Operating Reactors

Return to service safety case for Reactor 4 following core inspection results in 2018 (NP/SC 7785), Graphite structural integrity assessment

Assessment Report ONR-OFD-AR-19-007
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EXECUTIVE SUMMARY

This report summarises my assessment of the Hunterston B (HNB) Reactor 4 (R4) return to service safety case (NP/SC 7785) and the supporting documentation submitted by EDF-Energy Nuclear Generation Limited (NGL). The return to service case proposes a four-month period of operation, i.e. up to a core burn-up of 16.025TWd and is based on, but extends, the methodology of the currently permissioned NP/SC 7716. My assessment has focused on the structural integrity of the graphite core and is part of a set of ONR assessments that will be brought together by the Project Assessment Report (PAR).

This assessment must be placed in the context of the recent inspection history for both Reactor 3 (R3) and R4 of HNB and the recent developments by NGL in the analysis methodology which supports the safety case. NP/SC 7785 is NGL's first graphite core safety case submission after these developments, and although the submission is for a short period of operation my assessment must nonetheless take them into account.

In March 2018 HNB R3 was shut down for the purposes of an interim inspection of the graphite core. The inspection revealed that crack opening of fuel bricks was causing other fuel bricks to crack, this was termed 'induced cracking' and required NGL to update its core state prediction methods. The inspections also showed instances of fuel bricks containing one or two full-height axial cracks with additional partial-height axial cracks emanating from the brick ends. This indicated the potential for bricks to crack into three or more vertical parts if those partial-height cracks were to grow to full-height; such a potentially cracked brick was referred to as a multiply-cracked brick (MCB). Although NGL had considered such forms of cracking eight years earlier, the extant graphite core safety case (NP/SC 7716) had not explicitly justified safe operation with MCBs. Further to these observations, brick cracking was also found in some instances to be generating graphite debris, i.e. small pieces of graphite separating from the brick, the consequences of which would need addressing in any return to service case. NGL subsequently set to developing the safety case justifications for continued operation with MCBs and graphite debris.

In October 2018 HNB R4 was shut down for a scheduled graphite inspection, at that time R4 was behind R3 in terms of core age by approximately 9 months. The inspection confirmed expectations that R4 had fewer cracked bricks than R3 and that R4 remained within the permissioned operational allowances of the extant safety case (NP/SC 7716) of 350 cracked bricks. However, continued operation of R4 might be expected to lead to a situation where those allowances were soon exceeded and any justification to increase them would require NGL to develop the seismic tolerance arguments as per recommendations made by ONRs assessment of the extant safety case (NP/SC 7716).

Although this safety case submission is for a short period of four months, it nonetheless includes significant revisions to the safety case methodology that need to be assessed before a permissioning decision can be made, namely:

- Revised core state predictions which include induced cracking and MCBs;
- Improvements to the graphite core seismic tolerance arguments;
- Justifications for safe operation with MCBs and graphite debris;
- Increasing the safety case allowances for cracked brick numbers, i.e. the Operational Allowance (OA) and the Currently Established Damage Tolerance Level (CEDTL).

I have assessed the revised core state predictions and I am content that the phenomena of induced cracking and the potential for MCBs has been conservatively included using a sufficient scope of inspection evidence. The extensive inspection of the leading reactor (HNB R3), the targeted inspection of a number of HSBs in HNB R4, and the associated learning,

has provided important additional confidence in the prediction of the HNB R4 core state at the end of its four-month operating period. This is an important factor in my acceptance of the safety case claims because some of NGL's past predictions of core degradation have been shown in the absence of leading data to be not wholly accurate when data became available.

The Licensee has shown that the small number of more advanced cracked morphologies predicted to exist by the end of the four-month operating period means the rate of generation of graphite fragments and debris is likely to be low during that period. Based on the evidence presented, I consider that a safety significant blockage of element 1 with debris is a low frequency event for the proposed four-month period of operation. However, because there is significant uncertainty in determining the true likelihood, a precautionary approach should be taken. I have consequently recommended that when considering this case the fault studies inspector should treat the initiating event frequency of a safety significant blockage at the fuel element 1 grid as a 10^{-4} pry design basis event.

It must be expected that debris will become more frequent during operation beyond the current core condition of HNB R3. I have therefore made a recommendation that before any further permission for operation is requested, NGL should provide more robust arguments for mitigating the risks posed by graphite debris, and for the determination of graphite debris production and its migration.

NGL has expended substantial effort in developing the graphite core seismic tolerance arguments. This has been in two major respects: firstly, the treatment of component failures during a seismic event; and secondly, updating the predicted seismic input motion to the graphite core. I am content that the revised treatment of component failures represents an improved methodology and satisfies the recommendations made by ONR's previous assessment of NP/SC 7716. The updated seismic input motion has been assessed by a civil engineering specialist inspector; the inspector was satisfied but recommended I take into account the effect of an upper bound seismic input case on the channel distortions. I have taken those considerations in to account and I am content with the seismic tolerance claims.

I am content that the supporting analyses show control rod channel distortions are acceptable in normal operation and in a 1 in 10,000 year seismic event, even when accounting for MCBs up to the OA and CEDTL. I am also content that the channel distortions allow a safety margin for unimpeded control rod entry to be maintained even when the possibility of more severe, but less likely, distortions are considered. Whilst I am content with the arguments presented for channel distortion, I consider it reasonable to expect future safety cases to reinforce the supporting evidence that outlier configurations that might impede control rod entry are sufficiently unlikely.

I am content that the approximate methods for predicting the influence of MCBs on free movement of control rods and fuel have been done conservatively, but only with respect to channel distortion. In extreme cases, MCBs might be capable of creating local sites of fuel stringer ledging or snagging and this has been considered by fault studies inspectors. Whilst I am content with the approximate method of the MCB implementation in this case, I have recommended that NGL should set out a plan to move to a more accurate implementation because it is entirely achievable and would benefit future safety cases.

However, I consider that the licensee has conservatively accounted for the effect of core distortion on fuel movement and fuel sleeve gapping.

Through ONRs assessment activities to date it has become clear that particular aspects of graphite core ageing will provide challenges to making robust safety cases for more advanced states of graphite core damage than has been predicted for the four-month operating period of this case. For example, this includes but is not limited to, the reliability of the damage progression model, the potential for key disengagement, the local influence of MCBs on fuel snagging frequency and the generation of graphite debris. These matters will require continued scrutiny in addition to the specific recommendations I have made, and NGL will need to make progress on these aspects should safety cases for further operation be proposed. This will be through the regular and ongoing interactions between ONR and NGL.

I will be raising a regulatory issue to monitor progress on the recommendations made by my assessment.

I would therefore not object to further operation of HNB R4 for a period of four months, i.e. up to a core burn-up of 16.025TWd.

LIST OF ABBREVIATIONS

AGU	Anti-Gapping Unit
ALARP	As Low As is Reasonably Practical
CBNA	Cracked Brick Neighbourhood Array
CEDTL	Currently Established Damage Tolerance Level
DCB	Doubly Cracked Brick (a fuel brick with two full-height through-wall cracks)
DHD	Diverse Hold Down
DTA	Damage Tolerance Assessment
EC	Engineering Change
EIM	EDF-Energy Integrated Model
ESD	Enhanced Shutdown
FGLT	Fuel Grab Load Trace data
FHA	Full Height Axial
GAP	Graphite Assessment Panel
GTAC	Graphite Technical Advisory Committee
HNB	Hunterston B Nuclear Power Station
HOW2	(ONR) Business Management System
HPB	Hinkley Point B Nuclear Power Station
HPC	Hinkley Point C Nuclear Power Station
HSL	Health and Safety Laboratory
INA	Independent Nuclear Assurance
INSA	Independent Nuclear Safety Assessment
JPSO	Justified Period of Safe Operation
KWRC	Keyway Root Cracking
LC	Licence Condition
MCB	Multiply Cracked Brick (a fuel brick with more than two full-height through-wall cracks)
NGL	EDF-Energy Nuclear Generation Ltd.
OA	Operational Allowance
ONR	Office for Nuclear Regulation
PAR	Project Assessment Report
PHA	Partial Height Axial
R3	Reactor 3
R4	Reactor 4
SACR	Super Articulated Control Rod
SAP	Safety Assessment Principle(s)
SCB	Singly Cracked Brick (a fuel brick with one full-height through-wall crack)
TAG	Technical Assessment Guide(s) (ONR)
TSC	Technical Support Contractor

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1 INTRODUCTION

1 This report summarises my assessment of the Hunterston B (HNB) Reactor 4 (R4) return to service safety case (NP/SC 7785, Reference 1) and the supporting documentation submitted by EDF-Energy Nuclear Generation Limited (NGL). The return to service proposal is for a four-month period of operation, i.e. up to a core burn-up of 16.025TWd and is based on, but extends, the methodology of the currently permissioned NP/SC 7716 (Reference 2). My assessment has focused on the structural integrity of the graphite core and is part of a set of assessments that will be brought together by the Project Assessment Report (PAR).

2 This assessment must be placed in the context of the recent inspection history for both Reactor 3 (R3) and R4 of HNB and the recent developments by NGL in the analysis methodology which supports the safety case. NP/SC 7785 is NGL's first graphite core safety case submission after these developments, and although the submission is for a short period of operation my assessment must nonetheless take them in to account. The following section provides some initial context and background to this assessment.

1.1 Background

3 In March 2018 HNB R3 was shut down for the purposes of an interim inspection of the graphite core, which I and another inspector attended (Reference 3). NGL's inspection of the graphite core was to consist of the visual inspection and dimensional measurement of 26 fuel channel bores. Of those 26 channels, 23 were selected to provide a representative description of the graphite core state. To provide further information on crack development the remaining 3 were targeted to re-inspect 3 of the 5 channels already known to contain keyway root cracks (KWRC) from the previous year's outage. The remaining 2 of the 5 channels were planned to be inspected in the next outage, however, towards the end of the outage NGL's Graphite Assessment Panel (GAP) made the decision to inspect them at this outage on the basis of the inspection findings.

4 Prior to the R3 outage NGL informed myself and other ONR inspectors at a Level 4 meeting (Reference 4) of the expected numbers of KWRCs and provided the strategy that would be adopted following different outcomes from the March 2018 outage. These outcomes were categorised as Routes A, B and C (Reference 5) and consisted of many different criteria that defined whether the inspection observations showed the core state was within the existing safety case or not. The outcomes of Routes A, B and C are summarised as follows.

Route A: The observations lie within or below expectations and will not adversely affect the pre-defined Justified Period of Safe Operation (JPSO), i.e. return to service is supported for a period of operation up to September 2018 under NP/SC 7716.

Route B: The observations lie broadly within expectation but could result in a potentially reduced JPSO under NP/SC 7716 (operation would be covered up to the 60 day EC).

Route C: The observations lie sufficiently outside of expectation that a new safety case is required to support return-to-service.

5 The inspection findings were found to be within the majority of the criteria for Routes A and B, but the findings were considerably outside the number of axially cracked bricks expected in the representative channels. In total NGL identified 14 new KWRC bricks, but the inspections revealed that KWRCs had induced full height cracking in 11 other

bricks, i.e. a total of 25 axially cracked bricks were identified. This equated to Route C, which was defined as more than 13 new axially cracked bricks, and required NGL to revise the core state prediction methodology to include induced cracking and a revised rate in the generation of KWRC.

6 After consultation with ONR, NGL made the decision to keep R3 shut down until a longer-term safety case could be made. This instigated a series of regular Level 4 meetings throughout the year where NGL communicated its safety case developments to ONR. In June/July of 2018, NGL used the opportunity to make further inspections of the graphite core to increase confidence in the graphite core state. This round of inspections was referred to as Phase 2, the March 2018 inspections being referred to as Phase 1, both inspections were summarised in References 6 and 7. Phase 2 initially inspected 38 additional fuel channels which were selected for their proximity to channels known to contain cracks, as opposed to the largely representative selection of Phase 1. A total of 70 bricks containing full height axial cracks were observed in 26 of the 38 channels, this was a proportionately higher number of cracks than observed by Phase 1. Because the higher proportion might infer bricks were cracking during the offload state NGL made a further inspection by re-inspecting 17 channels from the Phase 1 selection. Of the 17 re-inspected channels, most showed no change during the off-load period. However, some changes were observed: a brick observed to be uncracked in Phase 1 was found to contain a single full-height axial crack thought to be induced by an existing crack in the brick below; a partial height crack in another brick was now full-height and the brick below it had developed a new partial height crack. Further to these observations, brick cracking was also found in some instances to be generating graphite debris, i.e. small pieces of graphite separating from the brick. ONR indicated that the consequences of this debris would need addressing in any return to service case.

7 The Phase 1 inspections also showed instances of fuel bricks containing 1 or 2 full-height axial cracks with additional partial-height axial cracks emanating from the brick ends. This illustrated there was the potential for bricks to crack in to 3 or more parts if those partial-height cracks were to grow to full-height; such a potentially cracked brick was referred to as a multiply-cracked brick (MCB). Whilst NGL had considered such forms of cracking eight years earlier (Appendix B of Reference 8) the extant graphite core safety case did not explicitly justify safe operation with MCBs. NGL subsequently set to developing the safety case justifications for continued operation with MCBs and graphite debris.

8 In October 2018 R4 was shut down for a scheduled graphite inspection, at that time R4 was behind R3 in terms of core age by approximately 9 months and subsequently expected to have fewer cracked bricks than R3. The inspection made visual observations and dimensional measurements of 34 fuel channels, 23 of which were representative and 11 targeted. The inspections identified a total of 36 fuel bricks with full-height axial cracks including 1 doubly cracked brick (DCB), no MCBs were observed. This was presented by NGL to equate to a core state of 319 cracked fuel bricks at a 99.9% confidence level which was substantially less than the 505 predicted for R3 at the same confidence level. Whilst this provided evidence that R4 continues to be behind, and by inference bounded by R3, it also showed R4 remained within the permissioned operational allowances of the extant safety case (NP/SC 7716) of 350 cracked bricks. However, continued operation of R4 would mean that the number of cracked bricks would soon be expected to exceed 350, which would require those allowances to be increased or addressed in some other way. To achieve that, NGL would need to address issues I had previously raised with NGL's justifications for the seismic tolerance of the graphite core.

9 I had previously indicated (Reference 9) to NGL that an increase to the operational allowances would require improved confidence that the graphite core was tolerant to

the required 1 in 10,000 year seismic event by improving how damage to graphite components was modelled during the event. NGL subsequently made those improvements, which are now referred to as the inclusion of runtime damage.Subsequently, NGL also updated the seismic model of the pre-stressed concrete pressure vessel (PCPV), which transfers the seismic ground motion in to the graphite core. NGL made the revisions to the PCPV seismic model to remove what it considered to be unrealistic constraints causing excessive PCPV motion.

10 Although this safety case submission for the return to service of HNB R4 is for a short period of four months, it nonetheless includes significant revisions to the safety case methodology which need to be assessed here, namely:

- Increasing the safety case allowances for cracked brick numbers, i.e. the Operational Allowance (OA) and the Currently Established Damage Tolerance Level (CEDTL);
- Revised core state predictions which include induced cracking;
- Justifications of safe operation with MCBs and graphite debris;
- Improvements to the graphite core seismic analysis methodology via the runtime damage method;
- Revisions to the seismic input to the graphite core via the updated buildings model.

11 It is therefore the purpose of this assessment to determine whether NP/SC 7785 provides sufficient justification that it is safe for the HNB R4 graphite core to return to service for four months, i.e. up to a core age of 16.025TWd.

12 This assessment was undertaken in accordance with the requirements of the ONR How2 Business Management System (BMS) guide NS-PER-GD-014 (Reference 10). The ONR Safety Assessment Principles (SAP) (Reference 11) and the supporting Technical Assessment Guides (TAG) (Reference 12) have been used as the basis for this assessment.

1.2 Scope

13 The scope of this report covers return to service of HNB R4 for a period of four months (up to 16.0125 TWd) on the basis of the graphite core safety case NP/SC 7785 (Reference 1).

14 In the period prior to the March 2018 inspection of HNB R3, NGL had developed the extant safety case (NP/SC 7716) to increase the OA via three separate addenda: Addendum 1; Addendum 2A; and Addendum 3. This new case, NP/SC 7785, effectively supersedes the need to permission these addenda.

1.3 Methodology

15 The methodology for the assessment follows How2 guidance on mechanics of assessment within the ONR (Reference 13).

2 ASSESSMENT STRATEGY

16 The intended assessment strategy for NP/SC 7785 is set out in this section. This identifies the scope of the assessment and the standards and criteria that have been applied.

2.1 Standards and Criteria

17 The relevant standards and criteria adopted within this assessment are principally the SAPs (Reference 11) and internal ONR Technical Assessment Guides (TAG) (Reference 12). The UK fleet of AGR power stations are unique to the UK, there are subsequently little or no relevant national or international standards or relevant good practice specific to the ageing of AGR reactors on which to establish the safety case beyond the currently permissioned NP/SC 7716. HNB R3 does however lead R4 in terms of core age and brick cracking, therefore further operation of R4 will be limited to remain less than the age of R3 in this case. Relevant good practices can also be maintained by assuring the safety case is delivered in terms of claims, arguments and evidence and that the level of supporting evidence is commensurate with the claim. ONR also utilises expert advisors to ensure inspectors can make robust challenge to the safety case on an independent and diverse basis (see Section 2.3).

2.2 Safety Assessment Principles

18 The key SAPs applied within the assessment are included within Table 6 (Reference 11) of this report.

2.2.1 Technical Assessment Guides

19 The following Technical Assessment Guides have been used as part of this assessment (Reference 12):

- Graphite Reactor Cores NS-TAST-GD-029 Revision 4. ONR, July 2018. http://www.onr.org.uk/operational/tech_asst_guides/index.htm

2.3 Use of Technical Support Contractors

20 As part of the ONRs ongoing regulation activities of AGR graphite core structural integrity, TSCs are utilised to develop modelling methods independent of NGL and provide broader advice on graphite integrity. I and other inspectors have consulted with technical support contractors (TSCs) on current graphite issues at a number of meetings, and where TSCs have been consulted for this assessment it has been made clear in the appropriate sections of this report.

21 The TSCs are statistical experts from the Health and Safety Laboratories, analytical and materials experts from the University of Manchester and the University of Birmingham and independent experts on the Graphite Technical Advisory Committee (GTAC).

2.4 Integration with Other Assessment Topics

22 This assessment integrates with the civil engineering and fault studies assessment topics.

23 The output of the civil engineering inspector's assessment has informed me of the validity of inputs used in the seismic damage tolerance assessment. NGL has reduced the seismic input motion to the graphite core by revising the PCPV buildings model. This is a significant change for the safety case and thus been the subject of a separate ONR assessment report by a specialist civil engineering inspector.

24 The fault studies assessment has drawn on my views with regard to the predictions of fuel sleeve gapping, fuel snagging/ledging and frequency of coolant flow blockage due to debris.

2.5 Out of Scope Items

25 NP/SC 7785 provides a description of the previous safety case, NP/SC 7716, including its addenda: Addendum 1; Addendum 2A; and Addendum 3. Only NP/SC 7716 has currently been permissioned by ONR, its addenda have not. Any recommendations made by this assessment of NP/SC 7785 to restart, or otherwise, HNB R4 do not apply to those addenda.

3 LICENSEE'S SAFETY CASE

3.1 Operational Allowances and Currently Established Damage Tolerance Level

26 To allow further operation of HNB R4 NGL's proposal, NP/SC 7785, extends the previous OA and CEDTL from the extant NP/SC 7716. The purpose of the OA was to set a bounding level of cracking in the core that would not be exceeded during any given period of operation. The CEDTL was a higher level of cracking than the OA and was used to show the core was tolerant to damage levels substantially in excess of the OA. Both the OA and CEDTL were supported by inspection observations and analysis. The OA set by NP/SC 7716 is as follows.

- No more than 350 axially cracked bricks, of which:
  - No more than 100 are SCBs open by more than 12mm;
  - No more than 20 are SCBs open by more than 18mm;
  - No more than 180 are DCBs.

27 The CEDTL set in NP/SC 7716 was 700 SCBs of which no more than 350 are DCBs.

28 Using NP/SC 7785, NGL has proposed the following increase to the OA.

- No more than 700 axially cracked bricks, of which:
  - No more than 350 are SCBs open by 6mm to 12mm;
  - No more than 100 are SCBs open by more than 12mm;
  - No more than a combined total of 200 are DCBs and MCBs;
  - No more than 100 are MCBs.

29 NGL then sets the CEDTL by approximately doubling the revised OA to the following.

- No more than 1331 axially cracked bricks, of which:
  - No more than 700 are SCBs open by 6mm to 12mm;
  - No more than 200 are SCBs open by more than 12mm;
  - No more than a combined total of 400 are DCBs and MCBs;
  - No more than 200 are MCBs.

30 The CEDTL of 1331 is derived from all the fuel bricks in layers 3 to 7 of the central region of the core (rings 1 to 9) being cracked, plus an additional 20% of bricks in rings 1 to 9 of layer 8.

3.2 Claims and Arguments

31 In this section it is my intention to describe the claims, arguments and evidence of the licensee's safety case. I will reiterate the claims and arguments of the case and provide an outline of the evidence presented by the licensee. My restatement of NGL's safety case arguments does not imply my agreement; my own assessment is contained in Section 4.

32 The safety case consists of two claims, with five arguments under claim 1 and three arguments under claim 2. I have collated these in the Tables 1 and 2 below with reference to the key points of evidence presented by the case.

Claim 1:	**Graphite core degradation over the proposed JPSO will not undermine the required reliability of the Primary Shutdown (PSD) system for shutdown and holddown or prevent the graphite core from meeting its other fundamental nuclear safety requirements (fuel movement and fuel cooling).**
Argument 1.1	***The current state of the core has been conservatively established through recent reactor monitoring and inspections.*** *Evidence 1.1.1: Summary of the 2018 inspection. Reference 14.* *Evidence 1.1.2: Results from recent reactor monitoring. References 15, 16 and Reference 17.* *Evidence 1.1.3: Comparison of HNB R3 and R4 2018 inspections confirms that R4 results are broadly within expectation. References 6, 14 and 18.* *Evidence 1.1.4: Established R4 whole core state is consistent with pre-inspection expectations. References 19, 20 and 21.*
Argument 1.2	***The predicted state of the core at the end of the proposed JPSO has been conservatively established.*** *Evidence 1.2.1: Ageing processes associated with fuel brick cracking. References 22, 23 and 24.* *Evidence 1.2.2: Consistency of R3 2018 Phase 1 and Phases 2 & 3 inspections. Reference 7.* *Evidence 1.2.3: CrackSim forecasts of brick cracking. References 19, 25, 23 and 24.* *Evidence 1.2.4: Sensitivity studies on CrackSim forecasts. Reference 23, 26, 27 and 28.* *Evidence 1.2.5: Simple alternative checks on predicted MCB occurrence. References 19 and 29.*
Argument 1.3	***At the end of the proposed JPSO, core distortion will not prevent successful insertion of the control rods during normal operation, plant faults or following a seismic event.*** *Evidence 1.3.1: Established damage tolerance for normal operation and non-seismic faults. References 30, 31, 32, 33, 34 and 35.* *Evidence 1.3.2: Established damage tolerance for seismic hazard. References 36, 37 and 38.* *Evidence 1.3.3: Demonstration of margin between the forecasted core state and appropriately defined OA and CEDTL.* *Evidence 1.3.4: Unplanned reactor shutdowns will not challenge the predicted core state at the end of the proposed JPSO. References 39, 40 and 41.*
Argument 1.4	***At the end of the proposed JPSO, core distortion will not prevent the graphite core from meeting its other fundamental nuclear safety requirements in relation to fuel movement and fuel cooling.*** *Evidence 1.4.1: The calculated margins for other safety-related parameters such as fuel sleeves and core components under normal operation and non-seismic faults are acceptable. References 31, 42, 43, 44, 45, 46 and 47.* *Evidence 1.4.2: The calculated margins for other safety-related parameters such as fuel sleeves and core components under seismic faults are acceptable. Reference 37.* *Evidence 1.4.3: Effect on other safety cases. Reference 30, 37, 38, 44 and 48.*
Argument 1.5	***The R4 core state (in terms of the level of cracking) at the end of the 4 month operating period (16.025 TWd) is expected to remain within the current R3 core state (16.185 TWd).*** *Evidence 1.5.1: The baseline R4 whole core state established at 99.9% calculational confidence from the 2018 inspections has fewer predicted cracks than the current R3 whole core state established at 99.9% calculational confidence from its 2018 inspections. Reference 19 and 27.* *Evidence 1.5.2: Comparison of forecast R4 cracking following return to service with current R3 cracking. Reference 19.* *Evidence 1.5.3: Acceptable confidence that R4 at 16.025 TWd will remain less cracked than R3 is at 16.185 TWd. Reference 7, 19 and 27.*

Table 1: Claim 1 arguments and evidence.

Claim 2:	**All reasonably practicable measures have been taken in order to ensure that the risk associated with continued operation of HNB R4 is As Low As Reasonably Practicable (ALARP).**
Argument 2.1	***The decision to inspect and the extent of the inspections provides the necessary confidence in the core state at the end of the JPSO.***
Argument 2.2	***All reasonably practicable measures have been taken to reduce the risk associated with return to service of HNB R4.*** *Evidence 2.2.1: There are no reasonably practicable measures to reduce the risk associated with core distortion preventing control rod insertion.* *Evidence 2.2.2: There are no reasonably practicable measures to reduce the risk associated with fuel handling.* *Evidence 2.2.3: It is not reasonably practicable to maintain HNB R4 shutdown.*
Argument 2.3	***Monitoring techniques will be employed within the proposed JPSO to confirm that core degradation remains within the basis of this proposal.*** *Evidence 2.3.1: Significant changes in fuel brick bore diameter will be detected from Fuel Grab Load Traces. References 49 and 50.* *Evidence 2.3.2: Control Rod Drop Tests and Movement. References 15 and 16.* *Evidence 2.3.3: Channel Power Discrepancies.*

Table 2: Claim 2 arguments and evidence.

33 It is worth clarifying at this point the meaning of the term *core state* that NGL uses in its evidence. NGL uses the term to describe the core state in terms of the number and type of cracked fuel bricks. ‘Core state’ does not refer to core aspects such as channel distortion or component temperatures, where those aspects are considered they are explicitly stated.

3.3 Summary of Evidence for Claim 1

34 NGL argues that core degradation will not impact safe operation and shutdown of R4 during the proposed four-month period of operation. NGL argues this by: presenting evidence of the current core state (Argument 1.1) and the predicted core state at the end of four months (Argument 1.2); and that safe operation of the core is tolerable substantially beyond the predicted four-month core state (Argument 1.3 and 1.4); and that the R4 core state will not exceed that of the leading R3 (Argument 1.5).

