Office for Nuclear Regulation

Operating Reactors

An operational safety case for Hunterston B R3 to a core burn-up of 16.425TWd following the 2018 graphite core inspection outage NP/SC 7766: Stage Submission 1

Graphite structural integrity assessment

Assessment Report ONR-OFD-AR-19-053
Revision 0
August 2020

Published 08/2020

EXECUTIVE SUMMARY

This report summarises my structural integrity assessment of the Hunterston B (HNB) Reactor 3 (R3) return to service safety case (NP/SC 7766 Stage Submission 1 (SS1)), which is submitted by EDF-Energy Nuclear Generation Limited (NGL). HNB R3 has been shut down since March 2018 for inspection and the subsequent development of the SS1 case. The return to service proposal is for continued operation to a core burn-up of 16.425 TWd, which equates approximately to a 6-month period of operation. It is based on the analysis methodologies of the currently permissioned NP/SC 7716 case and the subsequent case for HNB Reactor 4 (R4), NP/SC 7785.

NGL has made a key change to the existing safety case methodology by dispensing with the Operational Allowance (OA). Previously, NGL would set the OA as an arbitrary core state limit that operation would not exceed before further inspections were made. NGL would also set a second arbitrary core state known as the Currently Established Damage Tolerance Level (CEDTL) that would be defined as approximately twice the OA in terms of cracked brick numbers. NGL would show the graphite core was tolerant to the CEDTL, thereby demonstrating margin existed substantially beyond the OA and mitigating uncertainty in the core state predictions. SS1 has removed the OA in favour of defining a 6-month and 12-month core state and setting a case validity limit of 6-months. It is my view this does not undermine the robustness of the SS1 methodology because damage tolerance arguments are still made for the CEDTL and a core state representative of the 12-month state, referred to as the intermediate state. These damage tolerance states effectively perform the same function as the OA and the CEDTL previously.

The core state predictions presented in SS1 are based on a methodology that ONR previously assessed via the R4 return-to-service safety case and takes account of both the brick cracking observations from the extended inspections undertaken on R3 since March 2018. Further brick cracking observations that had not been available during NGL's development of SS1 became available from the January 2020 inspection of R4. Although from R4, the observations nevertheless increased the pool of relevant data beyond those available to SS1.

To ensure the SS1 case was assessed in the light of the latest information available, the specialist inspector requested that NGL update the R3 SS1 core state predictions with the January 2020 R4 observations. A good comparison to core state prediction by ONR independent advisors offers further confidence in the core state predictions. Based on this, I am content that appropriate core states have been predicted by NGL with sufficient confidence and are bounded by the damage tolerance assessments.

Inspections have shown that brick cracking can generate brick fragments by branching of cracks. If those fragments become mobile in the coolant gas flow, where they become known as graphite debris, the ultimate concern is the debris may migrate to safety significant locations and impede fuel cooling. The overall risk to fuel cooling from graphite debris is covered by a separate fault studies assessment, but the likelihood of debris production and its migration to safety significant locations is considered here. The bulk of those considerations were originally made in the HNB R4 return-to-service assessment and limited to being bounded by the HNB R3 operational experience. In those considerations, the specialist inspector concluded that the likelihood of graphite debris migrating to safety significant locations should be considered as a design basis event with a potential frequency of 10^{-4} per year. The inspector also concluded that since HNB R3 is not bounded in terms of brick cracking by the operational experience of any other AGR, SS1 must provide more robust arguments than had been presented for HNB R4.

It is the view of the specialist inspector that SS1 has provided arguments on the likelihood of fragment generation that are more robust via a review of all graphite fragment and debris observations. A primary observation of the review is that fragments have only become mobile once there is significant crack opening around the fragment. The review concluded that the majority of fragments in R3 would not have sufficient crack opening conditions to be released for at least 12 months of operation.

It is the specialist inspector's view that SS1 has not improved the arguments for the likelihood of fragments migrating to safety significant locations. It is the specialist inspector's view that those arguments are inherently subjective and not as strong as arguments that consider the consequences of such an event, which have been considered in the fault studies assessment. However, the specialist inspector concludes the likelihood of graphite debris significantly blocking the fuel element 1 grid should be maintained as a design basis event with a potential frequency of 10^{-4} per year during the next six months of operation of HNB R3. The specialist inspector confirmed that the fault studies assessment made due consideration of this potential event frequency as part of their assessment of NP/SC 7766.

An important structural integrity aspect of safety cases for AGR graphite cores is the damage tolerance assessment (DTA) that focuses on the prediction of channel distortions in two scenarios: the full-power normal operating condition and a 1 in 10,000 year seismic event. Although NGL has submitted separate safety cases for R4 and R3, the two reactors are common in design and NGL consider the two reactors share common graphite material properties and ageing processes. I am in agreement with NGL that this is the case and that aspects of my previous assessment of R4 continue to be directly relevant to this assessment of R3. Where appropriate, I have therefore drawn on the previous R4 assessment instead of repeating that assessment here. In particular, I am content that there is sufficient equivalence between R3 and R4 that the R4 normal operating condition DTA that has been accepted under the R4 case is applicable to SS1.

However, NGL identified two issues that required SS1 to revise the R4 seismic DTA. Firstly, that the seismic input to the graphite core had been underestimated and secondly, that the load capacity of the end-face keying system is lower than had been estimated. SS1 also implements upper bound seismic building properties, which increases the severity of the best estimate seismic input to the graphite core used in the R4 DTA. The use of upper bound building properties in SS1 has been separately assessed by a specialist civil engineering inspector.

Channel distortion predictions from the revised seismic DTA are presented for the intermediate core state and for the CEDTL. I have considered the seismic DTA and it is my view the intermediate core state shows acceptable channel distortion margins for control rods. A key difference between SS1 and previous cases is that SS1 does not show margin beyond the CEDTL. The CEDTL defined by SS1 appears to be a limit of tolerance, but only when neglecting several conservatisms. I have not sought to quantify those conservatisms in my assessment, but instead I have sought to be assured that the margin between the 6-month core state and the CEDTL is adequate. This, in conjunction with the consequences of the revised seismic DTA, has led me into substantial regulatory interaction with NGL on an issue that has become known as in-event cracking.

In-event cracking is the methodology implemented in SS1 that addresses the increased damage to the graphite core keying system caused by the seismic DTA revisions: i.e. upper bound building properties; the increased seismic input; and the reduced end-face key load bearing capacities. In-event cracking considers an alternative outcome to keying system failures that is potentially more onerous than previous seismic DTA's have reasonably assumed. Specifically, end-face key failures could manifest as additional cracked bricks (instead of the currently assumed local failure of the key or keyway) in sufficient numbers to substantially change the core state during the seismic event.

With the in-event cracking assumption, it is plausible that a 1 in 10,000 year seismic event during the 6-month operating period could lead to a core state exceeding the intermediate DTA core state. This could undermine the channel distortions margins that SS1 quotes at the intermediate core state. It was necessary then for NGL to confirm that the in-event core state did not substantially exceed the intermediate core state and was not approaching the CEDTL, and in a more substantive manner than initially presented.

NGL therefore developed the in-event cracking methodology to show that should a 1 in 10,000 year seismic event occur in the 6-month operating period, the core state at 6-months combined with in-event cracking would not substantially exceed the intermediate core state, and that a substantial margin exists between the in-event core state and the CEDTL. After assessing the in-event cracking methodology, and taking account of the uncertainties and inherent conservatisms in the methodologies, I am satisfied that sufficient margins between the 6 month core state and the CEDTL have been adequately demonstrated when taking account of in-event cracking.

I did however identified room for improvement in the ageing methods employed for predicting keying system load capacities. This did not amount to a shortfall in SS1 but was an opportunity for improvement should those methods be deployed in future cases. I therefore introduced this as Recommendation 1.

I am subsequently content that channel distortion margins for control rods are acceptable and have confirmed that adequate core state margin continues to exist between the in-event core state and the CEDTL.

