Office for Nuclear Regulation

Agreement to NP/SC 7800 – HPB R3 and R4 Graphite Cores – Post Keyway Root Cracking Safety Case

Hinkley Point B Power Station
Project Assessment Report

Project Assessment Report ONR-OFD-PAR-20-026
Revision 0
16 March 2021

Published 03/2021

EXECUTIVE SUMMARY

Title

Agreement to NP/SC 7800 – HPB 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 7800 which is the Hinkley Point B Reactor 3 and 4 post keyway root cracking safety case.

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 a seismic event.
- To ensure that fuel and core component cooling remains acceptable in normal operation and faults including a seismic event.
- 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 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.

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 4 in September 2017. At Hinkley Point B the first keyway root cracks were first observed in March 2019 in Reactor 3 and in February 2018 in Reactor 4. In order to monitor the core condition and the number of cracks, the reactor cores at Hinkley Point B 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 7800 which is the Hinkley Point B Reactor 3 and 4 post keyway root cracking safety case produced to support a return to service from the last core inspections and subsequent operation (split into two ~6-month periods) of Reactor 3 to a core burn-up of 17.55 TWd and Reactor 4 to a core burn-up of 17.3 TWd. The case specifies the controls and compliance requirements that will need to be satisfied to support operation to those core-burn-up limits. These controls are based on core inspections after an appropriate period of operation, assessment of the inspection findings and ongoing core monitoring. NP/SC 7800 builds upon the evidence from previous safety cases with:

- Damage tolerance assessments updated to reflect improved understanding of the effects of core degradation and results used to demonstrate that for further operation brick cracking does not impede control rod entry, and
- Additional assessments to address the potential risk and consequences of fragments and debris for cooling of fuel in-situ and fuel movement.

Core inspection results after ~6 months of operation will be reviewed by ONR to ensure that the number of cracks are in line with crack predictions made by EDF NGL.

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

ONR's assessment of NP/SC 7800 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 Hinkley Point B Reactors. Taking this and previous assessments carried out on Hinkley Point B and Hunterston B into account, an assessment has been carried out by the following specialist inspectors:

- External hazards which has focussed on the validity of the new seismic model.
- 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.
- Graphite structural integrity which has focussed on:
  - The 2020 core inspection findings of the Hinkley Point B reactors.
  - The core state forecasts over the proposed periods of operation.
  - The damage tolerance assessments for normal operation and fault conditions and for an infrequent seismic event.
  - The adequacy of margins between the predicted core states and the limits of the damage tolerance assessments.
  - Fuel cooling and handling risk due to graphite debris; in terms of fragments and debris formation.
  - Controls and arrangements for demonstrating compliance with the safety case.
- 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 all specialist inspectors consider that the issue of ONR’s Agreement to the Hinkley Point B Reactor 3 and 4 post keyway root cracking safety case, NP/SC 7800, 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 Hinkley Point B Reactor 3 to a core burn-up of 17.55 TWd and Reactor 4 to a core burn-up of 17.3 TWd has been adequately justified by EDF NGL and that a Licence Instrument should be issued to EDF NGL. Core inspections will take place after a period of ~6 months operation the results of these inspections will be examined by ONR to ensure that they are within the modelling presented by EDF NGL.

Recommendations

It is recommended that:

Licence instrument 564 is granted to Hinkley Point B to allow implementation of safety case NP/SC 7800.

LIST OF ABBREVIATIONS

AGR	Advanced Gas Cooled Reactor
AGRIGID	A computer program used to generate ABAQUS finite element models of the AGR core for displacement and loading analysis in normal operation and plant fault conditions.
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.

TABLE OF CONTENTS

Figures

Tables

1. PERMISSION REQUESTED

1. Under EDF Energy Nuclear Generation Limited's (EDF NGL) arrangements made under Licence Condition 22(1) (Ref. 1), EDF NGL has requested (Ref. 2) that the Office for Nuclear Regulation (ONR) issues an Agreement to NP/SC 7800 which is the Hinkley Point 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 17.55 terawatt days (TWd) for Reactor 3 and up to a total of 17.3 TWd for Reactor 4. This equates to two periods of approximately six months operation for each reactor, with graphite core inspections between the periods of operation.

2. BACKGROUND

2. Hinkley Point 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 825 mm high and 460 mm 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.

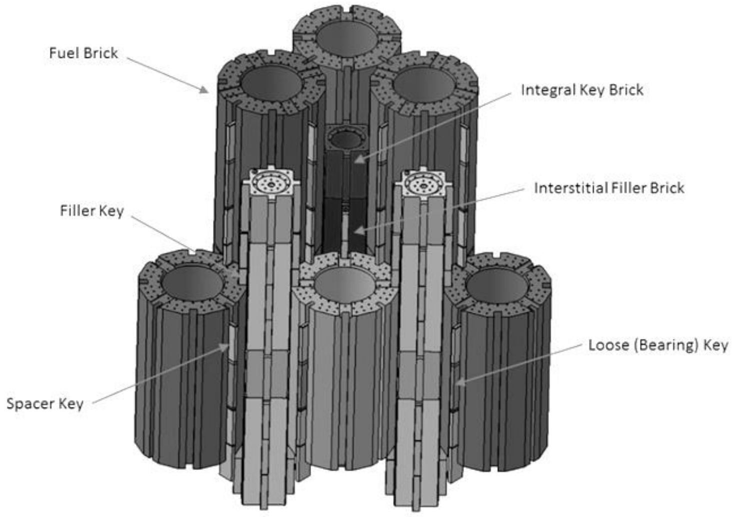

Figure 1 – Graphite Core Arrangement

3. 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.

