



**Agreement to NP/SC 7799 – HNB R3 and R4 Graphite Cores – Post Keyway Root
Cracking Safety Case**

**Hunterston B Power Station
Project Assessment Report**

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EXECUTIVE SUMMARY

Title

Agreement to NP/SC 7799 – HNB R3 and R4 Graphite Cores – Post Keyway Root Cracking Safety Case

Permission Requested

Under EDF Energy Nuclear Generation Limited's (EDF NGL) arrangements made under Licence Condition 22(1), EDF NGL has requested that the Office for Nuclear Regulation (ONR) issues an Agreement to NP/SC 7799 which is the Hunterston B Reactor 3 and 4 post keyway root cracking safety case. EDF NGL has requested permission for operation up to a total of 16.7 terawatt days (TWd) For Reactor 3 and up to a total of 16.52 TWd for Reactor 4. This equates to approximately six months operation for each reactor. EDF NGL has previously announced that Hunterston B reactors will enter the defuelling phase by 7 January 2022. NP/SC 7799 is intended to justify the final period of operation before moving into the defuelling phase.

Background

The key nuclear safety requirements of a graphite core are:

- That the graphite core will not impede control rod entry thereby ensuring robust shutdown and hold down in normal operation and faults including seismic hazard.
- To ensure that fuel and core component cooling remains acceptable in normal operation and faults including seismic hazard.
- The fuel handling risks due to graphite core cracking remain acceptable.

It has long been understood that irradiation of the fuel channel graphite bricks would eventually lead to shrinkage and cracking of these bricks late in reactor lifetime. Such cracking is termed keyway root cracking. This has the potential to affect the graphite core nuclear safety considerations above and consequently it needs to be demonstrated that these considerations continue to be met in normal operation, fault conditions and after a design basis seismic event.

Keyway root cracking was first observed in Hunterston B Reactor 4 in August 2014, although this was in one of a small number of bricks with a high shrinkage, known to be more susceptible to cracking. The first observation in the main population of graphite fuel bricks was at Hunterston B Reactor 3 in October 2015, and then in September 2017 in Reactor 4. In order to monitor the core condition and the number of cracks, the reactor cores have been regularly inspected. Inspection results and modelling are used to determine an appropriate period of safe operation to the next core inspection.

This Project Assessment Report (PAR) considers NP/SC 7799 which is the Hunterston B Reactor 3 and 4 post keyway root cracking safety case. The safety case supports operation of Hunterston B Reactors 3 and 4 until end of generation when a core burn-up of 16.7 TWd at Reactor 3 and 16.52 TWd at Reactor 4 is reached based on ensuring that the nuclear safety risks are acceptably low. It also specifies the controls and compliance requirements that will need to be satisfied to support operation to those core-burn-up limits. The safety case builds upon the evidence from previous safety cases with:

- An updated ground motion for the seismic assessments
- An updated and improved representation of Multiply axially Cracked Bricks (MCBs)
- Inclusion of friction within the core seismic model.

Both reactors at Hunterston B are currently shut down. Restart of Hunterston B Reactor 3 and Reactor 4 under NP/SC 7799 is subject to satisfactory findings from graphite inspections. These take place in March and April 2021 and the findings will be evaluated in terms of whether they challenge the core state predictions presented in NP/SC 7799.

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

Based on the potential for cracked bricks to affect the fundamental nuclear safety requirements of the Hunterston B Reactors and taking into account the previous assessment, an assessment has been carried out by the following specialist inspectors:

- Civil engineering which has focussed on:
 - Soil structure interaction (SSI),
 - Pre-stressed Concrete Pressure Vessel (PCPV) bearings,
 - Displacements occurring at the charge face level
 - The effects of any changes to input motions resulting from the modelling of the PCPV compared with previous ONR assessments.
- External hazards which has focussed on the validity of the new seismic model.
- The graphite structural integrity assessment focussed on:
 - Core state predictions and margin.
 - Damage tolerance to normal operation and plant-based faults.
 - Damage tolerance to design basis and beyond design basis seismic events.
- Fault studies which has focussed on:
 - Assessment of the requirement to allow unimpeded movement of control rods and fuel.
 - Assessment of the requirement to direct gas flows to ensure adequate cooling of the fuel and core.
 - Assessment of the requirement to provide neutron moderation and thermal inertia.

Matters arising from ONR's work

Following assessment of NP/SC 7799 all specialist inspectors consider that the issue of ONR's Agreement to the proposed modification of NP/SC 7799 is acceptable. In support of their assessments, ONR's specialist inspectors have engaged extensively with EDF NGL in technical discussions to ensure that key issues have been adequately addressed.

Conclusion

It is concluded that the operation of Hunterston B Reactor 3 to a core burn-up of 16.7 TWd and Reactor 4 to a core burn-up of 16.52 TWd has been adequately justified by EDF NGL and that a Licence Instrument should be issued to EDF NGL.

Recommendations

It is recommended that:

Licence instrument 570 is granted to Hunterston B to allow implementation of safety case NP/SC 7799.

LIST OF ABBREVIATIONS

AGR	Advanced Gas Cooled Reactor
ALARP	As Low As is Reasonably Practicable
AR	Assessment Report
ASK	Axial Shear Key (Model)
CEDTL	Currently Established Damage Tolerance Limit
CoF	Coefficient of Friction
DCB	Doubly Cracked Brick
DTA	Damage Tolerance Assessments
DTB	Damage Tolerance Boundary
EDF	Électricité de France
EC	Engineering Change
EFK	End Face Key
EIM	EdF Integrated Model
FHA	Full Height Axial
GCORE	A computer program used to generate ABAQUS finite element models of the AGR core for displacement and loading analysis for the seismic hazard.
HSB	High Shrinkage Brick
KWRC	Keyway Root Crack
LC	Licence Condition
LI	Licence Instrument
LNOA	Limit of Normal Operations Assessment
MCB	Multiply Cracked Brick
NGL	Nuclear Generation Ltd
ONR	Office for Nuclear Regulation
PAR	Project Assessment Report
PCPV	Pre-stressed Concrete Pressure Vessel
PSA	Probabilistic Safety Assessment
RGP	Relevant Good Practice
SCB	Singly Cracked Brick
SEECA	Seismic End-of-Event Cracking Assessment
SFAIRP	So Far as is Reasonably Practicable
SSI	Soil Structure Interaction
TWd	Terawatt Day
UHS	Uniform Hazard Spectra

