model mass (Te) (Ref. 22)	Notes
PCPV concrete structure	43,140	44,411	Total mass increased due to error found in the mass of the pile cap in the legacy model
Vessel contents	8,644	5,081	Only the mass of the internals supported by the diagrid have been considered in the preliminary model. The boilers are supported from the pile cap and have not been included.
Gas Bypass Duct at 66’ level	278	0	Not included in preliminary model – considered insignificant
Fuel Box Store at 109’ level	129	0	Not included in preliminary model – considered insignificant
Charge Machine/Gantry	795	795	
Concrete floor beams spanning between the PCPV and Central Block	113	0	Not included in preliminary model – considered insignificant
Total mass	53,099	50,287	

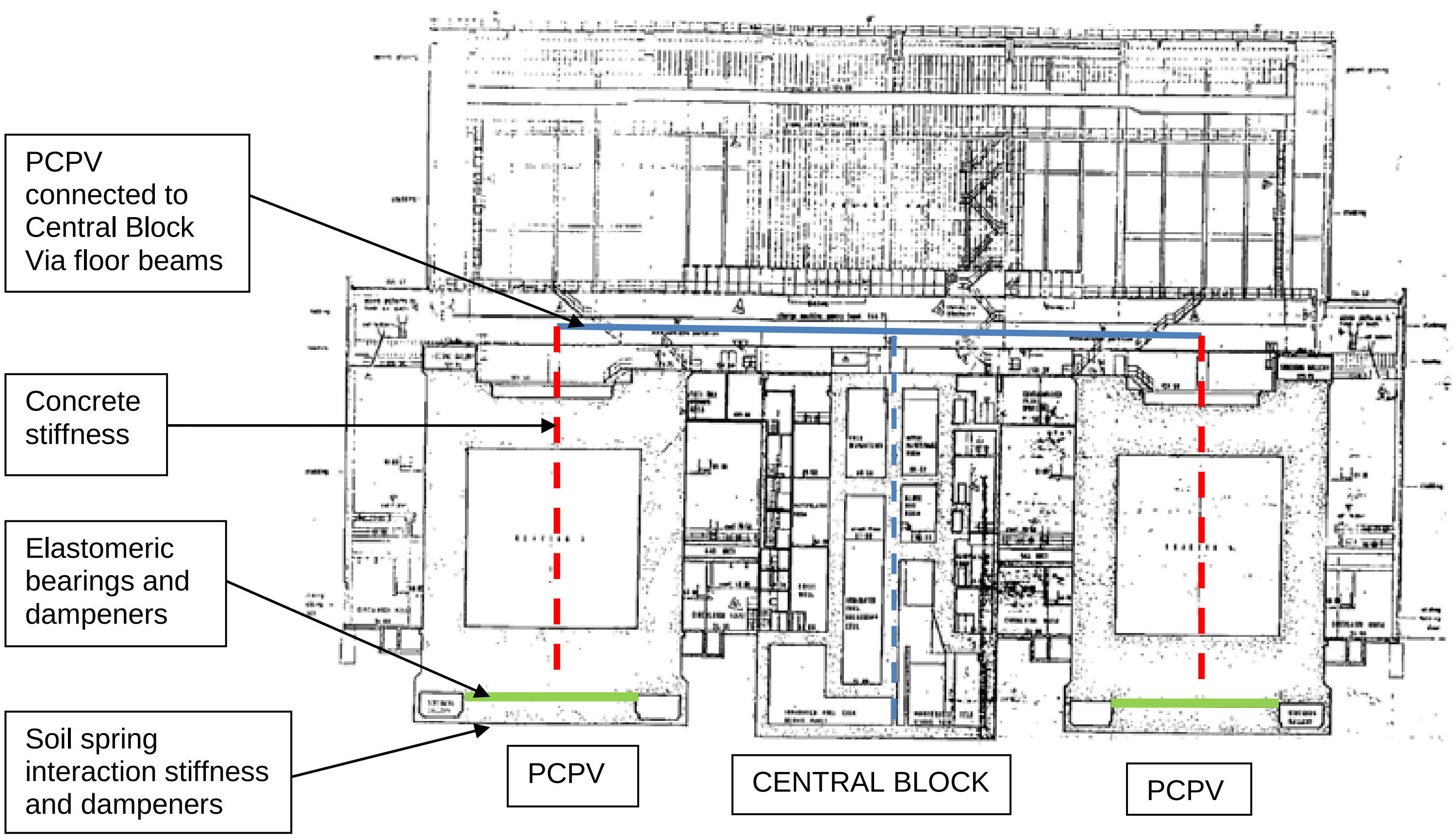

Figure 1: PSR1 Model - North-South Section through Reactor Building showing model idealisations

