Agreement to NP/SC 7810 - Graphite Core: Safety Case for Operation After the Onset of Keyway root Cracking

Heysham 2 and Torness Power Stations

Project Assessment Report

Project Assessment Report ONR-OFD-PAR-22-004
Revision 1
June 2022

Report ONR-OFD-PAR-22-004
CM9 Ref: 2022/32318

Published 06/2022

For published documents, the electronic copy on the ONR website remains the most current publicly available version and copying or printing renders this document uncontrolled.

EXECUTIVE SUMMARY

Title

Agreement to NP/SC 7810 – Heysham 2 and Torness Power Stations, Graphite Core: Safety Case for Operation After the Onset of Keyway root Cracking EC 366563 (Heysham 2) and 366568 (Torness).

Permission Requested

EDF Energy Nuclear Generation Limited (EDF NGL), under arrangements made under Licence Condition 22(1), has applied for Review and Consideration from the Office for Nuclear Regulation (ONR) for NP/SC 7810, Graphite Core: Safety Case for the Operation After the Onset of Keyway Root Cracking for the reactor cores of Heysham 2 and Torness Power Stations.

ONR subsequently notified EDF NGL, under the arrangements made by the licensee under Licence Condition 22(1) of Schedule 2 attached to Nuclear Site Licences 60 and Sc.14 to control any modification or experiment carried out on any part of the existing plant or processes, that the licensee shall not commence nor thereafter proceed with NP/SC 7810 without the Agreement of the ONR, which will be issued via a licence instrument following ONR's assessment of NP/SC 7810.

Background

The graphite core of each of the reactors at Heysham 2 and Torness power stations consist of a large assembly of graphite components that are keyed together to form channels for fuel assemblies and control rods. The fundamental nuclear safety requirements of a graphite core are to:

- Allow unimpeded movement of control rods and fuel.
- Direct gas flows to ensure adequate cooling of the fuel, core and related structures.
- Provide neutron moderation and thermal inertia. This is not significantly affected by brick cracking and is addressed by graphite weight loss safety cases.

It has long been understood that the irradiation of the graphite leads to dimensional and material changes. These changes could eventually lead to the generation of cracking in the fuel channel graphite bricks. There are two types of cracking:

- one associated with the early reactor life referred to as bore cracking; and
- another associated with the late reactor life referred to as keyway root cracking (KWRC).

Bore cracking is limited in nature, but keyway root cracking is an active mechanism late in the reactor life that can lead to wide-spread cracking of fuel channel graphite bricks.

This cracking has the potential to affect the key nuclear safety requirements above and consequently it needs to be demonstrated that these requirements continue to be met in normal operation, fault conditions and after a design basis seismic event.

This Project Assessment Report (PAR) considers NP/SC 7810 which is the post keyway root cracking safety case for the reactor cores at Heysham 2 and Torness. The proposed case, NP/SC 7810, underwrites the safety justification beyond the 'essentially intact' limitation defined in the extant safety case NP/SC 7663. The validity of the proposed case NP/SC is limited by a core burn-up of 16.5 TeraWatt day (TWd).

NP/SC 7810 presents evidence of:

- Damage tolerance Assessments to define a Damage Tolerance Boundary on the number and type of cracked bricks.
- Core cracking forecasts after further periods of operation, based on inspections and analytical and statistical tools, that are bounded by the Damage Tolerance Boundary with adequate margin.

Future core inspection results throughout the validity period of the proposed case will be reviewed by ONR to ensure compliance with limits of the proposed case.

Assessment and inspection work carried out by ONR in consideration of this request

ONR's assessment of NP/SC 7810 has focussed on whether cracking observed or predicted to occur in the graphite bricks that form the reactor core could compromise the key nuclear safety requirements of the Heysham 2 and Torness reactors. Assessments have been carried out by the following specialist inspectors from:

- External Hazards Specialism;
- Civil Engineering Specialism;
- Structural Integrity Specialism - Graphite; and
- Fault Studies Specialism.

Matters arising from ONR's work

Following assessment, all specialist inspectors consider that the issue of ONR's Agreement to the Heysham 2 and Torness post keyway root cracking safety case, NP/SC 7810, is acceptable. In support of their assessments, ONR's specialist inspectors have engaged with EDF NGL in technical discussions to ensure that key issues have been adequately addressed.

Conclusions

It is concluded that EDF NGL has provided an adequate justification underpinning NP/SC 7810, the Post Keyway Root Cracking safety case for Heysham 2 and Torness reactors up to a core burn-up of 16.5 TWd and that a Licence Instrument should be issued to EDF NGL. Core inspections will take place regularly and the results of these inspections will be examined by ONR to ensure compliance with the safety case.

Recommendation

It is recommended that:

Licence instruments 638 and 564 are granted to Heysham 2 and Torness Power Stations, respectively, Agreeing to implementation of the proposed safety case NP/SC 7810.

LIST OF ABBREVIATIONS

AGR	Advanced Gas Cooled Reactor
AFoO	Annual Frequency of Occurrence
ASCE	American Society of Civil Engineers
ALARP	As low as reasonably practicable
DCB	Doubly Cracked Brick
DTA	Damage Tolerance Assessment(s)
DTB	Damage Tolerance Boundary
EA	Environment Agency
EDF NGL	EDF Energy Nuclear Generation Limited
fpy	Full Power Year
HPB	Hinkley Point B Power Station
HNB	Hunterston B Power Station
HYB	Heysham 2 Power Station
INA	Independent Nuclear Assurance
INSA	Independent Nuclear Safety Assessment
JPSO	Justified Period of Safe Operation
KWRC	Keyway Root Crack, Keyway Root Cracking, Keyway Root Cracked
LC	Licence Condition
MCB	Multiply Cracked Brick
NSC	Nuclear Safety Committee
ONR	Office for Nuclear Regulation
PAR	Project Assessment Report
PCPV	Pre-stressed Concrete Pressure Vessel
PSD	Primary Shutdown System
R	Reactor
RGP	Relevant Good Practice
SAP	Safety Assessment Principle(s)
SCB	Singly Cracked Brick
SEPA	Scottish Environment Protection Agency
SHWP	Seismic Hazard Working Party
SRGW	Seal Ring Groove Wall

SSD	Secondary Shutdown System
SSI	Soil Structure Interaction
TOR	Torness Power Station
TSD	Tertiary Shutdown System
TWd	TeraWatt Day
URS	Uniform Risk Spectra

TABLE OF CONTENTS

Figures:

1 PERMISSION REQUESTED

1. EDF Energy Generation Limited (EDF NGL), under arrangements (Ref. 1) made under Licence Condition 22(1): *Modification or experiment of existing plant*, has applied for Review and Consideration (Refs. 2 and 3) from the Office for Nuclear Regulation (ONR) for NP/SC 7810, Graphite Core: Safety Case for the Operation After the Onset of Keyway Root Cracking for the reactor cores of Heysham 2 and Torness Power Stations (Refs. 2 and 3).