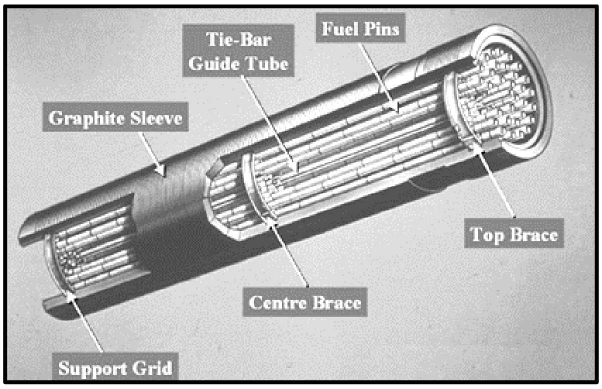

Figure 2 – Fuel Element Example

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 shutdown 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 licensee 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, during a core inspection. KWRC has the potential to affect the nuclear safety requirements above and consequently the safety case needs to demonstrate that there are no significant implications for these requirements arising from KWRC in order to permit further operation. KWRC was first observed in the main population of graphite moderator fuel bricks at Hunterston B Reactor 3 in October 2015, and in Reactor 4[1] in September 2017. At Hinkley Point B the first KWRC were first observed in March 2019 in Reactor 3 and in February 2018 in Reactor 4.

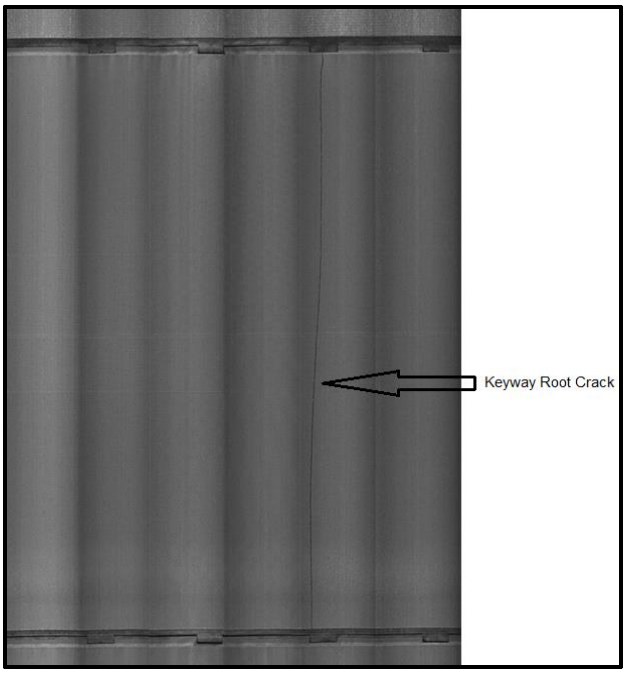

Figure 3 – Keyway Root Crack Example

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

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 multiply cracked bricks have yet to be observed at Hinkley Point B or Hunterston B during graphite core inspections.

8. In March 2019, Hinkley Point B Reactor 3 was shut down for a periodic inspection and a number of KWRC were observed. Both Hinkley Point B reactors then operated under the extant safety case NP/SC 7792 (Ref. 4) up to the burn-up limits set in EC 366104 (Ref. 5) for operation under NP/SC 7792. These burn-up limits were set to coincide with the graphite inspection outages in 2020 for both Hinkley Point B reactors.

9. Hinkley Point B Reactor 4 was shutdown in February 2020 and Reactor 3 was shutdown in June 2020 for graphite core inspections. Both reactors have remained shutdown awaiting the production and assessment of the proposed safety case NP/SC 7800. Both inspection campaigns yielded fewer cracked bricks than EDF NGL’s predictions prior to the outages. The Hinkley Point B Reactor 3 and Reactor 4 current core burn-ups are 17.031 TWd and 16.775 TWd, respectively.

10. The key changes in the safety case since NP/SC 7792 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 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).
- A defined limit of normal operation (LNOA) which bounds the Damage Tolerance Boundary (DTB), and for which there is high confidence in the graphite core not impeding control rods (see section 3.1.3.3).
- A Seismic End-of-Event Cracking Assessment (SEECA), which accounts for in-event damages, and for which there is high confidence in the graphite core not impeding control rods (see section 3.1.3.3).
- Updated keying system capacities; (see section 3.1.3.4).

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

11. Based on the changes in the proposed safety case and the potential for cracking to affect the key nuclear safety requirements of a graphite core, NP/SC 7800 has been subject to assessment by inspectors in the following specialisms:

- External Hazards
- Civil Engineering
- Structural Integrity – Graphite
- Fault Studies

12. It should be noted that, in order to support the assessment of NP/SC 7800, ONR specialist inspectors have engaged with 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

13. EDF NGL has updated the ground motion used in the analysis of the response of the graphite cores to a seismic event and derived a Uniform Hazard Spectra (UHS) to support its post KWRC safety case.