Argument 1.1: The current state of the core has been conservatively established through recent reactor monitoring and inspections.

35 NGL presents evidence to support this argument by showing that: information on the core condition is gathered via inspections and monitoring (Evidence 1.1.1, and 1.1.2); that R4 is ageing in a similar manner to R3 and therefore R3 data can be utilised for R4 (Evidence 1.1.3); and that the R4 inspections are consistent with pre-inspection expectations (Evidence 1.1.4).

Evidence 1.1.1: Summary of the 2018 inspections.

36 The findings from the October 2018 inspection of HNB R4 are summarised in Reference 14 and includes the rationale for the channel selection.

Evidence 1.1.2: Results from recent reactor monitoring.

37 NGL states that the results to date from reactor monitoring of HNB R4: control rod performance (References 15 and 16); review of fuel grab load trace (FGLT) analysis;

and channel power discrepancies (Reference 17), show that the graphite core is consistent with design expectation and fulfils its key nuclear safety function under normal operation (i.e. does not impede control rod entry). This includes the latest fuel movements from the R4 low power refuelling campaign in August 2018. NGL note, however, that given only one refuelling campaign is likely to take place during the JPSO, the additional confidence provided by FGLT for this submission is limited.

Evidence 1.1.3: Comparison of HNB R3 and R4 2018 inspections confirms that R4 results are broadly within expectation.

38 NGL compares the extent of observed axial cracking within R4 (Reference 14) with that of R3 (Reference 6) in Table 1 of the safety case (Reference 1). NGL states the table shows clearly that R4 is lagging R3 with regards to the existing damage and that this is to be expected given the lower core burn-up of R4.

39 NGL describes in Reference 18 that there is substantial evidence from weight loss data, graphite materials properties data (modulus, strength) and measured bore shapes to suggest that the behaviour of the graphite material in the main population of graphite fuel bricks R3 and R4 is identical. This supports the expectation of similarity in the rates of cracking of R3 and R4 main population bricks.

40 There is considered to be a sub-population of graphite fuel bricks in the R4 core referred to as High Shrinkage Bricks (HSBs), NGL states that the existing safety case recognises that a small number of bricks may exhibit high shrinkage behaviour and be at risk of early KWRC compared to the main population of bricks.

Evidence 1.1.4: Established R4 whole core state is consistent with pre-inspection expectations.

41 NGL uses a numerical simulation code called *CrackSim* which is based on a technique called Bayesian Updating and estimates the current and future core state on a probabilistic basis using the inspection data. CrackSim uses “process models” to represent the important components of reactor evolution, for example brick cracking and crack opening. These are parameterised and uncertainty is represented through prior distributions for those parameters. Existing data, for example from monitoring and inspections, constrains what that parameter value might be.

42 NGL and its contractors develop and run CrackSim which takes estimates of the timing and rate of axial cracking and combines these with uncertainty envelopes for the onset age, cracking and crack opening rates to produce probabilistic estimates that certain events will occur within defined periods. To predict future core states, CrackSim establishes a whole core state by extrapolating the available inspection data.

43 NGL states that the CrackSim analysis of the cracking observations to date, as reported in Reference 19, shows that R4 remained within its NP/SC 7716 OA during the last operating period.

44 Prior to the inspections, NGL predicted (Reference 20) the extent of cracking that would be present in R4 using statistical analysis that was conditioned using R3 inspection data but recognised that R4 has a population of HSBs. Reference 20 established that the most likely inspection outcome for the 23 representative channels would be 24 new full-height axial cracks. This compares to the 18 observed bricks with full-height axial cracks, and the 5 bricks with observed partial height axial cracking. NGL also notes that slightly higher or lower actual occurrences of induced cracking could significantly change the observed axial cracking, therefore NGL considers the observed R4 core state to be broadly in line with expectations.

45 Prior to the October 2018 inspection, the GAP approved criteria (Reference 21) referred to as Route A/B/C to define how the findings would fall in to the requirements of a return-to-service safety case. NGL states the findings of the October 2018 inspection were in Route A, i.e. return-to-service under the extant NP/SC 7716, but also that the total number of full-height axial cracks fell into Route B and subsequently required NP/SC 7785 for return-to-service.

46 NGL states that crack opening and damage progression of the previously-observed KWRC bricks was at the lower end of the expected range.

Argument 1.2: The predicted state of the core at the end of the proposed JPSO has been conservatively established.

47 NGL presents evidence to support this argument by showing that: the ageing processes of brick cracking are understood (Evidence 1.2.1); that the differences in inspections results separated by several months in the offload condition do not equate to an unaccounted for ageing mechanism (Evidence 1.2.2); and that the core state at the end of the proposed operation can be reliably and conservatively predicted (Evidence 1.2.3 and 1.2.4).

Evidence 1.2.1: Ageing processes associated with fuel brick cracking.

48 NGL summarises its understanding of brick cracking in Reference 22 and 23 which is taken from the HNB R3 2018 inspection, noting that R3 is leading R4 in terms of core burn-up by approximately 9 months (equivalent to ~0.3TWd) and in the observed extent of cracking.

49 Reference 24 assesses the HNB R4 October 2018 observations of bricks with multiple cracking. The implications upon the processes and parametrisation within CrackSim are then considered. NGL states Reference 24 confirms that the observations at HNB R4 are in line with those at HNB R3, and that the evolution of damage within HSBs can be used alongside that of main population bricks in R3.

50 NGL states the assessment indicates that ageing processes are being driven by systematic mechanisms, but also recognise that further information and inspection evidence is still required to distinguish between observational correlation and causal mechanisms for the limited number of cases considered.

Evidence 1.2.2: Consistency of R3 2018 Phase 1 and Phases 2 & 3 inspections.

51 NGL states that the R3 inspections of 2018 consisted of 28 channels inspected in March (Phase 1) followed by further 75 inspections in June and July (Phase 2 and 3), of which 17 were repeat inspections. As discussed in Argument 1.1, NGL considers the R3 core state to be well described by the combination of the R3 Phase 1 and Phases 2 & 3 inspections. NGL supports this with Reference 7, which confirms that whilst the populations are not identical, they are similar. NGL established this position through statistical treatment of the results and through providing a physical basis and rationale for the observed differences. NGL is therefore confident that a misleading bias has not been inadvertently introduced. However, to achieve the position of ‘the null hypothesis of equivalence cannot be rejected’ (i.e. the different populations are consistent), a bias in the average channel dose (considering dose to a subject channel from the surrounding channels also) has to be taken into account.

Evidence 1.2.3: CrackSim forecasts of brick cracking.

52 NGL states its confidence in the CrackSim code to produce reliable and conservative results is discussed in Reference 25.

53 The core state predictions (Reference 19) are conditioned using the inspection findings of both the 2018 R4 inspections and the 2018 R3 inspections (combining Phases 1 to 3 of the inspections). NGL states that through investigating the inspection data for representative channels, Reference 19 confirms that both reactors can be treated as equivalent. Confidence in this position is presented in Reference 23 which considers the number of cracked representative channels across R3 and R4 together with SABRE 2018 predictions.

54 I should note here that SABRE is an analytical tool, which uses stress analysis of graphite fuel bricks accounting for the uncertainty in the graphite material properties to estimate the rate at which keyway root cracks accumulate in the core. This does not include secondary cracking mechanisms such as induced cracking which are accounted for via CrackSim.

55 With regard to the development of DCBs and MCBs, the calculations in Reference 19 are based upon the processes and process parameters developed in Reference 24. It is noted that a higher rate of induced cracking near to cracked HSBs has been used in previous estimations of cracking across the whole core. In Reference 19, normal rates of induced cracking are now assumed, as informed by the October 2018 R4 observations. This change, however, is shown in Reference 19 to have a negligible effect upon the estimates of the extent of cracking across the whole core.

Evidence 1.2.4: Sensitivity studies on CrackSim forecasts.

56 NGL recognised that there remains some uncertainty relating to the true variability of the material properties and that other parameters may contribute to variability, e.g. configurational variability associated with cracking behaviours in the differing end face key orientations. Sensitivity studies have therefore been performed to address (a) uncertainty in the forecasts associated with variability and (b) that only a small number of DCBs have been observed and that no MCBs have been observed (and hence there is little direct validation of the processes implemented in the baseline CrackSim estimates).

57 NGL presents the following sensitivity studies:

- A wider uncertainty for the rate of a DCB to transition into an MCB (Reference 26);
- Removal of the constraint that R4 will age on an equivalent basis to R3 (Reference 23 and 27);
- Assume partial-height cracks longer than a given criterion are full-height axial cracks (Reference 28).

58 NGL presents the results of the sensitivity studies in a table which shows at the 99.9th percentile confidence level the number of MCBs remains within the OA after 12 months of operation.

Evidence 1.2.5: Simple alternative checks on predicted MCB occurrence.

59 NGL provides a simple statistical check on the number of MCBs in the R4 core via References 19 and 29 which do not include any mechanistic understanding of MCB formation. NGL states the check predicts 54 MCBs at 16.130TWd, i.e. beyond the

16.025TWd after the four months of operation proposed. NGL also states 54 MCBs includes a highly conservative assumption that all 30 HSBs in R4 progress to MCBs during that period.

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

60 NGL presents evidence in the form of whole core model analyses which predict the influence of graphite core ageing, i.e. graphite shrinkage, strength degradation and brick cracking, on the distortions of fuel channels and control rod channels. NGL presents evidence to support this argument by showing that: the tolerability of the graphite core to ageing can be established (Evidence 1.3.1 and 1.3.2); that the 99.9th percentile core state at the end of the proposed operating period is less than the tolerable levels (Evidence 1.3.3); and that unplanned shutdowns during the proposed operating period will not significantly alter the core state beyond that predicted to exist at the end of the period (Evidence 1.3.4).

Evidence 1.3.1: Established damage tolerance for normal operation and non-seismic faults.

61 NGL presents in References 30 and 31 the evidence from whole core model analyses, known as AGRIGID, for:

- A range of core burn-ups (16.7TWd, 18.6TWd and 19.8TWd).
- A range of cracking percentages (up to 100% or 1,792 SCB in layers 3 - 9 and rings 1 to 9 in the central core, and up to 50% or 896 singly and 50% or 896 DCB).
- A range of crack width distributions (12mm uniform opening (at periphery) and variable opening up to 25mm).

62 For the above conditions NGL states AGRIGID predicts no instances of overloaded fuel sleeves or overloaded interstitial brick spigot / recess connections, and that the predicted control rod channel distortion could be 2.8 times greater before free movement of the control rod might be challenged. NGL also notes where there is a potential for radial keys to disengage with their keyways it is not of significant concern.

63 NGL presents sensitivity studies in References 32, 33 and 34 to address observations of crack alignment in fuel channels and the influence such alignments might have on the core distortion. NGL concludes the assessment to date shows that the levels of fuel channel and control rod channel distortion with vertically aligned cracks are no worse than cases with random crack orientation.

64 In Reference 35, NGL also presents the evidence from whole core model analyses which include MCBs, namely, 200 MCBs in combination with 200 DCBs and 931 SCBs, i.e. 1,331 axially cracked bricks. Reference 35 is presented in Appendix B of NP/SC 7785 and states the results from AGRIGID with MCBs support NGL's view that channel distortions are primarily driven by the opening of singly cracked bricks, and so a reduction in constraint [from MCBs] has a relatively small effect.

Evidence 1.3.2: Established damage tolerance for seismic hazard.

65 The core boundary input motion used for previous GCORE assessments, including those supporting the currently permissioned NP/SC 7716, was based upon the PCPV response calculated by the 'legacy' reactor buildings seismic assessment that was

performed in the 1990's to support the first periodic safety review (PSR). NGL states that unrealistic constraints have been identified in the legacy model and these have been found to cause excessive PCPV motion. NGL has therefore developed a new finite element model of the PCPV (Reference 36) to update the core boundary input motion for the GCORE assessments. The 'best estimate' core boundary time history produced by the updated model is greatly reduced in severity from the corresponding time history used in previous assessments. This is mainly attributed to the legacy model including connections between the top of the PCPV and the reactor building, which unrealistically tie the two structures together leading to excessive excitation of the top of the PCPV.

66 In Reference 37, NGL presents the evidence from whole core model analyses, known as GCORE, which considers most of the central region of the core being cracked. NGL includes in those considerations cases with uniform distributions of SCB openings of 6mm and 12mm, and includes 200, 400 and 1000 DCBs. For those conditions, NGL states GCORE predicts the control rod channel distortion could be 2.69 times greater before free movement of the control rod might be challenged and that there is no significant extent of keying system failures during the seismic event. NGL also notes the GCORE results show there is no significant potential for keys to become disengaged from their keyways.

67 NGL also presents in Reference 38 the evidence from whole core model analyses which include MCBs, namely 200 MCBs in combination with 200 DCBs and 931 SCBs, i.e. 1,331 axially cracked bricks in total. Reference 38 is presented in Appendix B of NP/SC 7785 which states the results from GCORE are in line with expectations and understanding, in that an increase in core mobility leads to greater channel distortions under seismic loading. NGL also states the analysis also shows no sudden deterioration in control rod entry margins in the presence of small clusters of MCBs e.g. a vertical triplet. NGL concludes that the analysis of MCBs includes good coverage of different configurations of damage (including vertical MCB triplets) and large control rod entry margins have been demonstrated.

Evidence 1.3.3: Demonstration of margin between the forecasted core state and appropriately defined OA and CEDTL.

68 NGL states that the CEDTL is conservatively set by taking the lowest of the assessed parameters (e.g. the number of SCB open to a given width, the number DCBs or the number of MCBs) used in either of the seismic or static assessments, whilst ensuring the combinations of cracking types are bounded by the DTA assessments. NGL then ensures a margin is placed on the OA by setting the OA to be less than CEDTL. The OA then forms the safety case limit for operation.

69 NGL states that the baseline forecasted core state following the proposed four months of operation is well within the proposed OA. NGL adds that this remains to be the case even for a forecasted 9 months of operation and that the core state sensitivity studies provided under Argument 1.2 remain within the OA.

Evidence 1.3.4: Unplanned reactor shutdowns will not challenge the predicted core state at the end of the proposed JPSO.

70 NGL argues that brick cracking is more likely to occur during cold shutdown when control rods have already entered the core (Reference 39). NGL supports this by two sets of stress analyses that use diverse computer codes and material property models (referred to as EIM v1.2 and COMSOL), which both conclude that cracking at shutdown occurs in advance of cracking at power (References 40 and 41).

71 NGL qualifies this evidence by stating the core condition will remain acceptable if R4 is shut down during the JPSO and remains 'hot'. This is because NGL considers that crack opening widths will remain narrow in the 'hot' state. If a 'cold' shutdown occurs, the HNB GAP will meet to discuss the reasonable practicability of performing additional core inspections and to confirm the continued validity of the proposal.

Argument 1.4: At the end of the proposed JPSO, core distortion will not prevent the graphite core from meeting its other fundamental nuclear safety requirements in relation to fuel movement and fuel cooling.

72 NGL presents evidence to support the safety case view that the effects of graphite core ageing on fuel stringers, fuel handling and the core restraint system are acceptable. NGL uses Evidence 1.4.1 and 1.4.2 to show the integrity of the fuel sleeves, the fuel stringer tie bar and the fuel cladding is maintained when considering mechanical loads, cooling gas flow disruption and debris. NGL uses Evidence 1.4.3 to show the effects of graphite ageing on the fuel handling risk and core restraint safety cases is acceptable.

Evidence 1.4.1: The calculated margins for other safety-related parameters such as fuel sleeves and core components under normal operation and non-seismic faults are acceptable.

73 In this evidence NGL refers to *other safety-related parameters* and *core components*, which refer to the following items.

- Inter-element fuel sleeve gapping due to core distortion, debris and handling and its effect on: fuel clad temperatures; fuel fission gas pressure; and tie bar integrity.
- The effect of normal operation and faults and graphite debris on fuel-sleeve integrity.
- The ability of brick cracking and debris within the fuel sleeve to disrupt the cooling gas flow.

74 NGL presents evidence in References 31, 42 and 43 to show the effect of fuel sleeve gapping on fuel clad temperature is negligible. NGL describes in the evidence that gapping is predicted to be less than 1mm and that gapping of 4mm to 7mm has been shown not to threaten clad integrity or exceed the 870°C limit. It is NGL's view that any undetected gapping that results in a peak clad temperature exceeding the limit would be limited to one or a few channels and would be readily detected and the fuel removed. Evidence is also presented (Reference 44) that tie bar integrity is secure to a total gapping of up to 6mm, which should be compared to the less than 1mm gapping predicted.

75 NGL refers to the whole core modelling evidence presented in Reference 31 to show the forces acting on fuel sleeves during the normal operation and fault conditions are small compared to their load bearing capacity. NGL also acknowledges that fuel sleeves could conceivably be loaded by graphite debris causing the fuel sleeve to distort, leading to inter-element gapping. However, NGL states any graphite debris that is produced from the channel wall is expected to be small and friable and that there would be no driving force to lodge any graphite debris between the fuel channel and fuel sleeve.

76 NGL acknowledges that the temperature of fuel bricks and sleeves may change due to coolant flow leakage through SCB openings and the gaps between DCB halves from the spaces between fuel and interstitial columns to the annulus between the fuel brick

bore and the fuel sleeves. The effect of brick cracking on cooling is considered in References 45 and 46 for fault and normal operations respectively. It has been demonstrated that fuel can, sleeve and core temperatures will remain below the acceptable limits in normal operation. NGL also acknowledges that References 45 and 46 did not explicitly cover MCBs, however, Appendix B of NP/SC 7785 reviews the analysis and testing results and NGL concludes that MCBs will have no significant effect on the gas flow pattern and hence cooling.

77 NGL states the most significant concern with debris for gas flows is the potential for debris to become lodged within the fuel stringer, but it is unlikely debris of any significance could enter the fuel stringer whilst the stringer is in the channel. NGL provides evidence in Reference 47 to support its view that debris blocking up to 16.5% of the flow area (or 1/6th of the total free flow area) will ensure compliance with the existing technical specification limit of 870°C limit. NGL does not consider the scenario credible that larger debris could be released from the fuel bricks then subsequently reach the bottom of the fuel stringer and cause such a blockage. NGL also notes that Gaseous Activity Monitoring detects fuel failures in the unlikely event that debris causes excessive increases in fuel pin temperatures.

Evidence 1.4.2: The calculated margins for other safety-related parameters such as fuel sleeves and core components under seismic faults are acceptable.

78 NGL presents evidence from Reference 37 to show the calculated margins for other safety-related parameters such as fuel sleeves and core components under seismic faults are acceptable. For the proposed operating period, NGL concludes that it is clear the fuel sleeves will retain integrity in a seismic event.

Evidence 1.4.3: Effect on other safety cases.

79 NGL states core degradation will affect the Fuel and Non-Fuel Handling safety case and the Core Restraint and Core Support safety cases.

80 NGL reviewed the effects of core distortion resulting from the various core ageing mechanisms on the refuelling safety cases (Reference 44) and identified two main issues. These were that axial shrinkage of fuel elements due to irradiation could potentially increase the 'hangman's drop' distances, and that the frequency of fuel snags could be affected. NGL states that temporary technical specification limits are in place to ensure that the hangman's drop risk remains sufficiently low whilst the existing lifting integrity safety case is being updated. NGL supports this with the evidence presented in Argument 1.3 (Reference 30) to show that fuel movements will be possible without any significant interaction in load cases with up to 1,792 SCB and for cases that have modelled 716 SCB and 716 DCB for a core age of 16.7TWd. NGL provides additional evidence in Appendix A of NP/SC 7785 to conclude:

- A hypothetical increase by a factor of ten in the snag frequency in the core region is tolerable without exceeding tolerable targets for Fuel Route risk;
- A hypothetical increase by a factor of one hundred in the snag frequency will result in Dose Band 5 risk above the upper tolerable target. Regarding conservatisms in the analysis the actual risk is expected to be further reduced as to fall in the Tolerable if ALARP region.

81 NGL concludes that in the light of the presented supporting analysis and operational measures in place, the refuelling safety cases remain valid, provided that the graphite core degradation does not result in a significant and sudden increase in the snag frequency associated with fuel handling.

82 The core restraint system helps to maintain the graphite core lattice structure under all operating conditions by transmitting core reaction loads to the boiler shield wall. NGL states the validity limit of the core restraint safety case is confirmed in NP/SC 7716 as 17.1TWd, which is well beyond the proposed four-month operating period for NP/SC 7785. The GCORE assessments, presented as evidence to Argument 1.3 (References 37 and 38) all include the core restraint structure strength checks, consistent with NP/SC 7716. NGL notes that a small number of core restraint components are at risk of failure, but states the graphite core response would not be significantly worsened. NGL also states that core restraint material properties have been updated following detailed thermal analysis and dosimetry estimates and concludes there is increased confidence that the current and future core restraint condition can be justified up to 19.75TWd (Reference 48).

Argument 1.5: The R4 core state (in terms of the level of cracking) at the end of the 4 month operating period (16.025 TWd) is expected to remain within the current R3 core state (16.185 TWd).

83 To date HNB R3 is ahead of R4 in terms of core age and brick cracking. To maintain this condition, NGL presents evidence that the R4 core state at the end of the proposed four-month operating period will continue to be bounded by the current R3 state. NGL presents Evidence 1.5.1 to support its view that the amount of cracking in R4 is currently less than in R3. NGL uses Evidence 1.5.2 and 1.5.3 to show the expected level of cracking in R4 at the end of the proposed operating period will be less than is currently present in R3.

Evidence 1.5.1: The baseline R4 whole core state established at 99.9% calculational confidence from the 2018 inspections has fewer predicted cracks than the current R3 whole core state established at 99.9% calculational confidence from its 2018 inspections.

84 NGL provides Reference 19 and 27 which uses the 2018 inspections to show the current R4 core state established at 99.9% confidence has less predicted cracks than the current R3 core state at the same confidence level. NGL states the R3 data is bounding of the R4 data, for example there are predicted to be 505 cracked bricks in R3 at 99.9% confidence compared to 319 in R4 at the same confidence level.

Evidence 1.5.2: Comparison of forecast R4 cracking following return to service with current R3 cracking.

85 NGL use Reference 19 to show confidence that the number of cracked bricks predicted to be present in R4 after the proposed four-month operating period is less than the current state of R3. NGL acknowledges however that the R3 data is not bounding of R4 for other parameters associated with the OA, e.g. the number of SCBs open wider than 6mm and the number of DCBs. NGL states a contributor to this are the assumptions made in the R4 forecast pertaining to HSBs. These heavily influence the predicted numbers of DCBs and MCBs and also the crack opening widths of SCBs.

Evidence 1.5.3: Acceptable confidence that R4 at 16.025 TWd will remain less cracked than R3 is at 16.185 TWd.

86 NGL states the core state forecasts presented Reference 19 are developed from a scientific understanding of the ageing process for the graphite bricks, as well as empirical correlation to the most recent inspection observations. NGL uses Reference 27 to show sensitivity studies do not incur large changes in the forecast extent of cracking. NGL considers the ageing seen within both R3 and R4 to be broadly consistent for the main population fuel bricks. Hence, with R4 core burn-up at the end

of the proposed operating period remaining below the current R3 burn-up, there is confidence that the extent of main population cracking in R4 will remain below that in R3. To support this, NGL provides evidence of equivalence between R4 and R3 cracking behaviour in Reference 7.

3.4 Summary of Evidence for Claim 2

87 NGL argues that all reasonably practical measures have been taken to reduce the risk associated with continued operation by: providing evidence that the core state can confidently be defined (Argument 2.1); that existing measures for shutdown and holddown are reasonable as far as is practical (Argument 2.2); and that the core can be monitored during the operating period (Argument 2.3).

Argument 2.1: The decision to inspect and the extent of the inspections provides the necessary confidence in the core state at the end of the JPSO.

88 NGL states the decision to inspect HNB R4 in October 2018 was taken to provide an updated understanding of the core state relative to the last inspections in September 2017, and to reduce uncertainly in the core state prediction at the end of the proposed operating period. NGL is of the view that the 34 fuel channels inspected in October 2018 is more than sufficient, on a statistical basis, to extrapolate the whole core state. To reinforce confidence in the adequacy of the inspections NGL adds that the GAP ensures the inspection programme provides the necessary confidence to underpin the arguments made in NP/SC 7785.

Argument 2.2: All reasonably practicable measures have been taken to reduce the risk associated with return to service of HNB R4.

89 NGL argues that sufficient measures have already been taken to reduce risks associated with core distortion and fuel handling and that it is not reasonably practical to improve upon those measures (Evidence 2.2.1 and 2.2.2). NGL then refers to Claim 1 via Evidence 2.2.3 to argue the proposed operating period will not result in any significant increase in the risk of an off-site radiological release.

Evidence 2.2.1: There are no reasonably practicable measures to reduce the risk associated with core distortion preventing control rod insertion.

90 NGL states the ALARP position established in the currently permissioned NP/SC 7716, on which this case is based, is considered to remain broadly unchanged and that a number of systems are in place to reduce the risk associated with partial failure of the primary shutdown system (PSD). Those systems are:

- Enhanced Shutdown System (ESD);
- Super Articulated Control Rods (SACRs);
- Nitrogen Injection

91 To protect against brick cracking, NGL does not consider further enhancement of the ESD system to be reasonably practicable. This is because the system was designed to protect against faults, which prevent the electromagnetic clutches from disengaging, it will not offer any protection against core distortion. Subsequently a redesign of the system would be necessary, which NGL considers would likely result in the PSD system no longer being ‘fail safe’ on loss of supplies.

92 As mitigation against core distortion affecting control rod insertion, NGL states 12 of the 44 bulk control rods in HNB R4 have been replaced with SACRs. Insertion of the SACRs alone is sufficient to shut down the reactor and maintain it held down for up to 16 hours.

93 A Diverse Hold Down (DHD) system is provided at HNB in the form of a nitrogen injection system, which uses ambient vaporisers to convert liquid nitrogen into gaseous nitrogen and inject it at high pressure into the reactor. NGL states that due to the way in which the DHD system operates, it is not feasible to use this system to provide initial reactor shutdown. NGL further states that attempting to modify the HNB reactors to provide initial reactor shutdown to match the capability of Heysham 2 and Torness reactors would require extremely invasive modifications to the reactor core, reactor pressure vessel and guardline systems. NGL adds that it would also require the installation of additional high pressure nitrogen storage vessels which could introduce new missile hazards.