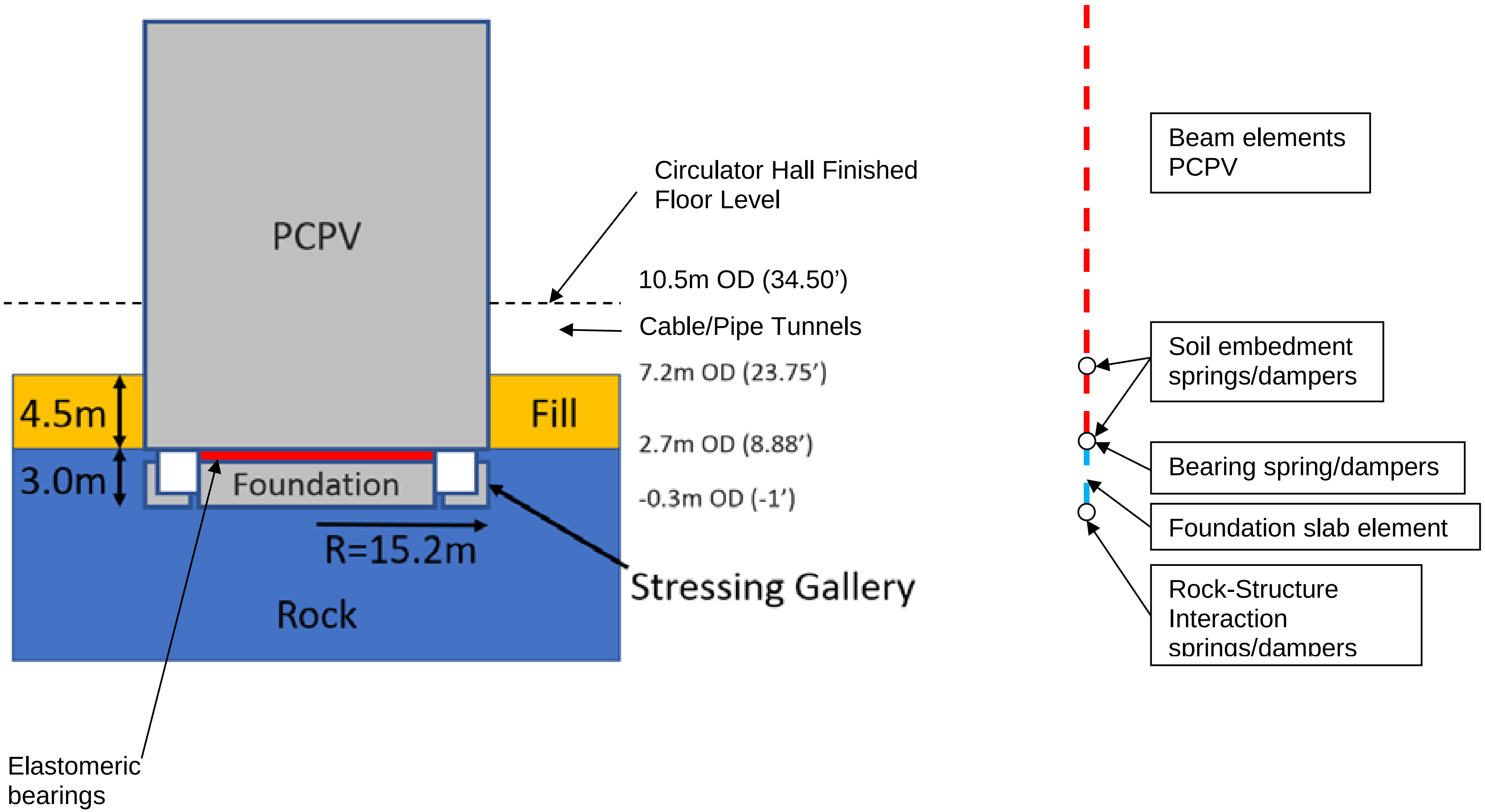

Figure 2 – New PCPV Model idealisation

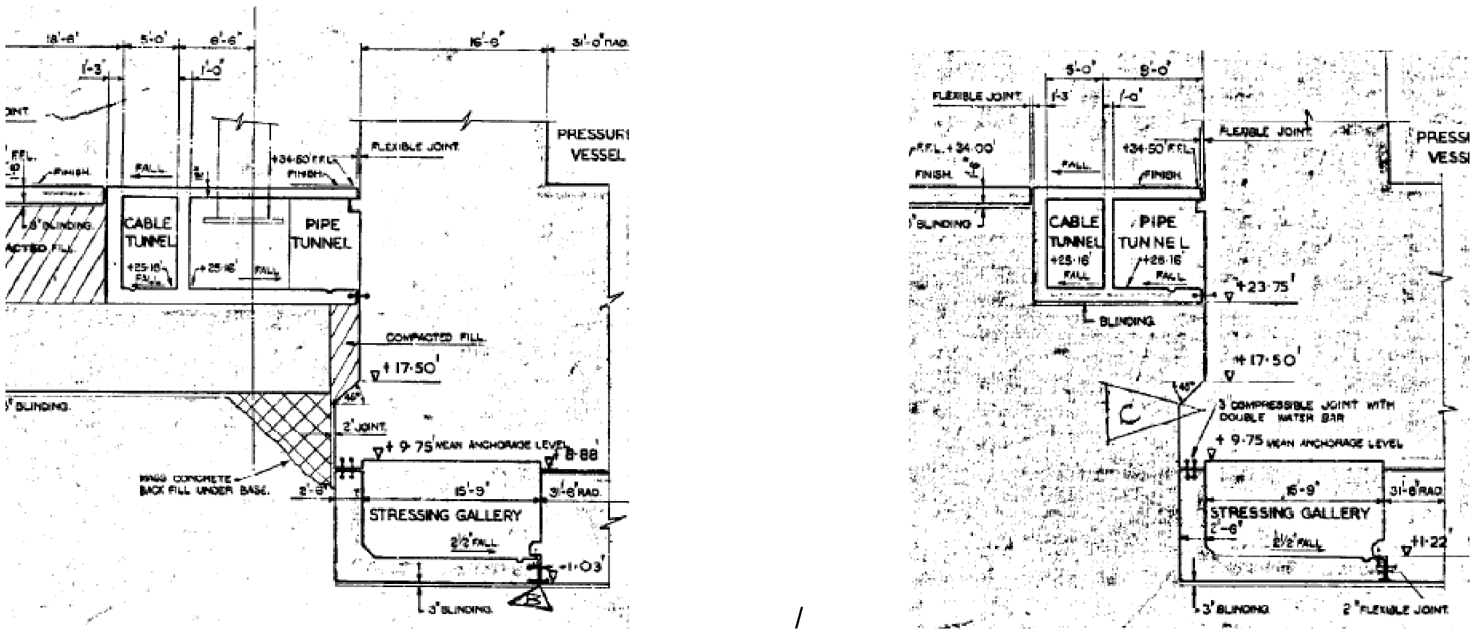

Figure 3 – Extracts from original construction drawings

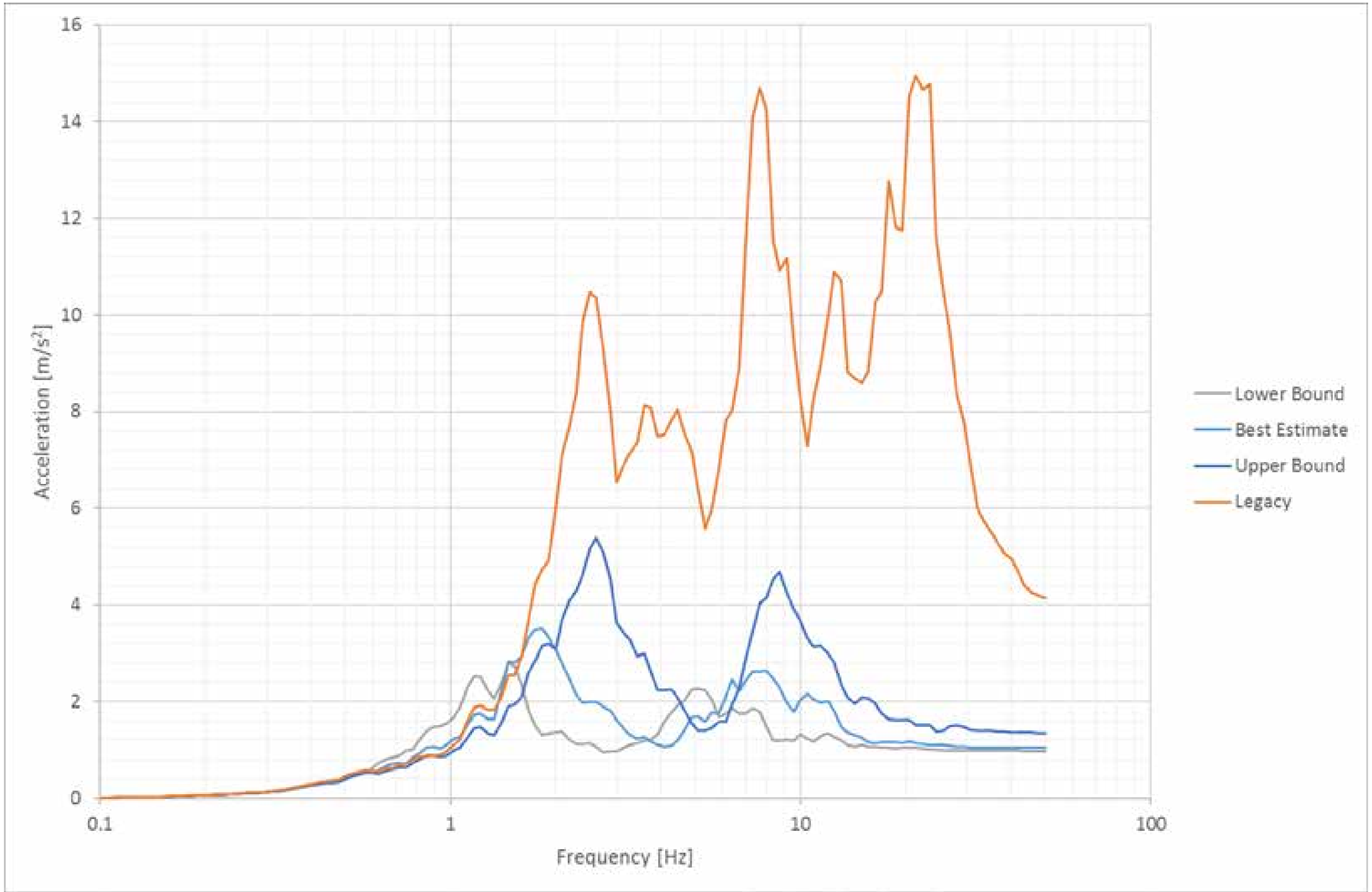

Figure 4 - SRS comparison at core boundary for PML synthetic input motion for Legacy and Preliminary PCPV models (After Ref. 17, Figure 33)