14. EDF NGL's assessment derives the mean, 84th percentile and beyond design basis UHS. The 84th percentile UHS with an annual frequency of exceedance of 10^{-4} (a 1 in 10,000 year earthquake) is intended to be a conservative assessment of the design basis seismic hazard in accordance with relevant good practice (RGP).

15. ONR has utilised its Expert Panel on Natural Hazards (Seismic) to review EDF NGL's UHS assessment for HPB for its alignment with RGP commensurate with an existing facility (Ref. 6). The panel advises ONR External Hazards inspectors on seismic hazards including recent developments in the field and providing expert advice on specific assessments produced by licensees.

16. The specialist external hazards inspector's assessment strategy was as follows:

- A review of NGL's post KWRC safety case and its supporting references to sample key aspects of the safety case that were not considered by the ONR Expert Panel review
- A summary of the findings from with conclusions about the adequacy of EDF NGL's seismic hazard assessment for HPB in relation to RGP.

17. The specialist external hazards inspector has assessed the validity of this modification to the safety case and the adequacy of the licensee's UHS assessment to ensure that the resultant safety margins for the graphite cores are adequate (Ref. 7).

18. Based on their assessment, the specialist external hazards inspector judged that the Hinkley Point B UHS is adequate when compared with RGP and that residual uncertainties have been reduced to ALARP.

3.1.1.1 EXTERNAL HAZARDS CONCLUSION

19. 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 Hinkley Point B Reactor 3 and Reactor 4 can return to service and operate up to a core burn-up of 17.55 TWd and 17.3 TWd respectively.

3.1.2 CIVIL ENGINEERING ASSESSMENT

20. From a civil engineering perspective, the most significant nuclear safety risk addressed by NP/SC 7800 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.

21. The specialist civil engineering inspector has assessed the relevant claims and supporting arguments with civil engineering content and sampled supporting evidence (Ref. 8).

22. The specialist civil engineering inspector has focused their assessment 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.

23. The specialist inspector judged that the design basis event (DBE) and beyond design basis (BDB) event assessment is achieved for the primary shutdown case in terms of the arguments and evidence relating to the civil engineering aspects of the claims considered. Conservatisms considered 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

24. 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 Hinkley Point B Reactor 3 and Reactor 4 can return to service and operate up to a core burn-up of 17.55 TWd and 17.3 TWd respectively.

3.1.3 STRUCTURAL INTEGRITY - GRAPHITE ASSESSMENT

25. The specialist structural integrity inspector focussed their assessment (Ref. 9) of NP/SC 7800 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 over the proposed period of operation. This included consideration of:

- The 2020 core inspection findings of the Hinkley Point B reactors.
- The core state forecasts over the proposed periods of operation.
- The damage tolerance assessments for normal operation and faults conditions and for an infrequent seismic event.
- The adequacy of margins between the predicted core states and the limits of the damage tolerance assessments.
- Fuel cooling and handling risk due to graphite debris; in terms of fragments and debris formation.
- Controls and arrangements for demonstrating compliance with the safety case.

26. The methodologies underpinning the evidence supporting the claims and arguments of the proposed safety case, NP/SC 7800, are the same as those presented in recent safety cases justifying operation of the Hinkley Point B and Hunterston B reactors. However, some new developments to the methodologies have been adopted and new results have been presented. The specialist inspector also 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 MODELLING OF MULTIPLY CRACKED BRICKS

27. 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.