Evidence 2.2.2: There are no reasonably practicable measures to reduce the risk associated with fuel handling.

94 NGL refers back to Evidence 1.4.3 to demonstrate understanding of how debris or fragments will behave for the four-month operating period, and that the risk of debris or fragments resulting in hard snags is sufficiently low not to challenge the assumed snag frequency. NGL adds that FGLT during refuelling in the next four months may detect any significant steps between bricks, which might indicate an increased risk of snagging.

95 NGL considers steps to reduce risk further and judges that there are no reasonably practicable measures which could be taken for the four-month operating period, for example, refuelling in off-load pressurised conditions instead of on-load, or suspending fuel radial shuffling, especially given that there will only be one low power refuelling campaign during the operating period.

Evidence 2.2.3: It is not reasonably practicable to maintain HNB R4 shutdown.

96 NGL states that an unplanned shut down of HNB R4 for a period of some months would result in substantial lost generation and the associated commercial implications. NGL also refers back to Claim 1 for demonstration that the proposed operating period will not result in any significant increase in the risk of an off-site radiological release. NGL also argues that waiting for further substantiation for operation with MCBs (e.g. rig validation of the methodologies implemented) is judged to be grossly disproportionate to the increase in nuclear safety risk. On that basis, NGL considers it is not reasonably practicable to delay the return to service of HNB R4 until a long-term justification for continued operation can be produced.

Argument 2.3: Monitoring techniques will be employed within the proposed JPSO to confirm that core degradation remains within the basis of this proposal.

97 NGL presents evidence to support this argument from three separate sources: FGLT data from on-load refuelling; control rod movements; and channel power discrepancies.

Evidence 2.3.1: Significant changes in fuel brick bore diameter will be detected from Fuel Grab Load Traces.

98 NGL has compared FGLT data taken from refuelling campaigns prior to the 2018 R3 outage (Reference 49). They conclude that FGLT can identify axially cracked bricks

where there was a 1.25 mm change in diameter between fuel brick ends. NGL states FGLT data taken during the HNB R4 2018 outage (Reference 50) successfully identified all axially cracked bricks with interface steps greater than 1mm at each end of the brick and twenty-seven axially cracked bricks in total. NGL therefore expects that FGLT will identify any significant increase in the opening of axially cracked bricks, but NGL notes there is likely to be only one refuelling campaign during the proposed operating period therefore additional monitoring data provided will be minimal.

Evidence 2.3.2: Control Rod Drop Tests and Movement.

99 NGL states that routine and continuous monitoring of grey rod movements (in response to auto-control demands) is expected to detect any gross core distortion. In addition to satisfying this requirement, the insertion characteristics following a Reactor or Guardline trip are routinely assessed for which NGL provides the latest reported results in References 15 and 16.

Evidence 2.3.3: Channel Power Discrepancies.

100 NGL states that Channel Power Discrepancies and Changes in Channel Power Discrepancies are monitored weekly and would give an indication if there were any significant inter element gapping that could have been caused by core distortion. NGL notes there have been no instances of anomalous channel power discrepancies recorded as a result of core distortion.

4 ONR ASSESSMENT

101 This assessment has been carried out in accordance with How2 guide NS-PER-GD-014, “Purpose and Scope of Permissioning” (Reference 10).

4.1 Scope of Assessment Undertaken

102 I will assess each claim of NP/SC 7785 via its arguments (Sections 4.3 to 4.10). Whilst my assessment of NP/SC 7785 follows the safety case structure on an argument by argument basis, my assessment has not been led by or limited to those arguments. There are numerous aspects of core ageing, from causes to consequences, that need to be considered and it is inevitable that in some instances further information has been required from NGL. Where this has been necessary, I have made it clear. I have provided Table 3 below to help make clear the topic areas of my assessment and the associated safety case arguments.

Outline of the assessment subject areas		
Argument	**Section**	**Subject area**
1.1	4.3	Considers the adequacy of the prediction of the current core state.
1.2	4.4	Considers the adequacy of the prediction of the core state at the end of the proposed four-month operating period.
1.3 & 1.4	4.5	Considers the evidence to support continued free movement of fuel and control rods within the graphite core.
1.4	4.6	Considers the consequences of graphite debris on safe operation.
1.5	4.7	Considers the evidence that the current R3 core state will continue to bound the R4 core state at the end of the proposed four-month operating period.
2.1	4.8	Considers whether the currently available scope of inspections provides sufficient confidence in the prediction of the R4 core state at the end of the four-month operating period.
2.2	4.9	Considers NGL’s ALARP position.
2.3	4.10	Considers the available techniques that monitor the core state during operation.

Table 3: Outline of assessment subject areas.

103 Some overlap exists in argument 1.4 between considerations of the graphite core’s damage tolerance and the formation and consequences of debris. These have been considered separately in Sections 4.5 and 4.6.

4.2 Operational Allowances

104 Whilst NGL makes particular claims and arguments in NP/SC 7785 to support a four-month return to service of HNB R4 up to 16.025TWd, the case also extends the OA and CEDTL from those of the currently permissioned NP/SC 7716. It is important to recognise that NGL has evaluated the OA and CEDTL at a core age of 17TWd, which would need approximately two full power years of operation to reach. The OA and CEDTL do not represent a prediction of the cracked brick configuration at 17TWd, they are intended to represent a bounding level of damage which is then evaluated with graphite material properties at a bounding core age, i.e. 17TWd.

4.3 Argument 1.1 – Current Core State Prediction

The current state of the core has been conservatively established through recent reactor monitoring and inspections.

105 The increased scope of inspection of HNB R3 in 2018 has improved NGL's understanding of its core state and provided greater information on the development of cracking. In particular:

- *Prompt double cracking*, i.e. the transition of an uncracked brick into a DCB by means which bypass a period of operation in the SCB state;
- *Secondary cracking*, i.e. the formation of additional cracks in an SCB due to crack opening;
- *Delayed cracking during shutdown*, i.e. cracking that occurs in the offload state sometime after a shutdown instead of during the shutdown process;
- *The extent of induced cracking*; i.e. the formation of full-height, through-wall cracks in fuel bricks due to crack opening in neighbouring bricks.

106 As a result of the new information from the HNB R3 2018 inspection, the assumptions within CrackSim were updated regarding induced cracking, rate of crack opening and the underlying SABRE cracking rate. The greater extent of induced cracking which was observed in HNB R3 also served to increase the overall cracking rate used by CrackSim.

107 HNB R4 was inspected in October 2018 with a core burn-up of 15.89TWd compared to that of HNB R3 of 16.16TWd.

108 CrackSim 2.1.2 predicted that the most likely number of observed cracks in 23 representative channel of HNB R4 would be 24 cracks with cracking being found in approximately half of the representative channels (Reference 20). The observed number of singly cracked bricks in HNB R4 was 18 in 9 representative channels with no cracking observed in the other 14 representative channels.

109 Targeted inspections of some of the HSBs was performed and found generally that their crack morphologies were greater in extent than observed in the main population of bricks in HNB R4 and similar to the most advanced crack progression in HNB R3. NGL determined from inspection measurements that the rate of crack opening of the HSBs was similar to that of the main population bricks and less than the rate used in CrackSim.

110 Overall, NGL inspected approximately 10% of the HNB R4 core in 2018, sampling 23 representative channels and targeting 11 which included HSBs. In my opinion, NGL has shown that the condition of HNB R4 agreed well with its CrackSim predictions. Its best estimate predictions of SCBs slightly over predicted the observations and the measured rate of crack opening was less than used by CrackSim for both the main population and the HSBs. The good agreement between the CrackSim prediction and the inspection results is primarily due to the revisions made to the CrackSim model following the inspection of the HNB R3 core at its higher burn-up.

111 In my opinion, NGL has appropriately established the current HNB R4 core state.

4.4 Argument 1.2 – End of Period Core State Prediction

The predicted state of the core at the end of the proposed JPSO has been conservatively established.

4.4.1 Crack Opening

112 NGL has summarised its view of crack opening rates in Reference 54. NGL has determined unconstrained crack opening rates (measured at the fuel brick bore) of between 7 and 12mm/TWd using finite element stress analysis models of single unconstrained fuel bricks. NGL's multi-brick finite element model, referred to as the 'Cracked Brick Neighbourhood Array' (CBNA), predicted that the constrained crack opening rate of a brick surrounded by intact neighbours would be approximately 3mm/TWd. This is similar to the average opening rate determined from all inspection data up to and including HNB R3 2018 of 2.68mm/TWd. NGL also found an average crack opening rate between 2017 and 2018 of 3.09mm/TWd. Finally, an update following the HNB R4 inspection in 2018 showed consistency between R3 and R4 and gave a range between 2.55 and 2.75mm/TWd for R4.

113 The crack opening rate used in NP/SC 7785 was informed by the inspection results above and was included in the predictive tool used to simulate crack opening, 'CrackSim', as 3.65mm/TWd. That was intended to represent a degree of conservatism over the currently observed rates and the rate determined by the CBNA analysis. I comment on the possible effect on the core of the results of the different assumptions on crack opening rate below. CrackSim also assumes that the HSB population is opening faster, based on the enhanced rate of shrinkage determined from bore measurements. Inspection of HSBs in HNB R4 has however found no discernible faster opening rate in the HSBs compared to that determined from R3 inspections. Hence, I consider that the predicted rate of crack opening deployed in CrackSim for HSBs is currently conservative with respect to that observed in the core.

114 In terms of the prediction of maximum crack openings, the OA and CEDTL place no upper limit on the amount of crack opening. However, CrackSim predictions (Reference 55) used by NP/SC 7785, which I have reproduced in Table 4, show that within the next four months of operation, crack opening in the core is unlikely to be greater than 18mm at the brick periphery (~10mm at the bore). The CrackSim predictions also indicate in Table 4 that it is unlikely there will be more than 21 SCBs open by more than 12mm, this includes the increased rates of opening applied to HSBs.

CrackSim forecast after four months of HNB R4 operation				
Brick State	HNB R3 (16.34 TWd)		HNB R4 (16.02 TWd)	
	50%	99.9%	50%	99.9%
Open by more than 12mm	10	31	3	21
Open by more than 13mm	5	23	1	13
Open by more than 14mm	2	17	0	8
Open by more than 15mm	1	11	0	4
Open by more than 16mm	0	7	0	2
Open by more than 17mm	0	4	0	1
Open by more than 18mm	0	2	0	0

Table 4: Crack opening breakdown after four months return to service.
(Reproduced from Reference 55)

115 In order to further refine these predictions NGL subsequently obtained further analysis in which other mathematical functions, rather than the single rate used by NP/SC 7785, have been fitted to the crack opening rate data (References 51 and 52). In these analyses, the mean rate of crack opening is not constant, but increases to a maximum of 5mm/TWd, although that rate only occurs beyond the period of relevance to NP/SC 7785. The more recent CrackSim analyses provide comparable forecasts, although in some cases there are predictions of a few cracks with openings greater than 18mm at the 99.9th percentile. ONR has also obtained an analysis from our advisors at HSL (Reference 53) which similarly indicates a small number of SCBs open by more the 18mm at the 99.9th percentile. Although the calculations in Reference 53 are marginally worse than those presented in Table 4, Table 4 predicts 18mm crack openings are being approached at the 99.9th percentile.

116 I recognise though that although these more recent calculations use a more sophisticated approach, in practice there is only limited data on crack opening rates, as it is only derived from those channels that have been found to have cracked at earlier inspections and which have also been re-measured at least once. This limits the dataset to about ten cracks. Hence, given the uncertainties and conservatism in the methods, it is reasonable to consider that the various calculations by NGL and ONR's advisors are predicting a similar state. Both calculations also show that the change in the number of 18mm crack openings is small over a 12 month period of operation and therefore unlikely to pose a challenge to the safety case claims. In the longer term, it will most likely be necessary for NGL to define limits to the extent of crack opening that include numbers of SCBs with openings greater than 18mm and greater confidence in crack opening rates can only come following the re-measuring of existing cracks following further operation.

4.4.2 Prediction of the numbers of singly cracked bricks

117 Following the extensive inspection of HNB R3 in 2018, induced cracking was found to affect a larger number of axially adjacent bricks than had previously been predicted and CrackSim was subsequently updated.

118 I consulted ONR's independent statisticians at the Health and Safety Laboratories (HSL) for their considered opinion on NGL's development of CrackSim since the HNB R3 inspections (Reference 56). In summary, HSL's statisticians advised that the NGL treatment and incorporation of the data from the HNB R3 inspections is reasonable. HSL has found no compelling evidence, either from its own studies or those performed by NGL, to suggest that the cracking rates of the main population bricks of HNB R3 and R4 are different at a statistically significant level.

119 Based on the evidence presented and the advice taken, I consider that NGL's use of the 99.9th percentile prediction of the number of singly cracked bricks at the end of the HNB R4 operating period to be a conservative estimate.

4.4.3 Double and multiple cracking

120 In order to predict the potential numbers of DCBs and MCBs that may be generated during the four-month operating period, NGL performed an event tree analysis of the potential cracking progression sequences following the first appearance of a KWRC in a channel (Reference 24). The final event tree analysis yielded a set of process parameters to be used in CrackSim. I asked a sub-group of ONR's independent Graphite Technical Advisory Committee (GTAC) to provide initial comments on the full version of NGL's event tree process model. The GTAC sub-group was asked to review the analysis and provide initial comments in a technical note (Reference 57).

121 Overall, GTAC noted that the observation of prompt double cracking events was low and that it was uncertain how a dynamic cracking event could lead to further prompt secondary cracking resulting in an MCB. GTAC found that NGL's argument that ***'…rates of transition from SCBs and DCBs to MCBs will be relatively slow, resulting in a small number of MCBs at the end of a single, short period of operation*'** were persuasive.

122 NGL had assigned a zero probability of prompt formation of an MCB in its event tree analysis. However, inspection of HNB R3 in 2018 had observed a brick in layer 7 of channel 08:80 which potentially challenges this assumption. The channel had been inspected in 2017 and was found to contain no cracked bricks. At its next inspection in 2018, the channel contained one cracked brick in layer 7, see Figure 1 below.

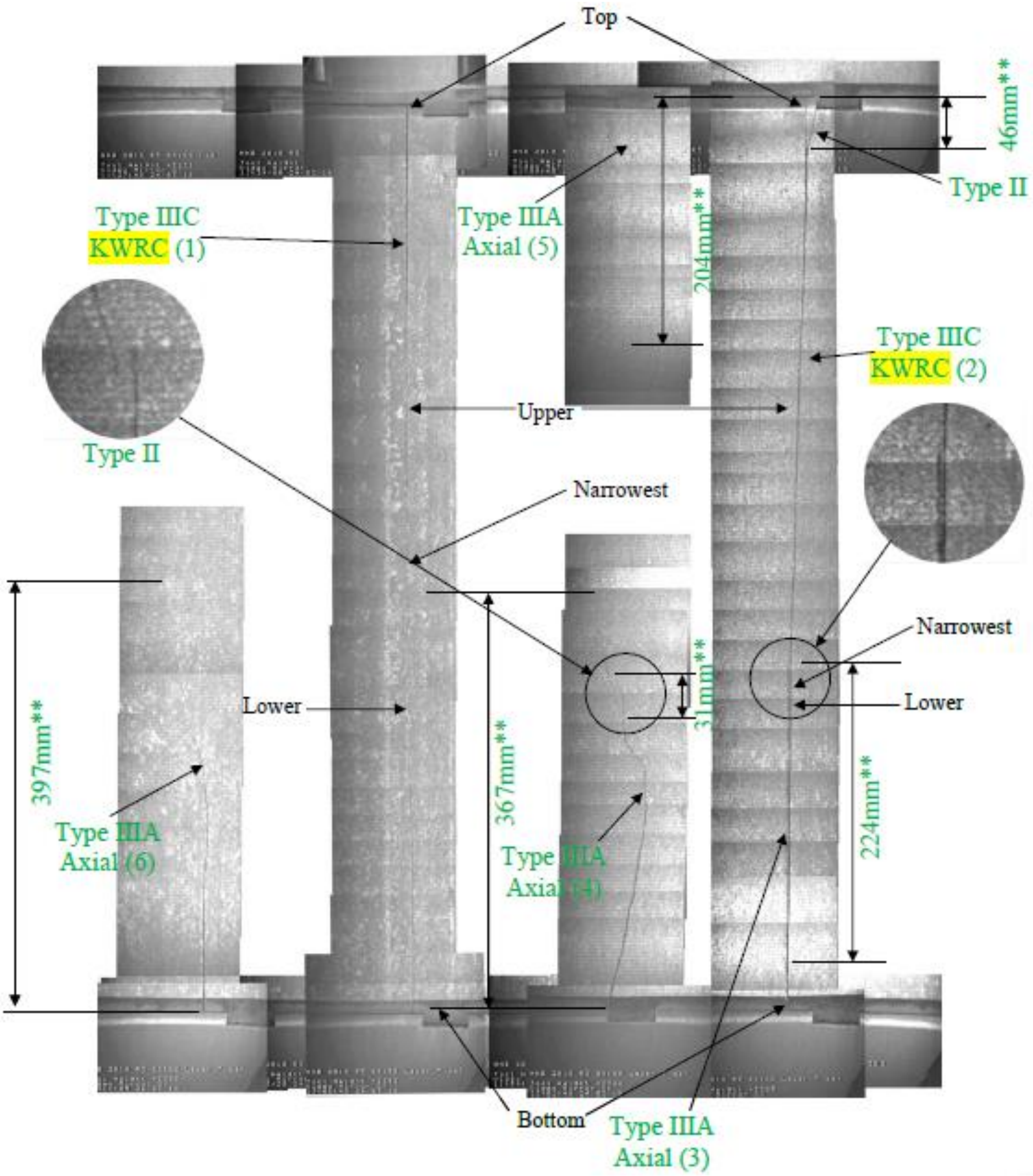

Figure 1: Assumed prompt DCB with secondary cracking.

(This figure is a collage of multiple images taken from inside a fuel channel during an inspection. The figure depicts the bore surface of a fuel brick, unravelled left to right, but with only the areas of interest having been photographed. The various notations in the figure are not used in this report so have not been defined here.)

123 The brick contained two full height axial (FHA) cracks and three partial height axial (PHA) cracks. Two of the PHA cracks were aligned axially at the top and bottom of the brick with a distance of approximately 300mm between their crack tips; noting the height of the brick is 800mm. This observation indicated that a brick might transition over a single 12 month period of operation from an intact state to a state containing three FHA cracks.

124 The GTAC sub-group were aware of the inspection result from channel 08:80 which prompted them to note:

125 ***'GTAC notes the zero probability of prompt MCBs assigned by EDF in the event tree, as indicated above. Although comfortable with a very low level of probability, the group feel that prompt MCB production cannot be eliminated completely at this stage (and this assumption is not demonstrably conservative).'***

126 Overall, GTAC concluded that;

'*there are inherent uncertainties and judgements in the methodology and the resulting estimates that have prompted us to encourage further development of the methodology (CBNA) and to perform more sensitivity analyses.*'

127 In response to the GTAC review, NGL undertook studies to test the sensitivity of the CrackSim model to changes in the assumed cracking rates at each reactor (Reference 26). These included prompt MCB generation and a 'worst case' in which partial height axial cracks promptly formed full height axial cracks.

128 I consulted ONR's independent statisticians at HSL for their considered opinion on NGL's development of CrackSim, particularly its use of the event tree analysis to predict numbers of DCBs and MCBs (Reference 56). HSL highlighted that the greatest uncertainty in the CrackSim predictions was related to the numbers of DCBs and MCBs due to the limited number of observations to date. Therefore, a simple 99.9% statistical confidence level of the best estimate case may not entirely bound the potential uncertainties within the assumptions in the model regarding DCBs and MCBs.

129 However, HSL consider that the sensitivity studies performed by NGL are a suitable way to bound the uncertainties within the model, particularly for DCBs and MCBs. I consider that because the OA proposed by NGL is greater than the numbers of potential cracked bricks predicted by the CrackSim, including the sensitivity studies, then NGL has adequately bounded the uncertainty associated with the prediction of DCBs and MCBs.

130 In my opinion, the evidence presented by NGL demonstrates that it has taken reasonable account of the uncertainty in its CrackSim predictions and has conservatively predicted the HNB R4 core state at the end of the four-month operating period.

131 It should be noted that my judgement has been significantly aided by the extensive inspection and associated learning from the leading HNB R3. NGL significantly under predicted the number of singly cracked bricks that were observed in the leading HNB R3 in March 2018. Furthermore, inspection of HNB R3 showed that greater consideration was needed of the safety implications of secondary cracking, multiple full height cracking and debris formation than NGL had previously considered necessary at this stage in the development of KWRC. This highlights the additional uncertainty associated with operation of the leading HNB R3 because only the leading reactor can validate NGL's predictions of the development of KWRC. Conversely, data from the leading reactor at HNB R3 provides some confidence that similar development of

KWRC will be observed in the lagging HNB R4, and hence its core state up to the core burn-up of the HNB R3 can be more confidently predicted.

4.5 Arguments 1.3 & 1.4 – Damage Tolerance

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

At the end of the proposed JPSO, core distortion will not prevent the graphite core from meeting its other fundamental nuclear safety requirements in relation to fuel movement and fuel cooling.

132 To date NGL has leaned heavily on the use of its own bespoke whole core modelling techniques to demonstrate the acceptability of core distortion over a proposed operating period, and continues to do so in the currently proposed NP/SC 7785 case. NGL has in fact extended the whole core modelling technique further to include MCBs to cover brick cracking that may occur should partial height cracks, which have been observed in HNB R3 and R4, grow to full height. I discuss the treatment of MCBs in Section 4.5.2 below.

133 There is no comparable form of modelling technique outside NGL that can be drawn on to help establish NGL's whole core model methodology as well-founded. I should acknowledge however the existence of whole core modelling techniques which were utilised in the past by the Magnox graphite safety cases. The Magnox graphite safety cases were driven by different requirements and ageing processes to the AGRs and the whole core modelling techniques were subsequently less complex. However, the basic principle of the model was the same. Over the years of developing the graphite core safety case, NGL has gone to significant efforts to support the validity of the model code by making cross-code comparisons and validation testing using a wide variety of test-rigs ranging from the simple to the complex. I have reviewed key elements of the validation and in my view the overall conclusion must be that the whole core modelling code can be relied upon to give a reasonable prediction of core distortion. It is also my view that the validation shows the modelling methodology carries a degree of conservatism in terms of the magnitude of channel distortion. Whilst there are various contributors to that conservatism, NGL's deliberate discounting of damping effects such as friction in the model is likely to be a significant one.

134 Whilst it appears that NGL's efforts to validate the whole core model have been largely successful, there are inherent limitations to it, which I outline below.

- The validation is of the code against test-rigs, not of the code against the graphite core. NGL has sought to improve on this by attempting to predict the channel distortions as measured by inspections, which I will discuss in more detail in Section 4.5.10.
- The validation is against test-rigs which include intact core states and core states with SCBs and DCBs, but not MCBs.
- The validation is largely against channel distortion. Whilst some validation exists against keying system forces, it is not as in-depth as the validation for channel distortion. Validation of keying system forces is important because channel distortions must be assumed to be worsened where keying system failures are predicted, for example in a seismic event. The absence of strong validation of the keying system forces is further highlighted by the inability of in-

core inspections to observe the condition of those parts of the keying system that connect channels together and prevent excessive channel distortion.

- The validation does not account for dynamic failure, for example failure of components in the test-rig during a seismic event.

135 There are a number of other aspects to consider in determining whether the whole core modelling is representative of the likely actual core's behaviour. As the flux is flattened across the core but not axially, cracking will initiate and progress within layers at different times and rates. However, within any one layer, the distribution of cracking has been observed to be essentially random. This is because the variability in the graphite properties and differences in channel fluences clearly makes prediction of precisely which bricks will crack a challenging task. NGL therefore models the core using semi-random distributions of cracked bricks across the affected layers. Each chosen distribution is likely to lead to a different set of calculated channel distortions. From a particular distribution of cracks, a particular distribution of channel distortions across the core is predicted. Both NGL and ONR currently consider that the peak distortion of any given distribution is the most important parameter, as this is the most relevant to the safety criterion that all control rods must enter the core without impediment. However, for a different distribution of cracks, but within the same overall total number of cracks, it should be expected that the peak distortion will vary. In some cases this variation is considerable and I discuss the significance of that variation in later sections. As all current inspection campaigns have only involved inspection of a proportion of the channels, it is not possible to claim that the peak distortion has been identified and recourse has to be made to the modelling in conjunction with the observed values.

136 Argument 1.3 and 1.4 are focused separately on control rod channels and fuel channels which are both simultaneously evaluated by the whole core model. I will therefore assess these aspects of Claim 1 together in the following sections:

- I assess the implementation of MCBs in to the whole core model in Section 4.5.2, this leads to further comment on key disengagements which I have made in Section 4.5.3;
- Then I will assess the channel distortion margins for the normal operating condition and the seismic event in Sections 4.5.5 to 4.5.15.

137 Firstly though, I think it is worth offering a brief note on how NGL quantifies a margin on channel distortion limits.

4.5.1 A Note on Channel Distortion Margins

138 Two of the fundamental requirements for the safe operation of the reactor is that control rod entry is not impeded and free movement of fuel is maintained. Those requirements may be challenged by distortion of the fuel channels and control rod channels which might arise as a consequence of brick cracking. NGL evaluates the channel distortions using specifically developed numerical analysis methods referred to as whole core models. The channel distortions predicted by the whole core models are quantified either in terms of a parameter known as m3dsf or a distortion utilisation (DU).

139 The parameter m3dsf is the factor required to scale a predicted channel distortion to a distortion where the fuel stringer or control rod cannot geometrically fit into that distorted channel. For example, an m3dsf of 2 on a control rod channel means the channel distortion can double before a control rod would be expected to approach its articulation capability to fully enter the channel. The DU is the reciprocal of m3dsf, it is not a different quantity to m3dsf, it is merely a means of describing the same distortion

but in terms of how much of the limiting distortion has been used. For example, a DU of 0.5 would mean the same as an m3dsf of 2, i.e. only half the available capacity of the control rods articulation capability to enter the channel has been utilised.

140 It is also important to appreciate that the DU (or the m3dsf) assumes the channel distortion is rigid, only the intended articulation capability of the control rod or fuel stringer is accounted for. The DU and m3dsf are purely geometric conditions, they do not account for material deformation or any possibility that the channel may straighten.

141 Where I refer to channel distortion margins, I will be referring to the DU as it provides a direct quantification of the utilisation. DU values less than 1 infer free movement of fuel stringers and control rods is maintained, and DU values greater than 1 infer some challenge to free movement may occur. It is important to recognise that no agreement has been made between NGL and ONR that a DU of 1 is a limit. A DU of 1 is a convenient marker for evaluation of channel distortions which I will consider on a case by case basis.