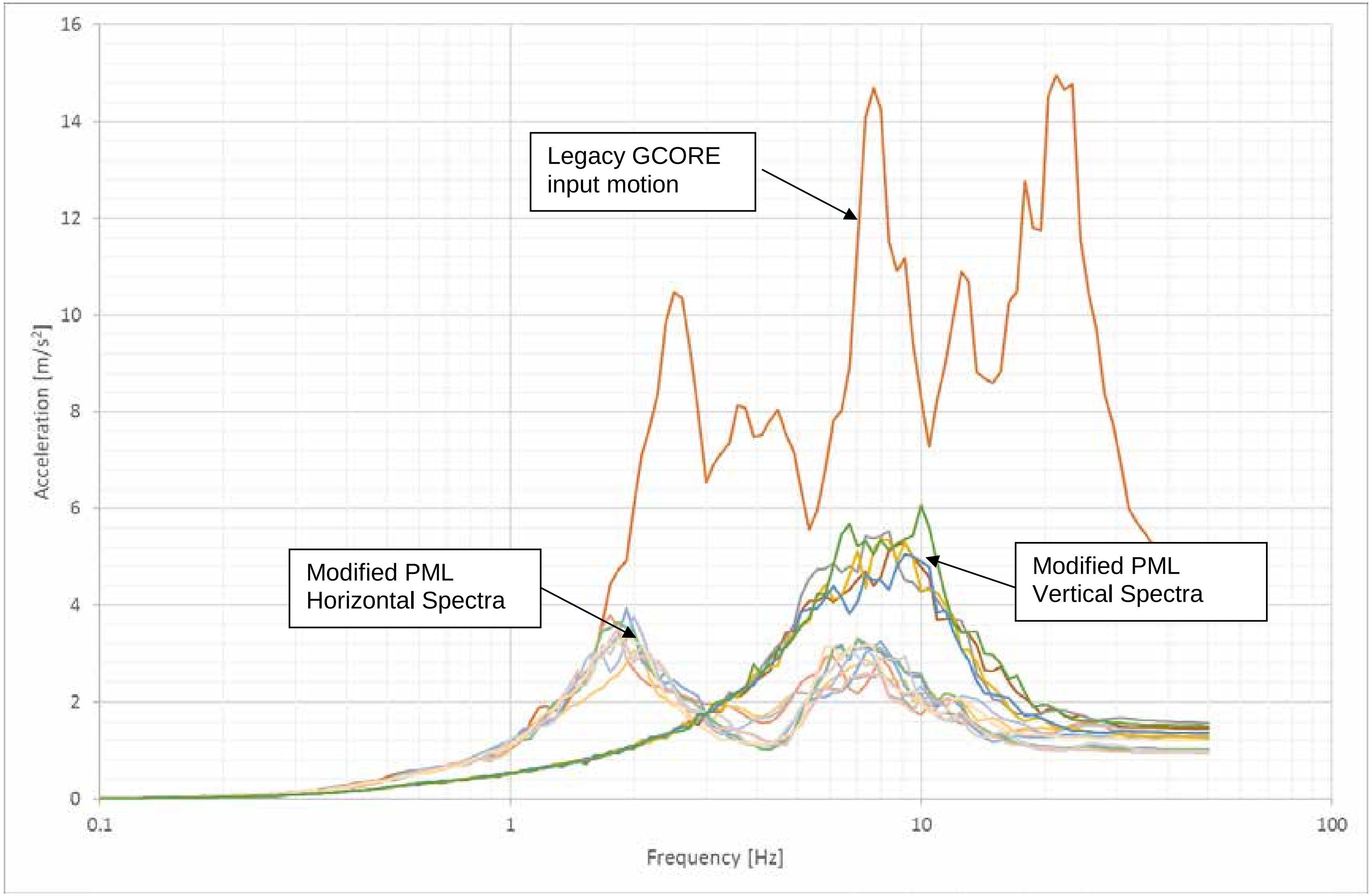

Figure 5 - Modified PML core boundary SRS (including legacy core boundary PML) for the BE preliminary model (After Ref. 17, Figure 34)

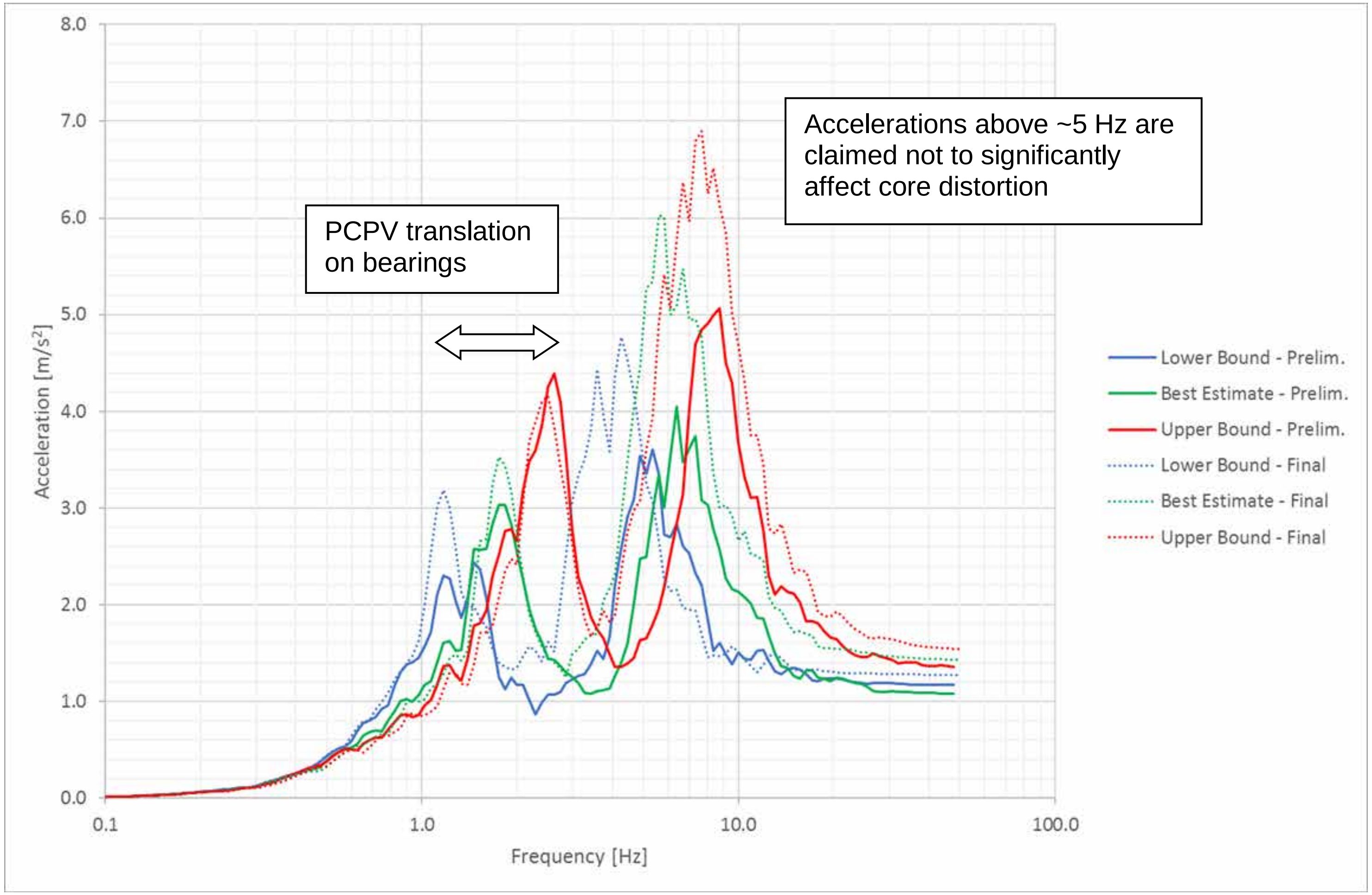

Figure 6 - SRS comparison at base of PCPV for Preliminary (prelim) and Final models (PML synthetic input motion) (after Ref. 24 - response to ABSC Comment 2i)