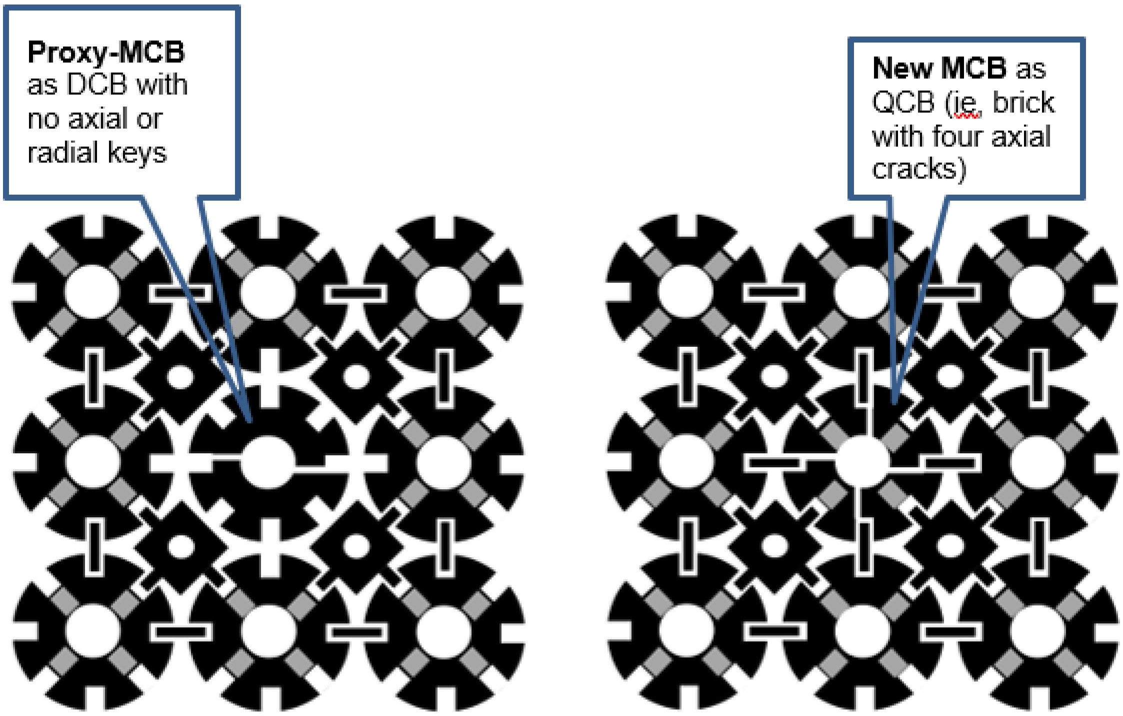

Figure 4 – Proxy-MCB representation

28. In NP/SC 7800, 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.

29. In the specialist structural integrity inspector's view, 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

30. 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. 10).

31. 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. Their 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

32. In the extant safety case NP/SC 7792 (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.

33. 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.

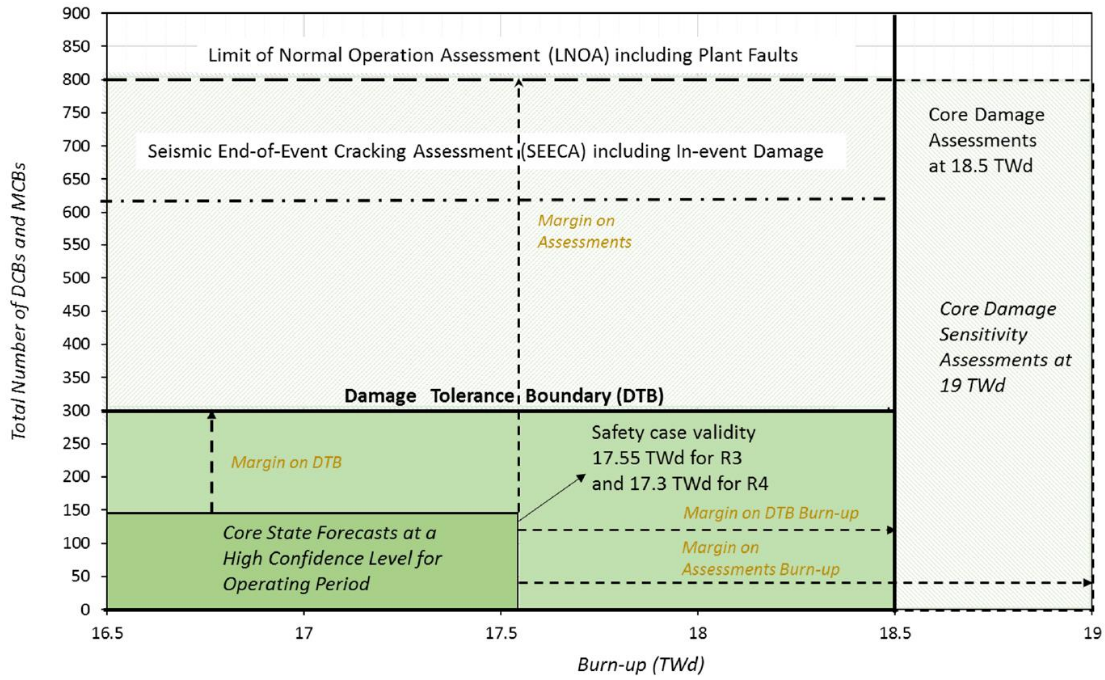

Figure 5 – General illustration of the safety case approach to demonstrating margins

34. In the specialist inspectors view, the new terminology does not lead to a change in approach from the extant safety case NP/SC 7792 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 MODELLING DEVELOPMENTS RELATED TO AXIAL KEY/KEYWAY IN THE SEISMIC MODELS

35. In previous safety cases a rule-based approach known as the ASK Tool was used prior to the seismic analysis to remove axial shear keys (ASK) based on geometrical incompatibility rules related to the assumed crack openings considered in the analysis. The axial shear keys refer to the end-face keys and so those terms are used interchangeably.

36. In NP/SC 7800, EDF NGL no longer uses the pre-analysis ASK tool (based on the geometrical incompatibility rules) to remove end-face keys prior to the analysis. End-face keys (or ASKs) are only removed during the static and dynamic phases of the seismic analysis based on their force capacities. This leads to a reduction in the number of removed end-face keys.

37. The specialist inspector is content that the new approach is more representative of physical behaviour of the core, albeit being less conservative than the ASK Tool.

38. In the proposed safety case, EDF NGL has also considered the effect of the irradiation-generated internal stress on the end-face key/keyway capacities. The specialist inspector is content that EDF NGL has addressed the potential effect of irradiation internal stress on end-face key capacities adequately (Ref. 9).

3.1.3.5 DAMAGE TOLERANCE ASSESSMENT

39. 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. The damage tolerance assessments are carried out at levels of cracking that are considerably higher than the levels of cracking forecast by modelling, to a high calculational confidence level (99.9%) over the proposed periods of operation of Hinkley Point B Reactor 3 and Reactor 4.