4.5.2 Multiply-Cracked Bricks

142 NGL considers that revising the whole core model codes to include MCBs in the at-power, off-load and seismic conditions will take a substantial period of time. NGL has therefore begun that development work but has in the meantime submitted in NP/SC 7785 a 'proxy-MCB' implementation. NGL considers the proxy-MCB representation to be conservative in terms of channel distortion. This section therefore considers the efficacy of that claim.

143 The proxy-MCB representation is essentially a DCB with its keying system removed. NGL has illustrated this in two figures which I have reproduced in Figures 2 and 3 below for reference. In Figures 2 and 3 the fuel bricks are represented by the large black circles, the black squares denote the interstitial bricks. Control rods are housed in the interstitial bricks, but not all interstitial bricks contain control rods.

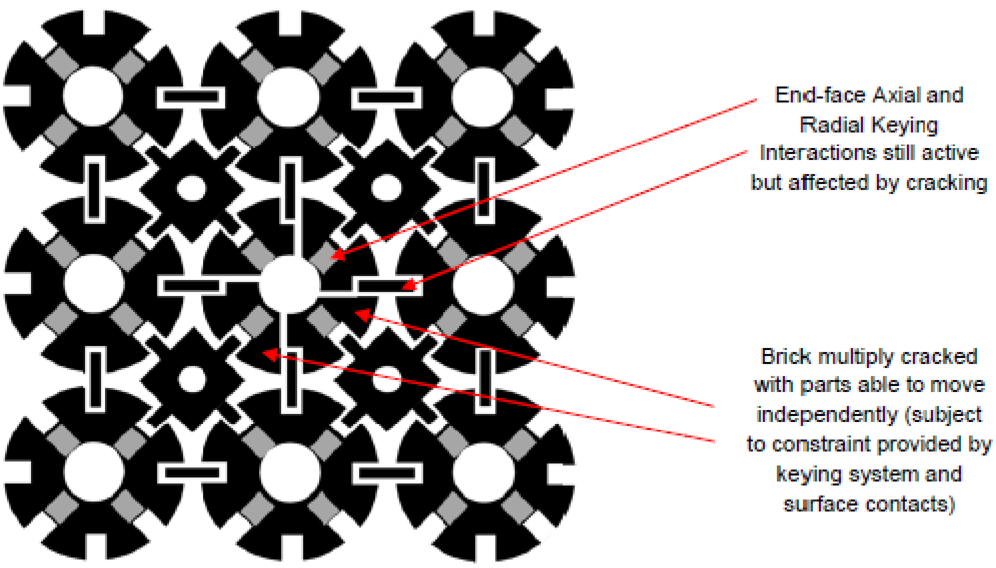

Figure 2: Potential Multiply-Cracked (Quadruple-Cracked) Fuel Brick.

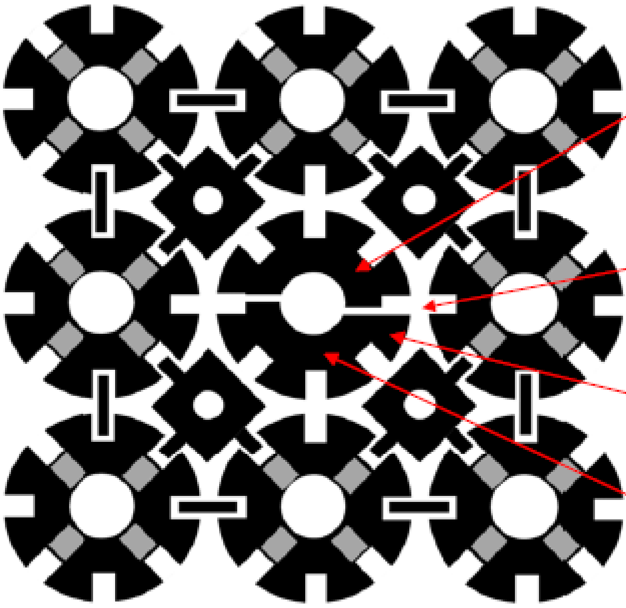

Figure 3: Representation of Multiply-Cracked Fuel Brick (Proxy-MCB).

144 It may at this point be beneficial to outline the design and purposes of the keying system. Overall, the keying system can be separated into two aspects: the radial keying system; and the end-face keying system. The radial keying system connects channels together: fuel bricks to fuel bricks are connected via “loose” keys which are free standing components; fuel bricks to interstitial bricks are connected via “integral” keys which are part of the interstitial brick. The end-face keying system connects a brick to the brick above and below it and this applies to both the fuel bricks and interstitial bricks, although there are geometric differences between the two. The purpose of the keying system is to ensure the bricks cannot move independently of other bricks, thereby maintaining channel alignment and thus aids free movement of fuel stringers and control rods.

145 Figure 2 illustrates an idealisation of an MCB. It indicates the MCB in the centre which is separated in to four axial pieces at the “loose” keys (fuel brick to fuel brick), but could equally be considered to be cracked at the “integral” keys 45° around (fuel brick to interstitial brick) or a mixture of both. Figure 3 illustrates the proposed proxy-MCB representation.

146 Figure 2 illustrates the radial and end-face keys still being in place compared to the proxy-MCB in Figure 3, which removes them. Whilst this may seem a grossly conservative implementation in terms of the potential for channel distortion, what would happen in reality is uncertain and it would seem a sensible approach to remove the key/keyway interactions entirely to erode as much of the keying system as possible. This may come with disadvantages, for instance by removing the integral keys the associated interstitial brick is no longer able to directly influence the position of the quarter piece of the MCB. This may be conservative for the seismic event where the absence of integral keys means the interstitial channels can distort more due to the seismic oscillation. But, in the at-power or off-load state, the integral key could be utilised by crack opening in neighbouring fuel bricks to pull the quarter piece of MCB away from the rest and create space for key disengagement and potentially fuel channel blockage from dislodged keys. Conversely, crack opening in neighbouring bricks might use the integral key to push the quarter piece into the fuel channel creating a ledging/snagging risk to the fuel. NGL has made its view clear in Reference 58, pointing out that the least reliable outcome from the use of proxy-MCBs is for the

movements of DCB halves, as the DCB half is itself supposed to be in two pieces but that additional mobility is not represented.

147 The main weakness of proxy-MCBs then does not seem to be with channel distortion but with the local displacement of the MCB brick pieces. Local movement of those brick pieces could lead to an increase in the number of potential key disengagements and increase the risk of ledging or snagging by translation of the brick pieces into the bore.. Assessment of the potential consequences of an increased risk in fuel stringer ledging or snagging is outside the scope of my assessment but is considered by fault studies inspectors. However, I do consider in the following sections how the proxy-MCB implementation might affect the prediction of key disengagement sites.

148 A key disengagement site is a location in the whole core model prediction where brick movement has created sufficient space that a radial key could move out of its keyway, thereby eroding the effectiveness of the keying system. NGL has always acknowledged that the whole core models and the validating test-rigs have predicted that sufficient space can be generated in the core as a result of core ageing for key disengagement to occur. NGL has also acknowledged that the whole core models do not account for the consequences of disengagement. This is because the whole core models maintain the normal behaviour of the key/keyway interaction even where there is space to allow for disengagement. Previous cases have subsequently considered analyses to be invalid if more than a certain number of disengagements (e.g. 100) are predicted, although this is essentially an arbitrary level. NGL also consistently states that although the space to accommodate a key disengagements may be predicted, there is no driving force to actually make the disengagement occur and that this is supported by test-rig evidence, I discuss this in more detail in Section 4.5.3. NGL therefore refers to the locations where space exists for disengagement to occur as 'sites of potential key disengagement'.

149 References 35 and 38 present NGL's evidence for core behaviour with proxy-MCBs in the normal operating condition and during a 1 in 10,000 year seismic event. The evidence consistently shows control rod channel distortions are low and have less than 100 sites of potential key disengagement. In all cases, the majority of those sites are where the brick halves of DCBs and proxy-MCBs have separated sufficiently to allow the keying system to be potentially disrupted there. Consequently, weaknesses in the implementation of proxy-MCBs could influence the whole core model predictions. References 35 and 38 allow comparisons to be made between the effects of DCBs and the proxy-MCB implementation, these show little difference in terms of key disengagement which is to be expected, since proxy-MCBs do not introduce any more crack sites than DCBs. For instance, a DCB has two full height axial cracks, if I place a limit of four full height axial cracks to each MCB as in Figure 2, the proxy-MCBs could be underestimating the number of sites of potential disengagement by up to two times, thereby increasing the potential for fuel snagging. However, those potential disengagement sites are connecting fuel bricks to fuel bricks and so do not directly affect control rod channel distortions because they are not directly influencing interstitial bricks. An increased number of disengagement sites might also increase the fuel channel distortions, but I consider the manner of removal of the keying system in proxy-MCBs to be a reasonable counter to that.

150 I am therefore content to accept the proxy-MCB implementation in the context of NP/SC 7785. I must note that NGL has implemented the proxy-MCB methodology as a time saving measure whilst a more detail methodology is developed. Whilst I am content with the proxy-MCB implementation, my view is that improvements in the methodology would benefit the safety case and are entirely achievable so I see no reason why they should not be provided in future safety cases.

Recommendation 1: *Before any further permission for operation of HNB R4 is requested, NGL should set out a plan to replace the implementation of proxy-MCBs in the whole core models with a full MCB representation.*

4.5.3 Key Disengagements: core states including MCBs and 12mm SCBs

151 In the previous section I stated NGL's view that no driving force exists to realise the sites of potential key disengagement into an actual disengagement. A seismic event might potentially provide sufficient driving force. When limiting core states to 12mm crack opening, NGL does predict small numbers of potential key disengagement sites in a seismic event, the majority of sites being where DCB or proxy-MCB brick halves separate sufficiently to allow key movement between the two halves. It is also important to mention here that NGL's seismic test-rigs consisting of an idealisation of the core have predicted similar levels of key disengagement (Reference 59 and 60). The testing shows disengagement sites can be realised between DCB halves but this appeared to require larger numbers of DCBs than the CEDTL. Whilst the seismic test-rig does not include MCBs, I am content with this position overall because the predicted control rod channel distortions from whole core models are low during and after the event. I take further confidence from NGL's whole core model prediction that only a single potential disengagement site occurs across all interstitial channels in all the proxy-MCB seismic analyses.

152 In normal operating conditions there are for example, vibrations from gas flows and vibrations from operation of the gas circulators that might provide a means for keys to disengage. Whilst normal operation vibrations are clearly expected to be less intense than a 1 in 10,000 year seismic event, they are continuous throughout the period of operation. It is not clear to me how likely vibrations from normal operating conditions are to generate key disengagements, but given the radial keying system cannot be observed by inspections I do not think it should be discounted. NGL predicts no potential key disengagement sites from brick to brick separation or SCB opening in all the proxy-MCB cases assessed for the normal operating condition. NGL does predict a small number of sites of potential key disengagement between the brick halves of DCBs and proxy-MCBs, i.e. where the brick halves have separated by more than one or two key widths. Therefore the propensity for key disengagement is very limited. The primary concern then is the effect of keys entering into the spaces between fuel bricks, which the geometry of the core seems to prevent, or entering the fuel channel and ultimately effecting fuel stringer movements through snagging or ledging events.

153 It is clear however that large separations of doubly cracked brick halves are required to allow the possibility of disengagement. In the normal operating condition the analyses suggest a substantially looser core than is evidence by inspections would be necessary for such separations to exist over the proposed four-month operating period. On that basis I am content to accept there is sufficient argument against the occurrence of key disengagement for core states with SCBs with crack openings up to 12mm.

4.5.4 Key Disengagements: core states including MCBs and 18mm SCBs

154 Whilst the above is applicable to the core states with SCB openings of up to 12mm, in Section 4.5.15, I have detailed a shortfall in evidence as the prediction of crack openings described in Section 4.4.1 indicates SCBs open by more than 12mm and up to 18mm. The shortfall was due to a lack of evidence supporting the claim that the core is tolerant to a particular configuration of the OA and CEDTL, i.e. a combination of MCBs and SCBs with 18mm crack openings. NGL subsequently provided that evidence in the form of whole core model results for the normal operating condition and the seismic event, References 61 and 62. The results of that work show that a

substantially larger number of potential sites for key disengagement are predicted than those presented for the crack configurations with up to 12mm crack openings.

155 The additional disengagement sites are all associated with the inclusion of 200 18mm crack openings. The 18mm opening separates the sides of the cracked keyway sufficiently that there is enough space for two keys to exist side by side. Because of the dimensions of the keys, and the crack opening being limited to 18mm, this type of disengagement is only possible at the fuel brick to fuel brick keyway and subsequently does not directly affect the interstitial channels. The fact that the space exists for such disengagement is not a guarantee that the disengagement will happen, but it is not possible to say with confidence what will happen. It is NGL's view that numerous factors would resist the disengagement from actually occurring, while those factors seem reasonable they are not definitive. It is my view that disengagements should not be wholly disregarded.

156 NGL has stated that the prediction of 200 sites is conservative. For instance, for the disengagement site to be viable, two horizontally adjacent fuel bricks must both have an 18mm crack opening at the same keyway, and potentially vertically adjacent bricks as well, but the model assumes only one keyway needs to be open. The sites are counted in that manner by the model simply to record them, hence the 200 sites is simply due to NGL specifying the 200 SCBs with crack openings of 18mm. NGL states that if only the viable disengagement sites are counted, the number of sites is substantially reduced.

157 I asked NGL to confirm how many fuel channels the 200 disengagement sites are distributed over and NGL stated it was approximately 150 fuel channels (Reference 63). When accounting only for the viable disengagement sites NGL estimated the number of fuel channels would be approximately 5.

158 Because any potential site of disengagement is associated with geometry such as crack opening width, brick-half separation of DCBs and proxy-MCBs, and brick to brick separation, direct observations through inspection can inform the likelihood of the core state being prone to such sites. For instance, bore crack opening widths can be extrapolated to the keyway opening width with some confidence, brick-half separation can be directly observed and, although indirect, the extent of brick to brick separation can be inferred from dimensional change measurements and measured core distortions. Therefore, there is some observation that can offer forewarning of the core developing distortions that are associated with sites of potential key disengagement.

159 I asked NGL to confirm whether the graphite inspections had revealed a trend of brick cracking where pairs of horizontally adjacent cracked bricks had their cracks at the same keyway. NGL confirmed in Reference 63 that between HNB R3 and R4, numerous instances of horizontally neighbouring cracked bricks had been identified but none had the cracks orientated towards each other.

160 In my view, the risk of key disengagement during normal operation or a seismic event should not be discounted. However, the predictions show the extent of potential disengagement is very limited. It is my view that those potential instances should be offset by considerations of the consequences of increased fuel snagging frequency detailed in the fault studies inspectors' assessment, Reference 66. It is also my view that where disengagement may occur, it is localised to directly effecting fuel channels not interstitial channels. I am therefore content to conclude that the risk from key disengagement is low.

4.5.5 Normal Operation – Channel Distortion Predictions

161 NGL's arguments for the acceptability of channel distortion margins during the normal operating condition are based on References 31 and 35. It is important to note at this point that NGL has previously reported fault condition cases alongside the normal operating condition and concluded to all intents and purposes that they give similar results. I see no reason to challenge this and am content that only the normal operating condition is being reported. Reference 31 addresses up to 100% of the central region of the core being cracked, some 1,792 cracked fuel bricks, and considers SCBs and combinations of SCBs with DCBs but no MCBs. Reference 35 addresses up to 75% of the central region of the core being cracked, some 1,331 cracked fuel bricks, and considers combinations of SCBs, DCBs and MCBs.

162 When evaluating fuel channel or control rod channel distortions, it must be recognised that all channels do not distort the same amount. There is a spread of values and the safety case is concerned with the single most distorted channel in the core. NGL has set its nuclear safety requirements to be the free movement of fuel and control rods, which is consistent with ONR guidance to its own inspectors (Reference 12). Therefore, whilst the bulk of channel distortions are predicted to be substantially lower than the peak channel distortion, the peak channel distortion is the key point of interest for evaluating the cores' damage tolerance.

163 In all instances of the presented analyses (Reference 31 and 35), the control rod channel DU is low. Conversely, the fuel channel distortions are approaching or are at a DU of 1. I have collated the key results presented by NGL in Figures 4 to 7 below.

164 In my view the primary conclusions to draw from Figures 4 to 7 are: that control rod channel distortion is low and does not substantially change once the number of cracked bricks has exceeded a small quantity; and that DCBs can create a step change in the peak fuel channel distortion. I consider the effect of DCBs on fuel channel distortions below in Section 4.5.6.

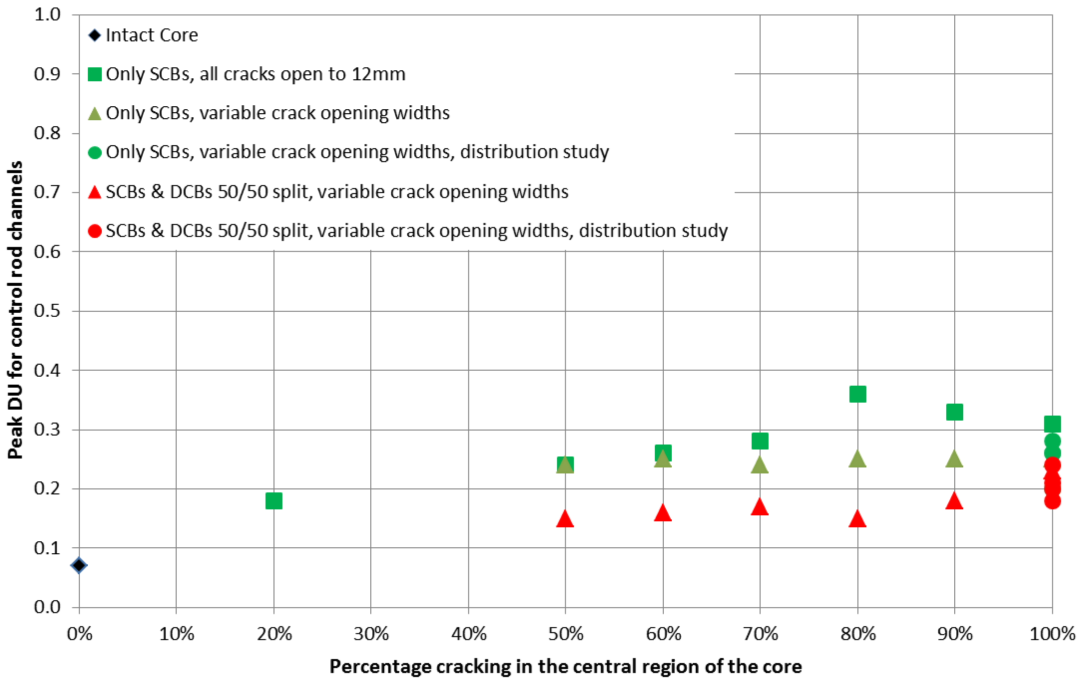

Figure 4: Control rod channel peak DUs for normal operation, SCBs and DCBs only.
(Reproduced from Reference 31)

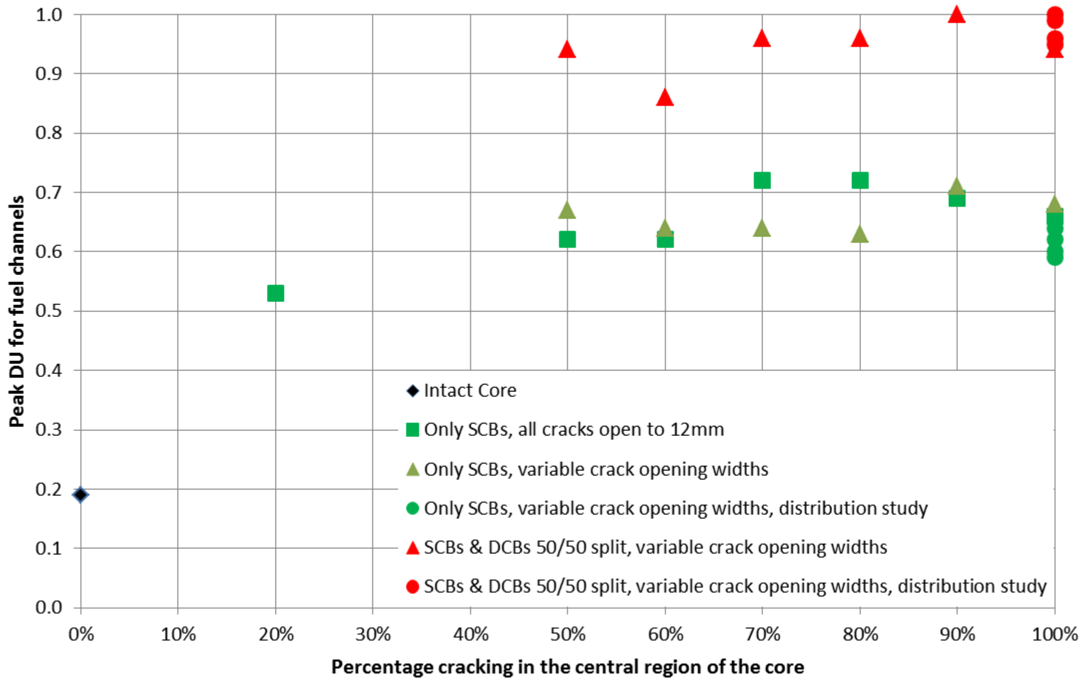

Figure 5: Fuel channel peak DUs for normal operation, SCBs and DCBs only.
(Reproduced from Reference 31)

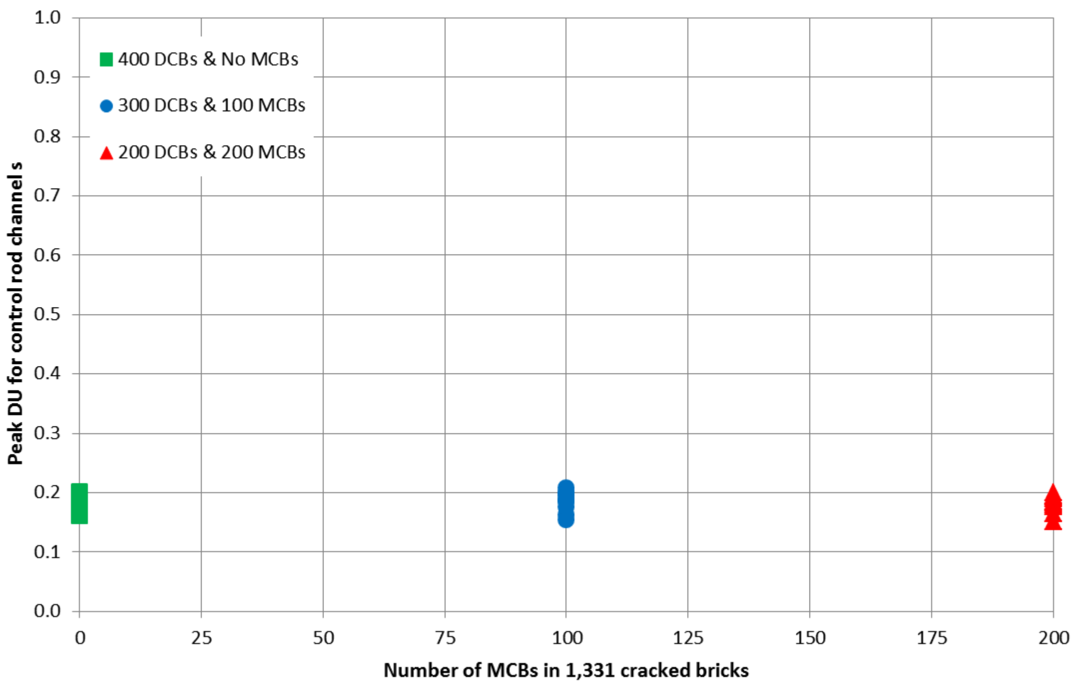

Figure 6: Control rod channel peak DUs for normal operation, SCBs, DCBs and MCBs.
(Reproduced from Reference 35)

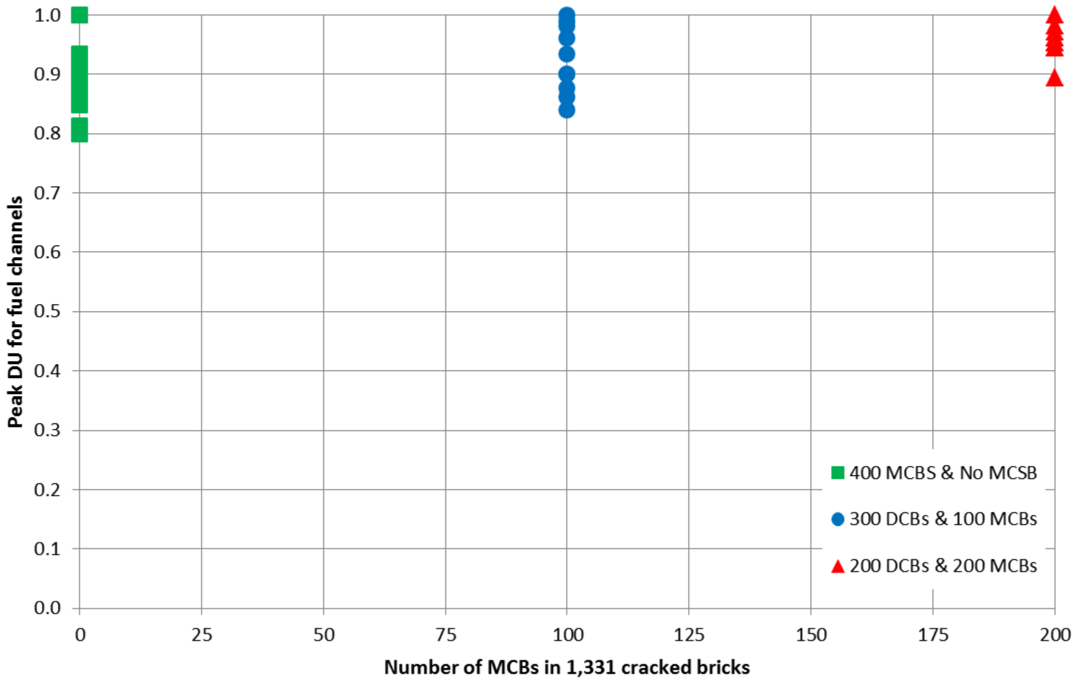

Figure 7: Fuel channel peak DUs for normal operation, SCBs, DCBs and MCBs.
(Reproduced from Reference 35)

165 The apparent invariance of the peak control rod channel distortion appears physically reasonable because the results are associated with the worst channel distortion identified for that configuration of cracking in the core. This is likely to be more influenced by the particular local configuration of cracking around a channel than the widespread distribution of cracking across the core. This makes the use of the CEDTL potentially misleading because the purpose of the CEDTL is to show margin exists beyond the OA in terms of the numbers of cracked bricks. The low sensitivity of the peak channel distortion to the numbers of cracked bricks was not established when the principle of the OA and CEDTL was defined, but was instead dealt with by NGL via other sensitivity studies. For instance, the channel distortion may also be dependent on the brick-to-brick clearances as well as the clearances and load capacities of the keying system, which will change with core age. These have though been studied by NGL in the supporting references and show little variation to core age.