With continued operation being sought at increasingly damaged core states, and the seismic load case showing more damage to the keying system in those states, NGL's graphite material model has been subjected to formal assessment by a specialist inspector. The specialist inspector concluded that I should consider the effect of uncertainties associated with the clearances and load bearing capacities of the keying system on the safety case claims. I have done so and concluded that the SS1 claims are not undermined by those uncertainties. It is my view, however, that NGL's safety case methodology is approaching its limit of viability in SS1 due to the assumptions and conservatism that constrain it. It is my view that a safety case that seeks operation beyond SS1 will need to reduce those conservatisms in some way. Under those circumstances, it is my view that NGL should identify the major conservatisms and uncertainties and should seek to quantify their combined effect on the graphite core's tolerability to ageing. This was introduced as Recommendation 2.

Overall then, I am satisfied that NGL has presented adequate arguments for the continued structural integrity of the graphite core over the proposed 6-month operating period. I would therefore not object to further operation of HNB R3 for a period of six months, i.e. up to a core burn-up of 16.425TWd.

NGL had to provide significant additional evidence to support the seismic damage tolerance arguments. It was my view this matter had to be resolved before my assessment could progress beyond it. ONR guidance is to rate the assessment against the licensee's original submission, and in accordance with the ONR assessment rating guide, I have assigned an amber rating to SS1 due to the significant additional evidence required. I and other inspectors will subsequently follow up my assessment findings with NGL through formal correspondence and interactions at appropriately levelled meetings.

LIST OF ABBREVIATIONS

AGR	Advanced Gas-Cooled Reactor
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
EFK	End-Face Key/Keyway
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
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)
MITS	Maintenance, Inspection and Test Schedule
NGL	EDF-Energy Nuclear Generation Ltd.
OA	Operational Allowance
ONR	Office for Nuclear Regulation
PAR	Project Assessment Report
PCPV	Pre-stressed Concrete Pressure Vessel
PHA	Partial Height Axial
R3	Reactor 3
R4	Reactor 4
RKW	Radial-Key/Keyway
SACR	Super Articulated Control Rod
SAP	Safety Assessment Principle(s)
SCB	Singly Cracked Brick (a fuel brick with one full-height through-wall crack)
SS1	Stage Submission 1
TAG	Technical Assessment Guide(s) (ONR)
TSC	Technical Support Contractor

TABLE OF CONTENTS

TABLES

FIGURES

1 INTRODUCTION

1 This report summarises my structural integrity assessment of the Hunterston B (HNB) Reactor 3 (R3) return to service safety case (NP/SC 7766 SS1, Reference 1), hereafter referred to as SS1, which is submitted by EDF-Energy Nuclear Generation Limited (NGL). HNB R3 has been shut down since March 2018 for inspection and the subsequent development of the SS1 case. The return to service proposal is for continued operation to a core burn-up of 16.425 TWd. Operation to a core burn-up of 16.425 TWd equates to a further period of operation of approximately 6-months; for convenience and consistency with other definitions I will use the ‘6-month’ terminology throughout this report to reflect burn-up validity limit.

2 SS1 is based on the analysis methodologies of the currently permissioned NP/SC 7716 case (Reference 2) and the subsequent case for HNB Reactor (R4). NGL has however made a key change to the methodology by dispensing with the Operational Allowance (OA). Instead, SS1 seeks to assure safe operation for core states substantially more advanced than the core state predicted to exist after a 6-month operating period.

3 In August 2019 ONR permissioned the return to service of R4 for a four month period via its assessment (Reference 3) of NP/SC 7785 (Reference 4). A key aspect to that permission was the similarities in core ageing and material properties between R3 and R4 and the evidence that four months operation would ensure R4 did not go beyond the core state of HNB R3, i.e. the core state established by the March 2018 inspections. This means that NGL now seeks to return R3 to service up to a core state that is beyond any current reactor in the UK AGR fleet, the adequacy of the SS1 case must subsequently be viewed in the context of greater uncertainty.

4 Substantial improvements were made in the HNB R4 case (NP/SC 7785) over its predecessor (NP/SC 7716), NGL claim them equally in SS1 and are as follows.

- An increase in the safety case allowances for cracked bricks.
- Core state predictions that are revised to include induced cracking.
- Justifications that multiply cracked fuel bricks (MCBs) and graphite debris do not challenge continued safe operation.
- Introduction of the runtime damage method, which enables in-event damage to the keying system during a seismic event.
- Revisions to the graphite core seismic input via the updated buildings model.
- The establishing of an initial level of tolerance to graphite debris and brick fragments.

5 The ONR assessment of the R4 return to service case determined the improvements were satisfactory, but made four recommendations that any cases seeking operation beyond that period should be further improved. Those recommendations are subsequently applicable to SS1 and are addressed in this assessment. The recommendations were targeted at the aspects of the safety case where a further operating period would generate greatest uncertainty.

6 Recommendation 1 was for NGL to update ONR on the progress for the development of the damage tolerance modelling of MCBs beyond that of proxy-MCBs used in NP/SC 7785. NGL has now addressed this recommendation by holding a level 4 meeting on the subject (Reference 5). At that meeting, NGL presented a comparison of proxy-MCBs and its improved representation of MCBs in its whole core models. The comparison showed that proxy-MCBs gave conservative results with respect to the

improved representation of MCBs (Reference 5). However, NGL stated that improvements in the MCB methodology would feature in follow-on safety cases and not NP/SC 7766. I note that the extent to which proxy-MCBs are used in NP/SC 7766 to support the CEDTL is no greater than was accepted in NP/SC 7785 and, overall, I consider it is acceptable for NP/SC 7766 to continue with the use of proxy-MCBs, pending the introduction of developments to the modelling of MCBs in follow-on safety cases.

7 Recommendation 3 advised the ONR fault-studies assessment on matters of graphite debris and is now closed. Therefore, only Recommendations 2 and 4 are taken forward here and are as follows.

HNB R4 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.*
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.*

8 Whilst the damage tolerance arguments in the R4 case (NP/SC 7785) are also applicable to SS1, in the intervening period NGL identified two issues that would require revision to SS1. Firstly, that the seismic input to the graphite core had been underestimated and secondly, that the load capacity of the end-face keying system is lower than had been estimated. This required the damage tolerance arguments for R3 to be revised and have subsequently been included in SS1. The revision includes the following changes.

- The seismic input to the graphite core uses upper-bound building properties instead of best-estimate properties.
- The rocking motion of the building has been included to the graphite core seismic input.
- The 'final' version of the revised building model is used instead of the 'preliminary' version, accounting for recommendations by independent peer review.
- End-face key/keyway capacities are reduced by 45%.

9 My structural integrity assessment of SS1 therefore draws on my assessment of NP/SC 7785, but focuses on Recommendations 2 and 4 from my previous assessment of NP/SC 7785 and the revisions to the damage tolerance assessment made by SS1.

10 My assessment is part of a set of assessments that will be brought together by the Project Assessment Report (PAR). The assessment has been made in accordance with the requirements of the ONR How2 Business Management System (BMS). The ONR Safety Assessment Principles (SAP) (Reference 6) and the supporting Technical Assessment Guides (TAG) (Reference 7) have been used as the basis for this assessment.

1.1 Scope

11 The scope of this report covers return to service of HNB R3 for a period of six months (up to 16.425 TWd) on the basis of the graphite core safety case NP/SC 7766 SS1 (Reference 1).

12 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. NP/SC 7716 was permissioned but not the Addenda, SS1 effectively supersedes the need to permission these addenda.

1.2 Methodology

13 The methodology for the assessment follows How2 guidance on mechanics of assessment within the ONR (Reference 8).

2 ASSESSMENT STRATEGY

14 The intended assessment strategy for NP/SC 7766 SS1 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

15 The relevant standards and criteria adopted within this assessment are principally the SAPs (Reference 6) and internal ONR Technical Assessment Guides (TAG) (Reference 7). 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.