GLOSSARY OF TERMS

Term	Definition
Currently Established Damage Tolerance Level (CEDTL)	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.
Core Burn-up	The total number of Terrawatt-Days for which the reactor has operated since it first started generating electricity.
Doubly Cracked Brick (DCB)	Doubly axially Cracked Brick (i.e. a brick containing exactly two full height, full thickness axial cracks).
Debris / Fragments	Brick fragments are pieces of graphite brick that remain approximately in position as part of the fuel or control rod channel. Pieces of brick that come free from the channel wall are debris.
Damage Tolerance Assessment	A prediction of channel distortions in two scenarios, the full-power normal operating condition and a 1 in 10,000 year seismic event.
Damage Tolerance Boundary (DTB)	Represents the limit of brick cracking for which seismic damage tolerance assessments demonstrate with high confidence that no control rod is impeded by the graphite core during an infrequent seismic event.
Full Height Axial	Full height axial crack, extending from top to bottom of a graphite brick.
High Shrinkage Brick (HSB)	High shrinkage bricks are a small number of bricks that, based on conditions during production, may exhibit high shrinkage behaviour and be at risk of early KWRC compared to the main population of bricks.
Keyway Root Cracking (KWRC)	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.
Limit of Normal Operations Assessment (LNOA)	For normal operation and plant-based faults, the level of brick cracking and crack opening that has currently been assessed and demonstrated to be tolerable, i.e. that does not challenge full insertion of control rods at all times.
Multiply Cracked Brick (MCB)	Multiply axially Cracked Brick (i.e. a brick containing three or more full height, full thickness axial cracks).
Seismic End-of-Event Cracking Assessment (SEECA)	For a seismic (frequent and infrequent) event, the level of brick cracking and crack opening that has currently been assessed and demonstrated to be tolerable, i.e. that does not challenge full insertion of control rods at all times.
Singly Cracked Brick (SCB)	Singly axially Cracked Brick (i.e. a brick containing exactly one full height, full thickness axial crack).
TWd	Terawatt-Day (core burn-up; one years' operation at 80% power is slightly under 0.5 TWd).

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Table 3: HNB R4 Core state forecasts at 99.9% confidence level and the DTB

1. PERMISSION REQUESTED

- Under EDF Energy Nuclear Generation Limited's (EDF NGL) arrangements made under Licence Condition 22(1) (Ref. 1), EDF Energy Nuclear Generation Limited (EDF NGL) has requested (Ref. 2) that the Office for Nuclear Regulation (ONR) issues an Agreement to NP/SC 7799 which is the Hunterston B Reactor 3 and 4 post keyway root cracking safety case (Ref. 3). EDF NGL has requested permission for operation up to a total of 16.7 terawatt days (TWd) For Reactor 3 and up to a total of 16.52 TWd for Reactor 4. This equates to approximately six months operation for each reactor. EDF NGL has previously announced that Hunterston B reactors will enter the defuelling phase by 7 January 2022. NP/SC 7799 is intended to justify the final period of operation before moving into the defuelling phase.

2. BACKGROUND

- Hunterston B power station has two advanced gas cooled reactors (AGR) termed Reactors 3 and 4. Each reactor core is made up of around 3,000 graphite fuel bricks measuring 825mm high and 460mm external diameter which are connected together by keys and keyways (see figure 1), bound by a steel restraint system and contained within a concrete pressure vessel which is over three metres thick.

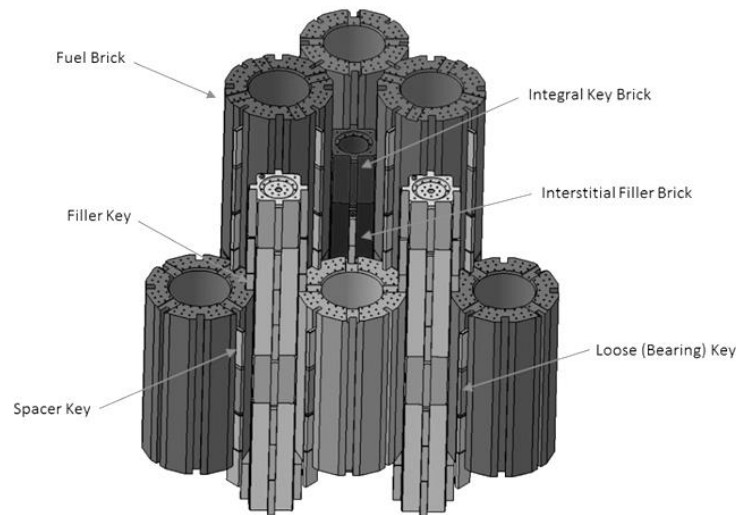


Figure 1 – Graphite Core Arrangement

- 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.