166 It is important then to consider what can challenge that apparent invariance, I have made those considerations in Sections 4.5.9 and 4.5.14.

4.5.6 Normal Operation – The Effect of DCBs on Fuel Channel Distortion

167 NGL's work, summarised in Reference 30, 31 and 35, shows that the peak fuel channel distortion margins in a core with cracked bricks are significantly degraded from the intact core condition (see also Figure 5). However, the work has also shown that once a certain amount of brick cracking has occurred, the margins do not substantially change over the range of cracked brick numbers evaluated by the work (Figure 5 for example). For instance, the peak DU for an intact core is predicted to be small, about 0.2, the introduction of SCBs with significant crack opening widths raises the DU into the region of 0.5 to 0.7. Exchanging some of those SCBs for DCBs further elevates the DU to 1.

168 Reference 31 states that the peak DUs above 0.35 are dominated by a particular interaction of DCBs with the fuel stringer referred to here as DCB shear. NGL has stated that DCB shear is associated with sites where two DCBs are vertically adjacent

and the cracks are aligned, i.e. one DCB on top of the other. In this instance the shear is in the crack plane and is limited to the brick-end interface of the two bricks (G40 of Reference 64), this creates a localised constriction of the fuel channel that elevates the DU value. This is important because it means the high DU value is not associated with a horizontal shear at the brick-ends which would create a hard ledge that might impede, or potentially prevent, fuel movement. Such horizontal shear is prevented by the end-face keying system and NGL has confirmed to me via a written response to a question (see G40 of Reference 64) that where end-face keys are removed from the analysis, no such end-face shearing is predicted. It is also important to note that no end-face key failure has been observed in the reactors to date that might allow end-face shearing.

169 When evaluating fuel channel distortion, the whole core models cannot predict a DU in excess of 1 because the fuel stringer is modelled in the channel. For instance, a DU greater than 1 would require the non-physical scenario of fuel bricks passing through the stringer, which is prevented by the stringer being included. The consequence then of a peak fuel channel DU of 1 is that there is a contact load between the fuel sleeves and the DCB halves. The whole core model offers prediction of that load and consistently predicts forces that are orders of magnitude lower than the load capacity of the fuel sleeves, and subsequently does not challenge the integrity of the fuel sleeves (Reference 30, 31 and 35).

170 I am therefore content with the analysis of the fuel channel distortion and that peak DUs of 1 are not indicative of hard-snagging sites or damage to the fuel sleeves.

4.5.7 Normal Operation - Fuel Sleeve Gapping

171 The fuel stringer is a complex assembly, which ends in a string of eight fuel elements. Each fuel element is approximately 1m long and is essentially a graphite cylinder known as the fuel sleeve which houses an array of fuel pins. In the centre of each fuel element is a hollow guide tube, eight fuel elements are stacked one on top of the other by threading the guide tube on to a long thin rod, referred to as the tie bar, which runs the full length of all eight fuel elements. A support plate fixed to the bottom of the tie bar carries the weight of the fuel elements. In the reactor, a proportion of the carbon dioxide coolant travels down the annulus space between the fuel channel bore and the outside of the fuel sleeves and is then redirected through holes at the bottom of the stringer upwards inside the fuel sleeves to exchange heat with the fuel pin bundle.

172 There is a risk that fuel channel distortions could cause the fuel sleeves to tilt as the fuel stringer rests in-situ or is being moved. The interface at the fuel sleeve ends is a convoluted pathway made from machined shoulders and recesses to act as a labyrinth seal. Nevertheless, sufficient tilt of the fuel sleeves will create a gapping at the interface. Gapping will offer a bypass route for the carbon dioxide coolant from the annulus into the fuel sleeve, this will reduce the effectiveness of cooling on the fuel pins below leading to elevated fuel temperatures. NGL evaluates this risk by calculating the total gapping of the sleeves over the whole stringer and limiting that gap to be less than 0.030 radians (~1.7°) to maintain effective cooling of the fuel. To demonstrate the validity of the approach, NGL has built full-size test-rigs that have shown their analytical approach is conservative compared to the test-rig (Reference 65).

173 The whole core models have consistently predicted low values of total gapping in previous safety cases and continue to predict gapping to be low in the HNB R4 proposal. In most instances the peak gapping was predicted to be small (reported as 0.000 radians), but in some instances the peak gapping reached up to 0.005 radians over the whole stringer (Reference 31 and 35), compared to the 0.030 limit.

174 The gapping predictions are made with the assumption of a straight fuel stringer. Due to the asymmetric dose profile received by a fuel stringer in fuel channels at the edge of the core, a stringer can be bowed as the graphite sleeves shrink asymmetrically. Those bowed stringers can then be shuffled to other locations in the core as part of normal reactor operations. I, and a fault studies inspector, asked NGL what effect that bow could have on the gapping predictions (see question FS18 of Reference 64). NGL stated that after re-evaluating the gapping predictions the maximum straight stringer gapping of 0.005 radians was increased to 0.010 radians for a bowed stringer and that this was distributed over two to three fuel sleeve interfaces.

175 The method of calculating sleeve gapping does not set a limit on the tilt of a single sleeve, I subsequently asked NGL to confirm the tilt of a single sleeve that would be necessary for the guide tube to touch the tie bar: NGL confirmed this could be 0.003 to 0.006 radians (G41 of Reference 64). Comparing this to the bowed stringer result of 0.010 radians over two or three sleeves it is conceivable that core distortion could impart transverse loads to the tie bar, the consequences of which are not made clear in the safety case. I asked NGL to make clear the effect of these potential transverse loads on the tie bar (Reference 63), NGL showed the stress induced in the tie bar would be small compared to the existing tie bar structural integrity assessment.

176 I have reviewed the method of evaluating the magnitude of sleeve gapping induced by fuel channel distortion. It is my view that whilst the gapping results could be presented more clearly I am content that the predictions are reasonably made and predict a low degree of gapping relative to the quoted limit of 0.030 radians. The fault studies inspector has commented on the effect of this amount of gapping on fuel cooling performance (Reference 66).

4.5.8 Normal Operation – Graphite Material Properties 'Best Estimate' Basis

177 To date, and in the NP/SC 7785 proposal, NGL has aimed for a best estimate approach to the graphite material property inputs to the whole core model, but this is not always possible due to the difficulty associated with collecting large data populations from the graphite core. For instance, where data is sparse, such as key/keyway strengths, NGL has erred on the conservative side. Usual engineering practice for evaluating a component in normal operating conditions is to provide an upper bound estimate by using, for example, a combination of the highest loads and the lowest strengths. This is echoed in SAP EGR.13 (see Table 6) which calls for the use of data that is soundly based and demonstrably conservative. However, it is not always clear how to define conservative properties in the graphite core. For instance, more graphite shrinkage will influence clearances between bricks and the clearances of the keying system by different amounts in different brick layers. Larger clearances might be associated with larger channel distortions but tighter clearances might also be associated with higher loads and hence failures in the keying system which may in turn also lead to larger distortions.

178 In my view then, a deterministic upper bound philosophy for graphite properties to determine upper bound channel distortions in the whole core models is potentially unreliable, impractical and likely to be flawed. This difficulty is manageable via the guidance provided in TAG 29 (Reference 12) which states the data should "lead to conservative outcomes".

179 To address the need for conservative outcomes, NGL has kept a best estimate philosophy to graphite material properties in the whole core models and investigated the sensitivity to those properties through sensitivity studies on core age. By advancing the core age by several years in terms of the clearances and the strength of the keying system, the whole core model predicts how the channel distortions have changed for the same level of cracking, which is then complemented by evaluating a wide range of

cracking levels. In my view the sensitivity studies have not shown any reason to doubt the validity of NGL's approach (Reference 31 and 35).

180 I am therefore content with the principle of NGL's 'best estimate' approach to specifying graphite properties.

4.5.9 Normal Operation – Local effects and the possibility of outliers

181 In terms of unimpeded movement of fuel and control rods, the peak channel distortion predicted from the whole core models for a given future core state is of primary interest (Figures 4 to 7). However, the peak channel distortion is specific to the particular crack distribution being analysed. For instance, ten analyses at the same core age but with different random distributions of the same amount of cracking around the core will predict ten different peak channel distortions. This results from the different crack distributions generating different configurations of local clusters of cracked bricks that have different effects on channel distortions. It follows then that it is likely a distribution of cracking exists which has not been presented in the safety case and which would lead to a larger channel distortion than is being reported. NGL has always acknowledged this, but also considers that enough safety margin and conservatism exists in the analyses to offset the likelihood of an adversely different set of channel distortions.

182 In the seismic analysis, this variability in the peak distortion has previously led to difficulties in the substantiation of safety case claims, which I will discuss later in Section 4.5.12. In the normal operating condition however, the variability in the peak channel distortion has consistently been narrow. For fuel channels, the peak DU has been around 1 which I have discussed in detail in Section 4.5.6. For control rod channels, the peak DU in previous safety cases has consistently shown the peak channel distortion to be low. It continues to be so in this proposal, see Figures 4 and 6 above (Reference 31 and 35).

183 In my view, these low control rod channel distortions are necessary to mitigate the real possibility that larger distortions could be achieved by the same level of cracking but occurring in a more onerous spatial distribution. Until recently no such configuration had been identified, but a sensitivity study (Reference 67) consisting of 64 different configurations of approximately 525 (~30%) cracked fuel bricks identified one such configuration, see Figure 8 below. The peak control rod channel DUs of 63 of the 64 configurations were tightly packed in the range of 0.1 to 0.3, but one of the 64 configurations returned a peak DU of 0.4 (the green dots in Figure 8).

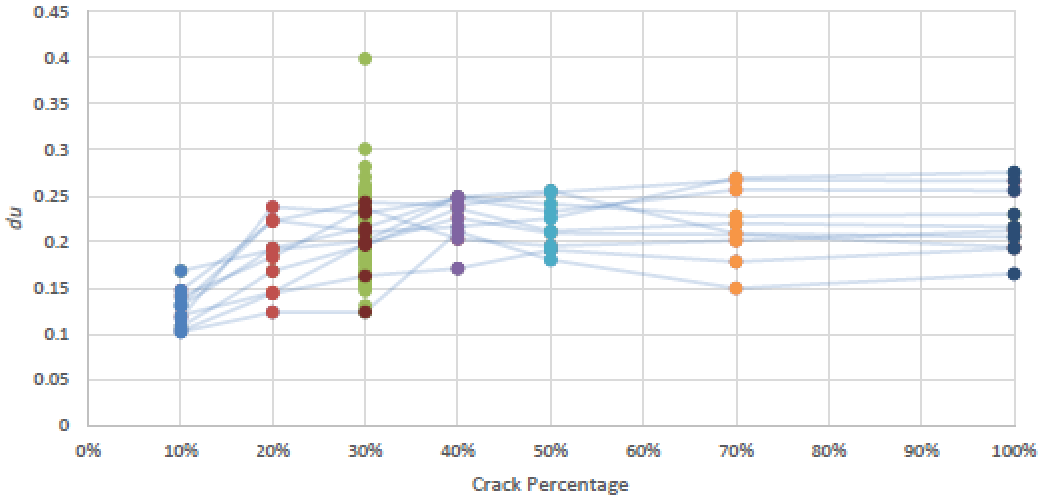

Figure 8: DU variation for different levels of cracking and random distributions.
(Taken from Reference 67, at 30% there are 64 different random distributions evaluated, at all other percentages there are 10.)

184 Although a DU of 0.4 is still low, it is singularly separate from the others and illustrates the potential for larger distortions to exist outside the main spread of results. NGL investigated this and found that the DU of 0.4 was entirely caused by a particular clustering of only 4 cracked bricks. In other words, even if no other bricks in the core were cracked, this 4-brick cluster would still return a DU of 0.4, I subsequently asked NGL to explain its cause. NGL provided further explanation that it was caused by a local clustering of 4 SCBs, with large crack openings, situated around a control rod channel. The SCB crack opening widths were large, i.e. 16mm to 22mm and the random orientation of the cracks was such that the crack opening was able to generate significant space around that control rod channel. The fact that this cluster occurred once in a set of 64 randomly generated distributions or in any of the other configurations with different numbers of cracked bricks (of which there are 60) is an indication to its likelihood, but this does not mean it can be discounted.

185 It is important however, not to focus on the specific 4-brick cluster identified in Figure 8, but more generally on the fact that such 'outlier' configurations could occur in normal operation. However, specifically arranged and advanced levels of damage are also necessary. For instance it is possible that more severe crack morphologies and clustering exist that are less likely than the 4-brick outlier but which are still likely enough to need consideration. It is also possible more severe clusters than the 4-brick outlier might allow an outlier at smaller crack opening widths. I acknowledge that this is speculation but I must also state that no work has been done to discount such possibilities. In my view then, when considering a requirement that all the control rods must be able to enter the core all of the time, these variations in the peak channel distortion must be considered. The damage tolerance assessment (DTA) methodology used by NGL generally evaluates only 10 randomly generated crack configurations at each cracking level. The distribution of channel distortions can therefore allow determination of a most likely minimum distortion value and a distribution thereof, but with only limited precision. It follows then that the safety margins on the peak channel distortions must be sufficient to accommodate the potential for outlier distortions. Even with the 4-brick outlier, the DU was 0.4, in other words, the distortion would have to be two and a half times worse. In my view, it is reasonable to expect that to obtain substantially larger distortions than the outlier, substantially greater damage than the OA and CEDTL would be required. I therefore conclude that the low distortions allow a safety margin for unimpeded control rod entry to be maintained even when the possibility of more severe, but less likely, distortions are considered.

186 I also take confidence from tests on control rod entry (References 65 and 68). References 65 and 68 summarise tests by NGL on full size mock-ups of control rod channels distorted into different shapes and amplitudes. My review of that work is not exhaustive and the tests do not inform me of the types of crack configuration that might cause the tested distortions or the likelihood of them. However, I find the test results provide additional confidence that NGL has demonstrated sufficient margin for control rod entry in the normal operating condition.

187 NGL has shown that outlier distortions are possible on control rod channels for the normal operating condition. It is my view that NGL should reinforce the evidence that those outlier configurations are sufficiently unlikely to challenge unimpeded control rod entry. I therefore make the following recommendation to NGL.

Recommendation 2: Whilst I am content with the arguments presented for channel distortion, I consider it reasonable to expect future safety cases to reinforce the supporting evidence that outlier configurations that would approach a control rod channel distortion utilisation of 1 in normal operation are sufficiently unlikely.

4.5.10 Normal Operation – Comparison against offload measured distortion

188 Validation of the whole core model to date has been against test-rigs and has been largely successful. NGL assumes that if the whole core model can reproduce the behaviour of the test-rigs then it is justifiable to extend the model to the graphite core. There is subsequently an inevitable validation gap between the behaviour of the test-rigs and the actual behaviour of the core. To mitigate this NGL has investigated whether the whole core model can reproduce the channel distortions measured by the offload inspections.

189 Inspection of the fuel channels, such that individual brick tilts can be measured, can only be done in the offload core state. From these measurements the offload channel distortions can be surmised and compared to predictions from the whole core model. NGL makes the comparison by reproducing in the whole core model the observed cracked bricks in terms of location, crack type, crack opening width and orientation. The fuel channels that were not inspected are then populated in the model by additional cracks generated randomly but consistent with the inspection observations. Those models are then evaluated twice: once where the brick tilts measured by inspection are imposed on the model; and again where the brick tilts are not imposed, i.e. the model is allowed to predict the brick tilts freely. NGL has reported the results of the work in References 69 and 70.

190 NGL does not provide a channel by channel comparison of the brick tilts, instead, NGL summarises the results in terms of cumulative frequency graphs of the channel distortion DU values. The graphs show that when the whole core model is left to predict the brick tilts, the resulting range of DU values closely matches those that can be derived from inspections.

191 Whilst some confidence can be taken from that comparison, some caution is necessary because measured tilts are not compared to predicted tilts on a channel by channel basis. The inspection measurements used will also always be from a limited set of representative inspections, therefore the channel distortions being predicted in this way must be considered as averages not the peak channel distortions of primary interest. However, in terms of the observed core state to date, I consider the comparison to be a powerful tool to support the overall behaviour of the whole core model and its capability to reproduce certain aspects of the inspection observations. In my view then, the offload comparison does add to the validation evidence supporting ongoing use of the whole core model methodology.

4.5.11 Normal Operation – Comparison with experimental tests

192 Whilst I am content that sufficient margin on control rod channel distortion has been supported, it is useful to compare the level of distortions being predicted with those of the control rod entry test rigs presented in References 65 and 68.

193 I asked NGL to provide a description of the shape and amplitude associated with the peak control rod channel distortions predicted from the whole core models (discounting the 4-brick outlier discussed in Section 4.5.9) for comparison against the control rod test rigs. NGL showed that the amplitudes of the predicted distortions were up to 10mm and in relatively benign distorted channel shapes (Reference 71). This is approximately twice the worst distortion amplitude measured to date in the HNB reactors. For similar channel shapes, the test rigs showed 20-30mm could be tolerated before significant interactions between the rod and bore were measured. For the most complex distortion shape tested, which in my view is more severe than the predictions, up to 15mm appeared to be tolerated. Whilst my consideration of this data does not represent an in-depth analysis, in my view it offers a diverse confirmation of margin for normal operation control rod channel distortion.

4.5.12 Seismic - Background

194 In the following sections I explain how and why NGL's analysis has been refined since the production of NP/SC 7716. I note here that the identification and resolution of various technical issues by NGL has informed me of what I currently believe to be the more important factors that affect the calculated margins.

195 Evaluating the performance of the graphite core in a seismic event is focussed primarily on control rod channel distortions and the integrity of fuel sleeves. Fuel channel distortions are not evaluated for the seismic event, but fuel sleeve integrity is, because the primary requirement for a seismic event is to ensure the reactor can be put into a safe state.

196 The existing permission for operation of HNB R4 is through the ONR assessment of NP/SC 7716. In my assessment of NP/SC 7716 (Reference 9) I stated that should NGL seek to increase the OA set in NP/SC 7716 then particular improvements should be made to the seismic whole core modelling methodology.

197 Those improvements related to how the model accounts for overloaded key/keyway connections that were predicted to occur during the seismic event. The original method did not remove those overloaded connections (or otherwise represent them as failed) as they occurred during the event, thereby maintaining a degree of integrity during the event that was unrealistic. Instead, the model was run three times through the event, with a fraction of the overloaded connection removed each time it was run. This method was referred to as the 'damage iteration method'. In my assessment of NP/SC 7716 I did not consider this to be a sustainable methodology for future safety cases that sought increases to the OA. I subsequently recommended an improved methodology should be developed for future safety cases.

198 Since then, NGL has developed a new methodology referred to as the 'runtime damage method' (Reference 72). The runtime damage method introduces the capability for the whole core model to remove overloaded key/keyway interactions at the time they become overloaded during the seismic event. Whilst maintaining the same basic principle of the whole core model methodology, the runtime damage method significantly overhauls particular aspects. This allows the model to predict the core response to those failures during the event in a more realistic manner.

199 I have reviewed the implementation of the runtime damage method and I am content that it addresses my recommendation for an improved method. The use of the method has however raised additional questions, which I discuss next.

4.5.13 Seismic – Control Rod Channel Distortions

200 Implementation of the runtime damage method meant the model had the freedom to fail key/keyway interactions as they became overloaded and redistribute the forces in the keying system as appropriate. NGL's initial efforts to use the runtime damage method revealed a pattern of key failures that caused a substantial increase in control rod channel distortions (References 73 and 74). For illustrative purposes I have reproduced the results in Figure 9 below as per the data contained in References 73 and 74. The DU exceeds 1 at the 5% and 10% SCB only cases, but also exceeds 1 where DCBs were included with 60% SCBs.

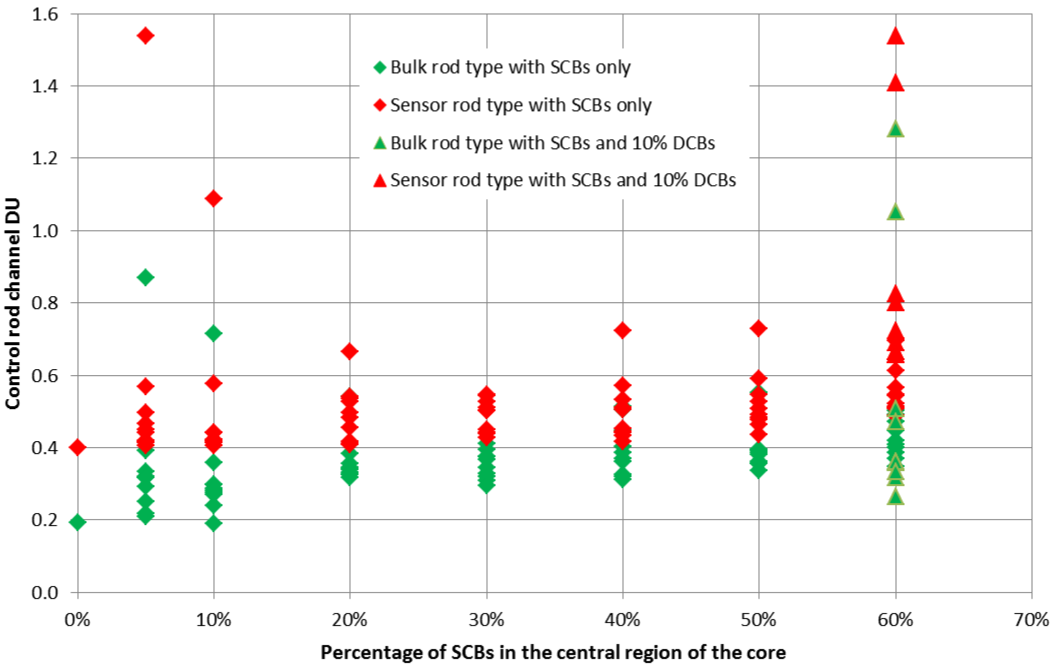

Figure 9: Control rod channel peak DUs for seismic, SCBs and DCBs only.
(Reproduced from References 73 and 74)

201 As part of the development of the runtime damage method, NGL reported the SCB only cases prior to analysing the effect of the runtime damage method on DCBs. NGL argued that the DU values which exceeded 1 at the 5% and 10% levels was due to an idealisation of the model and was non-physical and should therefore be discounted. Specifically, NGL found the runtime damage method had allowed the almost simultaneous failure of diametrically opposite integral keys on two or three vertically adjacent interstitial bricks. NGL considered such simultaneous failure to be non-physical and caused by a conservative idealisation, which applied the seismic input motion in one direction along a line of approximate symmetry in the core.

202 NGL further argued that those simultaneous failures did not occur in the cracking levels above 10% because those higher levels of cracking disrupted the symmetry and thus prevented simultaneous loading of the integral keys. To address this flaw, NGL provided further work in the form of a sensitivity study, which introduced the natural within-brick variation of graphite properties; this prevented the simultaneous failures and no examples of DU exceeding 1 were identified. However, it is important to note that NGL did not choose to incorporate the within-brick variability of properties into the whole core model methodology permanently.

203 It appears that a small change in the analysis inputs can lead to a slight redistribution of load. In turn, this may lead to different key/keyway interactions being overloaded and therefore lead to significant changes in the peak channel distortion DU and its location in the core. This means that sensitivity studies on core behaviour during a seismic event that are made with the runtime damage method would need to be carefully considered and would likely require multiple randomly generated configurations to be confident in any predicted trends. I am, however, willing to accept that the two DU values exceeding 1 at the 5% and 10% cracking levels were non-physical. Nonetheless, the work identified a weakness in the seismic event load case that the accumulation, either simultaneously or not, of a particular configuration of a very few integral key failures can generate unacceptable channel distortions. Whilst the majority of channel distortions may be acceptable, I nonetheless conclude that failure of only a few integral keys can cause aberrant and unpredictable behaviours in control rod channel distortions during the seismic event, and that these distortions are

not related to the general levels of distortion in the core. At present therefore, in my view, justification of operation has not been made for situations where significant integral key failures are predicted. It would be up to NGL to demonstrate in future safety cases that operation in such conditions was acceptable.

204 NGL then introduced 10% (~200) DCBs to the seismic case and again found DU values exceeding 1 (see Figure 9 at 60%), but did not commit to making arguments whether they were non-physical or otherwise. Instead, NGL assumed the DU values greater than 1 were real and relied on arguments that the seismic event itself was grossly conservative. At the time, NGL was reworking the seismic input to the graphite core on the basis that significant conservatisms had been identified in the translation of the ground motion to the graphite core via the building that houses it, the PCPV.

205 To obtain the seismic input to the graphite core, the ground motion for the seismic event must be translated from the ground through the PCPV and into the graphite core. NGL had originally done this through two models: one model evaluated the seismic response of the PCPV to the ground motion; and a second model (the whole core model) fed the PCPV response in to the graphite core. Keeping the same ground input motion, NGL re-evaluated the input to the graphite core by reviewing the PCPV model which was subsequently reworked and an updated input to the graphite core was predicted. This re-work of the channel distortions during the same seismic event was presented in References 37 and 38 which I have reproduced below in Figures 10, 11 and 12. Figure 10 shows the updated seismic input (referred to as the updated buildings model in Figure 10) is considerably less onerous than the original seismic input (referred to as the legacy buildings model in Figure 10). Figure 11 and 12 show the consequences of the update on the control rod channel distortions, where substantial numbers of DCBs and up to 200 MCBs are now considered tolerable with substantially reduced channel distortions.