16 The adequacy of the safety case can be tested 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 2.4).

2.2 Safety Assessment Principles

17 The key SAPs applied within the assessment are included within Table 5 (Reference 6) of this report. Of particular note are EGR.1, EGR.2, EGR.11 and EGR.12, which seek to assure tolerance of the graphite core to the effects of ageing through justifications for safe periods of operating with a demonstration of margin.

2.3 Technical Assessment Guides

18 The following Technical Assessment Guides have been used as part of this assessment (Reference 7):

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

2.4 Use of Technical Support Contractors

19 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.

20 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).

2.5 Integration with Other Assessment Topics

21 My assessment forms part of the ONR's decision on whether to permission the restart of HNB R3. This assessment integrates with the civil engineering and fault studies assessment topics.

22 As part of the R4 return to service case NGL reduced the seismic input motion to the graphite core by revising the PCPV (pre-stressed concrete pressure vessel) buildings model. This was a significant change for the safety case and was the subject of a separate ONR assessment report by a specialist civil engineering inspector. Since then, NGL has made further changes to the seismic model, which have been assessed by the civil engineering inspector (Reference 9). The output of the civil engineering inspector's assessment has informed me of the validity of inputs used in the seismic damage tolerance assessment (DTA).

23 The fault studies assessment (Reference 10) 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, which remain as per my assessment of the R4 case.

2.6 Out of Scope Items

24 NGL's graphite material model, which supports the analytical models, was subject to a separate assessment, Reference 11.

3 LICENSEE'S SAFETY CASE

25 Given SS1 presents a large number of arguments, this section aims to provide a short overview of the claims, arguments and evidence presented in SS1. A more detailed summary of the case is available via Reference 12.

3.1 Claims, Arguments and Evidence

26 SS1 presents five claims, which are as follows.

Claim 1: The effects of graphite core degradation on nuclear safety can be predicted with a suitable level of confidence.

Claim 2: Following graphite core degradation over the proposed operating period, control rod entry, fuel handling and fuel cooling are robust against core distortion and debris under normal operation and non-seismic faults.

Claim 3: Graphite core degradation over the proposed operating period will not undermine the required reliability of the primary shutdown system for shutdown and holddown under seismic faults.

Claim 4: The combination of SACRs and Nitrogen is functionally capable of providing shutdown and holddown of a very distorted core.

Claim 5: This proposal is consistent with the ALARP principle.

27 In the following sections, I provide an overview of the arguments and evidence to each of these claims. My restatement of NGL's safety case arguments does not imply my agreement; my own assessment and conclusions are contained in Section 4 and 5.

3.2 Summary of Evidence for Claim 1

Claim 1: THE EFFECTS OF GRAPHITE CORE DEGRADATION ON NUCLEAR SAFETY CAN BE PREDICTED WITH A SUITABLE LEVEL OF CONFIDENCE

28 In Claim 1, NGL argues it has sufficient confidence in the safety case methodology to predict the effects of core degradation on nuclear safety. The argument is outlined as follows.

- Core inspection and the prediction of current and future core states, arguments 1.1, 1.2 and 1.3.
- The effect of core state on core distortion, arguments 1.4, 1.5 and 1.6.
- The effect of core state on fuel performance, argument 1.7.
- The effect of degradation mechanisms not explicitly covered by the predictions, argument 1.8.
- Monitoring techniques that are available between inspections, argument 1.9.
- Methods of determining the reliability of the primary shutdown (PSD) and holddown system, argument 1.10.
- Sensitivity to assumptions, argument 1.11.

29 Arguments 1.1, 1.2 and 1.3 focus on the evidence that NGL understands graphite core ageing sufficiently to adequately predict the current and future core states. Through Argument 1.1 NGL presents evidence to argue that core inspection equipment and the methods to analyses the findings of inspection are sufficient. Through Argument 1.2 NGL argues the properties of graphite ageing are adequately predicted by the EIM (EDF-Energy Integrated Model), which uses data obtained from the UK AGR fleet and material test reactors. Through Argument 1.3 NGL presents evidence to argue that graphite degradation can be understood using the EIM and inspection observations, and that the understanding used to build a degradation model capable of forecasting future core states is sufficient.

30 Arguments 1.4, 1.5 and 1.6 focus on the evidence that NGL can adequately predict core distortions for ageing graphite cores. Through Arguments 1.4 and 1.5 NGL presents evidence to argue that core distortion can be predicted during normal operation, faults and seismic events, and that those prediction methods are supported by validation testing. Through Argument 1.6 NGL presents evidence of the predicted core distortions can be described in terms of safety margins.

31 Argument 1.7 presents evidence that the effects of core degradation, such as weight loss and graphite debris, on fuel cooling and reactor moderation are understood.

32 Argument 1.8 argues that consideration has been made for the credible degradation mechanisms such as MCBs, key disengagement and seismically induced brick cracking, which are not explicitly modelled in the DTA.

33 Argument 1.9 focuses on describing the monitoring techniques available whilst the reactor is at-power and the oversight that is in-place to review them. The techniques are:

- Fuel Grab Load Trace (FGLT);
- Fuel Machine Hoist Trips;
- Channel Power Discrepancies;
- At-Power Control Rod Movements;
- Control Rod Drops;
- Coolant Activity;
- Monitoring Assessment Panel.

34 Argument 1.10 argues that NGL has valid methods to determine the shutdown and holddown reliability based on control rod worth.

35 Argument 1.11 presents evidence to argue that predictions of the core state at the end of the 6-month operating period and of core distortion have been subject to sensitivity studies to ensure they are sufficiently bounding.

3.3 Summary of Evidence for Claim 2

Claim 2: FOLLOWING GRAPHITE CORE DEGRADATION OVER THE PROPOSED OPERATING PERIOD, CONTROL ROD ENTRY, FUEL HANDLING AND FUEL COOLING ARE ROBUST AGAINST CORE DISTORTION AND DEBRIS UNDER NORMAL OPERATION AND NON-SEISMIC FAULTS

36 Claim 2 argues that implementing the methods detailed in Claim 1 for the normal operation condition shows the core performance is robust against the effects of

substantially greater levels of core degradation than is predicted to exist at the end of six months operation. The argument is outlined as follows.

- Prediction of the current and future core states, arguments 2.1 and 2.2.
- Prediction of core distortion, arguments 2.3 and 2.4.
- The effect of degradation mechanisms not explicitly covered by the predictions, argument 2.5 and 2.6.
- Monitoring techniques safeguard inadequate conception of the core condition, argument 2.7.
- Adequate margins and a lack of cliff-edge, argument 2.8.

37 Arguments 2.1 and 2.2 provide evidence that the current and future core states have been predicted conservatively. NGL presents evidence that through comprehensive core inspections, a conservative estimate of the current and future core state has been determined, and that further confidence in the core states has been determined through sensitivity studies.

38 Arguments 2.3, 2.4 and 2.5 provide evidence that control rods will not be impeded for normal operation and faults. Argument 2.3 provides evidence that core distortions predicted for the normal operation load case are sufficient to also represent faults and hazards excluding the seismic hazard. Argument 2.3 also presents evidence to argue that a sufficient range of core states and configurations have been assessed to inform judgements on core distortion.

Argument 2.6 provides evidence to confirm other nuclear safety issues that are not directly addressed in the modelling do not undermine the safety case assumptions. NGL considers the following:

- Reduced moderation due to weight loss;
- Abnormal gas flows due to brick cracking and debris;
- Fuel and non-fuel handling safety cases;
- Core restraint and core support safety cases.

39 Argument 2.7 presents the plant monitoring evidence to argue that significant core distortions in control rod channels and fuel channels would be detected via control rod movement monitoring, fuel grab load trace monitoring and by monitoring of channel power discrepancies.