40. The methodologies employed to support the proposed safety case are largely unchanged from those employed in the extant safety cases. However, EDF NGL has introduced significant developments that are mainly related to the methodologies used in the seismic tolerance assessments and are discussed in sections 3.1.3.1, 3.1.3.2 and 3.1.3.4.

41. EDF NGL has supported the baseline GCORE and AGRIGID analyses 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 over the proposed periods of operation for both Hinkley Point B Reactor 3 and Reactor 4.

42. 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 7800.

Cracked Brick Type	LNOA	DTB	SEECA
	18.5 TWd	18.5 TWd	18.5TWd

All	1900	1500	1730
SCB 6-12mm	420	420	205
SCB 12-18mm	200	200	200
SCB > 18mm	20	20	20
DCBs+MCBs	**800**	**300**	**620**
MCBs	200	100	130

Table 1: Summary of LNOA, DTB and SEECA

3.1.3.6 INSPECTION FINDINGS

43. The safety case presents the findings of the 2020 graphite core inspections of both Hinkley Point B Reactor 3 and Reactor 4 which show that the cracking observations are on the low side of expectations. The specialist inspector is content that EDF NGL has carried out adequate graphite core inspections of Hinkley Point B Reactor 3 and Reactor 4 in 2020 to allow appropriate core state forecasts.

44. Two cracking observations were of note:

- **Brick Layer 7 of Channel S13**: S13 was previously inspected in 2019 and was found to contain axial cracking in bricks in Layers 6 to 3 (all SCBs with the Layer 3 brick containing only a partial-height crack). In the 2020 inspection, the Layer 3 partial crack has extended to full height and the cracks in the other bricks have widened. A further KWRC is now evident in Layer 7 brick, with two partial-height axial cracks 90º away from it. This crack is unusual in that it appears to have a wider crack opening, especially at the top (~5mm), than is generally observed with new cracks.
- **Brick Layer 4 of Channel M17**: M17 was previously inspected in 2017 and a bore crack was observed in brick Layer 7. In 2020, it was observed that brick Layer 3 has a full-height axial crack and Brick Layer 4 has one full-height axial crack and two aligned partial-height axial cracks 180° away from the full-height axial crack.

45. EDF NGL noted an unusual ovality at the top of the brick Layer 7 of S13, which was apparent in the previous 2019 inspection when the brick was still intact. EDF NGL believes that there is a link between this unusual ovality and the larger crack opening observed in 2020.

46. EDF NGL reports that brick Layer 4 of M17 will eventually become a doubly cracked brick and that it would be prudent to consider, in sensitivity studies, that this could occur following the next period of irradiation.

47. Following the comprehensive assessment of the observations of both Hinkley Point B Reactor 3 and Reactor 4 2020 inspections, there has been a number of refinements of core state modelling parameters of CrackSim in addition to sensitivity studies to cover the new observations.

48. The specialist inspector is satisfied with the detailed analysis carried out by EDF NGL and considers the modelling changes and sensitivity studies to be sufficient to cover the new observations in terms of consequences on core state forecasts. The specialist inspector is also of the view that carrying out re-inspections of channels S13 and M17 after a further operational period may provide further information to validate the changes and current understanding of damage progression. The following recommendation is therefore made:

49. ***Recommendation 1:** "NGL should consider re-inspecting channels S13 and M17 of HPB R3 at the planned graphite inspection outage after ~6 months of further operation."*

3.1.3.7 CORE STATE PREDICTIONS

50. EDF NGL uses the existing methodology, CrackSim, to forecast the core states over the proposed periods of operation of Hinkley Point B Reactor 3 and Reactor 4. EDF NGL has introduced some refinements to CrackSim parameters to cover the 2020 inspection findings. EDF NGL has also provided appropriate sensitivity studies to cover the uncertainties associated with the modelling assumptions, these are displayed in brackets for comparison. The specialist inspector is therefore content that EDF NGL has presented adequate and conservative cracking forecasts over the proposed periods of operation of both Hinkley Point B Reactor 3 and Reactor 4.

51. Table 2 and 3 below show the EDF NGL forecasted core states for both Hinkley Point B Reactor 3 and Reactor 4. The baseline forecasts and the most bounding forecasts from all the sensitivity studies at the 99.9% calculational confidence level are presented. The DTB is also shown. The forecasts for large cracking opening (i.e. SCB > 18mm) sometimes decrease over time, because they transition to DCBs.

Cracked Brick Type	6-month 17.261 TWd	12-month 17.491 TWd	18-Month 17.721 TWd	DTB 18.5 TWd
All	527 (630)	681 (797)	825 (938)	1500
SCB 6-12mm	27 (88)	94 (141)	129 (268)	420
SCB 12- 18mm	6 (17)	13 (21)	18 (46)	200
SCB> 18mm	2 (8)	0 (12)	3 (20)	20
DCB+MCB	**24 (101)**	**31 (145)**	**45 (192)**	**300**
MCB	5 (15)	9 (43)	14 (65)	100

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

Cracked Brick Type	6-month 17.005 TWd	12-month 17.235 TWd	18-Month 17.456 TWd	DTB 18.5 TWd
All	320 (454)	470 (634)	630 (806)	1500
SCB 6-12mm	13 (26)	10 (48)	33 (101)	420
SCB 12- 18mm	4 (8)	6 (13)	7 (15)	200
SCB> 18mm	0 (1)	0 (1)	2 (3)	20
DCB+MCB	**16 (60)**	**20 (98)**	**25 (143)**	**300**
MCB	3 (5)	3 (23)	7 (40)	100

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

52. The specialist inspector is content that there are adequate margins on the levels of cracking between the core state forecasts, including the most onerous forecasts from the sensitivity studies (the figures in brackets), and the DTB limit of the case over the proposed periods of operation. The planned inspections of each reactor after ~6 months of operation under the proposed safety case will provide further evidence to support that the margins remain acceptable.