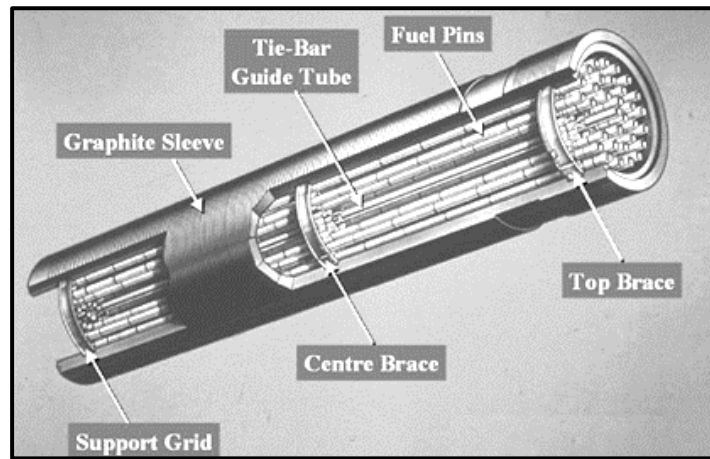


Figure 2 – Fuel Element Example

4. Each reactor has 81 control rods that are used to manage the power in the reactor by absorbing neutrons. 37 control rods are used to control reactor power and day to day operation of the reactor; the remaining control rods are used to shut down the reactor. 12 of these rods are referred to as super articulated control rods. The super articulated control rods are more flexible than the standard control rods which would enable them to enter their channels in the unlikely event of a higher core distortion. The super articulated control rods alone are able to shut down the reactor with longer term hold down of the reactor being provided by a nitrogen injection system. The super articulated control rods and the nitrogen injection system are provided as defence in depth and the safety case presented by the EDF NGL is based on all of the control rods going into the core when required.
5. In the context of this safety case the key nuclear safety requirements of a graphite core are:
 - That the graphite core will not impede control rod entry thereby ensuring robust shutdown and hold down in normal operation and faults including seismic hazard.
 - To ensure that fuel and core component cooling remains acceptable in normal operation and faults including seismic hazard.
 - The fuel handling risks due to graphite core cracking remain acceptable.
6. It has long been understood that irradiation of the fuel channel graphite bricks leads to shrinkage and cracking of the bricks late in reactor lifetime. Such cracking is termed keyway root cracking (KWRC) as it initiates due to stresses which concentrate at the keyways on the outer diameter of the bricks. Figure 3 below shows an example of a keyway root crack in a graphite brick, as seen from the fuel channel bore, from a core inspection. Keyway root cracking has the potential to challenge the safety requirements above and consequently the safety case needs to demonstrate that there are no significant implications for the nuclear safety requirements arising from keyway root cracking in order to permit further operation. 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 Reactor 4¹ in September 2017.

¹ A full height KWRC was first observed in 2014 in a high shrinkage brick.

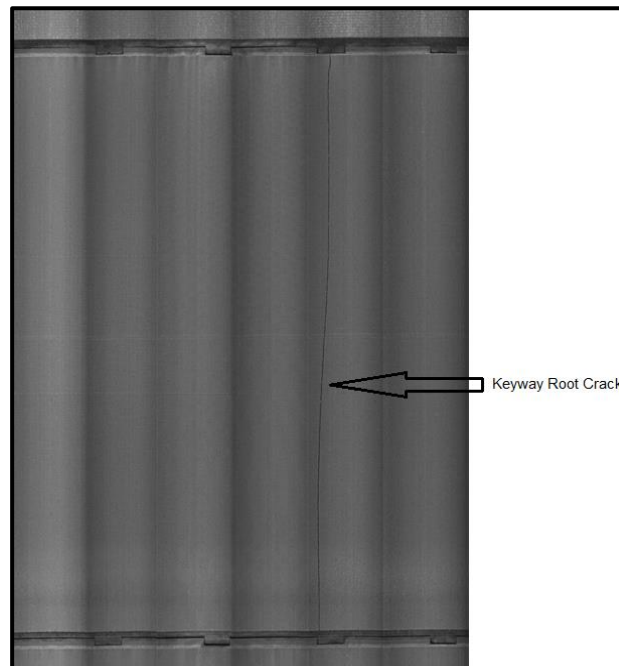


Figure 3 – Keyway Root Crack Example

7. KWRC can result in Singly Cracked Bricks (SCB), Doubly Cracked Bricks (DCB) or Multiply Cracked Bricks (MCB). Cracking of the fuel bricks and crack opening increases progressively and gradually with further irradiation, but it is important to note that no multiply cracked bricks have yet been observed during graphite core inspections.
8. The extant case for Hunterston B Reactor 3 is NP/SC 7766 (Ref. 4) which allowed operation of Reactor 3 to a core burn-up of 16.425 TWd and Reactor 4 under EC367341 (Ref. 5) to a core burn-up 16.25 TWd. Reactor 3 and 4 are currently shut down for graphite core inspections which commenced in March and April 2021. EDF NGL seeks to bring Reactor 3 and Reactor 4 back to power under NP/SC 7799 for a further period of approximately 6 months operation which will be limited to a core burn-up of 16.7 TWd for Reactor 3 and 16.52 TWd for Reactor 4.
9. The key changes in the safety case since NP/SC 7766 and the section of this report in which they are discussed are as follows:
 - An updated ground motion for the seismic assessments (see section 3.1.1).
 - An updated and improved representation of Multiply axially Cracked Bricks (MCBs) (see section 3.1.3.1).
 - Inclusion of friction within the core seismic model (see section 3.1.3.2).
3. **ASSESSMENT AND INSPECTION WORK CARRIED OUT BY ONR IN CONSIDERATION OF THIS REQUEST**
10. Based on the changes proposed in the safety case and the potential for cracking to affect the key nuclear safety requirements of a graphite core, NP/SC 7799 has been subject to assessment by inspectors in the following specialisms:
 - External Hazards
 - Civil Engineering
 - Structural Integrity – Graphite
 - Fault Studies
11. The scope of these assessments is described for each specialism in section 3 below. It should also be noted that, in order to support the assessment of NP/SC 7799, ONR specialist inspectors have engaged with the EDF NGL in numerous detailed technical

discussions and have raised and resolved a number of technical issues throughout their assessments. This report does not attempt to summarise all of the questions raised and answers provided.

3.1 ASSESSMENT FINDINGS

3.1.1 EXTERNAL HAZARDS ASSESSMENT

12. The characterisation of the seismic hazard at Hinkley Point B with the Hinkley Point C Uniform Hazard Spectra (UHS) has previously been assessed by a specialist external hazards inspector and it was judged to be adequate to support the Hinkley Point B post keyway root cracking safety case (Ref. 6). EDF NGL has used this Hinkley Point B UHS to bound the seismic hazard at Hunterston B power station. The specialist external hazards inspector has assessed the validity of this modification to the safety case (Ref. 7) and the adequacy of the seismic hazard assessment to gain confidence that the resultant safety margins for the graphite cores are adequate. The assessment included consideration of:

- Site conditions applicable to Hinkley Point B and Hunterston B.
- Bounding the Hunterston B hazard with the Hinkley Point B UHS
- Beyond design basis UHS

13. The assessment concluded that:

- Although there are some shortfalls against Relevant Good Practice (RGP) in the assessment of site conditions supporting the Hunterston B seismic hazard characterisation, the specialist inspector is satisfied with the qualitative judgements regarding the site characterisation.
- Whilst there are some shortfalls against RGP in the supporting arguments, the specialist inspector is satisfied with the overall judgement that the Hinkley Point B UHS bound the seismic hazard at Hunterston B for the critical frequencies.
- The methodology employed does not derive the site specific beyond design basis hazard in accordance with RGP. Notwithstanding this, the assessment of additional information provided by the EDF NGL in response to technical questions on beyond design basis (BDB) events demonstrates adequate safety margins for 10^{-5} annual frequency of exceedance beyond design basis events.