40 Argument 2.8 is essentially a summary of the prior arguments.

3.4 Summary of Evidence for Claim 3

Claim 3: GRAPHITE CORE DEGRADATION OVER THE PROPOSED OPERATING PERIOD WILL NOT UNDERMINE THE REQUIRED RELIABILITY OF THE PRIMARY SHUTDOWN SYSTEM (PSD) FOR SHUTDOWN AND HOLDDOWN UNDER SEISMIC FAULTS

41 Claim 3 argues that implementing the methods detailed in Claim 1 for the seismic condition shows the core performance will not be undermined by the effects of substantially greater levels of core degradation than is predicted to exist at the end the 6-month operating period. The argument is outlined as follows.

- Prediction of the current and future core states, argument 3.1, which is as per arguments 2.1 and 2.1.
- Prediction of core distortion, arguments 3.2 and 3.3.
- Assurance that fuel temperatures will remain acceptable following the seismic event, argument 3.4.
- Adequate margins and a lack of cliff-edge, argument 2.8.

42 Argument 3.1 regards the core state predictions and so the evidence for Argument 3.1 is the same as presented under arguments 2.1 and 2.2.

43 Argument 3.2 focusses on the core distortion predictions, presenting evidence that there can be confidence in the predictions for a 1 in 10,000 year seismic event. NGL presents an updated seismic response of the PCPV that is used to define the seismic input to the graphite core. NGL then presents evidence that the channel distortions, core restraint integrity and fuel sleeve integrity provide sufficient margin to accommodate the uncertainties.

44 Arguments 3.3 and 3.4 are effectively summaries of the evidence already presented in prior arguments.

45 Argument 3.5 uses the monitoring techniques already outlined in Arguments 1.9 and 2.7 to state that if the core was to degrade significantly outside SS1 it would be identified. NGL also refers to the evidence presented under Argument 1.9 to state that, overall, the available monitoring provides a degree of confidence that the core state has not significantly diverged from the basis of the safety case, but provides limited support to the leg covering tolerability to a seismic event.

3.5 Summary of Evidence for Claim 4

Claim 4: THE COMBINATION OF SACRS AND NITROGEN IS FUNCTIONALLY CAPABLE OF PROVIDING SHUTDOWN AND HOLDDOWN OF A VERY DISTORTED CORE

46 In Claim 4, NGL argues that shutdown and holddown can be achieved with only the twelve super-articulated control rods (SACRs) in conjunction with the Nitrogen Injection System. The argument is outlined as follows.

- That the SACRs will enter a very distorted core, argument 4.1.
- That of the 81 controls rods, only the twelve SACRs are needed for shutdown and short-term holddown, argument 4.2.
- That long-term holddown is achieved by the addition of the Nitrogen Injection System, argument 4.3.
- There is resilience to more severe levels of earthquake, argument 4.4.

47 Argument 4.1 presents evidence that the SACRs will insert into a very distorted core. The evidence is a comparison between the core distortion predictions and control rod drop test-rigs. NGL presents evidence that the distorted channel shape predictions are substantially less onerous than the shapes shown to be tolerant by the test-rigs.

48 Argument 4.2 states the capability and reliability of the SACRs to provide shutdown and short-term holddown has been substantiated previously in NP/SC 7585 Stage Submission 1. NGL states a nominal 1 Nile of negative reactivity is sufficient to provide rapid shutdown with fuel and clad temperatures retained within safety limits, and that

the SACRs have a nominal worth of 1.54 Niles. Subsequently, even in the worst fuel configuration, ten SACRs inserting is sufficient to achieve reactor shutdown.

49 Argument 4.3 presents evidence that in the event a reduced number of control rods enter the core the seismically qualified nitrogen injection system provides adequate holddown, i.e. long-term shutdown, of both R3 and R4. NGL states the nitrogen system has been substantiated previously in NP/SC 7557 Stage Submissions 1 – 6.

50 Argument 4.4 argues the protection is resilient to more severe levels of earthquake. NGL has not presented predictions of core distortion for a more severe earthquake than 1 in 10,000 years, instead NGL has presented qualitative judgements. Those judgements include reference to the core distortion margins evidenced in Argument 3.2 and the control rod drop tests evidenced in Argument 4.1. NGL also judge that there is no cliff-edge response in the plant or building response, and that a best-estimate hazard level that could challenge the safety function is judged greater than twice the seismic hazard design basis level.

3.6 Summary of Evidence for Claim 5

Claim 5: THIS PROPOSAL IS CONSISTENT WITH THE ALARP PRINCIPLE

51 In Claim 5, NGL argues that the residual risk is small and that NGL has taken all reasonably practical measures to reduce the risk. The argument is outlined as follows.

52 Argument 5.1 argues that the residual risk is small. NGL states that, based on Claims 2, 3 and 4, it has demonstrated that ageing of the graphite core over the proposed operating period has a negligible impact on the reliability of shutdown and holddown and that the overall station risk remains in the tolerable if ALARP region.

53 Argument 5.2 argues that all reasonably practicable measures to reduce risk further have been considered and implemented to this point and the future strategy is consistent with the ALARP principle. NGL concludes that:

- Adequate core inspections in 2018 support core state predictions at sufficient confidence level;
- Assessed risk to PSD reliability or fuel cooling limits remains low and allows for uncertainties in modelling;
- Defence-in-depth provided by earlier plant modifications limits radiological risk in the event of unknown mechanisms regarding core degradation or response to a seismic hazard.

4 ONR ASSESSMENT

4.1 Scope of Assessment Undertaken

54 SS1 consists of five separate claims, which I have summarised in Sections 3.2 to 3.6. There is some commonality between this and the previously assessed HNB R4 case (NP/SC 7785), I will therefore not assess each individual argument of SS1. Instead, I have focussed my assessment on three fundamental structural integrity aspects to the case, and resolving the remaining two Recommendations made by my previous assessment of NP/SC 7785 (paragraph 5). An outline of my assessment is as follows.

- Confidence that at the end of the 6-month operating period the number and type of cracked bricks has been conservatively defined.
  - The case details this in Claims 1 and 2.
  - Since there is a substantially larger pool of brick cracking observations from HNB R3 than HNB R4, much of the core state evidence that supported the R4 case is taken from the R3 inspections. Therefore my existing assessment (Reference 18) of the R4 case provides a basis for confidence in the R3 core state predictions. Further confidence can be drawn from the additional pool of inspection data drawn from the R4 inspections in January of this year. I outline this in Section 4.3.
  - Since its shutdown in December 2019 there have been further inspections of HNB R4 that have added to the available pool of brick cracking data. This data was not available during NGLs preparation of SS1, but is available for consideration here and has been drawn upon by NGL to respond to particular regulatory challenges (see Section 4.8).
- Confidence that the likelihood of graphite debris generation is acceptable.
  - The case details this in Claims 1 and 2.
  - Whilst arguments on the likelihood of graphite debris generation were considered acceptable for HNB R4 (Reference 18), Recommendation 4 was raised to ensure improved arguments were made for HNB R3. I assess this in Section 4.4.
- Confidence that the damage tolerance analysis bounds the 6-month core state and supports the unimpeded movement of fuel and control rods.
  - The case details this in Claims 2 and 3.
  - It is valid to apply my previous assessment (Reference 18) of the HNB R4 damage tolerance arguments for normal operation directly to R3. This is because the graphite material properties and brick cracking evolution of HNB R3 and R4 are sufficiently similar. I detail the reasoning to this in Section 4.5.
  - My HNB R4 assessment of the normal operation led to Recommendation 2 (Reference 18), i.e. to improve arguments that onerous crack configurations are sufficiently unlikely to challenge free movement of control rods. I assess NGL's response to Recommendation 2 in Section 4.6.
  - Revisions to the seismic analysis for SS1 (outlined in paragraph 8) mean my previous assessment (Reference 18) of the HNB R4 damage tolerance

arguments for a seismic event is no longer applicable. I have detailed my view of those revisions in Section 4.7.

- An outcome of those revisions is the necessity for a more detailed evaluation of in-event brick cracking. I detail my assessment of in-event brick cracking in Section 4.8.