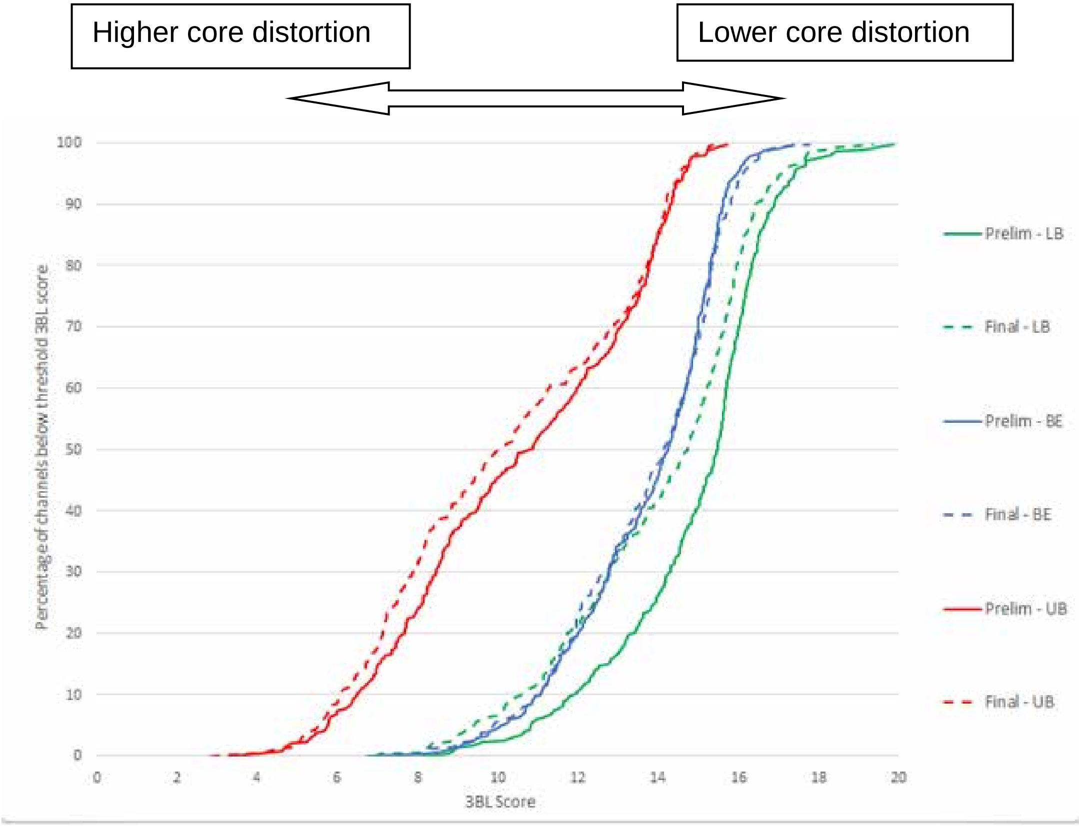

Figure 7 – Core distortion as measured by 3BL score – PML synthetic input motion - Sensitivity study for LB, BE and UB properties for Preliminary and Final models (After Ref. 24, response to ABSC Query 2i)

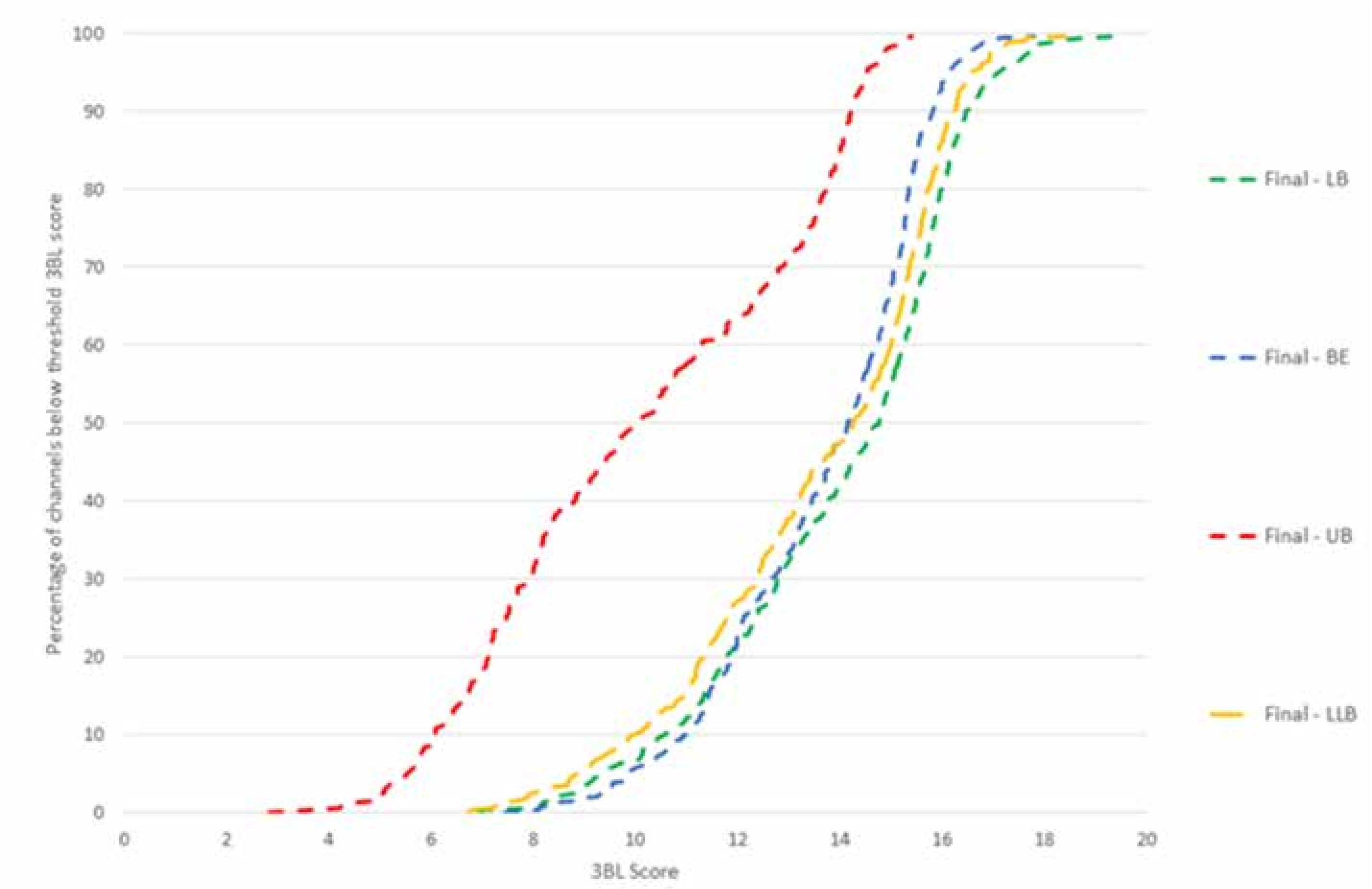

Figure 8 - Core distortion as measured by 3BL Score – Final Model – PML synthetic input motion - Comparison for LLB, LB. BE and UB properties (After Ref. 24, response to ABSC Comment 2i)