2. ONR subsequently notified EDF NGL (Refs. 4 and 5), under the arrangements made by the licensee under Condition 22(1) of Schedule 2 attached to Nuclear Site Licences 60 and Sc.14 to control any modification or experiment carried out on any part of the existing plant or processes, that the licensee shall not commence nor there after proceed with NP/SC 7810 without the Agreement of the ONR, which will be issued via a licence instrument following ONR's assessment of NP/SC 7810.

3. NP/SC 7810 is valid up to a core burn-up of 16.5 TeraWatt day (TWd) (i.e., ~ 30 full power years (fpy)).

4. This Project Assessment Report (PAR) has been produced to record ONR's decision on the adequacy of the proposed safety case.

2 BACKGROUND

5. Heysham 2 (HYB) and Torness (TOR) Power Stations each have two advanced gas cooled Reactors (AGR). The reactors of Heysham 2 are referred to as Reactor 7 (R7) and Reactor 8 (R8). The reactors at Torness are referred to as Reactor 1 (R1) and Reactor 2 (R2). Each reactor core is a large assembly of graphite bricks keyed together via a keying system, see **Figure 1**, to form channels for fuel assemblies and control rods. Each core contains around 3000 fuel channel graphite bricks. For brevity these bricks are referred to as fuel bricks. The core is supported by a steel structure and contained within a prestressed concrete pressure vessel (PCPV).

6. Ceramic uranium oxide fuel is contained within fuel assemblies in channels in the graphite core, see **Figure 2**. Control rods, containing boron, move within control rod channels in the graphite core to control the nuclear reaction and to shut-down the reactor.

7. The control rods are the primary means of controlling the nuclear reaction and shutting down the reactor. They make up the primary shutdown system (PSD). At HYB and TOR, a nitrogen injection system is available as another means of shutting down the reactor and is referred to as the secondary shutdown system (SSD). The SSD is supported by a tertiary shutdown system (TSD) of boron bead injection to maintain long term holddown.

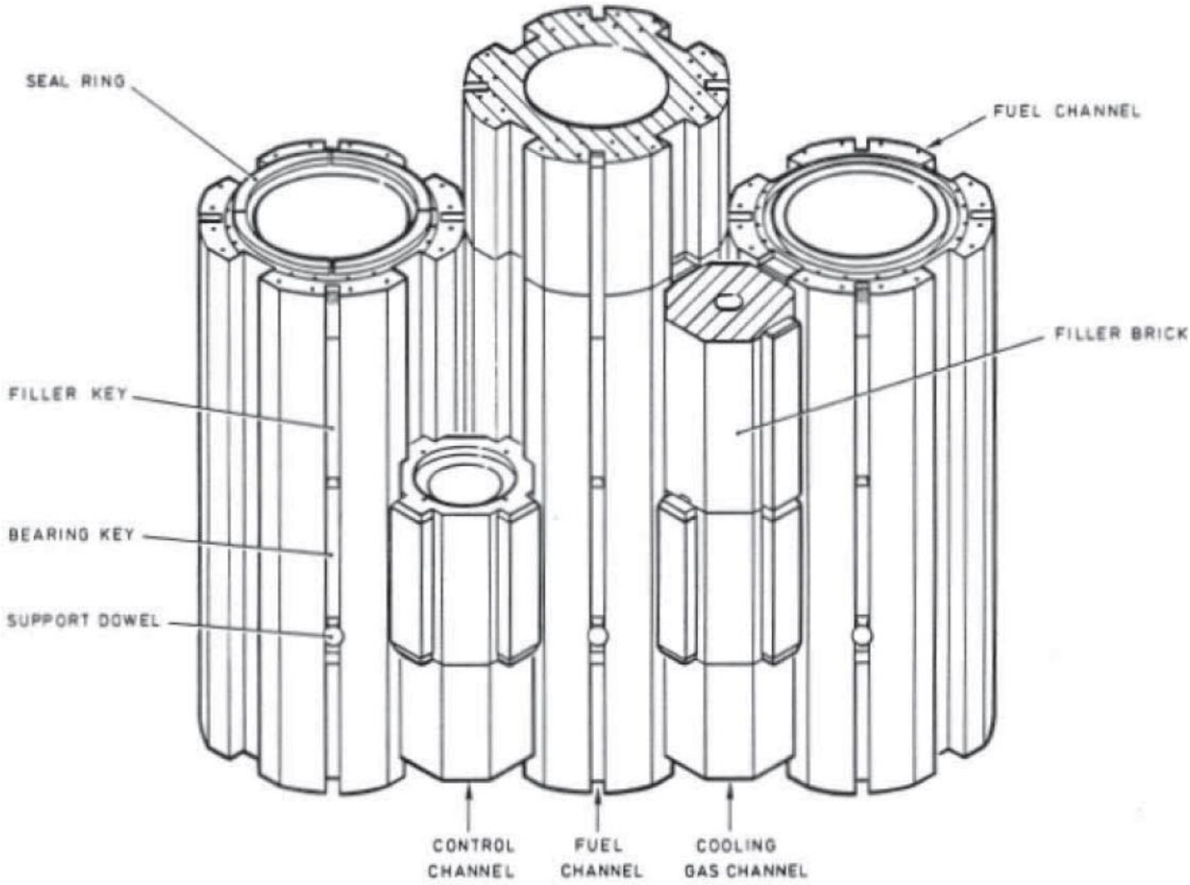

Figure 1. Graphite Core Arrangement.

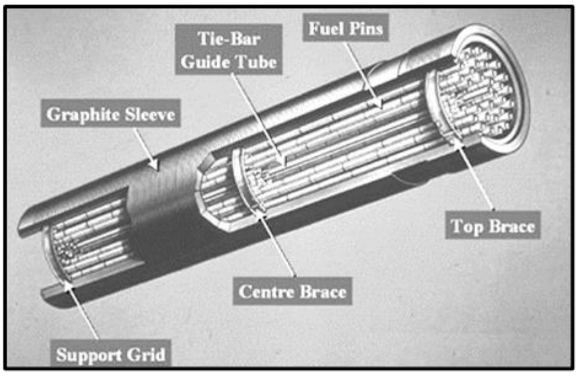

Figure 2. Example of an AGR fuel element.

8. The fundamental nuclear safety requirements of a graphite core are to (Refs. 2 and 3):

- Allow unimpeded movement of control rods and fuel.

- Direct gas flows to ensure adequate cooling of the fuel, core and related structures.
- Provide neutron moderation and thermal inertia. This is not significantly affected by brick cracking and is addressed by graphite weight loss safety cases.

9. The specific nuclear safety issues addressed by the proposed safety case NP/SC 7810 (Refs. 2 and 3) relate to the potential for fuel brick cracking and associated fragments and debris to:

- Impede the movement of control rods and fuel, with the former degrading primary shutdown system effectiveness in terms of shutdown and holddown capability;
- Degrade the cooling of the fuel, core and related structures;
- Affect fuel handling risk; and
- Reduce the very short term effectiveness of the nitrogen component of the Secondary Shutdown system.