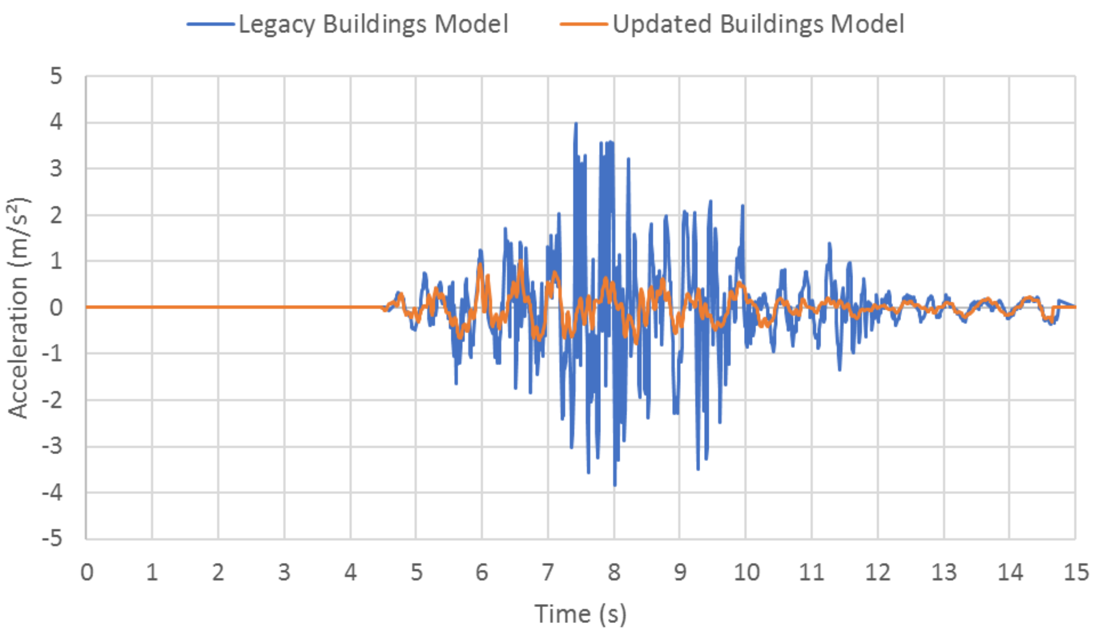

Figure 10: Legacy and revised seismic input to the graphite core.
(Reproduced from Reference 37)

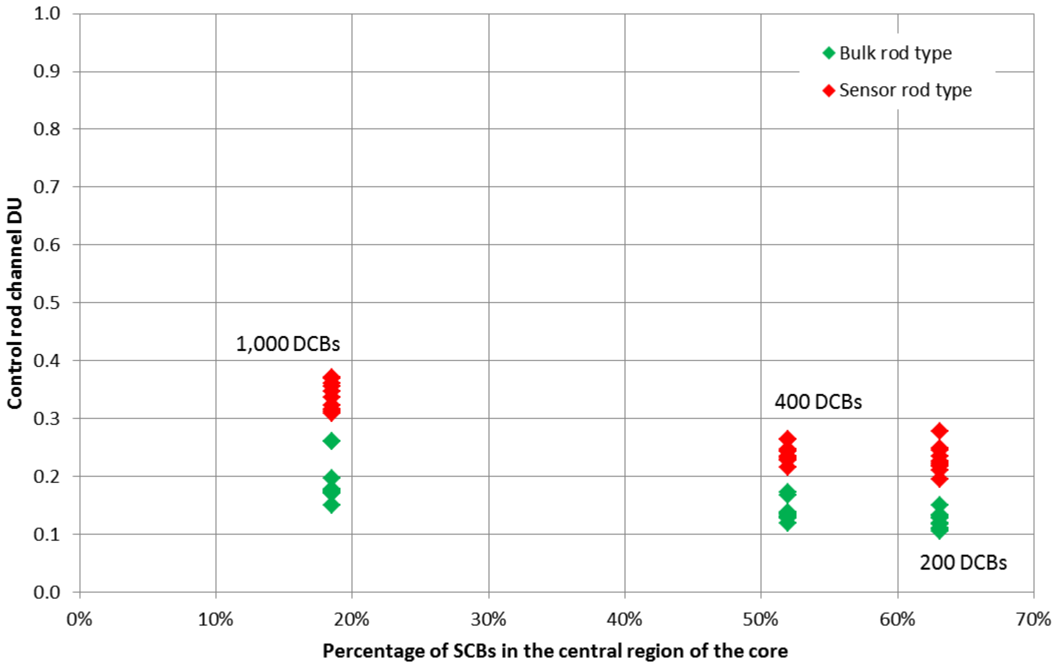

Figure 11: Control rod channel peak DUs for seismic, updated PCPV model.
(Reproduced from Reference 37)

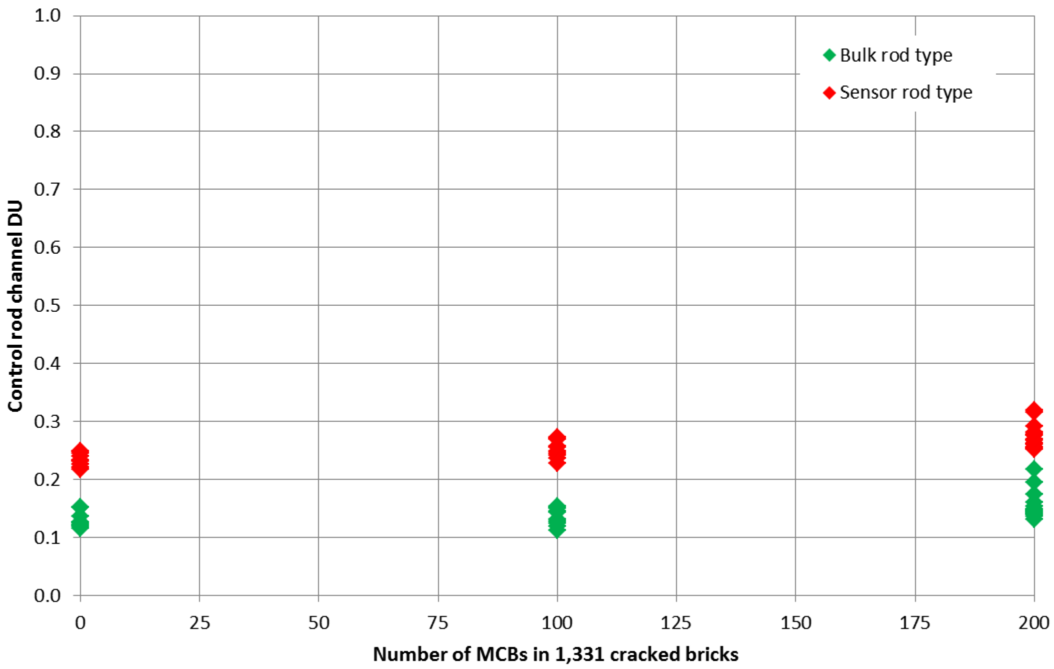

Figure 12: Control rod channel peak DUs for seismic, SCBs, DCBs and MCBs.
(Reproduced from Reference 38)

206 It became apparent that demonstration of seismic tolerance could only be achieved with the use of the updated buildings model. This was a significant shift in emphasis for the safety case and ONR determined to assess the updated buildings model. The specialist inspector’s assessment is summarised in Reference 75, and makes a particular recommendation for my assessment, which I consider in Section 4.5.16.

207 NGL claims the cause of the much reduced channel distortions (comparing Figure 11 and 12 with Figure 9) is due to the reduced seismic input causing far fewer failures in the keying system, illustrated by Figure 13 below.

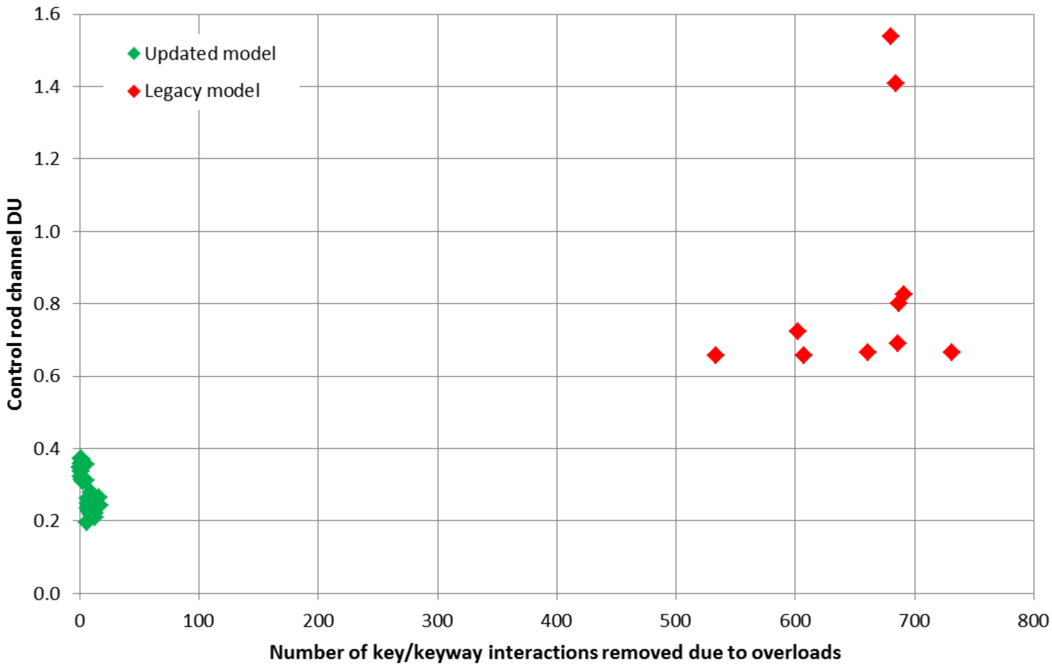

Figure 13: Correlation of peak DUs to keying system failures.
(Reproduced from Reference 37)

208 It is not surprising that the peak channel distortions would be reduced for such a significant reduction in the severity of the seismic input to the graphite core (Figure 10). However, I accept that fewer removals of key/keyway interactions will also reduce peak channel distortions by maintaining the intended constraints on brick movement and also preventing the kinds of localised failures I have described above in paragraph 201.

209 It is also important to note that the peak channel distortion DU values for the legacy model (see Figure 9) are for the most part less than 1. This further emphasises the causes of those few DU values that exceeded 1 to be associated with particular local configurations. Given that the revised model has shown tolerance with substantial numbers of DCBs, I conclude that particular attention must be made to the number of key/keyway interaction overloads and in particular integral key overloads. Focus subsequently shifts to the margin on the keying system forces, which I discuss next.

4.5.14 Seismic – Margins on the Keying System Forces

210 The updated seismic input model appears to have had a substantial effect on reducing the channel distortions, but confidence that excessive channel distortions cannot be generated must come from confidence that the keying system will not be overloaded. Because the radial keying system cannot be observed or its strength directly measured, substantial margins on the predicted strength of the keying system are necessary.

211 Whilst NGL routinely reports the number of predicted overloads in the keying system for the load cases assessed, the corresponding load margins were not generally reported. I asked NGL to provide evidence that shows the keying system load margins (see G27 of Reference 64). NGL provided the load margins from two cases: the legacy

model case with highest reported DU of 1.54 (see the 60% cracking level in Figure 9); and a case from the updated model with a comparable cracking level and an associated DU of 0.22 (see the 200 DCBs cracking level in Figure 11).

212 NGL was also able to show for the legacy model that there were not large numbers of key/keyway interactions approaching their strength. This indicates the opportunity for onerous arrangements of keying system failures is limited.

213 For the updated model, NGL was able to show that the highest loaded integral key was between 70% and 80% of the assumed strength, and that the majority of integral keys were substantially less loaded. Where loads exceeded the strength for loose keys, NGL was able to show this occurred on a small numbers of keys. As in the legacy model, NGL was able to show that there were not large numbers of key/keyway interactions approaching their strength in the updated model. It is my view that those two results offer some confidence that uncertainties in the keying system strength do not lead to an undue concern.

214 NGL also provided the results of a sensitivity study into the effect of reducing the keying system load capacity, Reference 77, using the updated buildings model. In the study the keying system load capacity was reduced by 10%, 15% and 50%. The work did not report the load margins for these cases but did report that no integral keys were overloaded when the keying system load capacity was reduced by 10% and 15%. In the case where the load capacity was reduced to 50%, 1 integral key was predicted to overload.

215 In my view, the above sensitivity studies provide confidence that there is margin on integral key forces, but there are two aspects that need further consideration: the scope of evidence to support the proposed OA and CEDTL (Section 4.5.15); and the use of upper bound properties in the updated buildings model (Section 4.5.16).

4.5.15 Shortfall in the Evidence Supporting the Proposed Allowances

216 NGL claims through the proposed OA and CEDTL that the graphite core is tolerant up to 200 SCBs open by more than 12mm. NGL has conservatively predicted, at a 99.9th percentile, that there will be 24 singly cracked bricks open by more than 12mm in the core at the end of the four-month operating period (Table 4). However, none of the analyses using the updated model originally provided to support the case include singly cracked bricks with openings greater than 12mm. In my view, this is a clear shortfall in evidence because NGL has not provided any direct analytical support for seismic tolerance to a core state that includes cracked brick openings greater than 12mm when using the updated model.

217 However, it should be recognised that the updated model has led to a reduction in the keying system forces compared to the legacy model, due to reduced accelerations. This leads to the load capacity margins I have discussed above in Section 4.5.14. Whilst the reduction of forces in the keying system is clearly a valuable advancement for the safety case, the inclusion of greater than 12mm crack openings can conceivably increase those forces. An increase in the keying system forces would erode the load capacity margins to some extent increasing the risk of outlier distortions.

218 NGL has subsequently provided the evidence in Reference 62 to fill the shortfall. The results presented in Reference 62 cover ten crack configurations all including 200 MCBs and 200 SCBs with crack opening widths of 18mm. The results show a single integral key failure in one of the ten configurations, which suggests the load capacity margins have reduced due to the increased crack opening widths. Further discussion with NGL showed the highest loaded integral key in each of the ten runs varied

between 75% and 100% meaning there is also some variability on the highest load capacity margins. Therefore, in my view, small numbers of integral key failures cannot be discounted at levels of damage associated with the OA and CEDTL. Any subsequent permissioning of the OA and CEDTL therefore cannot be based on a criterion of zero integral key failures.

219 Having discussed this issue further with NGL (Reference 76) I am willing to accept that the extent of damage associated with the OA and CEDTL is small, up to the 17TWd core burn-up used in Reference 62, and that the likelihood of that damage leading to unacceptable channel distortion margins is sufficiently low. This is based on the following.

220 Whilst I am of the view that unacceptable channel distortion margins can arise from a few particularly placed integral key failures, this must be in the presence of additional failures that reduce the constraint on neighbouring fuel channels. For instance, the unacceptable channel distortions shown in the legacy model appear to be associated with a relatively widespread level of damage to the system of loose key/keyways than is predicted by the updated buildings model. This is because a higher level of damage to the system of loose key/keyways means the fuel channels are less constrained and so there is greater potential for interstitial channels to generate unacceptable distortions. The low level of damage evidenced by the updated buildings model therefore suggests unacceptable distortions are not likely.

221 It might be considered that reduced constraint on fuel channels can arise from sources other than the failures in the system of loose key/keyways, for instance the presence of large numbers of DCBs or MCBs as per the OA and CEDTL. NGL has however identified a small number of locations where clusters of integral keys have been removed as part of the proxy-MCB implementation. Those clusters have not led to an increase in the peak channel distortion generated by the revised buildings model.

222 Although the OA and CEDTL do not specify an upper limit on crack opening, the supporting whole core model evidence is valid only up to 18mm crack openings. Therefore, any core state with a SCB opening exceeding 18mm would effectively be outside the supporting evidence. Section 4.4.1 discussed the predictions of crack opening widths and showed there is low probability that crack openings might exceed 18mm, and the number of instances would be small in number. It is my view that substantially more instances of crack openings exceeding 18mm would be necessary to undermine the judgements made by the safety case.

223 I am therefore content to conclude that at the OA and CEDTL, although some damage to the keying system may occur during a seismic event, NGL has shown the level of damage is not likely to generate outlier distortions that would impede a control rod entry.

4.5.16 Seismic Upper Bound Load Case

224 In ONRs assessment of the updated seismic model (Recommendation 2 of Reference 75), the specialist civil engineering inspector makes the following recommendation to my assessment:

“The ONR graphite assessment should take into account when assessing core margins for seismic events that the GCORE analysis reported in the safety case is based on the use of the best estimate PCPV model only. Sensitivity studies have indicated that the upper bound PCPV model is bounding for PCPV accelerations of significance to the core and for core distortion margins.”

225 To illustrate the point, I have taken a figure from the specialist civil engineering inspector's assessment and presented it below in Figure 14.

226 Figure 14 shows a comparison of the best estimate to the upper bound property models in terms of the channel distortions predicted by the whole core model. The distortion of all interstitial channels (some of which house control rods) is presented by a cumulative frequency curve, but it is the minimum values from that which are of primary interest.

227 The distortion of each channel is quantified by a parameter known as the SRL score, which is an approximate version of m3dsf (see Section 4.5.1), therefore the lowest SRL value is associated with the channel with greatest distortion in that prediction. Although the SRL value is only an approximation to m3dsf, I am content with its use for the purposes of this sensitivity study.

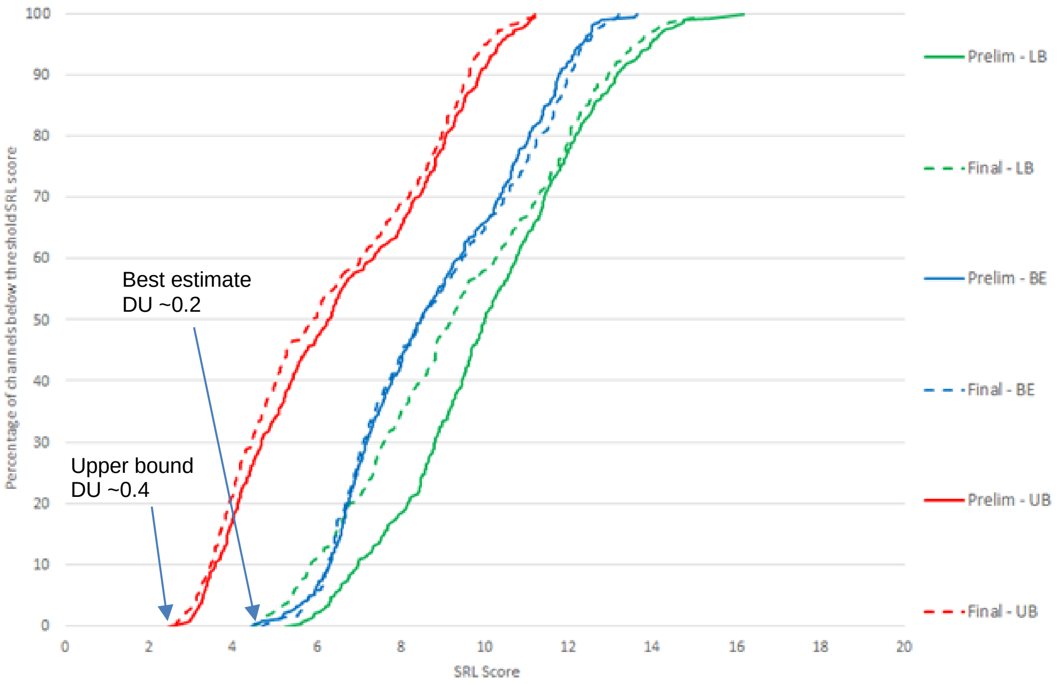

Figure 14: Effect of the updated model property bounds on channel distortion.
(Figure taken from Reference 75)

228 In the same way as m3dsf, the SRL value can be inverted so that it describes an approximate DU, I have indicated in Figure 14 the approximate peak DU value for the best estimate and upper bound cases, i.e. ~0.2 and ~0.4 respectively. For reference, the crack configuration of the upper bound and best estimate cases is consistent with the 'sensor rod' results presented in Figure 11 at 400 DCBs.

229 The sensitivity study shows the use of upper bound properties in the updated PCPV model effectively doubles the peak distortion, but this may be an underestimate. Usual practice by the damage tolerance assessment is to evaluate multiple crack configurations to explore the uncertainty associated with the variations caused by the distribution of cracking, but Figure 14 presents only a single crack configuration. In other words the approximate DU values of 0.2 and 0.4 that I have indicated in Figure 14 are not definitive; there is scope for those values to be larger or smaller by some amount due to variations that may be caused by different crack configurations. Inspecting Figures 11 and 12 suggests that variation could change the DU by up to 0.1 if the upper bound case was to be passed through NGL's current damage tolerance

assessment. I am therefore content to conclude that although upper bound properties may more than double the distortion quoted by the safety case, there is still sizeable margin.

230 As I have described in Section 4.5.14, it is important to deal with the possibility that outlier distortions could undermine the results presented. However, supporting information for this was not provided with the upper bound sensitivity study. Subsequently, I asked NGL to confirm there were no failures of the integral keying system in the upper bound case and that the keying system load margins were not significantly eroded from those of the best estimate case (G43 of Reference 64). NGL provided further evidence, which confirmed the loads on the keying system would be marginally increased by the upper bound case thereby eroding some of the load capacity margin I had taken confidence from in Section 4.5.14. However, NGL also confirmed the upper bound case was marginally worse, but did not fully erode the margin or significantly increase the damage to the keying system. It is also NGL's view that the seismic hazard used to date is conservative and therefore the margins will be larger. I am therefore content that channel distortion margins remain acceptable when the upper bound case of the updated seismic model is considered.

4.6 Argument 1.4 – Debris

At the end of the proposed JPSO, core distortion will not prevent the graphite core from meeting its other fundamental nuclear safety requirements in relation to fuel movement and fuel cooling.

231 The observed morphology of secondary cracked bricks provides a mechanism for the more widespread formation of graphite fragments than has been considered in earlier safety cases (Reference 44). Displacement of fuel brick fragments is a potential source of debris in the reactor circuit. When fuel is present the clearance between the fuel sleeve and fuel brick (referred to here as the annulus) is small (≤13mm) and means fragments from fuel bricks would need to be thin enough to enter the annulus in order to form debris. When the fuel is vacated, the channel has an approximate diameter of 255mm to 263mm depending on graphite shrinkage. Therefore, when fuel is being moved, larger fragments could also be displaced and form debris. Finally, fragments formed at the fuel brick periphery could be displaced to form debris in the arrowhead coolant passages. The size limitations for displacement of fragments into the arrowhead passages is less clear from the safety case, but based on Reference 47, fragments with dimensions of the order of 30mm to 50mm would have to be considered capable of entering the arrowhead passages.

232 Debris or displacement of fragments have the potential to interfere or affect the following:

- Fuel handling at reactor;
- Integrity of fuel sleeves;
- Core Distortion;
- Tie bar temperatures;
- Fuel clad temperatures due to partial blockage of the fuel element 1 grid;
- Fuel clad temperatures due to debris within the fuel element.

233 I discuss each of these items in turn in the following sections.

234 In determining my view of NGL's arguments on the safety significance of debris, I have discussed all the debris that has been observed in HNB R3 and R4 with the fault studies inspector and ONR's independent statistical advisor at HSL.

4.6.1 Fuel handling at reactor

235 In this section, I assess NGLs arguments that graphite debris will not lead to a significant increase in fuel snagging frequency. The potential consequences of an increased probability of fuel snagging has been considered by the fault studies inspector (Reference 66).

236 Small pieces of debris, with a significant dimension extending radially from the bore of the brick, are unlikely to have sufficient room to work their way into the fuel annulus and interfere with fuel movement. The most likely debris to move into the fuel annulus would be that produced from the high weight loss material close to the bore. NGL argues that the strength of this material would be low and likely to crush rather than prevent fuel removal. This argument is supported by measurements taken from graphite that has been trepanned from the fuel brick bore.

237 In my opinion movement of larger fragments are potentially more challenging to fuel movement. While fuel is present, there is little space in the fuel annulus (8 – 13mm) for a significant ledge to be created by the movement of a large fragment. NGL argues that removal of fuel would simply push such a displaced fragment out of the way, which I consider is a reasonable judgement.

238 However, when a fuel channel is vacated there is greater potential to form a more significant ledge in a vacated channel or a blockage in the vacated channel with a displaced fragment. NGL argues movement of large fragments is unlikely, as the end-face keying system would be expected to constrain such shear and, even if not, brick/column weight and friction would be expected to resist such movement. NGL concedes a potentially possible scenario is where brick/column weight may be driving the inward movement through local instability. Whole core models suggest these driving forces could be present when a number of vertically adjacent DCBs and or MCBs are present in a channel. NGL argues that for four months of operation of HNB R4, the numbers of DCBs and MCBs are likely to be low and vertically adjacent DCBs and MCBs are unlikely.

239 I accept these arguments and I judge that generation of fragments and debris are unlikely to present a significantly increased challenge to fuel movement during the next four months of operation of HNB R4.

4.6.2 Integrity of fuel sleeves

240 NGL's whole core modelling results in normal operation and fault conditions have determined that the contact forces applied by large pieces of graphite (i.e. DCB and MCBs) on the fuel sleeve as a result of distortion are small, at around 200 N, compared to the critical fuel sleeve load of 10kN (Reference 35). I therefore accept NGL's argument that large fragments of debris will not challenge the integrity of the fuel sleeve.

241 Small debris has the potential to become trapped between the fuel sleeve and fuel brick bore. This could cause damage to the fuel sleeve or progressive inter-sleeve gapping by a 'jacking' mechanism as a result of repeated cycles of core motion (Reference 79). NGL has performed sensitivity studies of fuel sleeve jacking and determined from simple geometrical calculations that the inter-sleeve gap would be less than 2mm whilst claiming that 7mm gapping is tolerable. The tolerability to fuel

sleeve gapping has been considered by a fault studies Inspector in a separate assessment. However, I accept NGL's further argument that small debris which could fall into the fuel annulus is likely to be composed of high weight loss graphite with low strength. Therefore, there is a reasonable likelihood that the debris would be crushed as a result of any jacking of the fuel sleeve.

242 Based on the low instance of observed debris in HNB R4 and the leading reactor R3, I consider that the production of debris over the next four months of operation will be relatively low. I find NGL's argument that any debris capable of entering the fuel annulus would be of high weight loss and low strength is supported by strength measurements of reactor graphite. Therefore, I judge that over the next four months of operation the risk of fuel sleeve jacking as a result of debris is acceptably low.

4.6.3 Core distortion

243 NGL states that debris which migrates into clearances between bricks could, if appropriately shaped (such as a wedge), progressively wedge those components apart following hot and cold core cycles contributing to core distortion. NGL argues that the likelihood of graphite debris generation at the present time is low. NGL also argues that debris that may wedge components apart is likely to be crushed and have very limited effect on core distortion.