53. It is noted that the core burn-ups used for the core state forecasts after 12 months of further operation are slightly less than the proposed burn-up limits of the case for both Hinkley Point B Reactor 3 and Reactor 4. EDF NGL argues that the end of generation burn-up limits of the proposed safety case reflect two operating periods of 6 months (±

1 month) or up to 14 months operation in total. The ± 1 month is to allow for some flexibility to inspection outage planning in a staggered manner across the Hinkley Point B and Hunterston B reactors. EDF NGL argues that there are no consequences on the safety case because the 18-month core state forecasts provide healthy margins to the limits of the damage tolerance assessments supporting the case (i.e. the DTB).

54. The specialist inspector is content with EDF NGL's argument noting that the limits of the safety case are the core burn-up of 17.55 TWd for R3 and 17.3 TWd for R4 and that the margins between the core state at these burn-ups and the limits of the damage tolerance assessments supporting the case (i.e. the DTB) are adequate.

3.1.3.8 BRICK FRAGMENTS AND DEBRIS

55. The overall risk to fuel cooling from graphite debris is covered in section 3.1.4.2 however, debris formation and the likelihood of migration to safety significant locations have been considered by the specialist structural integrity inspector. The uncertainty in the rate of production of fragments and debris is mitigated by the proposed graphite core inspections after ~6 month of operation and the improvements EDF NGL has made to the consequences argument which demonstrates tolerance to larger free flow blockage sizes than assumed in the previous safety cases. The specialist inspector has found no reason to change their existing position determined by previous assessments (Ref. 11) that the graphite debris risk should be considered a design basis event during the validity of the proposed safety case.

3.1.3.9 EXISTING ISSUES AND RECOMMENDATIONS

56. This section details the existing Issues and Recommendations relevant to the assessment of NP/SC 7800.

57. The specialist inspector notes that EDF NGL has extended the distribution of cracked bricks to Ring 10 in both normal operation (AGRIGID) and seismic (GCORE) whole core models in the evidence supporting the proposed safety case. This completes the actions of Regulatory Issue 7379 which was raised based on a recommendation from the graphite structural integrity assessment (Ref. 12) of the Hinkley Point B Reactor 3 return to service safety case following its statutory outage in 2019. The specialist inspector therefore makes the following recommendation:

Recommendation 2 of ONR-ODF-AR-20-110 "*(to ONR graphite structural integrity inspector): to consider closing Regulatory Issue 7379. NGL has extended modelling of cracked bricks to Ring 10 in both normal operation (AGRIGID) and seismic (GCORE) whole core models."*

58. The graphite structural integrity assessment of NP/SC 7766 - ONR-OFD-AR-19-053 (Ref. 13) and an assessment of the graphite materials properties model ONR-OFD-AR-19-093 (Ref. 14) made a number of relevant recommendations. The recommendations are recorded in regulatory issue 8482 and are discussed below.

59. **Recommendation 1 of ONR-OFD-AR-19-053**: "*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."*

60. The specialist inspector considers EDF NGL's use of lower bound virgin values for the proposed HPB NP/SC 7800 safety case to be supportable and demonstrably conservative.

61. The specialist inspector also considers that EDF NGL has satisfied the second aspect of the recommendation related to the methodology for co-location by providing a method

which refines the co-location methodology of the internally and externally induced stresses with the local strength.

62. **Recommendation 2 of ONR-OFD-AR-19-053**: "*Safety case arguments for operation beyond SS1 should identify the major conservatisms and uncertainties and seek to quantify their combined effect on the DTA."*

63. Based on their assessment, the specialist inspector is satisfied that EDF NGL has identified the major conservatisms and uncertainties in the methodology and illustrated an overall conservative bias.

64. **Recommendation 3 of ONR-OFD-AR-19-093:** "*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."*

65. In the specialist inspector's opinion, EDF NGL has provided extensive sensitivity studies in the damage tolerance assessments for both seismic and normal operation and faults conditions. In the seismic analysis which bounds the normal operation and faults analysis, it was shown that the margins are gradually reduced with increasing clearances and reducing capacities.

66. It is judged, therefore, that EDF NGL has satisfied the expectations of this recommendation through the sensitivity studies provided to support the proposed safety case.

Recommendation 4 of ONR-OFD-AR-19-093: *"That NGL be advised that ONR would have greater confidence in EdF Integrated Model (EIM) predictions if recalibration was made with the most recent inspection data. This applies particularly to the dimensional change and creep/coefficient of thermal expansion 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."*

67. The ONR specialist inspector who made this recommendation is satisfied that EDF NGL has answered this recommendation by showing that the recalibration makes a comparatively small difference to the parameters of relevance to the DTA. The specialist inspector is satisfied that the parameters used in the DTA remain appropriate and conservative.