3.1.1.1 EXTERNAL HAZARDS CONCLUSION

14. To conclude, the specialist external hazards inspector is satisfied with the claims, arguments and evidence laid down within EDF NGL's 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) that Hunterston B Reactor 3 and Reactor 4 can operate up to a core burn-up of 16.7 TWd and 16.52 TWd respectively.

3.1.2 CIVIL ENGINEERING ASSESSMENT

15. From a civil engineering perspective, the most significant nuclear safety risk addressed by NP/SC 7799 relates to the justification that core damage and distortion will not prevent acceptable control rod entry during and following a seismic event. This justification is based on the previously revised seismic modelling of the pre-stressed concrete pressure vessel (PCPV). Within this assessment the specialist inspector has focused on areas which have the greatest potential implications for the input motions to the graphite core.

16. The specialist civil engineering inspector has assessed the relevant claims and supporting arguments with civil engineering content and sampled supporting evidence (Ref. 8).
17. The specialist civil engineering assessment has focused on soil structure interaction (SSI), PCPV bearings, displacements occurring at the charge face level and the effects of any changes to input motions resulting from the modelling of the PCPV compared with previous ONR assessments.
18. The specialist inspector judged that the design basis event (DBE) and beyond design basis (BDB) event assessment is satisfactory for the primary shutdown case as it is bounded by the case for Hinkley Point B in terms of the arguments and evidence relating to the civil engineering aspects of the claims considered. The conservatisms considered for Hunterston B similarly arise from adherence to recognised codes and standards, the use of conservative PCPV modelling properties, including consideration of worst combinations for foundation stiffness parameters, and the use of conservatively biased worst combinations of time history sets.

3.1.2.1 CIVIL ENGINEERING CONCLUSION

19. To conclude, the specialist civil engineering inspector is satisfied with the claims, arguments and evidence laid down within EDF NGL's 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) that Hunterston B Reactor 3 and Reactor 4 can operate up to a core burn-up of 16.7 TWd and 16.52 TWd respectively.

3.1.3 STRUCTURAL INTEGRITY - GRAPHITE ASSESSMENT

20. The scope of the specialist structural integrity assessment (Ref. 9) was to assess the structural integrity aspects related to the distortion of the graphite core and to the damage of graphite components. EDF NGL details those structural integrity aspects in the Damage Tolerance Assessment (DTA) of NP/SC 7799, the principle of which is to show tolerance to substantially greater levels of damage than is predicted to exist with high confidence at the end of generation. The assessment therefore focused on the following:
 - Core state predictions and margin.
 - Damage tolerance to normal operation and plant-based faults.
 - Damage tolerance to design basis and beyond design basis seismic events.
21. Also included in this section is a summary of the changes made to the DTA since the extant case NP/SC 7766. These were assessed outside of the NP/SC 7799 structural integrity assessment but are included here for completeness:
 - A revision to the modelling of multiply cracked bricks (MCBs).
 - A revised seismic input.
 - The introduction of dynamic friction to the seismic model.

3.1.3.1 MODELLING OF MULTIPLY CRACKED BRICKS

22. In previous safety cases, EDF NGL modelled multiply cracked bricks (MCBs) using an approximate representation, termed proxy-MCB, where an MCB was represented as a Doubly Cracked Brick (DCB) but with its radial and axial key/keyway connections removed.

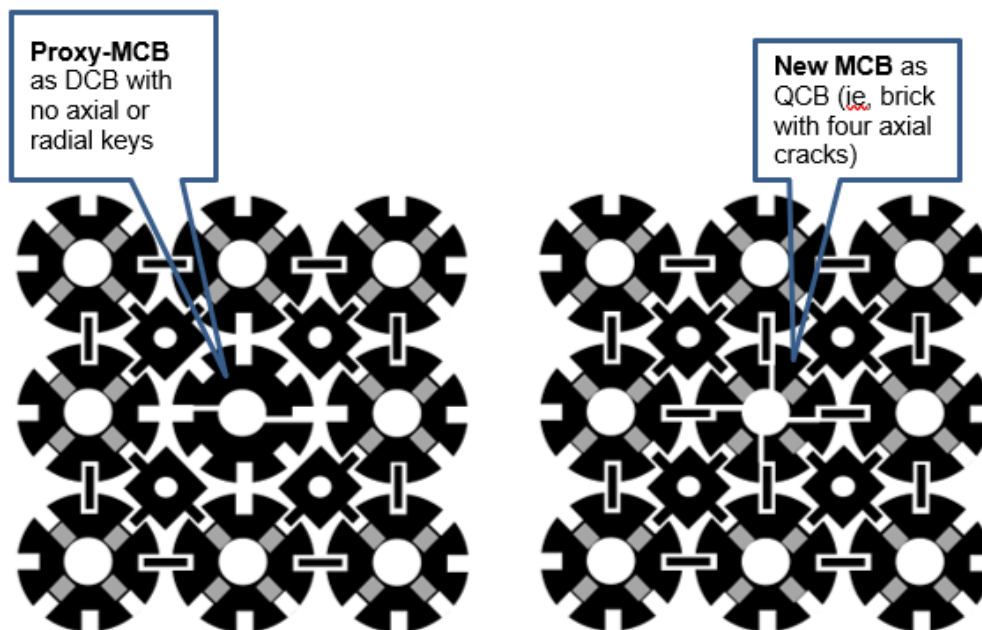


Figure 4 – Proxy-MCB representation

23. In NP/SC 7799, EDF NGL has updated the way MCBs are modelled. An MCB is modelled as a fuel brick with four full-height axial KWRCs, such that the brick is split into four symmetrical quarter segments which can move independently, while keys are maintained. The same approach was adopted in the normal operation and the seismic whole core models.
24. In the specialist structural integrity inspector's view (Ref. 10), the new MCB representation is not particularly novel as it applies the same principles used for modelling doubly cracked bricks (DCBs). It is also more representative of the physical behaviour of a cracked brick with multiple segments. The change in MCB representation is therefore considered to be acceptable for use in the whole core models.