10. It has long been understood that the irradiation of the graphite leads to dimensional and material changes. These changes could eventually lead to the generation of cracking in the fuel channel graphite bricks. There are two types of cracking:

- one associated with the early reactor life referred to as bore cracking; and
- another associated with the late reactor life referred to as keyway root cracking (KWRC). A KWRC could also bring forward cracking in a neighbouring fuel brick and this is referred to as ‘induced cracking’.

11. Bore cracking is limited in nature, as the tensile stresses at the brick bore reverse into compressive stresses as the reactor core ages, reducing the likelihood of crack initiation from the bore significantly.

12. The keyway root cracking is an active mechanism late in the reactor life that can lead to wide-spread cracking of the fuel bricks. This is because at high irradiation, i.e., later in the reactor life, tensile stresses are generated at the outer section of the brick wall where keyway features are present by design, see **Figure 1**. These keyway features at the brick periphery act as stress concentration sites where cracks could initiate from the keyway root and propagate through the brick wall to the bore leading to a keyway root crack. **Figure 3** shows an example of a keyway root crack in a graphite brick, as seen from the fuel channel bore, during a core inspection.

13. Further irradiation of a keyway root cracked brick could lead to crack opening and/or the generation of further cracking. Therefore, keyway root cracking has the potential to affect the first two nuclear safety requirements above (see

paragraph 8) and consequently the safety case needs to demonstrate that there are no significant implications for these requirements arising from KWRC.

14. Keyway root cracking has been observed in the leading reactors at the stations of Hunterston B and Hinkley Point B since 2014. The reactors at HYB and TOR are at an age, in terms of core burn-up, where keyway root cracking is predicted to occur. Inspection observations have confirmed that keyway root cracking has started at HYB R7 and TOR R1. No KWRC has been observed in HYB R8 and TOR R2 to date.

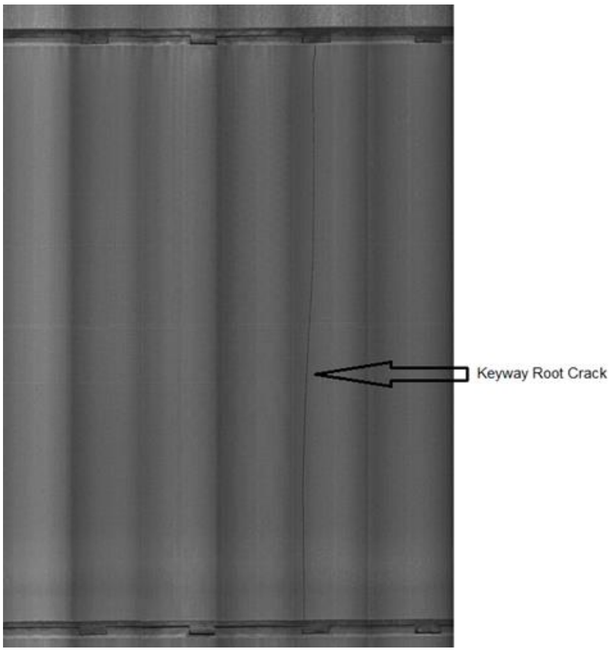

Figure 3. Example of an AGR keyway root crack in a fuel channel graphite brick.

15. A single KWRC was observed in HYB R7 during the 2021 inspection campaign. Further KWRCs were observed in the same reactor during an inspection campaign in March 2022. No KWRC was observed at HYB R8 to date with latest inspections carried out in the January 2022.

16. Three KWRCs were observed at TOR R1 in January 2022 and no KWRC was observed in TOR R2 to date with latest inspections being carried out at the time of writing this PAR.

17. A fuel brick with a single full height KWRC as shown in the example in **Figure 3** is termed a Singly Cracked Brick (SCB). If a second KWRC crack develops, the cracked brick is termed a Doubly Cracked Brick (DCB). A brick with more than two full height axial cracks is referred to as a Multiply Cracked Brick (MCB).

18. Current understanding from reactor observations and analysis work is that the progression of cracking from SCB to DCB to MCB in a subject brick as well as the increase in the opening of a crack in an SCB are gradual with further

irradiation. It is important to note that no DCB or MCB associated with keyway root cracking has been observed in the HYB or TOR reactors.

19. The HYB and TOR reactors currently operate under the extant graphite core safety case, NP/SC 7663 (Ref. 6). This case supports operation up to a core state that is considered 'essentially intact'. An 'essentially intact' core is defined as a core with fewer than 10% axially cracked bricks (singly or doubly cracked) and a single cracked brick opened by no more than 12 mm at the outer diameter.

20. Following the observation of a KWRC in HYB R7, NGL produced operational safety cases, ECs 369321 / 369716 (Ref. 7), imposing core burn-up limits in compliance with the essentially intact limit of the extant safety case NP/SC 7663. Following the inspection campaigns in 2022 at HYB R8 and TOR R1, NGL produced a further operational safety case referred to as the "Bridging Case", ECs 370264 / 370263 (Ref. 8), which extends operation under the same principle of compliance with the essentially intact limit defined in NP/SC 7663.

21. The onset of KWRC in HYB R7 and TOR R1 have indicated that the "essentially intact" limit could be reached after a limited period of further operation. Therefore, a safety case to operate with a larger extent of cracked bricks in fuel channels is required. The proposed safety case (Refs. 2 and 3) presents Damage Tolerance Assessments (DTA) to underwrite safe operation of the reactor cores beyond the 'essentially intact' limitation defined in the extant safety case, NP/SC 7663. The Damage Tolerance Assessments consider up to and including cracking of 100% of the fuel bricks in the central core region.

22. The core configurations analysed in the DTA for the 100% cracked core are used to define the Damage Tolerance Boundary (DTB) for the proposal in terms of the number and type of cracked bricks and crack width distribution. The supporting analysis is mainly performed at a core irradiation of 17 TWd. To provide margin, the safety case restricts operation up to a core burn-up of 16.5 TWd. This limit is supported by core state projections that show the crack configurations assessed at the Damage Tolerance Boundary bound those expected at a core irradiation of 16.5 TWd with a margin.

23. The fuel bricks in HYB and TOR reactors utilise a sealing ring arrangement within a thin-walled groove in the brick end faces, see **Figure 1**. This feature is predicted to crack in bricks affected by keyway root cracking and generating fragments and debris. This feature is unique to the HYB/TOR reactors. Justification for operation with this potential SRGW debris is the subject of other parallel safety cases. The safety cases for SRGW debris that are currently in place and being progressed impose limits on allowable levels of core cracking and core burn-up that are more restrictive than those arising from the proposed KWRC safety case.

24. The main aspects of the proposed safety case and the sections of this report in which they are discussed are as follows:

- An updated ground motion for seismic assessments; see Section 3.1.1.
- Core state forecasts and defining a Justified Period of Safe Operation (JPSO), see Section 3.1.3.1.
- Normal operation, fault and seismic damage tolerance assessments (DTA) to define a damage tolerance boundary (DTB), see Section 3.1.3.2.
- Consequences of core distortion on fuel cooling and fuel handling, see Section 3.1.4.
- Resolution of safety case anomaly associated with the nitrogen injection system (i.e., the SSD), see Section 3.1.4.2.