- At the root of the DTA is NGL's graphite material model, referred to as the EIM. The EIM feeds two crucial inputs to the DTA, the clearances in the keying system and the load bearing capacity of the keying system. It has become necessary to subject the EIM to formal assessment by a specialist inspector, Reference 11, who concluded my assessment should take consideration of particular uncertainties. I detail my consideration of the matter in Section 4.9 and 4.10.

55 It is my view that the structural integrity aspects and ALARP position stated in Claims 4 and 5 continue to be consistent with the previously assessed claims of the HNB R4 case (NP/SC 7785), which is summarised by the respective PAR (Reference 3). I am therefore content with the structural integrity aspects of Claims 4 and 5.

56 Before detailing my assessment of the above areas, it is important that I explain a change in approach by SS1, namely, the removal of the Operational Allowance (OA). I detail my view of the validity of that approach in the following section.

4.2 Validity of Removing the OA from NP/SC 7766 Stage Submission 1

57 It is helpful to firstly outline the purpose of the OA and CEDTL.

58 The OA and CEDTL were first introduced by NP/SC 7716 (Reference 2) where they were applicable to the HPB and HNB reactors and were assessed by ONR in Reference 20. The OA defined a tolerable future level of core damage that was effectively arbitrary but was expected to exceed the damage predicted to exist at the end of the proposed operating period. The OA was defined in that way to cover the uncertainty associated with the core state prediction for the end of the proposed operating period. Therefore, showing the OA was tolerable in terms of core distortion meant the core was tolerant to the proposed operating period. In other words, the OA was an expression of confidence from NGL that the core state at the end of the proposed operating period would not exceed the OA.

59 The purpose of the CEDTL was to illustrate that safety margin in terms of core distortion still existed at damage levels substantially beyond the OA. The CEDTL was generally set to be twice the damage level of the OA and, like the OA, NGL showed tolerance to it. In this way, NGL was stating that even if the predicted core state at the end of the proposed operating period was ill conceived, exceeding the OA, margin continued to exist even at twice the damage levels of the OA. In addition to this, because NGL was able to show margin still existed at the CEDTL, the limit of tolerability was in fact further beyond the CEDTL.

60 Exclusion of the OA from NP/SC 7766 SS1 may therefore appear counterproductive. However, in the same manner as cases previously permissioned by ONR (NP/SC 7716 and NP/SC 7785) the CEDTL is still present, as is the core burn-up limit that limits operation to 16.425TWd. Whilst NGL has removed the OA, and with it the commitment to prevent operation beyond it, NGL continues with its commitment not to exceed a given core burn-up. In other words, whilst the OA has been excluded, there remains the commitment not to exceed six months of operation unless further safety case justifications are permissioned by ONR.

61 Nonetheless, with the removal of the OA NGL appears to have removed the expression of confidence that the core state at the end of the proposed operating period will not exceed a given state. NGL continue to implicitly state this confidence by limiting the operating period to six months (16.425TWd) and evaluating tolerance to a defined intermediate core state, which is representative of the 12-month core state, and to a CEDTL.

62 Thus, the exclusion of an explicitly stated OA in SS1 is in my view of no practical consequence and does not degrade the quality of the safety case methodology. I am therefore content with the removal of the OA. Regardless of this however, the margin between the intermediate core state and the CEDTL can be challenged by the introduction of in-event cracking. I discuss in-event cracking later in section 4.8.

4.3 Core state predictions

63 The core state is a description of the number and type of cracked fuel bricks in the core at a given core age. The core state does not specify the precise location of the cracked bricks in the core, but it does specify in which layers the cracked bricks will occur and at what core age. It is important that there is confidence in the core state because it affects the likelihood of graphite debris and influences the prediction of channel distortions that inform judgements on the likelihood of fuel and control rod movements being impeded.

64 The predictions are based on visual observations taken during fuel channel inspections. The inspections take place during a reactor shutdown and inspect a minimum 10% sampling of all the fuel channels at any given inspection. Since the shutdown of R3 in March 2018, in addition to the original 10% sampling, there has been two sets of further inspection. The additional inspections consists of previously uninspected channels to improve the core state predictive confidence and previously inspected channels to confirm the stability of the core state during the shutdown period. The original 10% sampling plus the additional inspections total approximately 30% of the fuel channels.

65 Over the years, NGL has built a database of all the brick cracking observations from HNB R3 and R4 and utilises the database via a Bayesian statistical methodology to predict the current and future core states. NGL has encoded that methodology in to a bespoke code referred to as Cracksim. To test the confidence that can be had in CrackSim, NGL uses CrackSim to predict inspection outcomes. This informs the confidence that can be had in CrackSim predictions of future core states, which in turn, must be bounded by the core states specified in whole core model predictions of channel distortions.

66 SS1 presents predictions of the current core state of HNB R3 and of the core state after 6 and 12 months of operation. These predictions are based on the same methodologies implemented in the R4 case (NP/SC 7785) and detailed in References 15, 16 and 17. The methods were assessed by the specialist inspector for the HNB R4 return to service case (Reference 18) so I will not repeat that assessment here, other than to re-iterate that the specialist inspector considered them fit for purpose.

67 Using the extensive R3 inspections in 2018 (Reference 19) NGL revised the CrackSim methodology (Reference 15) with References 16 and 17 in an effort to improve the representation of brick cracking observations such as crack opening rate and induced cracking. The specialist inspector assessed the revisions in Reference 21 and considered them an improvement to the previous version of CrackSim. To ensure the SS1 case was assessed in the light of the latest information available, the inspector

requested that NGL update the HNB R3 SS1 core state predictions with the January 2020 R4 observations (Reference 22).

68 Based on the improved representation of the observations and the additional R4 observations it was the inspector's view (Reference 23) that increased confidence could be had in the core states being predicted under Reference 22 than were originally presented in SS1. The inspector did not view the difference between the two sets of predictions as a challenge to the safety case and noted that Reference 22 concluded the number of DCBs/MCBs would be lower than had been originally predicted by SS1. NGL would later utilise that reduction to respond to regulatory challenges to the seismic claims for what became known as in-event cracking, which I detail in Section 4.8 and 4.8.5.

69 For reference, I have collated the predictions for the current, 6-month and 12-month core states at the 99.9% confidence level in tables 1 to 3 respectively. I have also included in the relevant tables the associated predictions by the ONR independent advisor (HSL, Reference 24), and for reference, I have compared the relevant core state predictions with those specified in the DTA in table 4.

Predicted current core state (16.19TWd) at 99.9% confidence (1) Reference 15, (2) Reference 22, (3) Reference 24			
Cracked Brick Type	NGL		HSL
	SS1(1)	Including the R4 2020 observations(2)	Including the R4 2020 Observations(3)
All	505	570	550
SCB 6-12mm	105	48	49
SCB > 12mm	22	19	1
DCB+MCB	46	38	25
MCB	14	6	15

Table 1: The current core state (16.19TWd) at the 99.9% confidence.

Predicted 6 month core state (16.425TWd) at 99.9% confidence (1) Reference 15, (2) Reference 22, (3) Reference 24			
Cracked Brick Type	NGL		HSL
	SS1(1)	Including the R4 2020 observations(2)	Including the R4 2020 Observations(3)
All	786	781	760
SCB 6-12mm	201	109	98
SCB > 12mm	35	22	2
DCB+MCB	71	49	45
MCB	24	9	24

Table 2: The 6-month core state (16.425TWd) at the 99.9% confidence.

Predicted 12 month core state (16.64TWd) at 99.9% confidence (1) Reference 15, (2) Reference 22, (3) Reference 24			
All	960	943	920
SCB 6-12mm	351	224	176
SCB > 12mm	50	28	4
DCB+MCB	114	68	75
MCB	36	14	40

Table 3: The 12-month core state (16.64TWd) at the 99.9% confidence.