3.1.3.2 INCLUSION OF FRICTION IN THE SEISMIC MODELLING OF THE CORE

25. EDF NGL has included friction in the whole core seismic models supporting the proposed safety case. An assessment of the implementation of friction in the modelling has been carried out by a specialist structural integrity inspector (Ref. 11).
26. The specialist inspector is satisfied that the implementation of friction in the seismic whole core models is supportable and concluded that a coefficient of friction (CoF) of 0.08 is an appropriate value. The assessment of the seismic models supporting the damage tolerance assessments of the case therefore focuses on the margins provided using a CoF of 0.08.

3.1.3.3 DTB, SEECA AND LNOA

27. In the extant safety case NP/SC 7766 (Ref. 4), the currently established damage tolerance level (CEDTL) was used to demonstrate the margins in terms of core distortion at damage levels substantially beyond the core state forecast over the proposed period of operation.
28. The CEDTL term is no longer used, instead EDF NGL uses the following terminology to demonstrate more clearly margins on core state for both normal operation and seismic conditions:

- **Damage Tolerance Boundary (DTB):** Represents the limit of brick cracking for which seismic damage tolerance assessments demonstrate with high confidence that no control rod is impeded by the graphite core during an infrequent seismic event. The difference between a forecasted core state over a specified period of operation and the DTB represents the available margin on core state as shown in Figure 5.
- **Seismic End-of-Event Cracking Assessment (SEECA):** For a (frequent and infrequent) seismic event, the level of brick cracking and crack opening that has currently been assessed and demonstrated to be tolerable (Figure 5). The SEECA accounts for the potential for additional brick cracking that could develop at the DTB core state during a seismic event. Therefore, the SEECA is simply the DTB plus additional cracking that could develop during a seismic event.
- **Limit of Normal Operational Assessment (LNOA):** For normal operation and plant-based faults, demonstration that control rod entry is not impeded is undertaken for an extent of cracking which meets or exceeds that at the DTB. The difference between a forecasted core state over a specified period of operation and the LNOA represents the available margin on core state for normal operation and fault conditions as shown in Figure 5.

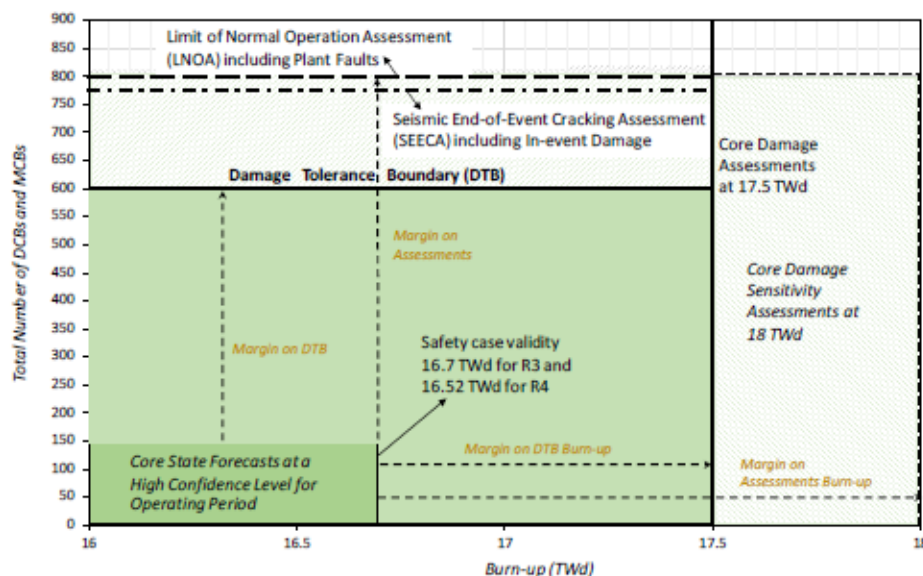


Figure 5 – General illustration of the safety case approach to demonstrating margins

29. In the specialist inspectors view (Ref. 10), the new terminology does not lead to a change in approach from the extant safety case NP/SC 7766 of how adequate margins between core state forecasts and assessment limits are demonstrated. The purpose of the DTB is equivalent to the purpose of the CEDTL (i.e. both are assessment limits).

3.1.3.4 DAMAGE TOLERANCE ASSESSMENT

30. To demonstrate tolerance to brick cracking, EDF NGL has provided damage tolerance assessments for normal operation and plant-based faults conditions using the AGRIGID methodology and for an infrequent seismic event (with frequency of exceedance of 10^{-4} (1 in 10,000) per annum) using the GCORE methodology. EDF NGL has adopted the same approach as the current case (NP/SC 7766) of showing tolerance to core states with a substantially greater degree of cracking than is expected to exist at the end of the proposed operating period. EDF NGL has explored the consequences of parameter uncertainty on its damage tolerance arguments through sensitivity studies and has implemented an improved methodology over the current case to address in-event damage.

31. Table 1 below provides the DTB, SEECA and LNOA in terms number of SCB's, crack opening and MCB's considered in the normal operation and seismic damage tolerance assessments for NP/SC 7799.

Cracked Brick Type	LNOA	DTB	SEECA
	17.5 TWd	17.5 TWd	17.5TWd
All	1900	1900	1980
SCB 6-12mm	420	620	490
SCB 12-18mm	200	200	200
SCB > 18mm	20	20	0
DCBs+MCBs	800	600	775
MCBs	200	200	215

Table 1: Summary of LNOA, DTB and SEECA

32. The SEECA has not included SCBs with large crack openings, i.e. greater than 18mm, but small numbers (up to 5) of this type of cracked brick are predicted in sensitivity studies. The specialist inspector has indicated this with a "0" in table 1. This does not infer there is no tolerance to this type of cracked brick, simply that it has not been explicitly included in the SEECA. This type of cracked brick has been assessed under the DTB, given its population is predicted to be small, there is no reason why its absence in the SEECA would affect core distortion any differently than under the DTB and the specialist inspector is content.

3.1.3.5 CORE STATE PREDICTIONS

33. The specialist inspector has assessed the core state predictions for Reactors 3 and 4 (tables 2 and 3), and their associated sensitivity studies (both at 99.9% confidence), at which the damage tolerance arguments are made. The value in brackets is the equivalent prediction, but instead of being the baseline it denotes the largest prediction obtained from a series of sensitivity studies. The case also conservatively assumes graphite material properties, which directly influence the core distortion predictions, to be aged by approximately two years of full-power operation beyond the end of generation expectations. The specialist inspector is therefore content that the assessed core states are sufficiently beyond those expected within the proposed operating period of ~6 months for both reactors.