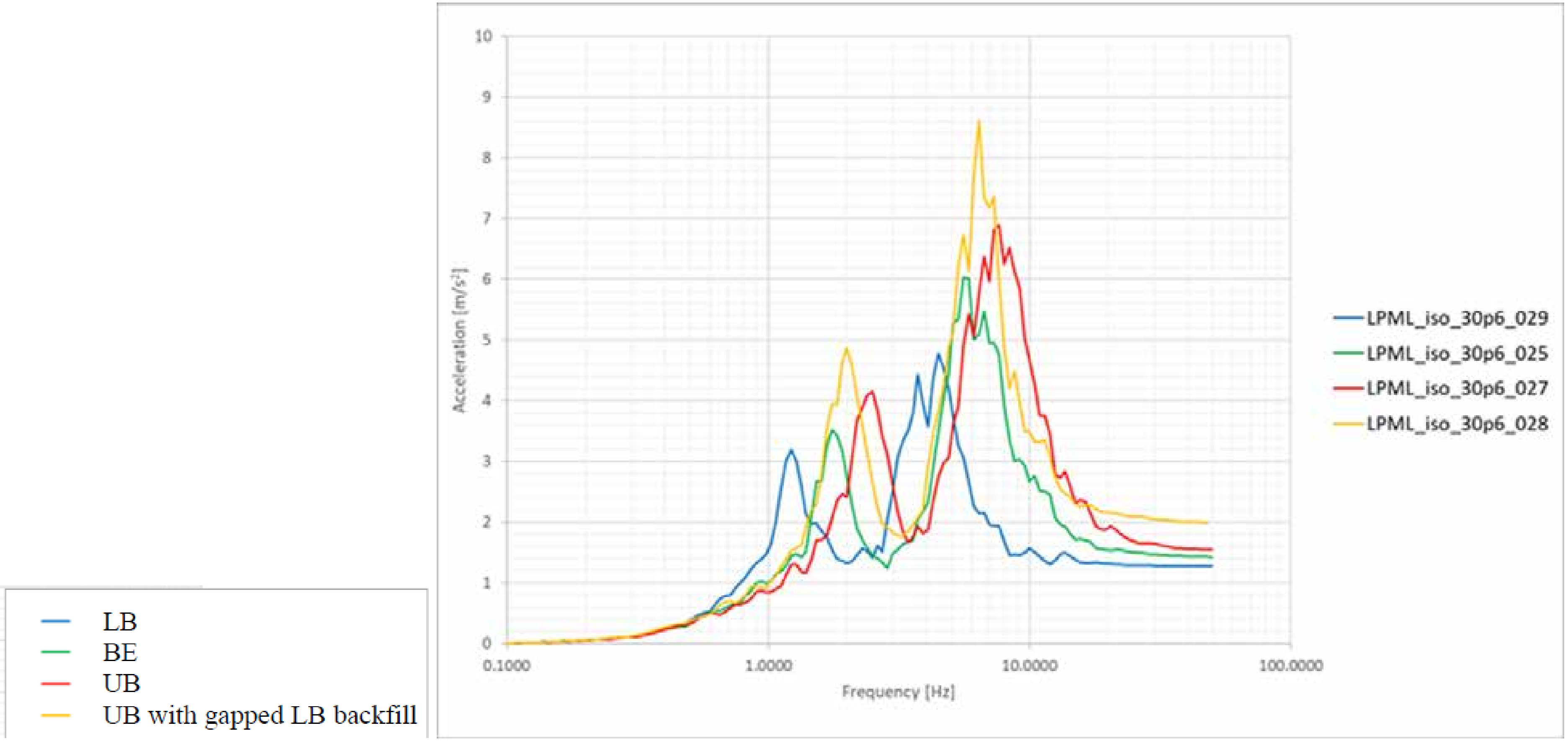

Figure 9 - Final Model SRS at base of PCPV - PML synthetic input motion - LB, BE and UB cases compared with sensitivity case of UB bearings and rock with LLB (gapped) backfill (case _028) - (After Ref. 24, response to ABSC Comment 25)

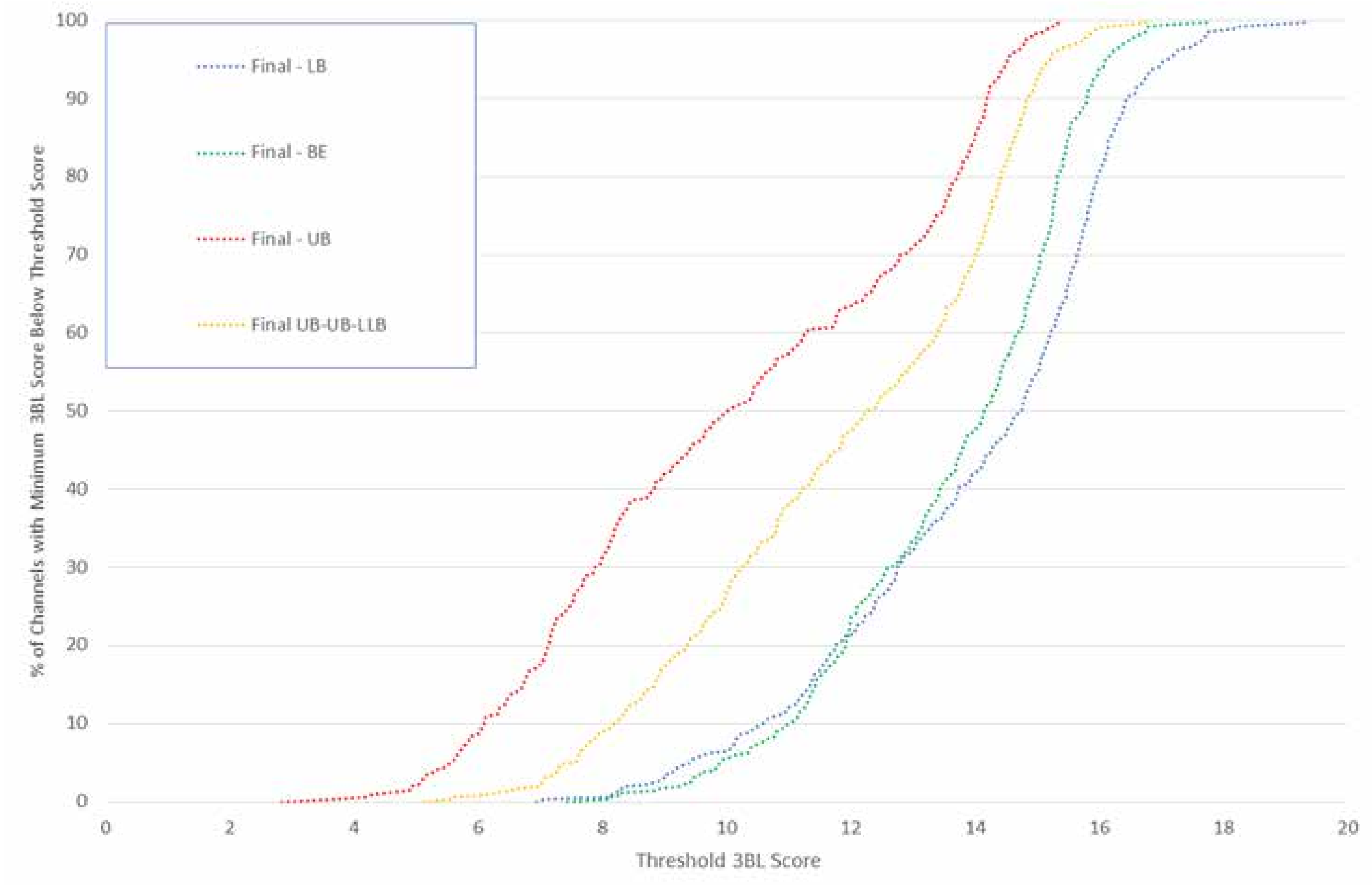

Figure 10 - Core distortion as measured by 3BL Score - Final Model - PML synthetic input motion - LB, BE and UB Cases and sensitivity case of UB bearings and rock with LLB (gapped) backfill (After Ref. 24, response to ABSC Comment 25)

Appendix 1: ONR Civil engineering assessment queries and responses

Query No.	Topic	Document Reviewed Ref.	ONR comments and queries	EDF Response Ref.
ONR 1	Evidence for SS1	17	Please provide a list of calculations and reports used to support this high-level summary report, together with an indication of their purpose and content	21
ONR 2	Scope of SS2 work	17	Please provide a list of further work that is being undertaken in support of SS2, what its purpose is and how it will be validated and verified.	21
ONR 3	Compliance with RGP	17	Please confirm the extent to which the modelling is compliant with ASCE 4-16 and identify any significant departures.	21
ONR 4	Effect of model changes on other SSCs	17	It has been identified that the changes to the seismic model will increase the axial load on the Long Travel Girders, and hence their supporting structures. Please confirm how this anomaly is being addressed, including its interface with safety case NP/SC 7762, which is currently being assessed by ONR? Please also confirm the evidence that the modelling changes do not have any adverse effect on the PCPV concrete or any of its penetrations?	21
ONR 5	Backfill properties	17	The fill material properties are estimated based on the HPB site. What evidence is there that the HNB fill falls within the assumed parameters for HPB?	21
ONR 6	Site inspections	17	Given the importance of confirming existing construction details, I would expect to see as evidence a report that confirms as far as is reasonably practicable that the existing details important to the new analysis have been checked and confirmed to be as assumed in the analysis. Such a report would also identify and discuss any remaining areas of uncertainty. Does such a report exist and if not please confirm the status of the evidence you have gathered in this respect?	21
ONR 7	General modelling assumptions	17	The model description is not very detailed. Please provide a more detailed description which confirms: · Finite element software used for the model and why it was chosen · Which parts of the analysis are linear and which non-linear and where non-linear clarify whether this is geometric and/or material non-linearity. · Justification of element and support types · What parameters have been taken from legacy models and how these have been verified · What loading is considered · What model variants have been used	21