Comparison of the predicted core states to the DTA (1) Reference 22				
Cracked Brick Type	Including the R4 2020 observations(1)		DTA	
	6 month	12 month	Intermediate	CEDTL
All	781	943	905	1331
SCB 6-12mm	109	224	755	831
SCB > 12mm	22	28	40	200
DCB	40*	54*	70	200
MCB	9	14	40	100
DCB+MCB	49	68	110	300

*The value stated is not an explicit calculation of the number of DCBs at 99.9% confidence interval. It is an approximation, derived from taking the 99.9% prediction of MCBs from the 99.9% prediction of DCB+MCBs.

Table 4: Comparison of the revised core state predictions to the DTA core states.

70 The current, 6-month and 12-month core state predictions are similar for the total number of DCBs and MCBs (labelled in the tables as DCBs+MCBs). However, the number of MCBs and crack opening tends to deviate between NGL and HSL. In terms of DCBs and MCBs, this is a reflection of the small numbers of observations of DCBs and no observations of MCBs leading to differences between the statistical forecasts of NGL and ONR's independent advisor. This is also true of crack opening where observations are limited to < 12mm and are few at this extent. I consider that the lack of leading data to support statistical projections of cracking and crack opening supports the need to limit safety case proposals to short periods (6-months) of operation. However, I note that the forecast numbers of more onerous cracking (DCB+MCB) and crack opening remain low compared to the CEDTL. It is also important to note that the intermediate DTA condition representing the 12-month state bounds the predictions of DCB+MCBs and crack opening when using the revised methods.

71 Previous cases typically set the CEDTL to be twice the OA (Section 4.2), table 4 shows this is easily the case between the intermediate and CEDTL for DCBs, MCBs and SCBs with crack openings of more than 12mm, but clearly not for narrower SCBs. The intermediate and CEDTL states have been defined purposefully in this way because narrow SCBs have little influence on core distortion. Therefore, NGL has conservatively weighted the composition of the core states modelled at the intermediate and CEDTL toward more onerous cracking and crack opening.

72 I am therefore content that appropriate core states have been predicted by NGL with sufficient confidence and that the DTA bounds the revised states.

4.4 Graphite debris generation

4.4.1 The Hunterston B reactor 4 case

73 In 2018, graphite core observations in HNB R3 and R4 had shown that brick cracking led to the generation of brick fragments measuring up to several centimetres. In some cases the fragments were no longer in place and at least one instance was identified where brick fragments were seen at the bottom of a fuel channel. These migrations of graphite debris increase the risk that the debris could interfere with fuel cooling and fuel clad integrity by blocking coolant paths into the fuel stringer, or interfere with the free movement of fuel.

74 The observations of graphite debris meant the HNB R4 return-to-service safety case (NP/SC 7785) needed to address the consequences of such debris and fragments on the safety functions of the graphite core. ONRs considerations in this area are recorded in the structural integrity and fault studies assessments (Reference 18 and 25). Of note was the evidence that continued operation of R4 would not surpass the core state of HNB R3, which had been subject to substantial inspections.

75 Beyond the inspection evidence of HNB R3 and R4, there was little quantitative evidence that NGL could bring to bear. However, given the inspection evidence, ONR considered it reasonable for NGL to assume that before debris generation would occur crack opening in a brick had to first develop over a substantial operating period. The specialist inspector was also content that the R4 core state would be bounded by the extant R3 observations during the proposed operating period. The specialist inspector was subsequently content that the rate of graphite debris generation would be low for the proposed operating period of R4. Overall, the specialist inspector recommended that the fault studies inspector’s assessment takes into account the 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 R4 (Reference 18).

76 R3 is the leading reactor in terms of brick cracking, so confidence cannot be drawn from operational experience to the same extent as was done for R4. Subsequently, the ONR specialist inspector made Recommendation 4 in the assessment of the HNB R4 return-to-service case (Reference 18). Recommendation 4 required that for continued operation of HNB R3 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. I discuss NGL’s response to Recommendation 4 in the following section.

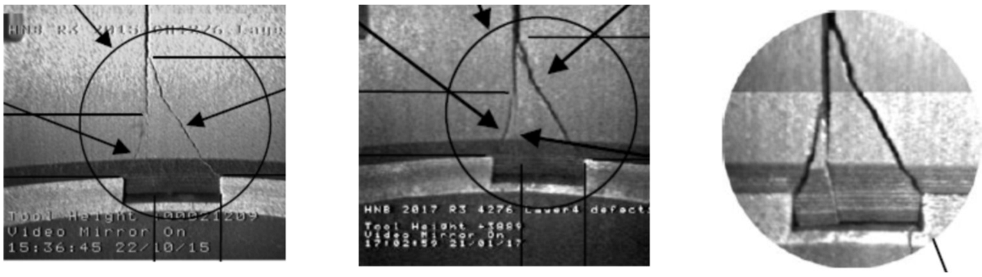
4.4.2 Debris generation (Recommendation 4 from Reference 18)

77 Recommendation 4 of Reference 18 is in three parts, that NGL should provide more robust arguments for:

- mitigating the risks posed by graphite debris;
- the determination of graphite debris production;
- the determination of graphite debris migration.

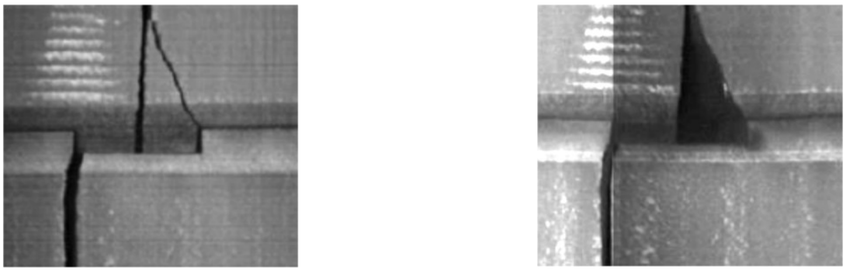
78 Mitigating the risks posed by graphite debris is covered in the Fault Studies assessment of SS1 (Reference 10). The specialist inspector considered NGL has presented sufficient additional arguments and evidence in the form of numerical simulations (computational fluid dynamics) to study debris induced flow blockage outside the range of the available experimental data.

79 To address the recommendation for more robust arguments on graphite debris production, NGL reported an in-depth review of the available debris evidence (Reference 27). SS1 concludes directly from Reference 27 that, over a further 12 months of operation, there is negligible likelihood that sufficient debris will be transported to give rise to flow blockage concerns. Whilst Reference 27 discusses many aspects of the observed fragments, the conclusion is based on a simple premise: that significant crack opening must be present before a fragment can become mobile. This is based on observations to date that show the majority of fragments are relatively recent and the crack surfaces are still closed. Those fragments that are known to have become mobile are where further operation has led to substantial crack opening, releasing the surfaces and increasing the ability of the fragment to be moved. To illustrate, I have extracted examples of crack face separation from Reference 27 and presented them below in figures 1 and 2.



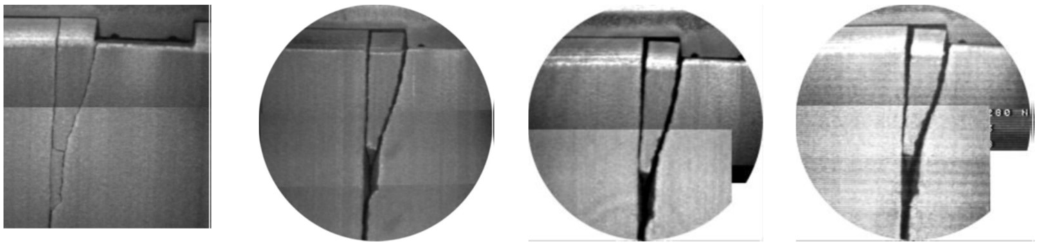
2015 2017 2018

2014 2018



2018 2019

Figure 1: Examples of fragment movement with core age (HNB R3)



2014 2016 2017 2018

Figure 2: Examples of fragment movement with core age (HNB R4)

80 Graphite debris migration is the relocation of a fragment of graphite from its original position to some other location that might have nuclear safety consequences. Of primary interest is the likelihood of whether debris could became entrained into the gas flow partially blocking the base of the fuel stringer and impeding proper cooling of the fuel and fuel cladding. The consequences of such an event are dealt with in the fault studies assessment. NGL's judgement on the likelihood of such an event was considered in the assessment of the HNB R4 safety case (Reference 18). It is necessary to state that whilst that judgement can be rationalised in to an event sequence and likelihoods assigned to each event, the likelihoods are essentially subjective and therefore uncertain. The specialist inspector subsequently concluded in Reference 18 that the likelihood should be treated as a design basis event with a potential frequency of 10^{-4} per year.