244 I consider that small debris is more likely to be generated at the brick bore where graphite weight loss is highest and hence strength is lowest. Therefore, I consider that over the next four months of operation, the propensity for debris production remains low at the periphery of the brick and that there is no significant risk that debris will contribute to any additional core distortion, beyond that defined within the current consideration of the damage tolerance assessment.

4.6.4 Tie bar temperatures

245 Carbon dust is present in the coolant circuit of all AGRs and is produced predominantly from the decomposition of methane, which has been added to the gas coolant to inhibit oxidation of the graphite core. Because of the narrow annulus between the tie bar guide tube and the tie bar NGL has, in earlier safety cases (Reference 2), considered 100% blockage of the guide tubes of all eight stacked fuel elements. NGL calculated that the maximum temperature increase occurs only under low power refuelling conditions and the tie bar temperature would rise by approximately 100ºC (Reference 80). NGL predict this increased temperature would accelerate the thermally induced damage mechanisms and potentially increase the failure probability of the tie-bar during refuelling. NGL has also calculated that a 60% blockage results in a smaller increase in temperature, ~16°C during normal operation, and hence the effect on tie-bar properties would be negligible. NGL argues in Reference 80 that 100% blockage of the tie bar guide tube is highly pessimistic because there is less carbon dust present in the reactors of HNB/HPB. Furthermore, the high pressure gas flows in the reactor means dust would flow through the annulus and is unlikely to form a complete blockage.

246 I consider that the additional dust that is generated as part of cracking processes is small compared to that already present in the reactor. Therefore, I consider NGL's existing arguments that 100% blockage of the tie bar guide tube is unlikely and will remain unchallenged by the small amount of additional graphite dust generated during cracking. A fault studies inspector has considered the risk associated with blockage of the tie bar guide tube annulus with graphite dust (Reference 66).

4.6.5 Fuel clad temperatures due to partial blockage of the fuel element 1 grid

247 Debris which is large enough to be prevented from entering the fuel elements by element 1 grid but small enough to have reached element 1 grid may lead to partial blockage of the coolant flow at that location. NGL argues that the likelihood of significant blockage is acceptably low. Figure 15 provides an illustration of the fuel element and grid.

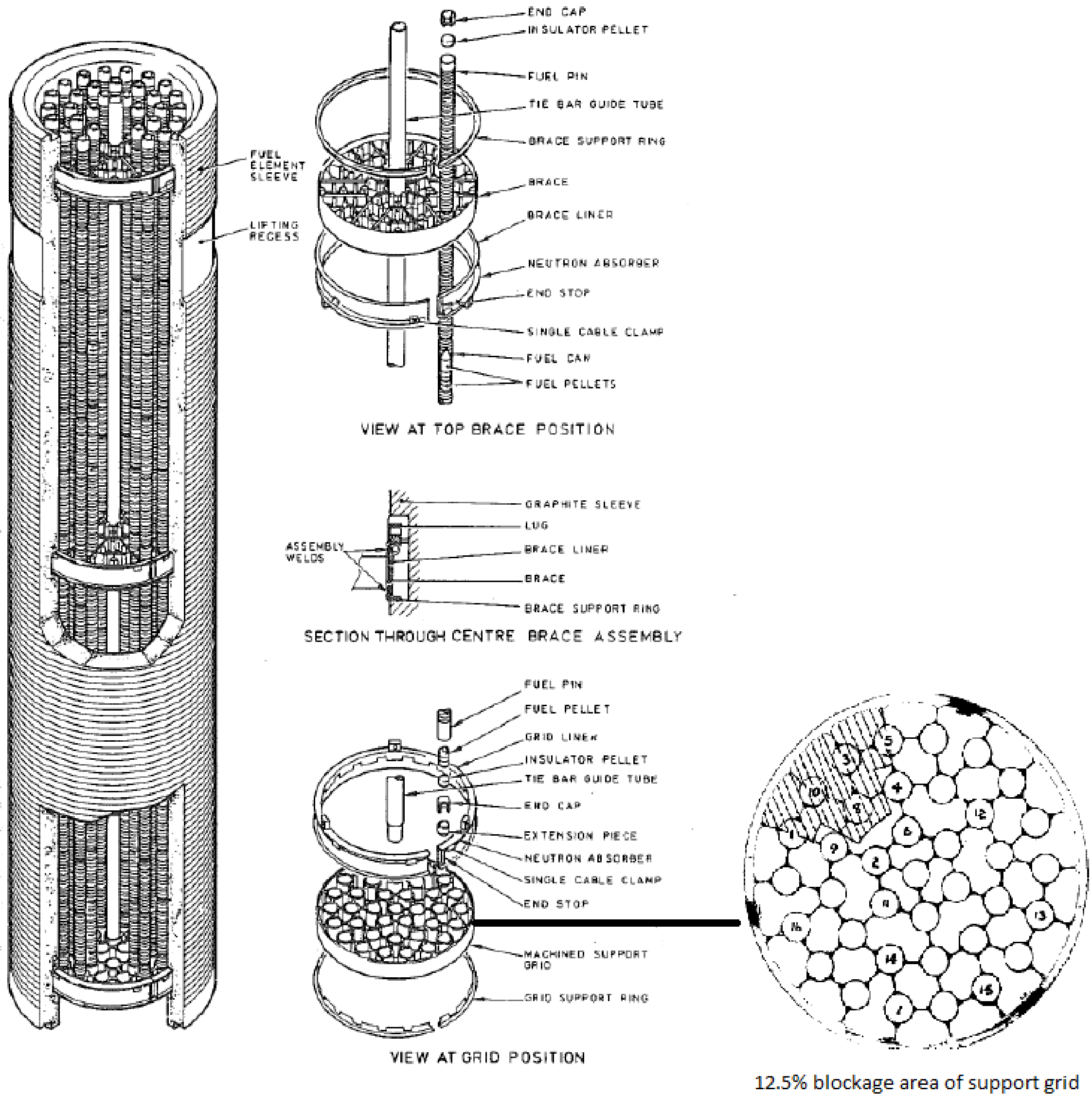

Figure 15: Illustration of an AGR fuel element.

(The figure shows the lower grid and illustrates the approximate 12.5% blockage size considered in NGLs experimental studies.)

248 Based on experimental studies by NGL (Reference 81) partial blockage of the fuel element 1 grid with graphite debris reduces the coolant gas flow to fuel pins immediately adjacent to the blockage and inhibits cooling. The experimental studies showed that gas flow turbulence restores the flow of coolant to all fuel pins a short distance above the blockage such that no increase in temperature is observed at a height of ~200mm above the blockage. NGL's experiments considered increasing areas of blockage up to 12.5% of the free flow area of the element 1 grid and measured the resultant temperature increases at the surface of each fuel pin adjacent to the blockage using a number of thermocouples. Based on Reference 81 NGL found that local to the blockage the maximum rise in fuel clad temperature was 219ºC,

reaching 659ºC; much lower than the technical specification limit of 870ºC (Reference 82).

249 More recently, NGL has conducted further analysis of the experimental data. NGL extrapolated the data and calculated that fuel clad temperatures reach the technical specification limit of 870ºC when the blockage area increases to 16.4% of the free flow area of element 1 grid (Reference 47). Furthermore, NGL calculated that the local maximum fuel clad temperature reaches melting point, 1350ºC, when the blockage area is increased to 17.6%. Therefore, NGL's recent analysis shows that there is a significant escalation of the local fuel clad temperature for a relatively small increase in blockage area. Furthermore, because the potential fault is localised to a small region of the fuel pins adjacent to the blockage, NGL has determined that reactor monitoring will not detect a channel power discrepancy (CPD) until >50% of the free flow area is blocked. Therefore, detection of the fault would only be possible by the Burst Can Detection (BCD) system once a sufficient amount (about 2.5cm) of fuel clad has melted. This has been considered by the fault studies inspector (Reference 66).

250 An ONR fault studies inspector and I met with NGL to discuss further its analysis of the consequences of the potential blockage of the fuel element 1 grid by graphite debris (Reference 83). I advised NGL to provide further justification to support the argument that the probability of a safety blockage occurring was so low that it did not present a safety concern. As part of this further justification the fault studies inspector advised NGL to make greater consideration of the potential consequences and the uncertainties and the conservatisms in the analysis. NGL provided further justification in Reference 84. In the remainder of this section I detail my considerations of NGLs justification for the probability of a safety significant blockage. Considerations of the consequences of such a blockage occurring are made in the fault studies assessment (Reference 66).

251 In its justification, NGL has outlined the potential paths for debris to reach the bottom of the fuel stringer where the coolant flow enters the fuel stringer. These paths are either downwards through the annulus when fuel is present, downwards through the fuel channel during fuel handling or downwards through the arrowhead passages and through the gas entry ports in brick layer 1, see Figure 16. Each path has a degree of tortuosity dictating the maximum size of debris that could feasibly travel along its path in one piece. However, the debris would be aided by a substantial gas flow of ~18m/s.

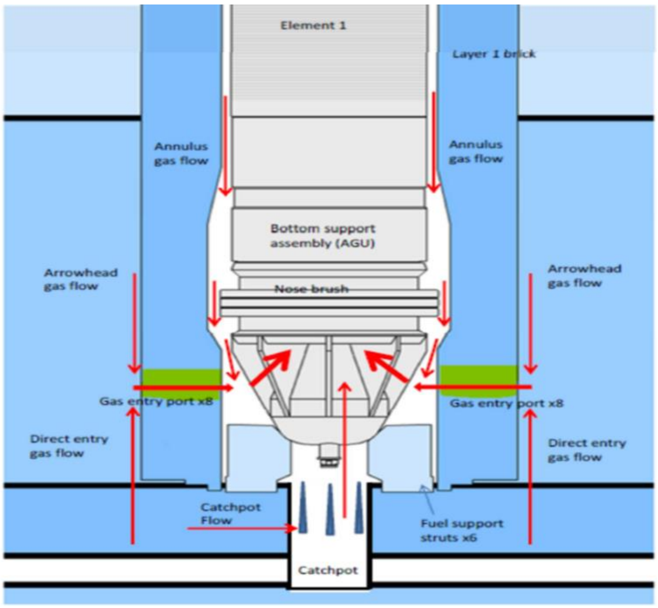

Figure 16: Illustrative flow paths at the base of the fuel channel for HPB/HNB.
(Figure taken from Reference 84)

252 At the bottom of the fuel stringer is the Anti-Gapping Unit (AGU) through which gas flows before entering the first fuel element through the element 1 grid at the top of the AGU (Figure 16). The AGU features 8 support fins at its bottom (adjacent to the gas entry ports in Figure 16), above those fins and just before the element 1 support grid is a further set of 6 support fins. The spacing of these fins limits the credible size of debris that can access the surface of the element 1 grid.

253 Having considered the various clearances that need to be negotiated in order for debris to migrate from the fuel brick to the element 1 grid, NGL approximate the maximum credible cross section of debris to be 30mm x 50mm. I consider this approximation to be reasonable having studied the design drawings provided by NGL.

254 NGL has judged that the likelihood of a safety significant blockage of the element 1 grid by graphite debris, referred to as the initiating event frequency, is very low because:

- there has been only a small amount of debris observed in HNB R3 and R4 at the current time;
- the pathways limit the credible size of debris that could feasibly form a blockage;
- the tortuosity of the pathways makes it difficult for debris to migrate to the element 1 grid;
- more than one piece of credible debris is required and they would need to form a contiguous blockage.

255 However, there are a number of factors which would increase the likelihood, such as:

- there are 308 fuel channels in the core with potentially 5 bricks in each channel that could reasonably produce debris;
- the observed morphology of cracking means that multiple pieces of debris could be generated at the same location;
- the gas stream is powerful and draws debris to the entrance of the AGU and up into the fuel stringer:
- Fuel movements may provide a mechanism for disturbing fragments and generating debris.

256 NGL has attempted to estimate the initiating event frequency noting that it is heavily reliant on engineering judgements and subject to significant uncertainty. NGL has considered two scenarios, one where fuel is present in the channel and one where fuel has been removed as per refuelling operations. For each case NGL has defined a specific type of bounding debris that it considers is the most likely to present a problem. When fuel is present, NGL considers the bounding piece to be a single piece of debris that is relatively large with limited depth that could travel down the annulus and break into pieces that can block a safety significant area of the element 1 grid. When fuel is removed from the channel NGL considers the bounding debris to be a single large piece of debris, i.e. one with a depth too large to be accommodated within the channel when fuel is present, which falls to the bottom of the channel and breaks up before entering the AGU and causing a safety significant blockage. It should be noted that NGL reported that 7 pieces of debris and 51 fragments had been observed during the recent inspection of HNB R3 and R4. However, NGL judged that the specific form of bounding debris had not yet been observed in either HNB R3 or R4 cores. Nonetheless, NGL then considered the probability of a number of steps or events thought necessary to cause a blockage, these can be summarised as:

- Debris production;
- Debris migration into the AGU;
- Accumulation of sufficient debris to cause a contiguous blockage.

257 Overall, NGL judged that with fuel present the initiating event frequency was <10^{-5} per reactor year (pry) and that for the 50 channels that are refuelled each year, there was an additional initiating event frequency of 2×10^{-6} pry (Reference 84). NGL judged that the lower stabilising brushes on the fuel would sweep small fragments upwards and out of the channel during fuel removal, and hence only large fragments posed a potential risk if they were to fall into the channel and break into smaller fragments when the fuel channel was vacated or during fuel recharge.

258 NGL's verification of Reference 84 noted that there were significant uncertainties associated with judgements of the initiating event frequency. The verifier stated that those judgements must be considered to be of a lower quality assurance grading (<QA grade 2). In reaching a conclusion, the verifier took a pragmatic viewpoint of the evidence presented and judged the likelihood of a safety significant blockage was in the infrequent range i.e. between 10^{-4} and 10^{-6} pry. I consider the verifier's viewpoint is a reasonable one.

259 I find NGL's judgements on the likelihood of safety significant blockages to be useful in breaking down the initiating event frequency into smaller components. However, NGL's decision to focus on specific bounding debris that has not yet been observed in the core, means NGL has ignored existing inspection observations of debris because it does not conform to the bounding debris definition in its consideration of the probability of debris formation. I consider that this approach has neglected the use of important inspection evidence that could help inform judgements about the current frequency of debris production.

260 In considering the inspection data from HNB R3 and R4 I note that to date there has been more debris observed in HNB R3 than R4; 6 pieces compared with 1 piece of debris. Approximately 2.5 times more fuel channels have been inspected at R3 than R4, but even taking this into account R3 appears to contain more debris consistent with the greater amount of cracking and higher core irradiation compared to R4.

261 The debris found in HNB R3 channel 38:82 was particularly relevant to the consideration of the initiating event frequency. Channel 38:82 contained a large triangular fragment (~111mm high x 34mm wide) that was observed to be missing. The resultant crater in the fuel brick showed the fragment had a limited depth of ~12mm. Although two such pieces would be required to cause a safety significant blockage of fuel element 1, once displaced the fragment was small enough to be able to travel down the annulus when the fuel stringer was present. Inspection showed that this fragment had been displaced, possibly during inspection. Several pieces of debris were also observed at the bottom of the channel and it was assumed that these were a result of the triangular fragment breaking up. This demonstrated that it was possible for debris to gather near the entrance of the AGU.

262 Having considered the justification presented by NGL, and the supporting statement provided by NGL's verifier, it is my view that there is significant uncertainty in determining the initiating event frequency of a safety significant blockage of the element 1 grid due to graphite debris. I consider that, at the present time, the inspection data provides the only meaningful evidence to support specific judgements on debris formation and migration in the event frequency analysis. However, NGL do not appear to have made full use of this evidence in deriving their estimate of the initiating event frequency.

263 I am of the opinion that the verifier has provided a reasonable and pragmatic assessment that the potential initiating event frequency is in the infrequent range of between 10^{-4} and 10^{-6}. I am also of the view that core ageing now presents a systematic mechanism for the production of debris and that there is uncertainty in the judgements on debris migration.

264 Based on consideration of the evidence presented, particularly the observed instances of debris in HNB R3 and R4, I agree with NGL's safety case verifier that blockage of element 1 with debris is a low frequency event for the proposed four-month period of operation. However, because there is significant uncertainty in determining the true likelihood, a precautionary approach should be taken. Hence, I judge the fault studies inspector should treat the initiating event frequency of a safety significant blockage of fuel element 1 grid as a 10^{-4} pry event during the proposed 4 months of operation of HNB R4. A frequency of 10^{-4} pry means that restricted coolant flow due to graphite debris should now be classed as a design basis event (Reference 85). Therefore, I make the following recommendation:

Recommendation 3: *I recommend that the fault studies inspector's assessment takes into account my judgement that the likelihood of debris significantly blocking the fuel element 1 grid should be treated as a design basis event with a potential frequency of 10^{-4} pry during the next four months of operation of HNB R4.*

265 The inspection evidence pertaining to debris from HNB R4, and more importantly from HNB R3 which is the leading reactor in terms of core burn-up and brick cracking, is a significant factor to my judgement. Inspection data from the leading reactor has provided me with confidence that the production of debris will be few during the next 4 months of operation of HNB R4.

4.6.6 Fuel clad temperatures due to debris within the fuel element

266 If graphite debris was to accumulate within a fuel element it may inhibit cooling of the fuel pins and elevate fuel and fuel clad temperatures. NGL has determined that the most onerous position that debris could lodge is at the location of the peak fuel clad temperature, at the top of fuel element 6. In order to enter the fuel element the debris must be suitably sized to pass between the gaps in the support grid and braces within each fuel element; NGL has determined the cross sectional area of such debris must be < 1cm x 1cm. Furthermore, in order for suitably sized debris to migrate to the fuel element 6 position, it must pass through 6 grids and 11 braces and become lodged.

267 Based on experimental work (Reference 86) NGL found that debris with a cross sectional area of approximately ≤1cm x 1cm would result in a peak fuel clad temperature rise of 6ºC. NGL also found that it would require two or three such pieces to form a contiguous seal around a fuel pin at element 6 for the temperature rise to challenge the peak fuel clad temperature limit of 870ºC.

268 Inspection observations have shown that cracking processes are generating small amounts of debris in the core, but as cracking increases with continued operation then more debris will be produced. Therefore, the likelihood of generating suitably sized pieces of graphite debris (≤1cm x 1cm) is increasing. However, based on inspection evidence from the leading reactor of HNB R3, I consider the increase in suitably sized debris over the next four months of operation of HNB R4 will be small. I consider that any debris that is small enough to pass through the gaps in a grid or a brace is more likely to pass through all the grids and braces in the stringer rather than become lodged. However, if debris has the propensity to become lodged within the stringer it is more likely to become lodged lower in the stringer where the temperature margins of fuel clad melt are larger. The requirement of accumulation of three pieces of debris at

the same position on one grid or brace within the stringer would reduce the likelihood of approaching the fuel clad temperature limit of 870ºC. Finally, NGL has demonstrated that there is still a significant margin of several hundred degrees before fuel clad melting temperatures are reached.

269 Overall, I consider that NGLs argument that it is highly unlikely that sufficient graphite debris will lodge within the fuel stringer to cause significant elevation of temperatures in the fuel or fuel clad during the next four months of operation of HNB R4 is adequate.

4.6.7 Overall Consideration of Graphite Debris

270 The last inspections of HNB R3 and R4 showed that the reactors have now entered a stage in which graphite debris can be systematically generated by keyway root cracking. It is likely that as the core continues to crack, increasing debris will be generated in the reactor. The inspection evidence pertaining to debris from HNB R4, and more importantly from HNB R3 which is the leading reactor in terms of core burn-up and brick cracking, has been a significant factor in forming my judgement. Inspection data from the leading reactor has provided me with confidence that the production of debris will be few during the next 4 months of operation of HNB R4 and the risk posed by small amounts of debris is low. The potential consequences of graphite debris and available lines of protection have been assessed separately by a fault studies inspector (Reference 66).

271 It must be expected that debris will become more frequent during operation beyond the current core condition of HNB R3. I therefore make the following recommendation.

Recommendation 4: *Before any permission for operation of HNB R4 beyond the proposed four-month operating period is requested, NGL should introduce to the safety case more robust arguments for mitigating the risks posed by graphite debris and for the determination of graphite debris production and its migration.*

4.7 Argument 1.5 – Current R3 Core State Bounds R4 Future State

The R4 core state (in terms of the level of cracking) at the end of the 4 month operating period (16.025 TWd) is expected to remain within the current R3 core state (16.185 TWd).

4.7.1 Main Population Bricks

272 In my opinion the evidence presented by NGL shows that the progression of KWRC in the main population bricks in HNB R4 is behind that of HNB R3; commensurate with the difference in their respective core burn-ups. Graphite property measurements from each reactor show that the graphite in each core exhibits similar behaviour (Reference 18). As such, while HNB R3 remains ahead of HNB R4 in terms of core irradiation it offers valuable insight into the likely main population core state of HNB R4 when it reaches a similar core burn-up. Therefore, in relation to main population bricks I accept that the R4 core state (in terms of the level of cracking) at the end of the four-month operating period (16.025TWd) is expected to remain broadly within the current R3 core state (16.185TWd).

4.7.2 High Shrinkage Brick Population

273 NGL states in Argument 1.5 that the level of cracking in terms of the total numbers of cracked bricks, which includes DCBs and MCBs, is expected to remain within the current HNB R3 core state. While this is true of the total numbers of cracked bricks the

predicted numbers of DCBs, MCBs and bricks with cracks open by 6 to 12mm is higher in HNB R4 at 16.025TWd than currently in R3 (16.185TWd), see Table 5 below.

274 The reason for this difference in prediction is because of the CrackSim assumptions regarding HSBs; in particular their assumed onset time of KWRC and their crack opening rate. These factors influence the predicted maximum crack openings and the numbers of DCBs and MCBs in CrackSim.

275 Therefore, I note that the core burn-up of HNB R4 after four months of operation will be less than that of HNB R3 in its current state, and NGL has adequately determined that the overall numbers of cracks in HNB R4 is predicted to be less than that currently in HNB R3.

276 However, the small population of HSBs in HNB R4 means that NGL has predicted that HNB R4 will contain slightly higher numbers of bricks with cracks open by 6mm to 12mm, DCBs and MCBs after four months of operation than is currently in HNB R3. NGL has addressed the tolerance of the core to the predicted numbers of cracked bricks as part of its damage tolerance claims.

Predicted Number of Different Cracked Brick Morphologies (safety case / sensitivity study)				
Brick State	**R4 4 months**	**R3 current**	**R4 4 months**	**R3 current**
Calculation confidence level	99.9%	99.9%	50%	50%
Full axially cracked (includes doubly and multiply cracked)	467 / 589	505 / 489	324 / 273	377 / 367
Full axial in channels with HSB	130 / 83	0 / 0	75 / 37	0 / 0
Open by 6mm to 12mm (at the brick periphery)	112 / 110	105 / 107	62 / 51	55 / 57
Open by more the 12mm (at the brick periphery)	24 / 20	22 / 24	3 / 3	5 / 6
Doubly cracked (includes multiply cracked, from the simplified model)	59 / 56	46 / 46	24 / 20	21 / 22
Doubly cracked (includes multiply cracked, from the full model)	49 / 44	39 / 40	19 / 15	16 / 17
Multiply cracked (from the simplified model)	12 / 11	14 / 16	1 / 1	1 / 2
Multiply cracked (from the full model)	5 / 4	5 / 5	0 / 0	0 / 0

Table 5: Cracked brick predictions for the current R3 and the four-month R4 core state.

(Reproduced from Table 5 of Reference 1. The row labelled *full axially cracked* represents the total number of cracked bricks and the individual quantities below it are intended to be inclusive of it. Cracked bricks predicted to be open by less than 6mm have not been listed.)

4.8 Argument 2.1 – Inspection Scope

The decision to inspect and the extent of the inspections provides the necessary confidence in the core state at the end of the JPSO.

277 The inspection of HNB R3 in 2018 highlights the benefits of gaining leading data through a more extensive inspection. By inspecting three times as many channels in HNB R3 than the normal statistical sample of 10% of fuel channels, important additional information was gained about brick cracking behaviours. This data has brought significant safety benefit in terms of the enhancement in the safety case with regards to core state predictions, additional damage tolerance analysis and consequence considerations.

278 Although the scope of inspection of HNB R4 was smaller than HNB R3, in my opinion it was sufficient to confirm that the extent of cracking was less than that in HNB R3. HNB R4 also benefited from targeted re-inspection of some HSBs, which are not present in HNB R3. In the HNB R4 core, the extent of cracking in the population of HSBs has been shown to be ahead of its main population of bricks. This was again confirmed in the October 2018 inspection. By targeting these bricks, NGL can perform an efficient survey of leading damage in the HNB R4 bricks, something which can only feasibly be achieved in HNB R3 by a more extensive inspection survey.

279 Therefore, based on the extensive inspection of the leading reactor (HNB R3) coupled with the targeted inspection of a number of HSBs, I consider NGL's claim that the inspection of HNB R4 provides the necessary confidence in the core state at the end of the four month operating period to be adequate. However, the corollary of this is that without extensive leading data to support predictions of core state, operation will be subject to greater uncertainty. This poses a problem for any leading reactor for which there will be an absence of core operating experience and this will need to be addressed by NGL.

4.9 Argument 2.2 – NGL's ALARP Position

All reasonably practicable measures have been taken to reduce the risk associated with return to service of HNB R4.

280 NGL's ALARP position remains essentially unchanged from that of the permissioned NP/SC 7716 case in that its strength lies in the installation of the SACRs and the DHD system. As noted in the assessment of NP/SC 7716 the SACRs have previously been assessed by ONR. The seismic qualification for the DHD system has recently been assessed by a specialist inspector (Reference 87).

4.10 Argument 2.3 – Monitoring Availability

Monitoring techniques will be employed within the proposed JPSO to confirm that core degradation remains within the basis of this proposal.

281 NGL's monitoring arguments remain largely the same as those of the currently permissioned NP/SC 7716 case, ONR considered those arguments in detail in Reference 9. The existing monitoring techniques will remain in place during the proposed operating period. Each of the monitoring techniques has a significant role to play and will remain in place during the proposed operating period, but with the exception of the FGLT technique, none provide leading indicators of significant axial cracking or core distortion.

282 NGL acknowledges that FGLT data from the proposed operating period will be minimal due to limited refuelling operations. This means FGLT data will be of limited value as a monitoring technique during the four-month operating period and has subsequently increased the importance of other aspects of the safety case.

4.11 ONR Assessment Rating

283 NGL had to provide significant additional evidence on the consequences of graphite debris generation (Section 4.6.5) and the safety margins describing the integrity of the keying system (Section 4.5.14) in order to support the case. It was my view that both these matters had to be resolved before my assessment could progress beyond them.