68. The graphite structural integrity assessment (Ref. 11) of NP/SC 7792 made the following recommendation:

69. ***"Recommendation 1 of ONR NP/SC 7792:*** *ONR should consider and plan an intervention to look at the effectiveness of NGL's measures in place to reduce potential errors in the development and assessment of the whole core models."*

70. ONR graphite specialist inspectors have planned and carried out an intervention which addresses the recommendation above (Ref. 15). For the purpose of this PAR, the specialist inspector is content that adequate progress has been made to address the intervention recommendations and that there are no concerns that would affect their decision on the overall adequacy of the proposed safety case.

3.1.3.10 STRUCTURAL INTEGRITY CONCLUSION

71. To conclude, the specialist structural inspector is satisfied with the claims, arguments and evidence laid down within EDF NGL's safety case. The specialist inspector is content that the Licensee's evidence is adequate to support the argument that control rod entry, fuel sleeve integrity and fuel cooling will not be challenged over the proposed periods of operation. 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 Hinkley Point B Reactor 3 and Reactor 4 can return to service and operate up to a core burn-up of 17.55 TWd and 17.3 TWd respectively.

3.1.4 FAULT STUDIES ASSESSMENT

72. The specialist fault studies inspector focussed their assessment (Ref. 16) 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.

73. 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

74. The specialist inspector judged that consideration of whether NP/SC 7800 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 therefore raised the following recommendation:

75. ***Recommendation 1 of*** **ONR-OFD-AR-20-094***: "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."*

76. The specialist structural integrity inspector is satisfied that EDF NGL has adequately demonstrated that all control rods will insert in normal operation and following a design basis seismic event (Ref. 17).

Fuel movement

77. The fault studies assessment of the extant case NP/SC 7792 (Ref. 18), 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 probabilistic safety assessment (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 graphite 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 two proposed ~6 month operating periods.

78. ***Recommendation 2 of*** **ONR-OFD-AR-20-094***: 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.*

79. 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.

80. 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. 17).

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

81. The arguments and evidence presented in NP/SC 7800 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 7800 which presents an up to date review of the evidence.

The effects of channel distortion – eccentric annulus

82. The fault studies assessment (Ref. 18), of the extant case NP/SC 7792 examined the arguments and evidence relating to the effects of an eccentric annulus. It 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

83. An extensive examination of the potential for sleeve gapping to occur has been performed by EDF NGL. Modelling of core distortion at levels of core degradation in excess of that predicted up to the proposed core burnup limits led on two instances to individual channels showing sleeve gaps in excess of 2mm (a trigger point for review which EDF NGL had imposed). In both instance the gap sizes were <3.5mm, and the review concluded that the temperature rise which may be induced by such a gap would be bounded by the allowances in the operating limits. 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.

84. The fault studies assessment considers 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. The specialist inspector therefore recommends that 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.

85. ***Recommendation 3 of* ONR-OFD-AR-20-094***: "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."*

86. The specialist graphite inspector is satisfied that the methodology employed by EDF NGL to predict sleeve gap sizes over the operating period is acceptable (Ref. 17).

87. In conclusion the specialist fault studies inspector judged that, since sleeve gapping is not predicted in excess of 4mm 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

88. The fault studies assessment of a previous graphite safety case (Ref. 19) 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 7800 now presents arguments to address the recommendation. The licensee states that the seismic assessments demonstrate that impacts between the fuel sleeve and fuel channel would not be significant enough to cause sleeve damage, and that reactor trip would occur following a seismic event through either automatic or manual means. The licensee also states that the effects of sleeve gapping on the fuel clad temperature would be significantly reduced following reactor trip due to the significant reduction in heat generation.

89. The arguments presented by EDF NGL are in the specialist inspectors view straight forward and logical and sufficient to address the intention of the recommendation and associated regulatory issue (8212).

3.1.4.3 DEBRIS

90. 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). This is 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 a recommendation was made that prior to granting permission to the modifications described in NP/SC 7800, the project inspector should confirm that the graphite inspector is satisfied that there is no significant increase in the probability of graphite debris migration.

91. ***Recommendation 4 of* ONR-OFD-AR-20-094***: 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.*

92. The graphite inspector is satisfied that there is not a significant increase in the probability of graphite debris migrating into fuel stringers (Ref. 17).

93. It is the specialist inspector's opinion that the previously discussed thermal hydraulic evidence demonstrated that fuel clad melt at the element 1 location due to flow obstruction from graphite debris need 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

94. 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 plausible effects on the neutron flux distribution from graphite brick cracking were examined in the ONR assessment of NP/SC 7792 (Ref. 18). This 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

95. 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 Hinkley Point B Reactor 3 and Reactor 4 can return to service and operate up to a core burn-up of 17.55 TWd and 17.3 TWd respectively.

4. MATTERS ARISING FROM ONR'S WORK

96. All ONR specialist inspectors agree that the proposed safety case modification of NP/SC 7800 (Ref. 3) is acceptable. On that basis I have prepared a licence instrument for Agreement to NP/SC 7800 HPB R3 and R4 Graphite Cores – Post Keyway Root Cracking Safety. This has been written according to ONR guidance, and for which the text and format have been agreed with the Government legal department. Further legal checking of this licence instrument is therefore unnecessary.