3 ASSESSMENT AND INSPECTION WORK CARRIED OUT BY ONR IN CONSIDERATION OF THIS REQUEST

25. In accordance with the regulatory permissioning strategy (Ref. 9), ONR has carried out the following specialist assessments:

- External Hazards (Ref. 10)
- Civil Engineering (Ref. 11)
- Structural Integrity – Graphite (Ref. 12)
- Fault Studies (Ref. 13)

26. It should be noted that ONR specialist inspectors have engaged with EDF NGL in detailed technical discussions and have raised and resolved a number of technical issues (Ref. 14) throughout their assessments of NP/SC 7810. This report does not attempt to summarise all the questions raised and answers provided. However, they are captured in the relevant specialist assessment reports.

3.1 ASSESSMENT FINDINGS

3.1.1 EXTERNAL HAZARDS ASSESSMENT

27. EDF NGL has utilised the Uniform Risk Spectra (URS) developed by the Seismic Hazard Working Party (SHWP) in the 1990s to define the seismic hazards for each station. The URS were based on site specific hazard evaluations and are different for each station.

28. EDF NGL has used the URS with an annual frequency of occurrence (AFoO) of 1×10^{-4} /yr to define an infrequent design basis seismic event.

29. To demonstrate lack of cliff edge effect beyond the design basis, EDF NGL has also considered beyond design basis seismic events with AFoO of:

- 5×10^{-5} /yr;

- 2.5×10^{-5} /yr; and
- 1×10^{-5} /yr.

30. EDF NGL has generated ground motions for each station based on spectral matching of time histories from real earthquake records to the site-specific URS. These ground motions are used as input to the analysis of the graphite core response to a seismic event.

31. For each AFoO event, EDF NGL has generated five sets of time histories for each station based on the guidance in American Society of Civil Engineers (ASCE) 43-05 (Ref. 15) and ASCE 4-16 (Ref. 16).

32. For the design basis analysis, EDF NGL has carried out a down-selection process to select a bounding set of ground motion time histories. This was done to reduce the large number of analysis runs required when using the five sets of ground motions.

33. The ONR External Hazards assessment (Ref. 10) has considered the adequacy of the aforementioned matters to ensure that the seismic input to the graphite core seismic analysis used in NP/SC 7810 is appropriate and complies with relevant good practice (RGP), and any deviations from relevant codes and standards are appropriate and justified.

34. The external hazards specialist inspector has found some minor shortfalls compared with relevant good practice. However, these are judged to not be significant given the overall conservative nature of the analysis that underpins the safety submission in NP/SC 7810. The specialist inspector raised two recommendations for NGL to:

- ***Recommendation**: The dutyholder should be explicit in future safety case documentation whether an external hazard is characterised on the basis of annual frequency of occurrence, or annual frequency of exceedance. The dutyholder should ensure that all supporting documentation are also explicit, and consistent with the over-arching safety submission. Any deviations should be explicitly highlighted and justified.*
- ***Recommendation**: The dutyholder should determine the implications for Heysham 2 and Torness seismic hazard arising from the independent peer review work currently being undertaken for Heysham 1 and Hartlepool. The implications should be communicated to ONR within a timely manner and, where appropriate, incorporated into relevant safety cases.*

35. These recommendations will be tracked through normal regulatory business to their completion by the specialist inspector.

36. Overall, the specialist inspector judges that NP/SC 7810 provides an adequate safety justification for the continued operation of Heysham 2 and Torness

reactors post keyway root cracking and to a core irradiation limit of 16.5 TWd. Inputs to the DTA are conservative and a range of sensitivity studies have been undertaken.

37. The specialist inspector judges the seismic hazard inputs meet the expectations of the relevant SAPs. The licensee has also provided an adequate beyond design basis analysis, which the specialist inspector judges, meets the expectations of the relevant SAPs. On this basis, the specialist inspector has recommended permissioning of the proposed safety case NP/SC 7810 from an external hazards perspective.

3.1.1.1 EXTERNAL HAZARDS CONCOLUSION

38. To conclude, the specialist external hazards inspector is satisfied with the claims, arguments and evidence presented within EDF NGL's safety case and the risks have been reduced to ALARP for the defined validity of the safety case. It is judged that the proposal is sufficient, from an external hazards perspective, to justify the issue of a Licence Instrument for ONR's Agreement, under arrangements made under Licence Condition 22(1), to the implementation of NP/SC 7810 by Heysham 2 and Torness Power Stations, with a validity period up to a core burn-up of 16.5 TWd.

3.1.2 CIVIL ENGINEERING ASSESSMENT

39. There are aspects of the proposed graphite safety case associated with the seismic DTA that fall within the scope of civil engineering.

40. The seismic input motions for the graphite core are transferred from the foundations, through the pre-stressed concrete pressure vessel (PCPV) and into the core. The models and judgements used to represent these civil structures have an important role in deriving the seismic input motions for the graphite core.

41. Consequently, the civil engineering specialist inspector has considered the adequacy of the data, modelling assumptions and judgements associated with the civil structures used to derive the core input motions (Ref. 11). The specialist inspector focused on the following areas:

- Concrete foundations and concrete restraining support ring;
- Bitumen in-fill;
- Elastomeric bearings; and
- A cross consideration with the external hazards assessment of the soil structure interaction (SSI).

42. The specialist inspector judges that due consideration has been taken, by the licensee, within the case to provide evidence of a set of bounding permutations and combination of the various parameters when deriving the seismic input motions for the graphite core.

43. The specialist inspector has found that the licensee has generally followed good practice within relevant codes and standards. However, the specialist inspector has noted that the ASCE 43-19 (Ref. 17) is the extant code and as such the licensee should have reviewed the requirements of this version against the previous 43-05 version used in the safety case. Therefore, the specialist inspector has made the following recommendation:

- ***Recommendation**: NGL should confirm review of extant ASCE 43-19 requirements were considered.*

44. This recommendation will be tracked through normal regulatory business to its completion by the specialist inspector.

45. The specialist inspector has concluded that they are satisfied with the civil engineering aspects of the claims, arguments and evidence presented within the proposed safety case. They therefore have no objection to recommending issuing of an Agreement to the proposed case from a civil engineering perspective.

3.1.2.1 CIVIL ENGINEERING CONCLUSION

46. To conclude, the civil engineering specialist inspector is satisfied with the claims, arguments and evidence presented within EDF NGL's safety case and the risks have been reduced to ALARP for the defined validity of the safety case. It is judged that the proposal is sufficient, from a civil engineering perspective, to justify the issue of a Licence Instrument for ONR's Agreement, under arrangements made under Licence Condition 22(1), to the implementation of NP/SC 7810 by Heysham 2 and Torness Power Stations, with a validity period up to a core burn-up of 16.5 TWd.