81 _Debris production:_ It is my view that NGL has further supported the arguments for the likelihood of debris production with evidence that is more robust, and that the specialist inspector's conclusions from the assessment of R4 (Reference 18) can be maintained. Namely that the likelihood should be treated as a design basis event with a potential frequency of 10^{-4} per year over the next six months of operation of HNB R3. I have confirmed that the Fault Studies inspector (Reference 26) made due consideration of this potential event frequency as part of their assessment of NP/SC 7766.

82 _Debris migration:_ NGL's review of graphite debris (Reference 27) does not significantly add to the existing arguments for the likelihood of graphite debris migration, and this is unsurprising given the subjective nature. It is important then to recognise the inherent weakness in arguments for the likelihood of graphite debris migrating to safety significant locations, and that emphasis should be placed more on the consequences and debris production arguments.

83 The recommendations raised under the HNB R4 assessment were tracked by Regulatory Issue 7332. Based on the above, I am content that Recommendation 4 of Reference 18 has been satisfactorily addressed.

4.5 Validity of the NP/SC 7785 DTA to NP/SC 7766 SS1

84 NGL has submitted separate safety cases for HNB R4 (NP/SC 7785) and R3 (NP/SC 7766 SS1). However, the two reactors are common in design and NGL consider the two reactors share common graphite material properties and ageing processes. This means some aspects of my previous assessment of R4 (Reference 18) are directly relevant to this assessment of R3. This section outlines those commonalities and the conclusions from my previous assessment of R4 that I consider equally relevant here, and will therefore not be re-assessed here.

85 It is ONR's expectation (Reference 7) that NGL demonstrate that all control rods will fully enter the core at all times, and that gas flow paths within the graphite core allow for sufficient cooling of the fuel. Core ageing can potentially challenge those expectations via brick cracking, which can induce additional core distortion that could potentially impede control rods and generate graphite debris that could potentially obstruct gas flow. Fundamentally this is a process driven by a number of phenomena and properties, principally these are:

- changes in the keying system clearances, and the clearances between bricks, caused by irradiation induced dimensional change in the graphite bricks;
- stresses in the graphite bricks induced by the dimensional changes;
- the load capacity of the graphite bricks and keys, i.e. the graphite strength;
- and external loads which enhance the stresses in the graphite such as from a seismic event or normal operating.

86 The first three of these points are concerned with graphite material properties. The graphite material properties can be analysed for differences between the two reactors via the trepanned data and dimensional change inspections. Brick cracking observations between R3 and R4 can also be compared. A sufficient difference in any of the above between R3 and R4 would potentially reduce the confidence that the DTA evidence can be shared between R3 and R4.

87 The fourth point is concerned with operational conditions and a seismic event. Since R3 and R4 are operated to the same requirements, are of the same design, and are geologically in the same location, it is reasonable to assume the external loads applied to the DTA are common to both R3 and R4. I therefore do not consider this last point any further.

88 In the R4 return to service case (NP/SC 7785) NGL presented evidence that R3 and R4 are subject to the same ageing processes (References 28 and 13). For instance, the increase in weight loss with increasing irradiation was shown in Reference 28 to be the same between R3 and R4, as were the degradation of Young's modulus and strength and the evolution of dimensional change. These are all strong driving mechanisms for the DTA evidence presented in NP/SC 7785 to be equally valid for use in SS1. However, the possibility that the ageing process is more complex than the ageing of material properties alone cannot be discounted. Therefore NGL has studied the brick cracking observations between R3 and R4 in Reference 13 and concludes in both NP/SC 7785 and SS1 that *'the assumption of equivalence of R3 and R4 with respect to underlying cracking rates as a function of burn-up remains the most appropriate.'*

89 Given the above, I am satisfied that there is sufficient evidence to support an underlying equivalence between the DTA for the normal operating and faults condition of R3 and R4. I am therefore content that the conclusions I drew in my previous

assessment of R4 (Reference 18) with respect to the normal operating and faults condition are equally applicable to R3. Specifically that the following applies.

- Excluding graphite debris, the normal operation and faults condition DTA shows the graphite core is tolerant to the distortions associated with the CEDTL up to a core burn-up of 17.2TWd. This includes the effects on channel distortion on fuel snagging frequency and fuel sleeve gapping. But, to continue R3 operation, further evidence should be shown to reinforce the possibility of outlier distortions is sufficiently low, i.e. Recommendation 2 from Reference 18, which states:
    - *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.*
- In terms of graphite debris, it must be expected that debris will become more frequent during operation beyond the current core condition of HNB R3. Subsequently, Recommendation 4 from Reference 18 must be resolved, which states:
    - *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.*

90 Recommendation 4 from Reference 18 specifically identifies R4 because it is stated within the context of the R4 assessment. However, Recommendation 4 is applicable to R3 because it is directed at operation to damage levels not yet experienced by other AGRs. Section 4.4 above has already detailed my assessment of NGL's response to Recommendation 4. I detail my assessment of NGL's response to Recommendation 2 below in Section 4.6.

4.6 Onerous crack configurations (Recommendation 2 from Reference 18)

4.6.1 Background

91 To demonstrate unimpeded movement of fuel and control rods, NGL predicts distortions of the fuel and control rod channels in a computer model referred to as a whole core model. The whole core model represents the graphite core in terms of the fuel bricks, the interstitial bricks and the keying system that connects the bricks together. By specifying a distribution of cracked fuel bricks in terms of the number of cracked bricks, the location of the cracked bricks in the core, the orientation of the crack and the type of cracked bricks, the whole core model aims to predict the distribution of fuel channel and control rod channel distortions.

92 Visual inspections of the graphite core is limited to a 10% sampling of fuel channels and therefore only reveals a fraction of the cracked bricks present at the time of the inspection. Therefore, the precise location, orientation and type of all the cracked bricks in the core is not known, they can only be estimated. Statistical analyses of the inspection findings determine a prediction for a future core state (see Section 4.3), which is then bounded by the DTA core states (table 4). A DTA core state is then randomly distributed into the whole core model. This randomness influences the channel distortions for any given core state, i.e. ten different random distributions of the same core state leads to a variance in the ten different results. Generally, the

whole core response is not significantly affected by the randomness but the most distorted channels are. It is therefore the most distorted channel that is used by the safety case to determine the channel distortion margin.

93 NGL then makes a judgement that weighs the variance of the most distorted channel from those multiple distributions against the safety margin. For the normal operating conditions, this process has typically shown substantial safety margin and relatively low variance of the most distorted channel. There has subsequently been high confidence that free movement of fuel and control rods is not impeded. A potential challenge to this was identified in the supporting evidence of the HNB R4 return-to-service case (NP/SC 7785, Reference 4).

94 In my assessment of the HNB R4 case, I referred to NGL's identification of an 'outlier' distribution that generated a distortion in a control rod channel approximately twice that of the other distributions. There were two instances of such an outlier occurring in the normal operating condition analyses. The first was identified in a set of sensitivity studies (Reference 29), the number of random distributions in those sensitivity studies suggested the 'outlier' might occur once in every hundred random distributions. The second was identified in the analyses supporting the DTA (Reference 30), the number of random distributions in those analyses suggested the 'outlier' might be expected to occur once in every ten random distributions. Although the 'outlier' still showed substantial safety margin it illustrated the reasonable possibility that substantially different margins could be achieved.