97. 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 7800.

98. I have liaised with the Environment Agency (EA) and it has confirmed that it has no objections to the operation of Hinkley Point B Reactor 3 to a core burn-up of 17.55 TWd and Reactor 4 to a core burn-up of 17.3 TWd, (Ref. 20).

99. I have confirmed that EDF NGL has followed its own due process. An INSA statement for NP/SC 7800 has been submitted (Ref. 21) and Nuclear Safety Committee (NSC) meeting minutes have been submitted (Ref. 22).

5. CONCLUSION

100. I have concluded that the operation of Hinkley Point B of Reactor 3 to a core burn-up of 17.55 TWd and Reactor 4 to a core burn-up of 17.3 TWd subject to inspection findings following ~ 6 months operation, has been adequately justified by EDF NGL and that a Licence Instrument should be issued to EDF NGL to allow implementation of NP/SC 7800.

6. RECOMMENDATIONS

101. I recommend that licence instrument 564 is issued to Hinkley Point B to Agree to the implementation of NP/SC 7800

7. REFERENCES

1. BEG/SPEC/DAO/020, Nuclear Generation Limited, Company Specification, Modification process, Revision 010, May 2020

2. NLS HPB 51441 R Request for Agreement under arrangements made under Licence Condition LC22 (1) Engineering Change (EC) 366147 - NP/SC 7800, 5 January 2021, CM9 2021/758

3. EDF NGL Safety Case: EC 366147 Ver 02, NP/SC 7800 HPB R3 and R4 Graphite Cores – Post Keyway Root Cracking Safety Case, December 2020. CM9 2020/323385

4. NGL, NP/SC 7792 V09, Justification for an Increase in the Operational Allowance for the Hinkley Point B Graphite Cores for Core Ages up to 17.2 TWd, CM9 2019/260009

5. EDF Energy, EC366104 Revision 000, Setting of Justified Period of Safe Operation for HPB R3 and R4 based on Graphite Core Safety Case NP/SC 7792, CM9 2019/354874

6. Review of Input Seismic Motions for Graphite Core Assessment for the Hinkley Point B Nuclear Power Plant, 14th Oct 2019, CM9 2019/308125

7. ONR-OFD-AR-20-105 Revision 0, Hinkley Point B R3 and R4 Graphite Cores – Post Keyway Root Cracking Safety Case NP/SC 7800, Seismic Hazard Assessment, CM9 2021/13008

8. ONR-OFD-AR-20-092 Revision 0, Civil Engineering Assessment of HPB EC 366147 and HNB EC EC366098 Graphite Cores – Post Keyway Root Cracking Safety Case modifications, CM9 2021/13781

9. ONR-ODF-AR-20-110 Revision 0, Graphite Structural Integrity Assessment of NP/SC 7800 HPB R3 and R4 Graphite Cores – Post Keyway Root Cracking Safety Case, CM9 2021/17308

10. ONR-OFD-AR-20-073 Revision 0, Assessment of the Implementation of Friction in GCORE, 2021, CM9 2020/294782

11. ONR-OFD-AR-19-073 Revision 0, NP/SC 7792 V09 Hinkley Point B – Graphite Structural Integrity Assessment, CM9 2019/355116

12. ONR-OFD-AR-19-016 Revision 0, Assessment of EC 365309 Hinkley Point B Reactor 3 2019 Graphite Core Inspection Results and Justification for Return to Service, May 2019, CM9 2019/142779

13. ONR-OFD-AR-19-053 Revision 0, Graphite Structural Integrity Assessment of HNB R3 NP/SC 7766, CM9 2019/264245

14. 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

15. ONR-OFD-IR-20-064 Revision 0, Whole Core Modelling used in EDF NGL's graphite safety cases, CM9 2020/312767

16. ONR-OFD-AR-20-094 Revision 0, Fault Studies Assessment of the Safety Case for Operation of Hinkley Point B Reactors 3 & 4 Up to Core Burnups of 17.55TWd and 17.3TWd, CM9 2021/5063

17. Email – RE: Links between Fault Studies and Graphite report – 04/03/2021, CM9 2021/18907

18. ONR-OFD-AR-19-056 Rev 00, Fault Studies Assessment of the Justification for an Increase in the Operational Allowance for the Hinkley Point B Graphite Core for Core Ages up to 17.2 TWd CM9 2019/274182

19. ONR-OFD-AR-20-003, Graphite Core Safety Case. NP/SC 7766 Stage Submission 1: An Operational Safety Case for Hunterston B R3 to a Core Burn-up of 16.425TWd Following the 2018 Graphite Core Outage, CM9 2020/131280

20. Email – RE: Hinkley Point B Return to Service, 23/02/2021, CM9 2021/15943

21. EDF Energy Nuclear Generation Ltd – Milestone Full INSA Statement – HPB R3&R4 Graphite Cores – Post Keyway Root Cracking Safety Cases, CM9 2020/323380

22. Meeting 12a/20, EDF Energy Nuclear Generation Ltd Nuclear Safety Committees Minutes of the Meeting, 15 December 2020, CM9 2020/323602