3.1.3 GRAPHITE STRUCTURAL INTEGRITY ASSESSMENT

47. The structural integrity specialist inspector has focussed their assessment (Ref. 12) of NP/SC 7810 on ensuring that the licensee has presented an adequate safety case to justify that the nuclear safety functions of the graphite reactor core are maintained in the presence of graphite brick cracking over the proposed period of operation. They therefore focussed on the following areas:

- Whether the licensee has adequately demonstrated confidence in the Primary Shutdown system (PSD) for normal operation, faults and during an infrequent seismic event (1 in 10,000 year event).
- Whether the licensee has adequately estimated the fuel sleeve gapping during normal operation and faults (excluding seismic events) such that the impact on fuel cooling can be determined.
- Whether the licensee has adequately estimated the interstitial brick gapping within the Secondary Shutdown system (SSD) channels such that the effect on the shutdown and holddown can be evaluated.

- Whether, from a graphite perspective, the licensee has provided confidence that the risk from operation with a higher level of brick cracking remains as low as reasonably practicable (ALARP).

48. The methodologies underpinning the evidence supporting the claims and arguments of the proposed safety case, NP/SC 7810, have been previously used for recent graphite core safety cases for the Hinkley Point B and Hunterston B reactors, which have already been considered by ONR (Refs. 18 and 19). However, some new developments to the methodologies have been adopted and new results have been presented for HYB and TOR. The specialist inspector therefore focussed on the adequacy of the new methodologies and the new results provided to support the proposed safety case, rather than re-examining existing methodologies.

3.1.3.1 CORE STATE FORECASTS

49. The proposed safety case is an overarching safety case under which operational safety cases will be produced defining a Justified Period of Safe Operation (JPSO) for each reactor following graphite inspections.

50. The licensee defines the JPSO as a period of operation during which it has been demonstrated the graphite core would not exceed any operational allowances or limits in the safety case associated with ageing and degradation. This includes limits enforced by the proposed safety case and the parallel extant graphite safety cases covering the Seal Ring Groove Wall (SRGW) Debris and graphite weight loss.

51. For the proposed brick cracking safety case, the safety case limits are set on core irradiation and the extent and morphology of brick cracking required to give confidence that a margin will be maintained to the Damage Tolerance Boundary (DTB).

52. The DTB defined in the proposed safety case is a core irradiation of 17.0 TWd, with crack configurations as described in the Damage Tolerance Assessments (DTA), including 100% cracking (1656 fuel bricks) within the central core. The licensee is proposing an operational limit on core burn-up of 16.5 TWd (~30 fpy) to provide a margin to the DTB.

53. The concept of defining a JPSO with a margin to a DTB is illustrated in **Figure 4**.

54. At 16.5 TWd, the licensee anticipates at a high calculational confidence level of 99.9% that ~ 43% - 45% of the graphite bricks of fuel channels will crack in the central core (layers 3 to 8 and rings 1 to 9). This has been generated through a methodology known as CrackSim. This method has been used extensively for HPB/HNB and HYB/TOR and has been reviewed by ONR previously.

55. Although the specialist inspector is content that the licensee has considered a core state which is conservative within the limits of NP/SC 7810, the specialist inspector states that there exists an uncertainty in all graphite core state forecasts which becomes more pronounced the further into the future a forecast is made. Because KWR cracking at HYB/TOR has just begun, the forecasts for HYB/TOR are based on a small number of observations at the time the case was made. Therefore, projecting a considerable length of time into the future, e.g., to 16.5 TWd (~ late 2023 for the leading reactor), inevitably includes significant uncertainty and forecasts are susceptible to changes based on inspection observations.

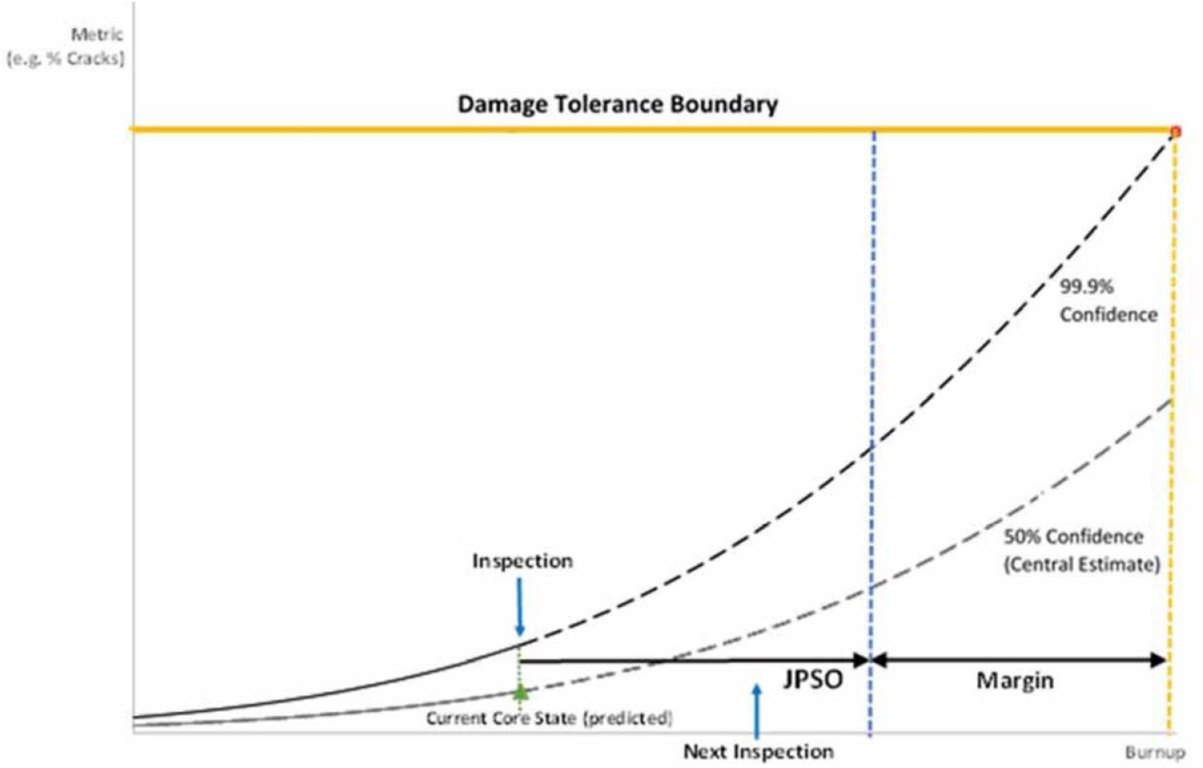

Figure 4. Illustration of Justified Period of Safe Operation, Margin and Damage Tolerance Boundary (Ref. 2).

56. The specialist inspector takes confidence from the available margins demonstrated by the licensee between the core state of ~45% cracking expected at a core burn-up of 16.5 TWd and the DTB of 100% cracking. The specialist inspector considers this margin to be adequate based on the expectation that the licensee will monitor the core states against the assumptions used to generate the DTB. ONR will have visibility of the future inspection observations through routine regulatory interactions and any challenge to the margin afforded by the DTB will be discussed at these interactions and justified by EDF NGL if necessary.