284 The case was also submitted for assessment with an apparent shortfall in evidence that supported claims of tolerance to the Operational Allowances (Section 4.5.15).

285 ONR guidance is to rate the assessment against the licensee's original submission, and in accordance with the ONR assessment rating guide (Reference 88), I have assigned an amber rating to NP/SC 7785 due to the shortfalls identified above. I and other inspectors will subsequently follow up my assessment findings with NGL through formal correspondence and interactions at appropriately levelled meetings.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

286 Through NP/SC 7785 (EC 364115 v11) the Licensee has sought to return HNB R4 to service for a period of four months, i.e. up to a core burn-up of 16.025TWd. This has required the Licensee to advance the operational allowances set by the extant safety case (NP/SC 7716). The Licensee also had to address a number of other issues: accounting for more advance cracking morphologies in future core state predictions; a lack of tolerance to particular core states during a seismic event; the need to demonstrate tolerance to MCBs; and an increase in the frequency of graphite debris generation.

287 My assessment has focused on the structural integrity aspects of NP/SC 7785, it is part of a set of assessments that will be brought together by the Project Assessment Report (PAR).

288 The conclusions I have drawn from my assessment are limited to the proposed four-month operating period for HNB R4 and are as follows.

1. The Licensee has adequately quantified and understood the current core state to provide a sound basis for describing the ageing phenomena occurring in the graphite core.
2. The Licensee has conservatively predicted the core state at the end of the proposed four-month operating period based on a sufficient scope of inspection evidence. The extensive inspection of the leading reactor (HNB R3), the targeted inspection of a number of HSBs in HNB R4, and the associated learning, has provided important additional confidence in the prediction of the HNB R4 core state at the end of its four-month operating period. This is an important factor in my acceptance of the safety case claims because some of NGL's past predictions of core degradation have been shown in the absence of leading data to be not wholly accurate when data became available.
3. The Licensee has shown that the small numbers of more severely cracked bricks predicted to exist by the end of the four-month operating period means the rate of generation of graphite fragments and debris is likely to be low during that period. Based on the evidence presented, I consider that a safety significant blockage of element 1 with debris is a low frequency event for the proposed four-month period of operation. However, because there is significant uncertainty in determining the true likelihood, a precautionary approach should be taken. Hence, I judge the fault studies inspector should treat the initiating event frequency of a safety significant blockage of fuel element 1 grid as a 10^{-4} pry event during the proposed 4 months of operation of HNB R4. I have subsequently made Recommendation 3.
4. It must be expected that debris will become more frequent during operation beyond the current core condition of HNB R3, I have subsequently made Recommendation 4.
5. The Licensee has shown the predictions of control rod channel distortions are low in normal operation and in a 1 in 10,000 year seismic event. I conclude that the low distortions allow a safety margin for unimpeded control rod entry to be maintained even when the possibility of more severe, but less likely, distortions are considered.
6. The Licensee has conservatively accounted for the potential presence of MCBs in the core in terms of channel distortion predictions. But, in extreme cases, MCBs might be capable of creating local sites of fuel stringer ledging or snagging. Assessment of the potential consequences of an increased risk in

fuel stringer ledging or snagging is outside the scope of my assessment but is considered by fault studies inspectors. Whilst I am content with the proxy-MCB implementation, my view is that improvements in the methodology would benefit future safety cases and are entirely achievable, I have therefore made Recommendation 1.

7. The licensee has conservatively accounted for the effect of core distortion on fuel movement and fuel sleeve gapping.

8. The updated seismic input motion has been assessed by a civil engineering specialist inspector; the inspector was satisfied but recommended I considered the effect of an upper bound seismic input case on the channel distortions. I have taken those considerations in to account and I am content with the seismic tolerance claims.

9. The Licensee has satisfactorily improved the modelling methodology of keying system failures when predicting the graphite core response to a seismic event.

10. Whilst I am content that NGL has provided sufficient evidence to discount unacceptable channel distortions within the bounds of the OA and CEDTL for the normal operating condition, NGL has shown that outlier distortions are possible on control rod channels for the normal operating condition. I therefore consider it reasonable to expect future safety cases to reinforce the supporting evidence that outlier configurations that would approach a control rod channel distortion utilisation of 1 in normal operation are sufficiently unlikely. I have recorded my view in Recommendation 2.

11. Through the assessment activities to date it has become clear that particular aspects of graphite core ageing will provide challenges to making robust safety cases for more advanced states of graphite core damage than has been predicted for the four-month operating period of this case. For example, this includes but is not limited to, the reliability of the damage progression model, the potential for key disengagement, the local influence of MCBs on fuel snagging frequency and the generation of graphite debris. These matters will require continued scrutiny in addition to the specific recommendations I have made, and NGL will need to make progress on these aspects should safety cases for further operation be proposed. Subsequently, these aspects will continue to be scrutinised as part of the regular and ongoing interactions between ONR and NGL.

289 Although there was an initial shortfall in evidence (see Section 4.5.15) that limited the conclusions of Revision 0 of my assessment the licensee has subsequently provided new evidence (References 61 and 62) that has dealt with this matter by increasing the scope of evidence to include crack opening widths up to 18mm. This effectively limits the validity of the supporting evidence to 18mm crack openings, but I am also satisfied that predictions of a low probability of small numbers of cracked bricks open by more than 18mm do not undermine the judgements made by the safety case.

290 I am satisfied that the Licensee has provided sufficient evidence to support continued operation up to the R3 core state, i.e. up to 16.025TWd, and that the licensee has shown margin on acceptable core distortion up to the OA and CEDTL.

5.2 Recommendations

291 I have made four recommendations (detailed in Sections 4.5.2, 4.5.9, 4.6.5, 4.6.7) which are as follows. I will be raising a regulatory issue to monitor progress on these recommendations.

Recommendation 1: *Before any further permission for operation of HNB R4 is requested, NGL should set out a plan to replace the implementation of proxy-MCBs in the whole core models with a full MCB representation.*

Recommendation 2: *Whilst I am content with the arguments presented for channel distortion, I consider it reasonable to expect future safety cases to reinforce the supporting evidence that outlier configurations that would approach a control rod channel distortion utilisation of 1 in normal operation are sufficiently unlikely.*

Recommendation 3: *I recommend that the fault studies inspector's assessment takes into account my judgement that the likelihood of debris significantly blocking the fuel element 1 grid should be treated as a design basis event with a potential frequency of 10-4 pry during the next four months of operation of HNB R4.*

Recommendation 4: *Before any permission for operation of HNB R4 beyond the proposed four-month operating period is requested, NGL should introduce to the safety case more robust arguments for mitigating the risks posed by graphite debris and for the determination of graphite debris production and its migration.*

6 REFERENCES

1 NP/SC 7785 (EC 364115) v11, Hunterston B Power Station Return to Service Safety Case for R4 Following Core Inspection Results in 2018. *Trim reference 2019/152966.*

2 NP/SC 7716 Proposal Version 04, EC 353778 Revision 000, EC 353779 Revision 000, Hinkley Point B & Hunterston B: Safety Case for the Graphite Core and Core Restraint: Operation After the Onset of Keyway Root Cracking, January 2016. *Trim Reference 2016/168297*.

3 ONR-OFD-IR-17-260, Inspection of the Hunterston B graphite core visual inspection, dimensional measurements and analysis arrangements 21-22 March 2018 including graphite assessment panel meetings, with final GAP meeting on 27 March 2018. *Trim Reference 2018/117830.*

4 ONR-OFD-CR-17-676, Graphite Level 4, Meeting to discuss the HPB/HNB Outage Inspection Expectations, *Trim reference 2018/63784*.

5 HNB R3 2018 Graphite Core Inspections: Routes A / B / C, version 3. *Trim Reference 2018/142017*.

6 DAO/REP/JIEC/357/HNB/18 Rev 002, Summary of HNB R3 Keyway Root Cracking Observations to Date, October 2018. *Trim reference 2019/119549.*

7 DAO/EAN/JIEC/282/HNB/18 Rev 000, An Investigation into the Apparent Differences in the Hunterston B R3 2018 Graphite Core Inspection Findings, November 2018. *Trim reference 2019/119557.*

8 NP/SC 7612 Version 02, Hinkley Point B Power Station, Hunterston B Power Station, A Revised Inspection Strategy for the Graphite Core and Core Restraint Safety Case. (EC 340545 Revision 000 (HPB), EC 340544 Revision 000 (HNB)), March 2011. *Trim reference 2011/236039.*

9 ONR-OFP-AR-16-053, Assessment of the NP/SC 7716 Keyway Root Cracking Onset Safety Case for the Hunterston B and Hinkley Point B Graphite Cores. *Trim reference 2016/228144.*

10 ONR How2 Guide NS-PER-GD-014 Revision 4 - Purpose and Scope of Permissioning. July 2014. http://www.onr.org.uk/operational/assessment/index.htm

11 Safety Assessment Principles for Nuclear Facilities. 2014 Edition Revision 0. November 2014. http://www.onr.org.uk/saps/saps2014.pdf

12 Graphite Reactor Cores NS-TAST-GD-029 Revision 4. ONR, November 2018. http://www.onr.org.uk/operational/tech_asst_guides/index.htm

13 Guidance on Mechanics of Assessment within the Office for Nuclear Regulation (ONR) – *Trim Reference 2013/204124*.

14 DAO/REP/JIEC/358/HNB/18 Rev 000, Hunterston B - Summary of HNB R4 2018 cracking observations, November 2018. *Trim Reference 2019/119609*.

15 HPS/TSSD/NS/BRF439 Rev 000, Hunterston Power Station Technical & Safety Support Department Nuclear Safety Group Brief Note: Analysis of the Reactor 4 Control Rod Insertion Characteristics, Statutory Outage – September 2017, September 2017. *Trim Reference 2019/119618*.

16 HPS/TSSD/NS/BRF445 Rev 000, Hunterston Power Station: Analysis of the Reactor 4 Control Rod Inspection Characteristics Core Inspection Outage - October 2018, December 2018. *Trim Reference 2019/121923*.

17 HPS/TSSD/NS/BRF391 Rev 000, Overview of Hunterston 'B' Core Follow Route, December 2010. *Trim Reference 2019/121927*.

18 DAO/EAN/JIEC/277/HNB/18 Rev 000, Estimation of the Hunterston B R4 Core State Following Inspection of R3 in 2018, September 2018. *Trim Reference 2019/121930.*

19 QRS-3031H-30 Version 1.0, Updated CrackSim Forecasts for HNB R3 and R4, Incorporating the HNB R4 2018 Inspection Results, November 2018. *Trim Reference 2018/405178.*

20 QRS-3031H-26 Version 1.2, CrackSim Calculations in Preparation for the Hunterston B R4 Inspection in 2018 Support to the JPSO and Definition of Route A/B/C, October 2018. *Trim Reference 2019/121946.*

21 Minutes from the Hunterston B R4 2018 Graphite Assessment Panel Meeting No. 8, 12th October 2018. *Trim Reference 2019/121950*.

22 DAO/REP/JIEC/354/HNB/18 Rev 000, Hunterston B - Summary of Understanding of Brick Cracking at Hunterston B 2018 Inspection, October 2018. *Trim Reference 2019/121959.*

23 DAO/EAN/JIEC/284/HNB/18 Rev 000, Understanding of Singly-Cracked Bricks at Hunterston B Reactor 4, February 2019. *Trim Reference 2019/121987.*

24 DAO/REP/JIEC/360/AGR/18 Rev 000, HNB – The Potential for Formation of Multiply Cracked Bricks in Hunterston B and Hinkley Point B: Update Following the HNB R4 Inspections in October 2018, November 2018. *Trim Reference 2019/121995.*

25 DAO/REP/JIEC/350/HNB/18 Rev 002, Graphite Assessment Process –Codes and Methodology Overview, October 2018. *Trim Reference 2019/122033.*

26 QRS-3031I-3 Version 1.0, Sensitivity Studies on Multiple Cracked Brick Forecasts at Hunterston B - CrackSim Calculations, January 2019. *Trim Reference 2019/122042.*

27 QRS-3031I-TN4 Version 1, Impact of Alternative Assumptions on HNB R3 and R4 Forecasts - Updated CrackSim Calculations, January 2019. *Trim Reference 2019/122048.*

28 QRS-3031I-TN5 Version 1, Implications of Finding Additional Doubly-Cracked and Multiply-Cracked Bricks on HNB R3 and R4 Forecasts - CrackSim Calculations, January 2019. *Trim Reference 2019/122057.*

29 Design Authority Task File Note E/TSK/HNB/15196 Item 5 Issue 1, Sensitivity Study on Number of Multiply Cracked Bricks at HNB R4 based on Cracked Brick Observations, November 2018. *Trim Reference 2019/122062.*

30 206680-AL09-DW30-RPT-0001 Issue 2, Hinkley Point B and Hunterston B Graphite Core: AGRIGID Assessment with up to 1,792 Cracked Bricks in Normal Operation, November 2017. *Trim Reference 2018/300895.*

31 206680-AL09-DW30-RPT-0002 Issue 2, Hinkley Point B and Hunterston B Graphite Core: LEWIS Assessment with up to 1,792 Cracked Bricks in Normal Operation", November 2017. *Trim Reference 2018/301080.*

32 206680-AL09-DW30-TLN-0002 Issue 2, Hunterston B Reactor 3: Return to Service 2018, Normal and Fault Assessment Sensitivity Study, April 2018. *Trim Reference 2018/140609.*

33 206680-AL12-DW30-TLN-0001 Issue 2, Hinkley Point B and Hunterston B Graphite Core: AGRIGID Assessment and Statistical Assessment of LEWIS assessment in Normal Operation with 1,792 Cracked Bricks Aligned by Channel, June 2018. *Trim Reference 2019/122137.*

34 206680-AL13-DW30-TLN-0003 Issue 1, Hunterston B Graphite Core: LEWIS Results for the AGRIGID Analysis of 1331 Aligned Singly-cracked Bricks, in Layers 3 to 9 and Rings 1 to 9, for Comparison of AGRIGID and GCORE Pre-Seismic Control Rod Channel Assessments, July 2018. *Trim Reference 2019/122140.*

35 206680-AL17-DW30-TLN-0001 Issue 3, HNB Graphite Core: Comparison of core distortions between cores with and without up to 200 multiply cracked bricks at 31.1fpy, February 2019. *Trim Reference 2019/122151.*

36 5152292/350/019 Issue 2, HPB/HNB Seismic Assessment PCPV Modelling, August 2018. *Trim Reference 2018/306583.*

37 5152292/350/020 Issue 01, Investigation of the Effect of the Updated Core Boundary Excitations for Non-Linear Seismic Assessments of a Reactor Core Containing Vertically Aligned Singly and Doubly Axially Cracked Fuel Bricks at 17 TWd, September 2018. *Trim Reference 2018/306580.*

38 5152292/350/033 Issue 1, Hunterston B Reactor Cores, Seismic Assessments with Approximate Representations of Multiply-Cracked Fuel Bricks (Proxy-MCBs) in Cores Containing Singly and Doubly Cracked Fuel Bricks at 17TWd. *Trim Reference 2019/46338.*

39 Design Authority Task File Note E/TSK/HNB/15031 Item Number 09, Cracking at Shutdown, April 2018. *Trim Reference 2018/117052.*

40 FNC 53835-019/46074R Issue 1 Support to the Graphite Lifetime and Safety Case Group Predictions of Keyway Root Cracking at Hinkley Point B and Hunterston B Using EDF Energy Integrated Methodology V1.2, August 2017. *Trim Reference 2019/122232.*

41 QRS-3031G-13 Version 1.1, A Diverse Assessment of Brick Shape and Stress Evolution for Hunterston B, August 2017. *Trim Reference 2019/122438.*

42 E/REP/BBEB/0036/AGR/06 Rev 000, The Effects of Sleeve Gapping on Can Temperature, and the Inclusion of this Effect in the SRU Dataset, August 2007. *Trim Reference 2011/111516.*

43 E/REP/BBEB/0046/AGR/07 Rev 000 Impact of Sleeve Gapping on Steady State Clad Temperatures, January 2008. *Trim Reference 2011/111521.*

44 DAO/REP/JIEC/326/AGR/17 Rev 001, Hinkley Point B and Hunterston B Power Stations. Head Document - Long Term Graphite Core Safety Case, October 2018. *Trim Reference 2019/122450.*

45 E/REP/FHRO/0028/AGR/01 Rev 001, Hinkley Point B and Hunterston B Power Stations: A Revised Core Safety Case: Part 3: Tolerance to Faults, May 2006. *Trim Reference 2011/499383.*

46 E/REP/RADA/0012/AGR/01 Rev 001, Hinkley Point B and Hunterston B Report, Revised AGR Core Safety Case: Part 1 – Acceptability of Fuel and Core Temperatures in Normal Operation, July 2002. *Trim Reference 2012/303711.*

47 E/EAN/BCDB/0159/AGR/18 Rev 000, Studies on Graphite Debris Levitation, Identification of an Upper Limit of Blockage Area and Debris Consequences for Hinkley Point B/Hunterston, January 2019. *Trim Reference 2019/122472.*

48 DAO/REP/JIEC/134/AGR/10 Rev 000, HPB/HNB: Core Restraint Position Statement – October 2010, October 2010. *Trim Reference 2011/239698.*

49 DAO/EAN/JIEC/258/HNB/18 Rev 001, Assessment of Fuel Grab Load Trace analysis compared to the results of the HNB R3 2018 Graphite Core Inspection, May 2018. *Trim Reference 2018/266653.*

50 DAO/EAN/JIEC/279/HNB/18 Rev 000, Assessment of Fuel Grab Load Trace analysis compared to the results of the HNB R4 2018 interim graphite inspections, December 2018. *Trim Reference 2019/122563*.

51 QRS-3031I-20 v1, Updated CrackSim Forecasts for HNB and HPB. *Trim Reference 2019/213857*.

52 QRS-3031I-TN12 v1.1,Impact of Alternative Crack Opening Assumptions on HNB and HPB Forecasts. *Trim Reference 2019/221048*.

53 Email: Re: HPE CM: Re: HPB R3 Current Burn-up, dated: 02/08/2019. *Trim Reference 2019/226468*.

54 DAO/REP/JIEC/352/HNB/18 Revision 000 Understanding singly cracked graphite bricks at Hunterston B 2018. *Trim Reference 2019/136912*.

55 QDS-3031I-M3 v1 - Crack Opening Breakdown. *Trim Reference 2019/133632.*

56 HSL responses to questions about CrackSim. *Trim Reference 2019/96197*.

57 Predictions of MCBs in HNB - Technical Note 21/12/2018 Final (2). *Trim Reference 2019/95089*.

58 E/TSK/HNB/15196 item 14 Revision 000, AGRIGID and GCORE Analysis using Approximately Represented Multiply-Cracked Fuel Bricks (Proxy-MCBs). *Trim Reference 2019/46335*.

59 5137642/301/005 Issue 02, GCORE Validation for Large Arrays of Radially Keyed Bricks Part 6: Response of the MLA3 Multi-Layer Array Containing 30% Uniformly Distributed Doubly Axially Cracked Lattice Bricks, March 2017. *Trim Reference 2017/369369.*

60 5137642/301/006 Issue 02, GCORE Validation for Large Arrays of Radially Keyed Bricks Part 7: Response of the MLA4 Multi-Layer Array Containing 50% Uniformly Distributed Doubly Axially Cracked Lattice Bricks, July 2017. *Trim Reference 2017/369370*.

61 206680-AL14-DW30-TLN-0004 Issue 2, Hunterston B Graphite Core: Assessment of core distortions between cores with 1,331 cracked bricks including up to 200 multiply-cracked bricks and 200 singly-cracked bricks opened to 18mm at 31.1fpy. *Trim Reference 2019/221366*.

62 5152292/350/033 Issue 2, Seismic Assessments with Approximate Representations of Multiply-Cracked Fuel Bricks (Proxy-MCBs) in Cores Containing Singly and Doubly Cracked Fuel Bricks at 17.0 TWd. *Trim Reference 2019/201192*.

63 Email: RE: NP/SC 7785 - Response to further TQs, dated 25/07/2019. *Trim Reference 2019/221419.*

64 NP/SC 7785 - Hunterston R4 Return to Service TQs and Document Requests. *Trim Reference 2018/388257*.

65 15548/TR/005 Issue 1, LEWIS validation against test rig work on HPB and HNB fuel stringer / channel interactions. *Trim Reference 2018/13061.*

66 ONR-OFD-AR-19-029, Fault Studies Assessment of the Hunterston B R4 Return to Service Safety Case Following Core Inspection Results in 2018. *Trim Reference 2019/176010.*

67 206680-AL12-DW30-RPT-0001 Issue 2, Hinkley Point B and Hunterston B graphite core: statistical analysis of the LEWIS assessment with up to 1,792 cracked bricks in normal operation. *Trim Reference: 2018/341138.*

68 13561/TR/001 Issue 1, Hinkley Point B and Hunterston B control channel distortions: Experimental work to determine tolerability of sensor rod insertion to distorted channel shapes. *Trim Reference 2018/12871*.

69 206680-AL13-DW30-TLN-0004 Issue 2, Hunterston B Graphite Core: Core distortion at inspection conditions with applied brick tilts as measured in R3 2018 interim outage inspection. *Trim Reference 2018/341142.*

70 206680-AL14-DW30-TLN-0002 Issue 3, AGRIGID and LEWIS analysis of Hunterston B R3 graphite core with brick tilts and crack openings from inspections of March and June 2018. *Trim Reference 2019/35442.*

71 Email, subject: Channel bow and amplitude, date: 08/05/2019. *Trim Reference 2019/145300.*

72 5142838/301/102 Issue 2, GCORE Seismic Assessments Implementation of Run-Time Damage using ABAQUS/Explicit. *Trim Reference 2018/337230*.

73 5152292/301/001 Issue 3, Seismic Assessments at 16.7 TWd(th) with up to 60% Single Axially Cracked Fuel Bricks. *Trim Reference 2018/372370*.

74 5152292/350/018 Issue 2, Non-Linear Seismic Assessment for a Reactor Core Containing Vertically Aligned Singly and Doubly Axially Cracked Fuel Bricks at 17TWd. *Trim Reference 2018/370346.*

75 ONR-OFD-AR-18-085, Return to service safety case for Reactor 4 following core inspection results in 2018 - NP/SC 7785, Civil engineering assessment. *Trim Reference 2019/90351*.

76 Email, subject: RE: HNB R4 RTS: question on seismic tolerance to OA/CEDTL, date: 05/08/2019. *Trim Reference 2019/225631*.

77 5152292/350/022 Issue 01, Investigation into the response of the GCORE model to the variations in either Horizontal Shear Key/Keyway Lost Motions of Force-Based Capacities about a Baseline Core State at 17TWd. *Trim Reference* 2019/122606.

78 Email, subject: Forces on interstitial keys, date: 09/05/2019. *Trim Reference 2019/159702.*

79 DAO/EAN/JIEC/275/AGR/18, Hinkley Point B / Hunterston B Graphite Cores: The Consequences of Multiply-Cracked Bricks. *Trim Reference 2019/31287.*

80 E/EAN/BREB/0133/AGR/15, Effect of blockage in the tie bar and guide tube annulus by carbon deposition on refuelling cooling safety case, Nov 2015. *Trim Reference 2019/172605*.

81 RD/B/N3611 The effects of debris on the heat transfer performance of CAGR fuel clusters, 1976. *Trim Reference 2019/172912.*

82 EPD/AGR/REP/0265/97, RACSC/P71 Issue 1, Thermal Hydraulics implications of core debris, December 1997, *Trim Reference 2007/167706*.

83 ONR-OFD-CR-19-057 - Hunterston B Reactor 4 Return to Service, Concerns with Debris and Allowances - 25 April 2019. *Trim Reference 2019/122093*.

84 DAO/REP/JIEC/375/HNB/19 Revision 000 Summary Statement on Production, Migration Paths and Potential Consequences of Graphite Debris for Clad Integrity, May 2019. *Trim Reference 2019/161109*.

85 Email, subject: RE: Cross reference to ARs, date: 11/06/2019. *Trim Reference 2019/167754*.

86 RD/B/N3832 The effects of small pieces of inner graphite sleeve on the heat transfer performance of CAGR fuel clusters, 1976. *Trim Reference 2019/172909.*

87 ONR-OFD-AR-19-003, Return to service safety case for Reactor 4 following core inspection results in 2018 - NP/SC 7785, Seismic Assessment for Diverse Hold Down System. *Trim Reference 2019/100264*.

88 ONR Assessment Rating Guide Table. *Trim Reference 2016/118638*.

SAP No	SAP Title	Description
EGR.1	Safety cases	The safety case should demonstrate that either: a) the graphite reactor core is free of defects that could impair its safety functions; OR b) the safety functions of the graphite reactor core are tolerant of those defects that might be present.
EGR.2	Demonstration of tolerance	The design should demonstrate tolerance of graphite reactor core safety functions to: a) ageing processes; b) the schedule of design loadings (including combinations of loadings); AND c) potential mechanisms of formation of, and defects caused by, design specification loadings.
EGR.3	Monitoring	There should be appropriate monitoring systems to confirm the graphite structures are within their safe operating envelope (operating rules) and will remain so for the duration of the life of the facility.
EGR.4	Inspection and surveillance	Features should be provided to: d) facilitate inspection during manufacture and service; AND e) permit the inclusion of surveillance samples for monitoring of materials behaviour.
EGR.7	Materials properties	Analytical models should be developed to enable the prediction of graphite reactor core material properties, displacements, stresses, loads and condition.
EGR.10	Effect of defects	An assessment of the effects of defects in graphite reactor cores should be undertaken to establish the tolerance of their safety functions during normal operation, faults and accidents. The assessment should include plant transients and tests, together with internal and external hazards.
EGR.11	Safe working life	The safe working life of graphite reactor cores should be evaluated.
EGR.12	Margins	Operational limits (operating rules) should be established on the degree of graphite brick ageing, including the amounts of cracking, dimensional change and weight loss. To take account of uncertainties in measurement and analysis, there should be an adequate margin between these operational limits and the maximum tolerable amount of any calculated brick ageing.
EGR.13	Use of data	Data used in the analysis should be soundly based and demonstrably conservative. Studies should be undertaken to establish the sensitivity to analysis parameters.
EGR.15	Extent and frequency	In-service examination, inspection, surveillance and sampling should be of sufficient extent and frequency to give confidence that degradation of graphite reactor cores will be detected well in advance of any defects affecting a safety function.

Table 6: Relevant Safety Assessment Principles considered during the assessment.