Query No.	Topic	Document Reviewed Ref.	ONR comments and queries	EDF Response Ref.
ONR 8	Allowance for uncertainty	17	What was the reason for using lower bound, best estimate and upper bound properties for key variables? Was there any consistent statistical basis to the LB and UB values? In terms of output from the analysis what use is made of the various results – is it intended to use an envelope of the results or is it intended to use best estimate and use LB and UB to demonstrate sensitivity to variance?	21
ONR 9	Bearing properties	17	Why has the bearing pad stiffness changed in the updated model?	21
ONR 10	Bearing properties	17	Please justify amending the legacy damping value for the bearings? Has the analysis considered the sensitivity to this parameter?	21
ONR 11	Bearing properties	17	The “recent” sample testing on bearings was done in the 1990s – Ref 14 refers to the following document: ED/AGR/REP/0119/95 Issue 2 – Elastomer Pressure Vessel Support Bearings – Material Properties – Revised January 1996. Whilst I am aware that a more recent test was done, I do not have the evidence for that. Please provide a copy of the 1996 report and a copy of the recent report describing the repeat bearing hardness test.	21
ONR 12	Bearing properties	17	Given the lack of evidence that the bearings were installed correctly (e.g. that there is no concrete or other construction debris between bearings) and the limited evidence that they are in good condition, I consider that caution is required when setting the model bearing stiffness. Please clarify the basis for the BE and UB properties for the bearings and confirm the reasons why the chosen values are appropriately conservative?	21
ONR 13	Rock properties	17	Please confirm the reasons for revising the rock-structure interaction properties.	21
ONR 14	Backfill properties	17	Please provide justification for the upper bound fill properties assumed. Given the lack of information, how can it be known for certain that mass concrete was not used rather than compacted fill?	21
ONR 15	Restraint to PCPV	17	Please clarify why the LB for LTG horizontal restraint is based on preload only (which may not exist).	21
ONR 16	Ground motions	17	Please clarify what ground motions are being used to support SS1 and what are supporting SS2.	21

Query No.	Topic	Document Reviewed Ref.	ONR comments and queries	EDF Response Ref.
ONR 17	Validation and verification	17	Please provide further details of the quality management arrangements for the validation and verification of the model, for example a quality plan for this work.	21
ONR 18	Restraint to PCPV	17	It is assumed that the full 25.4 mm nominal gap is available for movement without transferring load .What is the maximum compression of the joint materials without transferring load and what allowance has been made for joint gap tolerance and thermal movements?	21
ONR 19	General modelling assumptions	17	Please clarify the breakdown of the calculation for the mass of the PCPV. Has this calculation included for the masses of the gas bypass duct, fuel box store and concrete floor beams? If not included how have these masses been added to the model?	22
ONR 20	General modelling assumptions	17	The assumed mass of the reactor internals (5,081Tonnes) does not accord with the value provided in the legacy model calculations SEB/PIG/MC/0188 Sheet 2/5, which indicates a value of 8,644 kg. Please account for this mass difference.	22
ONR 21	Safety functional performance of bearings	17	Although the bearings have been modelled, the report appears to present no evidence that the bearings can perform their required safety function. Please confirm what checks have been carried out that demonstrates the adequacy of the bearing performance.	22

Appendix 2: ABSC Civil engineering assessment queries and responses

Query No.	Topic	Document Reviewed Ref.	ABSC comments and queries	EDF Response Ref.
ABSC 1	General modelling assumptions	17	The model proposed for core assessment has moved away from the legacy PSR1 work in which the PCPV's elastomeric pads provided lateral restraint to its base and the Central Block provided restraint to its top, to a model in which lateral restraint is close to its base through the combination of elastomeric pads and backfill. The reviewer has not been able to readily address the relative contributions to stiffness and the PCPV's response arising from the restraint from the elastomeric pads and that from the backfill. It would be expected that the analysts may well have examined extreme cases of no backfill, and of a very stiff backfill in which the PCPV is essentially held at its base and is only allowed to exhibit a rocking mode on the elastomeric pads. The reviewer would appreciate the sharing of any information over these extremes of response, even if they are regarded as unrealistic, in order that significant aspects may be focussed upon.	23, 24
ABSC 2	Damaging frequency range for core	17, 25	The presentation to ONR on 27th September 2018 included several plots with double headed arrows indicating a broad band of "*Frequency range of interest for PCPV core response*", although the extent of arrows varied somewhat. The ONR Contact Report states, "*the range of frequency of interest for core response was stated to be 1 to 8 Hz*". The reviewer is dependent on this statement when performing the subsequent review of the Atkins PCPV Modelling report. Furthermore, the rather wide range of frequencies indicates that it is not solely a displacement controlled problem, but velocities and accelerations are also likely to be of relevance to the core. For this reason, it has not been possible to always be focusing on those parameters leading solely to, for example, maximising the low frequency response and displacements. NGL are requested to confirm the range of important frequencies for the core.	23, 24
ABSC 3	General modelling assumptions	17	The rotational inertia of the PCPV will influence the tendency for the lateral shear mode of the PCPV on its elastomeric pads to combine with or be well separated from the rocking mode of the PCPV on its pads. Section 3.1 and Figure 8 of 350/019 Issue 2.0 explain that a stick model of the PCPV has been used without additional inertia elements, consistent with the legacy model. Whilst the distribution of mass up a central stick will result in some significant rotational inertia from "mr^2" type of terms, condensing all the	23, 24

Query No.	Topic	Document Reviewed Ref.	ABSC comments and queries	EDF Response Ref.
			mass to points confined to the vertical axis will have omitted some of the rotational inertia. Please justify this simplification.	
ABSC 4	Model validation and verification	17	Section 3.1.1, 5th para, and Table 2 of 350/019 Issue 2.0 discuss and present main frequencies and hand calculations. Please confirm the hand calculations are for the updated model; the wording in the first sentence of the fifth paragraph is not clear in this respect. Please also confirm, as would be expected at this stage of reporting the model development, that the updated model does not yet have any representation of the backfill.	23
ABSC 5	Bearing properties	17	Section 3.1.2 of 350/019 Issue 2.0. It is evident from later in the report (e.g. Figure 33) that when a range of parameters including those for the elastomeric pads are set at their LB values, the low frequency spectral peaks are shifted to the left, with exceedance of the original SRS being input into the core being demonstrated in Figure 33. Other inputs motions would be expected to show a similar trend if they were to be run on a LB basis, but from inspection of Figures 34 and 35, may be less likely to cause exceedances. The reviewer has some concern over the adoption of the sample test results as a LB stiffness value, arising from: (a) It appears that hardness is being used as an indicator of stiffness. Some uncertainty in the correlation would be expected which may not have been captured. (b) It appears that the results for all the pads (at both stations) have been based on a sample, but actual stiffnesses may exhibit a spread of values about the sampled value(s). (c) The report claims strain dependency as one of the reasons for adopting the sampled values as being LB. Whilst strain dependency might be a valid consideration for compression, the reviewer questions its validity for shear stiffness. (d) The report claims loading rate as the other reason for adopting the sampled values as being LB. In principle, this appears to be a valid argument to shift the BE value to higher than the sample value(s), but the extent of the shift may be limited for loading rates corresponding to the 1 to 2 Hz low frequency oscillations demonstrated in Figure 33. Overall, a more robust defence of using the sampled hardness value(s) as the basis of a LB stiffness is requested, or the LB value be adjusted.	23, 24