3.1.3.2 DAMAGE TOLERANCE ASSESSMENTS (DTA)

57. To demonstrate tolerance to brick cracking, EDF NGL has provided DTA for (a) normal operation and plant-based faults conditions using the AGRIGID methodology and (b) for an infrequent seismic event (with AFoO of 10^{-4} (1 in 10,000) per annum) using the GCORE methodology. The DTA are carried out at levels of cracking that are considerably higher than the levels of cracking forecast as referred to in Section 3.1.3.1 above, to a high calculational confidence level (99.9%) over the validity period of the proposed safety case of core burn-up of 16.5 TWd. The DTA are used to define the DTB.

58. The AGRIGID and GCORE methodologies employed to support the proposed safety case are similar to those employed in recent graphite safety cases for HPB and HNB. However, EDF NGL has introduced new developments specific to the core design of HYB/TOR. The specialist inspector focussed on the adequacy of the new developments and the new analysis results, rather than re-examining existing methodologies.

59. EDF NGL has supported the baseline GCORE and AGRIGID analyses, that define the DTB, with comprehensive sets of sensitivity studies to cover the uncertainties in the analysis parameters and to demonstrate that no sudden changes in core behaviour are expected within the DTB.

60. The baseline GCORE and AGRIGID analyses, defining the DTB, contained:

- up to 934 SCBs with different crack widths up to 18mm; and
- up to 722 DCBs.

That is, all the graphite bricks in the fuel channels of the central region of the core are assumed to have cracked.

61. EDF NGL stated that MCBs have not been explicitly included in the analyses. EDF NGL argues that within the period of validity of NP/SC 7810 (Refs. 2 and 3), it is their assumption that few if any MCBs are expected to be generated. The licensee has stated that work is already being progressed to introduce a MCB modelling capability into the models in order to support future safety case updates. The specialist inspector is of the opinion that whilst it is preferable that MCBs are included for the purposes of conservatism, the licensee has included sensitivity studies where 100% DCBs are assumed. The specialist inspector considers that this should bound the response if the small number of MCBs anticipated were included in the analysis.

62. Based on their consideration of the models and the predicted response of the core, the specialist inspector is content that the graphite core will not hinder the operation of the PSD within the validity period of NP/SC 7810 in normal operation, plant-based faults and during an infrequent seismic event.

3.1.3.3 ALARP POSITION

63. The licensee states that the proposed safety case NP/SC 7810 (Refs. 2 and 3) considers the potential for the fundamental safety functions of the graphite core to be challenged as a result of brick cracking, distortion and debris. The licensee argues that the safe operation of the reactor within the validity of NP/SC 7810 (16.5 TWd) has been justified.

64. The licensee has carried out an ALARP optioneering process to consider additional activities that could reduce the risk further. The specialist inspector has considered, from a graphite perspective, the following options:

- Use Failure Modes & Effects Analysis techniques to increase the level of understanding of core distortion mechanisms (in this case, brick cracking) in turn increasing confidence in the existing modelling regime.
- Diverse set of input data for core analysis models such that no single set of input data is relied upon for one or more core analysis routes i.e. material input data.
- Undertake inspections of control rod channels in-air.
- Lift and resit an additional selection of fuel stringers during refuelling to gather load trace data.

65. The licensee has concluded that all reasonably practicable options to ensure risk arising from core distortion and cracking are underway or have been identified for further investigation.

66. The specialist inspector has considered the option for control rod inspection further. The licensee states that control rod channel inspections are already performed and does not consider it necessary to increase the number of inspections to support the safety case. The specialist inspector notes that at this time only visual inspection of the control rod channels are performed. The specialist inspector is of the opinion that through visual inspections it is only possible to reveal gross changes (e.g., cracking or large displacements). They consider that it would provide greater confidence in the core distortion predictions if information on the bore diameter and the shape of the control rod channels could be obtained. Therefore, the specialist inspector has raised a recommendation to capture this observation which will be tracked through normal regulatory business to its completion by the specialist inspector:

- ***Recommendation:*** *To support the validation of the analyses, the licensee should consider the benefits of measuring the bore diameter of the control rod channels at HYB /TOR. If it is deemed not appropriate to conduct these inspections the licensee should provide a robust ALARP argument.*

67. However, the specialist inspector recognises that this activity is not simple and would take time to implement. Therefore, whilst they are raising this

recommendation, they do not think it undermines the basis for operation under NP/SC 7810.

68. The specialist inspector is content that the licensee, within NP/SC 7810 has, from a graphite perspective, reached an adequate ALARP position.

3.1.3.4 STRUCTURAL INTEGRITY CONCLUSION

69. To conclude, the graphite structural integrity specialist inspector is satisfied with the claims, arguments and evidence presented within EDF NGL's safety case and the risks have been reduced to ALARP for the defined validity of the safety case. It is judged that the proposal is sufficient from a structural integrity perspective to justify the issue of a Licence Instrument for ONR's Agreement, under arrangements made under Licence Condition 22(1), to the implementation of NP/SC 7810 by Heysham 2 and Torness Power Stations, with a validity period up to a core burn-up of 16.5 TWd.

3.1.4 FAULT STUDIES ASSESSMENT

70. The fault studies specialist inspector has focussed their assessment (Ref. 13) of NP/SC 7810 on determining whether EDF NGL has presented an adequate safety case to justify that the nuclear safety functions of the graphite reactor core are maintained over the proposed period of operation for the HYB and TOR reactors and that the risks associated with core distortion have been reduced to ALARP. Therefore, they have focused on the effects of core distortion on control rod entry, fuel movement and core cooling. They have also considered the effect of core distortion on the efficacy of the nitrogen injection of the Secondary Shutdown (SSD) System.

71. The scope of the fault studies assessment covered:

- Assessment of the risks associated with free movement of control rods and fuel assemblies.
- Assessment of the justification of shutdown capability.
- Assessment of the risks associated with core cooling.

72. Previous graphite safety cases for HNB and HPB, as well as for HYB and TOR have been assessed by ONR fault studies specialist inspectors. These safety cases employed some of the same arguments and evidence presented in the proposed safety case NP/SC 7810. The specialist inspector has therefore discussed the conclusions and applicability of these assessments where appropriate, rather than re-examining existing methodologies.

3.1.4.1 CONTROL ROD AND FUEL MOVEMENT

73. The effect of core distortion due to the presence of cracking on the free movement of control rod and fuel assemblies have been covered largely by the graphite structural integrity assessment (Section 3.1.3).

74. Therefore, the specialist inspector has focused on plant-based faults that could affect the control rod insertions that have not been covered by the damage tolerance assessments considered in the graphite structural integrity assessment.

3.1.4.2 SHUTDOWN CAPABILITY

75. Whilst the specialist inspector is satisfied that EDF NGL has adequately justified its claim that control rod entry is unaffected by core distortion (within the limits of 7810), it is their expectation that EDF NGL also demonstrates a diverse means of shutting down is also available with a sufficient reliability. EDF NGL claims that this capability at HYB and TOR is provided by the SSD (and TSD for hold-down).