Cracked Brick Type	6-month 16.65 TWd	12-month 16.88 TWd	DTB 17.5 TWd
All	947 (1024)	1057 (1122)	1900
SCB 6-12mm	148 (224)	167 (374)	620
SCB 12- 18mm	17 (24)	33 (37)	200
SCB > 18mm	0 (4)	0 (5)	20
DCB+MCB	42 (121)	71 (235)	600
MCB	4 (29)	7 (41)	200

Table 2: HNB R3 Core state forecasts at 99.9% confidence level and the DTB

Cracked Brick Type	6-month 16.48 TWd	12-month 16.71 TWd	DTB 17.5 TWd
All	929 (1039)	1045 (1136)	1900
SCB 6-12mm	85 (166)	223 (345)	620
SCB 12- 18mm	34 (39)	34 (41)	200
SCB> 18mm	0 (5)	5 (6)	20
DCB+MCB	59 (123)	89 (241)	600
MCB	9 (53)	19 (68)	200

Table 3: HNB R4 Core state forecasts at 99.9% confidence level and the DTB

34. The predicted core states for Reactor 3 and Reactor 4 are compared against the DTB in Tables 2 and 3 respectively. The specialist inspector is content that EDF NGL has shown sufficient evidence that the damage tolerance assessment is made at an appropriately higher level of damage than is predicted to be present in Reactor 3 and Reactor 4. This applies even when assuming the worst results of onerous core state sensitivity studies combined with the assumption that the core ages at twice the expected rate up to the end of generation burn-up.
35. It is important to recognise that core state margins must be considered together. For instance, a low core state margin on SCBs with narrow crack openings does not equate to a low margin on damage tolerance, this is because narrow SCBs are relatively benign to core distortions compared to the effect of SCBs with large crack openings, DCBs and MCBs.
36. The specialist inspector is content that EDF NGL has shown sufficient evidence that control rods will not be impeded and that fuel sleeve movements, fuel sleeve integrity and fuel sleeve gapping are not challenged in normal operation and plant-based faults. This applies even when assuming the worst results of sensitivity studies at a substantially more advanced core age, and, when combined with the assumption that the ageing rate of the core is twice the expected rate up to the end of generation burn-up.
37. Restart of Hunterston B Reactor 3 and Reactor 4 under NP/SC 7799 is subject to satisfactory findings from graphite inspections. These inspections commenced in March 2021 and the findings will be evaluated (by a specialist ONR structural integrity inspector) in terms of whether they challenge the core state predictions presented in NP/SC 7799 prior to restart of the reactors.

3.1.3.6 BRICK FRAGMENTS AND DEBRIS

38. EDF NGL's considerations of graphite debris were outlined in the extant case for a period of 12 months, this period includes the 6 months of operation under the extant cases (Ref. 4 and 5) and the further 6 months proposed under NP/SC 7799. EDF NGL's arguments for the generation of graphite debris and the risks posed therefore remain unchanged to the end of generation burn-up of NP/SC 7799. Those arguments have been assessed previously by ONRs graphite and fault studies specialist inspectors (Ref. 12 and 13). However, the considerations of the graphite structural integrity specialist were limited to the 6 month operating period of the extant case to ensure opportunity to re-evaluate those considerations with new inspections results. Providing the forthcoming inspections results are satisfactory in terms of graphite fragments and debris, the specialist inspector is content for EDF NGL's consideration of the 12-month period to continue to apply to the end of generation burn-ups. These arguments will however be revisited with the findings of the graphite inspections. As noted above the restart of

Hunterston B Reactor 3 and Reactor 4 is subject to satisfactory findings from the graphite inspections.

3.1.3.7 EXISTING STRUCTURAL INTEGRITY RECOMMENDATIONS

39. This section reviews the status of recommendations made by ONR in the previous assessments of the Hunterston B, safety cases.

40. From the assessment of the extant safety case NP/SC 7766 (Ref. 4):

- **Recommendation 1:** *“If the revised capacity methodology is to be used in future safety cases, NGL must show high confidence in the virgin end-face key capacity being taken forward. NGL must also refine the methodology for co-location of the combined irradiation and seismically induced stresses with ageing of the graphite strength.”*

41. EDF NGL has not implemented the revised capacity methodology in NP/SC 7799, instead EDF NGL has maintained the methodology applied to the current case (NP/SC 7766). Therefore, this recommendation does not apply.

- **Recommendation 2:** *“Safety case arguments for operation beyond SS1 should identify the major conservatisms and uncertainties and seek to quantify their combined effect on the DTA.”*

42. This recommendation was driven by the need to ensure clarity of the conservatisms in the DTA. EDF NGL provided details of the conservative position of the key aspects in the DTA. To avoid potentially compounding conservatisms to unreasonable levels, the recommendation also sought to quantify the combined effects of the conservatism in the DTA. Given their considerations of the DTA and having reviewed information that supports the conservative position, the specialist inspector is content with the conservative level of the DTA and EDF NGL’s response on this matter.

43. From the HPB/HNB core restraint safety case assessment (Ref. 14):

- **Recommendation 1:** *“The margins against control rod insertion for the additional seismic sensitivity studies on core restraint failure in the ‘long term’ safety cases for HNB and HPB are confirmed as remaining adequate.”*

44. Studies presented show practically no difference to the maximum core distortions when approximately 100 restraints rods are removed. Although the study is made with a coefficient of friction of 0.14, a similar study with effectively zero friction showed a similar result. The specialist inspector is therefore content that the study is adequate and does not challenge the claims of NP/SC 7799.

45. From the assessment of the graphite material model (Ref. 15):

- **Recommendation 3:** *“That NGL be advised that the apparent sensitivity of the DTA to variations in key/keyway clearances and capacity needs to be explored further for safety cases beyond SS1 i.e. beyond a burnup of 16.425TWd for HNB and for future operation of HPB.”*
- **Recommendation 4:** *“That NGL be advised that ONR would have greater confidence in EIM predictions if recalibration was made with the most recent inspection data. This applies particularly to the DC and creep/CTE relationships. For future safety cases, either a recalibration should be performed, or a detailed justification should be provided that any conclusions would not be affected by such a recalibration.”*

46. The specialist inspector is content that based on the core state predictions and damage tolerance assessments that Recommendation 3 has been addressed. EDF NGL's response to Recommendation 4 has been reviewed by a specialist structural integrity inspector (Ref. 16) who considered that EDF NGL has answered the recommendation by showing that the differences they would get with a recalibration are small, compared for example to the differences in key/keyway clearance that were suggested for sensitivity studies in previously.