Query No.	Topic	Document Reviewed Ref.	ABSC comments and queries	EDF Response Ref.
ABSC 6	Bearing properties	17	Section 3.1.2 of 350/019 Issue 2.0. 5% of critical damping has been used for the elastomeric pads (c.f. 10% in the legacy model). It is apparent from inspection of Table 3 that 5% has also been used in the LB and UB cases (since the values for the dampers used in the model follow the square root of the values of stiffness used in the model, thereby preserving the same level of critical damping at 5%). Please clarify whether 5% damping is being regarded as a LB value, conservatively used for BE and UB cases too, and what the LB value of 5% is based upon.	23, 24
ABSC 7	Rock properties	17	Section 3.1.3 of 350/019 Issue 2.0. It is apparent that the footprint of the foundation has been taken to include the area of the stressing gallery. However, from inspection of the drawings there are joints between the gallery's wall (3" joint) and slab (2" joint) where it connects to the PCPV and the foundation disc. Because of these joints, monolithic behaviour of the larger diameter disc cannot be considered to be justified. The report investigates this in a fashion, by reverting in a sensitivity study to the legacy RSI rocking properties. This is not the same as following the same approach for the derivation of the RSI parameters, but using the smaller footprint, and hence is not comparing like for like. Notwithstanding this, the sensitivity study presented in Figure 11 shows a slight shifting of the low frequency peak, and a more dominant higher frequency peak at 5Hz, with some reduction in response at some frequencies in between. (a) The reviewer considers the RSI parameters based on the smaller footprint without the galleries should be basis of the best estimate model. (b) It is logical to infer that both effects from the lower frequency peak and more significant higher mode (presumably from rocking) peak will increase the displacement at the top of the PCPV, but the changes to these displacements are not quantified in the present work. Adoption of the BE model as in (a) above would ensure such effects on displacement are reported.	23
ABSC 8	Backfill properties	17	Section 3.1.4 of 350/019 Issue 2.0 A major change from the previous modelling is the inclusion of springs and dampers to represent the backfill, and the reviewer assumes the properties assigned to these are of prime significance. The immediate priority is to address the response of HNB R3. However, the first paragraph of 3.1.4	23

Query No.	Topic	Document Reviewed Ref.	ABSC comments and queries	EDF Response Ref.
			explains the HPC site-won fill properties are used as the basis of what would have been adopted for HPB. Justification is required that the adopted properties are relevant to HNB.	
ABSC 9	Backfill properties	17	Section 3.1.4 of 350/019 Issue 2.0 The first paragraph reasons that the choice of fill properties based on the lowest grade backfill that is likely to be used for HPB has been adopted, because this approach minimises the restraint on the PCPV "*which is judged to be conservative for the assessment of potential gapping between the PCPV and the fill ....which is judged to be the worst case for the displacements of the PCPV and the core.*" This approach sounds reasonable, if maximising displacements is the primary concern. However, as discussed in general in Comments 2 and 1 above, velocities and accelerations may also be of concern, and the reviewer does not know the response for a completely restrained PCPV, which is only free to exhibit a rocking response on its elastomeric pads. Inspection of the drawings HIN/R/3004 and 3008 included in the Atkins report shows there are substantial concrete pads used beneath the double column locations RA7 & RB7 and RA8 & RB8 (see section 2-2). Similarly at column locations RD7 & RE7 and RD8 & RE8 (see section 3-3). At these locations, there is very limited horizontal width of "compacted fill" between the side of the PCPV and the double column bases founded on rock, with local pinch point near the corners of the bases at which the width reduces to approximately 2.25ft (686mm). The reviewer is of the opinion that sensitivity study results for a highly restrained PCPV should be investigated.	23
ABSC 10	Backfill properties	17	Section 3.1.4 of 350/019 Issue 2.0 A bi-linear spring in both compression and tension has been used to approximately account for gapping between the PCPV and the fill embedment. The report's author notes that this approach does not model the effect of the gap in detail. Noting that this approach results in the fill embedment springs always being connected, and that they have been assigned a damping value of 24% of critical damping, the reviewer has concerns that the fill may be acting as an unrepresentative damper in the current modelling. Any translational movement of the PCPV will involve participation of the fill embedment dampers, and hence its high damping value may be having a significant effect in reducing the motion of the PCPV, but this may not be realistic due gapping.	23

Query No.	Topic	Document Reviewed Ref.	ABSC comments and queries	EDF Response Ref.
			The reviewer notes the report states, "*Further work to refine this assessment will be undertaken in SS2, using the HPB UHS. The current model is adequate to support SS1 judgements based on high interstitial channel margins predicted by GCORE assessments.*" Purely from an analysis approach and the corresponding presented reduction in SRS for the core input motion at most frequencies, the reviewer cannot endorse the presented SRS reductions as being realistic without further investigation into the modelling of gapping. It is also noted that this approach is not in accordance with ASCE 4-16 Section 5.1.9.	
ABSC 11	Restraint to PCPV	17	Section 3.1.5 of 350/019 Issue 2.0 It is not understood how the Charge Face floor beam BE friction capacity of 0.777MN, plus that of the Gas Bypass duct and Fuel Box Store (values not quoted), if they were to be included with the Long Travel Girder maximum load capacity of 4.12MN, can claim to be bounded by the LTG sensitivity study in which Figure 15 shows results for only the BE frictional capacity and a LB frictional capacity. How does an UB frictional capacity, set at a value of 0.777 + 4.12 +? +? MN, affect the results presented?	23
ABSC 12	Restraint to PCPV	17	Sections 3.1.5 and 8 of 350/019 Issue 2.0. Figure 2 presents limited details of the construction surrounding the PCPV at the charge face level. No mention has been found regarding the beams being pre-cast. However, Slide 39 from the presentation of 27th September 2018 includes details of the beams showing them to be pre-cast. It would be expected that the nominal 1/2" (12.7mm) Flexell filled gap at the ends of the beam might show significant variation due to construction tolerances, on the assumption that the beams were lowered onto completed structures (as opposed to a Flexell board being positioned on the end of each pre-cast beam and the wet concrete of the Central Block or PCPV being poured around it). Closer inspection of the drawing (not readily possible from those supplied) might reveal a better understanding of details and the construction sequence. (1) Has any survey work been undertaken in order to confirm that the claimed 1/2" Flexell filled gap at each end of the beams does in fact exist? (2) In the 3rd paragraph of Section 8, it is stated, "Based on the legacy results, the Central Block is a stiff structure which is not expected to displace significantly relative to the ground." The reviewer considers it beneficial to include some quantitative values here so that a more informed judgement may be made over	23

Query No.	Topic	Document Reviewed Ref.	ABSC comments and queries	EDF Response Ref.
			the claim that the two 1/2" Flexell gaps are sufficient to prevent interaction between these two structures and to justify modelling the PCPV as isolated in this respect.	
ABSC 13	Validation and verification	17	Section 3.1.5 of 350/019 Issue 2.0 The validation and verification section is brief, and as presented appears superficial given the importance of the analysis output. There are some checks described for natural frequencies and displacements although no numbers are presented. Can such information be included to increase confidence in the work presented? Also, as the primary purpose of this work is to revise the input spectra for the core model, further checks would be expected to demonstrate that this output is also reasonable in terms of the natural frequencies and magnitude of the spectral peaks.	23
ABSC 14	Vertical input motion	17	Section 7 and its associated plots of 350/019 Issue 2.0 do not show any comparisons of vertical input motion with the vertical legacy motion.	23
ABSC 15	Terminology	17	There are several locations in the report where the term "HPB geometric mean" has been used. These include the title to Section 7.3, wording within section 7.3, Figure 29 to 32, and Figure 35. It is considered this should be replaced with "HPB mean UHS" so as to draw distinction with future reporting using the 84% confidence level UHS, and to be consistent with the wording in the first sentence of Section 9 Conclusions. The last sentence of Section 8 might similarly be improved by using "*The HPB mean UHS input motion...*" instead of "*The mean HPB input motion...*".	23
ABSC 16	Allowance for uncertainty	17	Table 7, Figure 34, Figure 35 and Section 5 of 350/019 Issue 2.0: It is apparent from the run log and the Figures showing results, that the UHS have not been run with variations to cover uncertainties. Also it appears that some of the sensitivity studies have been undertaken using only a single time history. It is acknowledged that Section 5 of the report states that sensitivity of the PCPV response to other combinations of LB/BE/UB will be included in a reissue of the report. The more extensive reporting is awaited. It would be expected that some consideration would be given to the correlation between LB stiffness and corresponding damping. In soil column degradation studies, high stiffness values with little degradation are typically taken in conjunction with low levels of the percentage	23, 24