76. The diverse shutdown system at HYB and TOR comprises the following:

- A nitrogen injection system which is initiated automatically, should insufficient control rods fall into the core on demand, to provide reactor shutdown and short-term holddown (referred to as SSD).
- A boron bead injection system which is initiated manually to provide long-term holddown following nitrogen injection (referred to as TSD).

77. The SSD and TSD are designed to inject the nitrogen and boron beads into interstitial channels. Whilst not designed to be completely sealed, the axial connections between the interstitial bricks were designed such that leakage into the adjacent arrowhead passages would be insignificant.

78. A safety case anomaly was identified in 2021 such that the current predicted levels of brick bowing, and core distortion could cause larger inter brick gaps between vertical SSD graphite bricks than were previously justified. This could cause nitrogen to leak from SSD channels at a higher rate than was previously modelled and challenge the claim on the nitrogen injection system to sufficiently reduce reactivity and nuclear heat generation in a fault where shutdown via the control rod system has been unsuccessful. The efficacy of the nitrogen injection secondary shutdown system is therefore also considered in NP/SC 7810.

79. The fault studies assessment has considered EDF NGL's analysis of nitrogen distribution and its effect on reactivity (and therefore peak cladding temperature). The assessment has considered the fault analysis methodology, the faults considered, the results of EDF NGL's nitrogen distribution analysis and peak cladding temperature assessment, and the uncertainty analysis.

80. EDF NGL has re-evaluated the predictions of inter-brick gapping for core state predictions up to 16.5 TWd using the AGRIGID model. In co-operation with the graphite structural integrity specialist inspector, the fault studies specialist inspector is content that EDF NGL has determined a suitable range of initial conditions for the analysis of the nitrogen distribution (Ref. 13).

81. The specialist inspector states that they are satisfied that the substantiation provided by EDF NGL for the nitrogen injection system is adequate for the proposed safety case and its period of validity. The specialist inspector considers that EDF NGL has undertaken a reasonable review of the conservatisms and uncertainties in the analysis methods.

82. The specialist inspector also notes that plant modifications are in progress at all four reactors to improve and seismically qualify the nitrogen injection and boron bead systems. These modifications are in progress and EDF NGL has not identified any additional reasonably practical measures. Therefore, the specialist inspector judges that EDF NGL has adequately demonstrated that risks related to reactor shutdown and hold-down over the proposed operating period are reduced to ALARP.

83. To better define the available margin and reducing uncertainty, the specialist inspector has raised the following recommendation which will be tracked to its conclusion via a regulatory issue:

- ***Recommendation**: NGL to supply to ONR when complete, the output of the modern standard 3D assessment of peak clad temperatures when using the nitrogen SSD system to shutdown the reactor.*

84. This recommendation will be tracked through normal regulatory business to its completion by the specialist inspector.

3.1.4.3 COOLING IMPLICATIONS

85. Core distortion and increased cracking of the graphite bricks have the potential to affect the gas flow paths within the core; this has the potential to reduce the cooling of fuel and other core components. Therefore, the specialist inspector has considered the potential implications of core aging on the cooling of the fuel and core components.

<u>Fuel Sleeve Gapping:</u>

86. Previous ONR assessment (Ref. 20) related to the HNB R4 safety case concluded that the limited validation of the sleeve gap flow resistances meant that there was significant uncertainty for individual sleeve gaps >5mm. Additionally, it highlighted that further validation of the sleeve gap flow resistances would be required should sleeve gapping in excess of 4mm be predicted. The specialist inspector judges that this conclusion also applies to HYB and TOR.

87. The specialist inspector notes that when considering core distortion alone, the predicted sleeve gaps up to a core burn-up limit of the case (16.5 TWd) are well within the 4mm limit considered in the ONR assessment (Ref. 20).

88. The specialist inspector noted that there is potential for debris and distortion to occur at the same interface and cause a single gap of >4mm. This could cause a gap of ~4.7mm – if the maximum gap due to debris is added to the maximum predicted gap due to core distortion. This would be above the upper limit on single gap size for which the clad temperature assessment methodology is considered to be reliable. However, EDF NGL argues that the scenario, in which a >4mm gap would occur, is highly unlikely since it would require two diametrically opposed pieces of debris to generate sleeve gaps at the same interface as the limiting core distortion. Additionally, EDF NGL states that sleeve gapping is more likely to occur at the element interfaces lower in the channel whereas peak clad temperatures arise in the upper elements.

89. The specialist inspector accepts that this is a reasonable judgement over the period of validity of the proposed case. However, as the cores continue to crack, the production of debris will become more likely and core distortion may become more significant, and as a result, the predicted sleeve gaps will likely increase in size. Therefore, for future safety cases the specialist inspector recommends that EDF NGL considers the position relating to the validation of the flow resistances and related uncertainties in the clad temperature analysis:

- ***Recommendation**: When considering sleeve gapping in future graphite safety cases, I recommend that NGL should:*
    - *Review the uncertainties in the methodology which evaluates clad temperature changes due to sleeve gapping against the available margin.*
    - *Investigate what is required to further validate the sleeve gap flow resistances.*
    - *Implement any reasonably practicable improvements identified.*

90. This recommendation will be tracked through normal regulatory business to its completion by the specialist inspector.

91. Overall, the specialist inspector is satisfied that EDF NGL has adequately considered the effects of fuel sleeve gapping and demonstrated that the risks due to sleeve gapping are low within the operating constraints of the proposed safety case.

Brick Cracking, Tilting and Dishing and Channel Eccentricity

92. Brick cracking, tilting and dishing can cause changes to the as-designed coolant flow paths which can potentially affect the temperatures of moderator bricks, fuel sleeves or fuel clad in normal operation and faults.

93. Channel eccentricity can arise due to distortion in the fuel channel shape or due to neutron flux gradients causing stringers to become bowed along their length, although such flux gradients are only significant in peripheral channels. The

result is eccentricity of the fuel channel annulus with potential impacts on moderator brick, fuel sleeve and fuel clad cooling.

94. The specialist inspector is content that EDF NGL has adequately considered the thermal effects due to brick cracking, tilting and dishing as well as channel eccentricity in the safety case and that they do not have a significant effect on core components, including graphite bricks, sleeves and fuel cladding.

3.1.4.4 FAULT STUDIES CONCLUSION

95. To conclude, the fault studies specialist inspector is satisfied with the claims, arguments and evidence presented within EDF NGL's safety case and the risks have been reduced to ALARP for the defined validity of the safety case. It is judged that the proposal is sufficient from a fault studies perspective to justify the issue of a Licence Instrument for ONR's Agreement, under arrangements made under Licence Condition 22(1), to the implementation of NP/SC 7810 by Heysham 2 and Torness Power Stations, with a validity period up to a core burn-up of 16.5 TWd.