3.1.3.8 STRUCTURAL INTEGRITY CONCLUSION

47. To conclude, the specialist structural integrity inspector is satisfied with the claims, arguments and evidence laid down within EDF NGL's 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) that Hunterston B Reactor 3 and Reactor 4 can operate up to a core burn-up of 16.7 TWd and 16.52 TWd respectively.

3.1.4 FAULT STUDIES ASSESSMENT

48. The specialist fault studies inspector focussed their assessment (Ref. 17) on ensuring that EDF NGL 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 up to the core burnup limits specified.

49. The scope of the assessment was:

- Assessment of the requirement to allow unimpeded movement of control rods and fuel.
- Assessment of the requirement to direct gas flows to ensure adequate cooling of the fuel including:
 - The effects of changes in coolant flow paths due to cracking
 - The effects of channel distortion – eccentric annulus
 - The effects of channel distortion – sleeve gapping
 - The potential effects of debris.
- Assessment of the requirement to provide neutron moderation and thermal inertia.

3.1.4.1 ASSESSMENT OF THE REQUIREMENT TO ALLOW UNIMPEDED MOVEMENT OF CONTROL RODS AND FUEL

Control Rod Movement

50. The specialist inspector judged that consideration of whether NP/SC 7799 had adequately demonstrated that the control rods insert in normal operation and following a seismic event is the main focus of the ONR graphite specialist inspector's assessment report and raised the following recommendation:
51. **Recommendation 1:** "Prior to ONR agreeing to the modifications to the safety case described in Reference 1, the project inspector should confirm that the graphite specialist inspector is satisfied that NGL have adequately demonstrated that all control rods will insert in normal operation and following a design basis seismic event."
52. I can confirm that the specialist structural integrity inspector is satisfied that EDF NGL have adequately demonstrated that all control rods will insert in normal operation and following a design basis seismic event (Ref. 18).

Fuel movement

53. The fault studies assessment of the previous Hunterston B graphite core safety case (Ref. 13) concluded that EDF NGL had demonstrated that a hypothetical increase in fuel snag frequency to 1.5 snags per reactor year (pry) was still tolerable. Since that assessment EDF NGL has carried out a global update to its fuel route PSA independent of the graphite safety case, resulting in a small increase in the assessed fuel route risk for dose band 5 (>1Sv) events. EDF NGL has therefore presented an updated sensitivity study which demonstrates that at 1.5 snags pry the risks remain tolerable. This gives a large margin to accommodate any increase in fuel handling risk due to debris. EDF NGL states that any increase in fuel snag frequency from core distortion or graphite debris would be small over the proposed operating period. In the specialist inspectors view the structural integrity specialist inspector should be satisfied that EDF NGL have adequately demonstrated that there would not be a significant increase in fuel snag frequency from core distortion or graphite debris over the proposed ~6 month operating period prior to ONR agreeing to the modifications to the safety case described in NP/SC 7799. The specialist inspector therefore raised the following Recommendation:
54. **Recommendation 2:** *“Prior to ONR agreeing to the modifications to the safety case described in Reference 1, the project inspector should confirm that the graphite specialist inspector is satisfied that NGL have adequately demonstrated that there will be no significant increase in fuel snag frequency from core distortion or graphite debris.”*
55. The specialist fault studies inspector has also reviewed the evidence presented with respect to fuel handling and considers EDF NGL’s judgement that the risks associated have been reduced ALARP to be valid. This judgement is conditional on Recommendation 2 above.
56. I can confirm that the specialist structural integrity inspector is satisfied that EDF NGL have adequately demonstrated that there will be no significant increase in fuel snag frequency from core distortion or graphite debris (Ref. 18).

3.1.4.2 ASSESSMENT OF THE REQUIREMENT TO DIRECT GAS FLOWS TO ENSURE ADEQUATE COOLING OF THE FUEL AND CORE

The effects of changes in coolant flow paths due to cracking

57. The arguments and evidence presented in NP/SC 7799 are the same as those presented in the previous graphite safety cases (Ref. 4) , although a new head document has been issued to support NP/SC 7799 which presents an up to date review of the evidence.

The effects of channel distortion – eccentric annulus

58. The fault studies assessment of the recent graphite core safety (Ref. 13) case examined the arguments and evidence relating to the effects of an eccentric annulus and judged that the effects of annulus eccentricity were acceptable, and that EDF NGL had taken adequate account of the effects of annulus eccentricity in fault conditions.

The effects of channel distortion – sleeve gapping

59. The assessment approach was to gain confidence that EDF NGL’s submission demonstrated that the effects of sleeve gapping on fuel clad temperatures are such that the operating limit on fuel clad temperature is not breached, and that adequate account has been taken of uncertainties.
60. EDF NGL have found no instances in which modelling of core distortion at levels of core degradation in excess of that predicted up to the proposed core burnup limits led to individual channels showing sleeve gaps in excess of 2mm (a trigger point for review

which EDF NGL had imposed). In the specialist inspectors view this - along with other conservatisms present in the analysis methodology - demonstrates a lack of cliff edge in the consequences beyond the proposed operating regime, and that there is adequate safety margin in the analysis.

61. The fault studies assessment considered the effects of fuel sleeve gapping on fuel temperatures; however, the predictions of the occurrence and magnitude of fuel sleeve gaps is considered in the graphite inspectors assessment report (Ref. 9). The specialist inspector therefore recommended that the project inspector confirms that the graphite inspector is satisfied that the methodology employed by EDF NGL to predict sleeve gap sizes over the operating period are acceptable.
62. **Recommendation 3:** *“Prior to ONR agreeing to the modifications to the safety case described in Reference 1, the project inspector confirms that the graphite inspector is satisfied that the methodology employed by NGL to predict sleeve gap sizes over the operating period is acceptable.”*
63. I can confirm that the specialist structural integrity inspector is satisfied that the methodology employed by EDF NGL to predict sleeve gap sizes over the operating period is acceptable (Ref. 18).
64. In conclusion the specialist fault studies inspector judged that, since sleeve gapping is not predicted in excess of 4mm (the justified limit) over the proposed operating period, EDF NGL has adequately demonstrated that the effects of sleeve gapping on fuel clad temperatures are acceptable up to the proposed core burnup limits.