Query No.	Topic	Document Reviewed Ref.	ABSC comments and queries	EDF Response Ref.
			of critical damping. Similarly, if damping is to be varied for the elastomeric pads, how is the percentage of critical damping correlated with the stiffness variations?	
ABSC 17	Effects on other SSCs	17	It is acknowledged that the primary purpose of this work is to revise the seismic input motion for subsequent analysis and assessment of the reactor core. However, the changes to the modelling may have broader implications for the seismic justification of the structures, cranes, charge machine and plant and equipment. Has this been considered and where is this presented?	23
ABSC 18	Rock properties	17	Appendix A to Issue 2 of this report describes the estimations of the damping considering rock-structure interaction based on NIST GCR 12-917-21. The PVPC's pad is circular. In order to use the equations for rectangular foundations listed in Table 2-3b NIST GCR 12-917-21, the circular foundation has to be approximately treated as an equivalent rectangular foundation. Accordingly, Page 5 of Appendix A deduces an equivalent L/B (L=B) for the circular foundation based on equation base area and second moments of area for the translation and the rotational modes, respectively. However, the use of this equivalent dimension might not achieve sufficient accuracy for soil damping. In fact, Section 19.3.4 of ASCE 7-16 provides a full set of equations for circular foundations based on NIST GCR 12-917-21. ABSC estimate the difference between using the equivalent equations and using the ASCE 7-16 equations for circular foundations may be more than 5% and therefore should not be ignored. NGL are requested to justify the damping levels adopted.	23, 24
ABSC 19	Rock properties	17	Section 4.1.1 of Appendix A to Issue 2 of this report details the procedure of estimating stiffnesses of soil springs. However, it seems that the reduction of shear modulus required in Tables 2-1 and 2-2a of NIST GCR 12-917-21 is not considered or described. According to the shear wave velocities listed in Table 3of Appendix B to Issue 2 of this report, the site class of HPB is B. Therefore, a relevant check on the reduction of soil shear modulus is necessary. NGL are requested to justify this apparent omission.	23
ABSC 20	Backfill properties	17	Section 4.2.2 of Appendix A to Issue 2 of this report states that "*The horizontal damper values for the fill were calculated in an exactly analogous way to the springs. Values for the surface damper value b were calculated based on Table 2-31 in NIST [3].*"	23, 24

Query No.	Topic	Document Reviewed Ref.	ABSC comments and queries	EDF Response Ref.
			It might be inappropriate to use the dynamic radiation damping equations for surface footings of NIST GCR 12-917-21 to estimate the damping of the fill, as the footing in the equations is assumed as rigid with infinite stiffness. As this method is an approximation, some consideration as to the sensitivity to stiffness and damping values would be expected. It is noted in Table 7 that some variations in the fill properties have been considered in the LB, BE and UB cases, although specific values for stiffness and damping are not quoted. Please can NGL confirm what values have been used in the sensitivity studies, along with justification that these variations are sufficient given the approximations adopted in the approach?	
ABSC 21	Beyond design basis	17	Little information on beyond design basis (BDB) considerations has been located in 350/019 Issue 2.0. In the presentation of 27th September 2018, slide 31 states that the general strategy is to "*demonstrate margin*", and then lists: "*- Adopt HPB UHS Mean Hazard* *- Conservatively bias GCORE and Deterministic Acceptance Criteria* *- Quantify beyond design basis "cliff edge" by scaling up input and compare against mean UHS at lower return periods"* The reviewer considers that care should be adopted with a scaling approach, if items such as limited clearances at Flexell joints become significant for larger events. The performance of the core may show a more rapid deterioration if significant "shock loads" were to be transmitted into it if different structures start to impact each other. The reviewer considers that NGL should enhance the report to describe BDB considerations.	23
ABSC 22	Rock properties	17	Figure 10 of 350/019 Issue 2.0 shows that the modelling of embedment effects is somewhat simplistic in that the lateral soil springs are attached to a node at foundation level, despite them being at height. The reviewer considers that this modelling does not capture the vertical variation of input motion with depth, in contradiction with ASCE 4-16, 5.4.1.3. The reviewer is of the opinion that this approach will have probably over-predicted translational input motion, but under-predicted the rotational driving of the structure from vertically propagating shear waves. However, overall the approach in this regard, noting the presence of the elastomeric pads and the	23

Query No.	Topic	Document Reviewed Ref.	ABSC comments and queries	EDF Response Ref.
			general low frequency (long wavelength) response, is potentially not unreasonable, but for completeness the reviewer considers the report should be expanded to discuss and justify this aspect.	
ABSC 23	Input motion for UHS	17	Section 4.2 of 350/019 Issue 2.0 states, "*The HPB target spectra have been derived for a reference target horizon defined at 0.0m OD, using input motions derived for HPC at the reference velocity horizon (bedrock level) and the HPC site response model adapted to consider the site-specific geology at the HPB site. All other input motions have been derived at the PCPV foundation level. The derivation of the HPB UHS is described in Appendix 2 of [1].*" The reviewer has not had sight of [1], but considers that PML is essentially a surface motion definition, but the HPC UHS site response study, adapted for the HPB profile, will not have resulted in a surface motion; it will have produced motion at the foundation level. (1) What checks have been performed to demonstrate the UHS foundation input response spectrum (FIRS) is suitable for use as SSI input motion? ASCE 4-16, 5.4.1.1 and commentary refers. (2) What is the justification for ignoring the rotational component of the input motion? ASCE 4-16, 5.4.1.3 refers, stating, "*For embedded foundations using the free-field ground surface motion as input at the foundation level results in conservative response. ... For embedded foundations and the control point at the foundation level in the free-field, rotational components of the foundation input motion shall be taken into account.*"	23
ABSC 24	Structure Soil Structure Interaction	17	Report 350/019 Issue 2.0 appears to be silent with regard to SSSI effects.	23
ABSC 25	Combination of bearing and backfill properties	17	The Reviewer does not accept that bearing stiffness and damping is correlated with backfill and/or rock stiffness and damping. Furthermore, the Reviewer does not understand why gapping (to be considered in a future LLB case) is only to be considered based on LB backfill, and in conjunction with LB rock and LB bearing properties. From examination of the Atkins V&V summarised properties in the NGL 1iii response, looking at the UB column in the tables, it is apparent that the bearing stiffness dominates the overall lateral translational stiffness K_Uxy. [1.52E+10 for bearings in series with 1.881E+11 for rock, gives 1.406E+10 combined, and	24

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			is dominated by the bearings. This compares to the backfill stiffness acting in parallel of only 8.581E+09. Hence the bearings dominate the lateral stiffness.] However, when making comparisons on the damping coefficients C_Uxy it is apparent that the damping is being dominated by the backfill. [5.28E+07 for bearings in series with 1.947E+09 for rock, gives 5.14E+07 combined, and is dominated by the bearings. This compares to the backfill damping coefficient acting in parallel of 3.078E+08. Hence the backfill dominates the lateral damping coefficient.] The Reviewer has a concern that a case consisting of e.g. UB bearing stiffness and damping, combined with a gapping case of LLB backfill, is a legitimate but omitted case. The overall stiffness might not be as high as the UB case in the tables but would still be high, and the damping (which in the UB case was previous dominated by the damping in the backfill) would be significantly reduced. [We might postulate the stiffness would be 1.52E+10 (UB bearings) in series with 1.881E+11 (UB rock), giving 1.406E+10 combined. This would be in parallel with 6.686E+08 (LLB backfill), to give a total stiffness of 1.473E+10. This stiffness lies between the BE and UB cases. The damping coefficients would be 5.28E+07 (UB bearings) in series with 1.947E+09 (UB rock), giving 5.14E+07 combined. This would be in parallel with	

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			will serve to illustrate the effect of change which principally alters the damping in the model, this arising from a change to the backfill.	