4 MATTERS ARISING FROM ONR'S WORK

96. All ONR specialist inspectors agree that the proposed safety case modification of NP/SC 7810 (Ref. 2 and 3) is acceptable. On that basis I have prepared a licence instrument for Agreement to NP/SC 7810 - Heysham 2 and Torness Power Stations, Graphite Core: Safety Case for Operation After the Onset of Keyway root Cracking EC 366563 (HYB) and 366568 (TOR). This has been written according to ONR guidance for derived power arrangements (Ref. 21).

97. Some Recommendations were raised by specialist inspectors which are discussed in this report. None of the recommendations prevents Agreement to NP/SC 7810.

98. I have liaised with the Environment Agency (EA) and the Scottish Environment Protection Agency (SEPA) and they have confirmed that they have no objections to the operation of Heysham 2 and Torness reactors to a core burn-up of 16.5 TWd (Ref. 22 and 23).

99. I have confirmed that EDF NGL has followed its own due process. An INSA statement for NP/SC 7810 has been submitted (Refs. 2 and 3) and Nuclear Safety Committee (NSC) meeting minutes have been submitted in support of the case (Ref. 24).

5 CONCLUSIONS

100. Based on the work carried out by ONR, I have concluded that the proposed safety case NP/SC 7810 has been adequately justified by EDF NGL and that Licence Instruments should be issued to HYB and TOR Agreeing to implementation of NP/SC 7810.

6 RECOMMENDATIONS

101. I recommend that ONR should issue licence instruments 638 and 564 to Heysham 2 and Torness Power Stations, respectively, to Agree to the implementation of NP/SC 7810.

102. I also recommend that ONR should maintain regulatory oversight and routinely monitor progress against the assessment recommendations identified by the specialist inspectors.

7 REFERENCES

1. BEG/SPEC/DAO/020, EDF Nuclear Generation Limited, Company Specification, Modification Process, Revision 010, May 2020, CM9: 2021/45093.

2. EDF NGL, Letter NSL HYB/51141R, NP/SC 7810 Proposal Version No: 03 and INSA Statement, Heysham 2 Application for Review and Consideration for NP/SC 7810, Graphite Core: Safety Case for Operation After the Onset of Keyway Root Cracking, EC 366563, CM9: 2022/1150.

3. EDF NGL, Letter NSL/TOR/50731R, NP/SC 7810 Proposal Version No: 03 and INSA Statement, Torness Application for Review and Consideration for NP/SC 7810, Graphite Core: Safety Case for Operation After the Onset of Keyway Root Cracking, EC 366568, CM9: 2022/798.

4. ONR, Letter GEN71425N, HYB: ONR Agreement Required for NP/SC 7810, Heysham 2 and Torness Power Stations, Graphite Core: Safety Case for Operation After the Onset of Keyway Root Cracking, EC 366563 And 366568, CM9: 2022/5834.

5. ONR, Letter GEN71426N, TOR: ONR Agreement Required for NP/SC 7810, Heysham 2 and Torness Power Stations, Graphite Core: Safety Case for Operation After the Onset of Keyway Root Cracking, EC 366563 And 366568, CM9: 2022/5826.

6. EDF NGL, Heysham 2 / Torness, Graphite Core Safety Case NP/SC 7663 Proposal Version 03, May 2017, CM9: 2017/457269.

7. EDF NGL, Justification for Continued Operation of the Heysham 2 and Torness Reactors following the First Observations of Keyway Root Cracked Bricks in the Graphite Core at Heysham R7 in 2021, ECs 369321 000 / 369716 000, CM9: 2021/59425.

8. EDF NGL, Justification for Continued Operation of the Heysham 2 and Torness Graphite Cores with Keyway Root Cracked Bricks, ECs 370264 000 / 370263 000, CM9: 2022/1003.

9. ONR-OFD-DR-21-079, Permissioning Decision Record: NP/SC 7810, Heysham 2 and Torness Power Stations, Graphite Core: Safety Case for Operation after the Onset of Keyway Root Cracking, EC 366563 and 366568, CM9: 2022/6217.

10. ONR-OFD-AR-21-088, External Hazards Assessment of the Seismic Hazard input to NP/SC 7810, Heysham 2 and Torness Power Stations, Graphite Core: Safety Case for Operation after the Onset of Keyway Root Cracking, CM9: 2022/14849.

11. ONR-OFD-AR-21-086, Civil engineering assessment of HYB/TOR post keyway root cracking NP/SC 7810, CM9: 2022/20992.

12. ONR-OFD-AR-21-081, Graphite Assessment of NP/SC 7810: Graphite Core: Safety Case for Operation after the Onset of Keyway Root Cracking, CM9: 2022/18704.

13. ONR-OFD-AR-21-097, Fault Studies Assessment of NP/SC 7810: Heysham 2 / Torness Graphite Core: Safety Case for Operation after the Onset of Keyway Root Cracking, CM9: 2022/20211.

14. Technical Queries (TQ) Tracker for HYB/TOR Post-KWRC CAT1 NP/SC 7810, Safety Case for Operation After the Onset of Keyway Root Cracking, EC 366563 and 366568, CM9: 2022/4830.

15. American Society of Civil Engineers, Structural Engineering Institute, Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities, ASCE/SEI 43-05, 2005 Edition.

16. American Society of Civil Engineers, Structural Engineering Institute, Seismic Analysis of Safety-Related Nuclear Structures, ASCE/SEI 4-16, 2017 Edition.

17. American Society of Civil Engineers, Structural Engineering Institute, Seismic Analysis of Safety-Related Nuclear Structures, ASCE/SEI 43-19, 2019 Edition.

18. ONR-OFD-AR-19-053, Graphite Structural Integrity Assessment of Graphite Core Safety Case NP/SC 7766 Stage Submission 1: An Operational Safety Case for Hunterston B R3 to a Core Burn-up of 16.425 TWd Following the 2018 Graphite Core Inspection Outage, August 2022, CM9: 2019/264245.

19. ONR-OFD-AR-20-110, Graphite Structural Integrity Assessment of NP/SC 7800 HPB R3 and R4 Graphite Cores – Post Keyway Root Cracking Safety Case EC366147 V02, March 2021, CM9: 2021/17308.

20. ONR-OFD-AR-19-029 Rev 00, Fault Studies Assessment of the Hunterston B R4 Return to Service Safety Case Following Core Inspection Results in 2018, CM9: 2019/176010.

21. OF-OR-IN-001 Issue 1, Permissioning Process for Operating Reactors, CM9: 2021/65766.

22. Environment Agency, Email Communication - RE: ONR Agreement to Safety Case NP/SC 7810 for Heysham 2 and Torness Reactors, 07 June 2022, CM9: 2022/34846.

23. Scottish Environment Protection Agency, Email Communication - RE: ONR Agreement to Safety Case NP/SC 7810 for Heysham 2 and Torness Reactors, 07 June 2022, CM9: 2022/34848.

24. EDF NGL, Nuclear Safety Committees, Minutes of the Meeting Held on 09 December 2021, CM9: 2021/92942.