Sleeve Gapping in a seismic event

65. The fault studies assessment of previous graphite safety cases (Ref. 13) recommended that EDF NGL should consider the potential for sleeve gapping to occur in a seismic event, and regulatory issue 8212 was raised; NP/SC 7799 presents arguments to address the recommendation. EDF NGL states that as reactor trip would be expected to occur through either automatic or manual means following a seismic event and that the effects of sleeve gapping on the fuel clad temperature would be significantly reduced due to the significant reduction in heat generation.
66. The arguments presented by EDF NGL are in the specialist inspectors view straight forward and logical and adequately consider the potential for sleeve gapping to occur in a seismic event. This addresses the intention of the recommendation and associated regulatory issue (8212).

3.1.4.3 DEBRIS

67. The specialist fault studies inspector concluded that EDF NGL has satisfactorily demonstrated that the risks associated with flow obstruction due to graphite debris have been reduced So Far as is Reasonably Practicable (SFAIRP) provided that there is not a significant increase in the probability of graphite debris migrating into fuel stringers and thus increasing the plausible blockage size. As such the specialist inspector recommended that prior to granting permission to the modifications described in NP/SC 7799, the project inspector should confirm that the graphite inspector is satisfied that there is not a significant increase in the probability of graphite debris migration.
68. **Recommendation 4:** *“Prior to granting permission to the modifications described in Ref. 1 the project inspector should confirm that the graphite inspector is satisfied that there is not a significant increase in the probability of graphite debris migrating into fuel stringers.”*

69. I can confirm that the specialist structural integrity inspector is satisfied that there is not a significant increase in the probability of graphite debris migrating into fuel stringers. (Ref. 18).
70. It is the specialist fault studies inspector's opinion that even though the previously discussed thermal hydraulic evidence demonstrated that fuel clad melt at the element 1 location due to flow obstruction from graphite debris should not be considered within the design basis, analysis carried out by EDF NGL provides further support to demonstrate that the consequences of such an obstruction have been reduced SFAIRP. It is also judged that EDF NGL have provided further evidence that there is not a significant cliff edge in consequences beyond the assumptions in the analysis.

3.1.4.4 ASSESSMENT OF THE REQUIREMENT TO PROVIDE NEUTRON MODERATION AND THERMAL INERTIA

71. The specialist fault studies inspector noted that there is no plausible effect on the thermal inertia of the graphite core due to graphite brick cracking. Other potential effects on the neutron flux distribution from graphite brick cracking were examined in the ONR assessment of NP/SC 7766 (Ref. 13), and concluded that EDF NGL had adequately demonstrated that the safety function of the graphite core to provide neutron moderation and thermal inertia was unaffected by the presence of graphite brick cracking. The specialist fault studies inspector therefore concluded that the safety function of the graphite core to provide neutron moderation and thermal inertia has been adequately demonstrated to be fulfilled over the operating periods proposed.

3.1.4.5 FAULT STUDIES CONCLUSION

72. To conclude, the specialist fault studies inspector is satisfied with the claims, arguments and evidence laid down within EDF NGL's 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) that Hunterston B Reactor 3 and Reactor 4 can operate up to a core burn-up of 16.7 TWd and 16.52 TWd respectively.

4. MATTERS ARISING FROM ONR'S WORK

73. All ONR specialist inspectors consider Agreement to the proposed safety case modification of NP/SC 7799 (Ref. 3) to be acceptable. On that basis I have prepared a licence instrument for Agreement to NP/SC 7799 HNB R3 and R4 Graphite Cores – Post Keyway Root Cracking Safety Case. This has been written according to ONR guidance and is of routine type, for which the text and format have been agreed with the Government legal department. Further legal checking of this licence instrument is therefore unnecessary.
74. Some Recommendations were raised by specialist inspectors which are discussed in this report. These Recommendations include those which require the project inspector to confirm assumptions made in the specialist fault studies assessment which I can confirm has been done. None of the other recommendations prevent Agreement to NP/SC 7799.
75. I have liaised with the Scottish Environment Protection Agency (SEPA) and it has confirmed that it has no objections to ONR issuing an Agreement to implement NP/SC 7799. (Ref. 19).
76. I have confirmed that EDF NGL has followed its own due process. An INSA statement for NP/SC 7799 has been submitted (Ref. 20) and Nuclear Safety Committee (NSC) meeting minutes have been submitted (Ref. 21).

77. As explained in section 3.1.3.5, restart of Hunterston B Reactor 3 and Reactor 4 under NP/SC 7799 is subject to satisfactory findings from graphite inspections which will be examined by a structural integrity specialist inspector prior to allowing the reactors to restart.

5. CONCLUSION

78. I have concluded that the operation of Hunterston of Reactor 3 to a core burn-up of 16.7 TWd and Reactor 4 to a core burn-up of 16.52 TWd has been adequately justified by EDF NGL and that a Licence Instrument should be issued to EDF NGL to allow implementation of NP/SC 7799.

6. RECOMMENDATIONS

79. I recommend that licence instrument 570 is granted to Hunterston B to allow implementation of NP/SC 7799

7. REFERENCES

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15. ONR-OFD-AR-19-093 Revision 0, Assessment of EDF's graphite materials properties model in NP/SC 7766 V10 SS1 (Operation of HNB R3 to a burn up of 16.425TWd) and implications for the predicted brick stresses, dimensions and overall damage tolerance assessment, July 2020, CM9 2020/151688
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17. ONR-OFD-AR-20-095 Fault Studies Assessment of the Safety Case for Operation of Hunterston B Reactors 3 & 4 Up to Core Burnups of 16.7TWd and 16.52TWd, 2021/4546
18. Email – HPE CM: RE: Recommendations from fault studies assessment of NP/SC 7799, CM9 2021/25491
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20. EDF Energy Nuclear Generation Ltd – Milestone Full INSA Statement – HNB R3 & R4 Graphite Cores: Post Keyway Root Cracking Safety Case, CM9 2020/316392
21. Meeting 11a/20, EDF Energy Nuclear Generation Ltd Nuclear Safety Committee Minutes of the Meeting, 02 November 2020, CM9 2020/316392