95 The 'outlier' was associated with core states that were expected to be beyond the proposed operating period for R4, I was subsequently content to accept the 'outlier' as tolerable. However, since NGL would be seeking the return to service of HNB R3 to more advanced core states I made Recommendation 2 to ensure NGL provided further evidence on the likelihood of 'outlier' configurations in the HNB R3 case.

4.6.2 'Outlier' Assessment

96 NGL responded to Recommendation 2 (Reference 31) with a further series of sensitivity studies reported in Reference 32. Reference 32 reproduced the ten distributions of Reference 30 and then extended the ten distribution to fifty to determine if additional 'outliers' were generated, none were. I am content to accept this suggests the 'outlier' is not straightforward to achieve and not a common occurrence.

97 An alternative to NGLs qualitative use of Reference 32 is to predict channel distortions from large numbers of random distributions, and use extreme value statistics to extrapolate the likelihood of a core state that could achieve a challenging channel distortion margin. In my view there is a risk such a method could be optimistic because there are multiple mechanisms that can act together to create channel distortions which might not be captured by the original sample. It is also likely that there is an upper limit on the possible channel distortions, which is unlikely to be properly appreciated by such statistical evaluations. I would therefore be reluctant to consider such statistical evaluations as they may lead to a false confidence.

98 In my view then it must be recognised that 'outlier' distributions of cracked bricks that double the normal operating condition distortions normally presented in the case are plausible. It is also my view that such 'doubling-outliers' for the core states assessed in SS1, whilst not a common occurrence, are likely enough in normal operation to need mitigation in the form of a substantial safety margin. It is my view that the channel distortion margins presented in SS1 for the normal operating condition are large enough (approximately 5, Reference 33) that they can absorb a potential doubling of the channel distortion and still be substantial.

99 I am therefore content that the matter of 'outliers' raised under Recommendation 2 of the HNB R4 assessment (Reference 18) does not challenge the claims of SS1.

100 The recommendations raised under the HNB R4 assessment were tracked by Regulatory Issue 7332. Based on the above, I am content that Recommendation 2 of Reference 18 has been satisfactorily addressed.

4.7 Changes to the Seismic Damage Tolerance Assessment

101 Since the HNB R4 return-to-service safety case (NP/SC 7785) NGL has implemented a number of changes to the seismic DTA. The changes are as follows.

- The prediction of the reactor building response to the seismic ground motion uses upper-bound building properties instead of best-estimate properties.
- The 'final' version of the reactor building response to the seismic ground motion is used instead of the 'preliminary' version, accounting for recommendations by independent peer review.
- The rocking motion of the building has been included to the graphite core seismic input.
- End-face key/keyway capacities are reduced by 45%.

102 During a seismic event, the ground motion is translated through the reactor building, otherwise known as the PCPV (pre-stressed concrete pressure vessel). The motion of the PCPV then dictates the accelerations experienced by the graphite core. For the HNB reactors, NGL has to date evaluated this by splitting the problem in to two separate simulations. The first uses the pre-defined ground motion of the 1 in 10,000 year seismic event to predict the PCPV response, and the second uses the predicted response of the PCPV as the input to a whole core model of the graphite core. I am content that this has already been established as an acceptable methodology, but demonstrating a robust safety case for continued operation beyond the validity of NP/SC 7716 has been problematic because of a perceived conservatism identified by NGL in the PCPV simulation. To resolve this, NGL revised the PCPV model to create what became known as the *revised building model*. A 'preliminary' version of the revised building model was used in the HNB R4 case (NP/SC 7785) and has since been revised to the 'final' building model used in the SS1. Both the preliminary and the final revised building models have been assessed by ONR via a specialist civil-engineering inspector (Reference 9).

103 As well as using the preliminary version of the revised building model, the HNB R4 case used best-estimate building properties whilst providing a sensitivity study that used the upper bound building properties. Because of the sparsity of data to define the building properties, there is uncertainty associated with them and little statistical confidence can be attached to the phrases 'best-estimate' and 'upper-bound'. SS1 has been submitted using the final version of the revised buildings model with upper bound properties. I am content for this to be the case as the specialist civil-engineering inspector concluded that this was within expectations (Reference 9).

104 During the development of revised building model, NGL identified that the graphite core would be subject to both translational and rocking motions during the seismic event, but the rocking motion had not previously been adequately captured by the graphite core model. The effect of the rocking motion on the graphite core response is significant and was first introduced by NGL in the latest Hinkley Point B safety case (NP/SC 7792) and assessed by ONR in Reference 34. During the development of

methodologies to support safety cases that justify operation beyond the validity of SS1, NGL also identified that the capacity of end-face key/keyways (EFKs) had previously been over-predicted and should be up to 45% lower than had been used to date. This error was first considered by ONR in the assessment of NP/SC 7792 (Reference 34). When the reduced EFK capacity is combined with the additional rocking motion and upper bound properties the number of overloaded EFKs was substantially increased over previous HNB cases. Subsequently NGL provided a more in-depth evaluation of the consequences of overloaded EFKs during a seismic event. This was referred to as in-event cracking.

105 In-event cracking is the assumption that where individual key/keyway connections are overloaded by the acceleration loads of the seismic event, a fuel brick can crack instead of the failure being localised to the key or keyway. This applies to both the radial and end-face keying system. NGL had previously developed a methodology to account for these overloads, referred to as runtime-damage, which was implemented in the previous HNB R4 and HPB cases by removing the key/keyway connections at the time they occur in the event. Removal of those overloaded connections was generally considered conservative because it adds additional degrees of freedom to the graphite core, especially in the radial keying system, which in turn increases the potential for larger channel distortions.

106 However, TV inspections of the fuel channels in the shutdown condition show that the formation of a keyway root crack and the slow crack opening induced by irradiation appear to lead to cracking in vertically adjacent fuel bricks. It is entirely reasonable then to assume brick cracking is plausible via interactions between the fuel brick-ends during a seismic event. Removal of a single EFK, as per the runtime damage method, is unlikely to be challenging because there are potentially three other EFKs maintaining alignment of that brick interface. However, assuming that the overloaded EFK generates a full-height axial crack means intact-cracked bricks or pre-existing cracked bricks can advance to higher damage states thereby generating a new, significantly different, in-event core state. This more damaged in-event core-state could potentially increase channel distortions, undermining the damage tolerance arguments being made by the established methods.

107 NGL addressed this with an approximate methodology to assure the CEDTL substantially bounded the in-event core state. I detail my assessment of NGL’s in-event cracking methodology in the next section.

4.8 In-Event Brick Cracking

108 In this section, I outline my assessment of NGLs consideration of in-event cracking. In-event cracking is the potential for a seismic event to increase the number of cracked bricks during the event through overloads in the keying system potentially challenging the established channel distortion predictions.

109 I outline in Section 4.8.1 NGLs position on this matter as per SS1, which is to state NGLs view that the CEDTL bounds the in-event core state. I then detail my view of the adequacy of the channel distortion predictions at the intermediate core state and at the CEDTL in Section 4.8.2. I detail in Section 4.8.3 why I consider the channel distortion predictions indicate the need for a quantified substantial margin between the in-event core state and the CEDTL, and that subsequently the SS1 position on in-event cracking is inadequate. I detail in Section 4.8.4 further work by NGL that argues a substantial quantified margin with the use of a revised EFK capacity, and I outline my judgement that this continues to be a conservative position in Section 4.8.5.

4.8.1 The Safety Case Position

110 NGL has detailed its consideration of in-event cracking in the SS1 (Reference 1) and considers the CEDTL would still bound the core state after a seismic event. However, the case fell short of providing a prediction of the in-event core state, which prevented demonstration of a clear margin to the CEDTL.

111 It is my view, and that of other specialist inspectors, that in-event cracking should not simply be bounded by the CEDTL, but there should be a defined and adequate margin between the in-event cracking state and the CEDTL. This is to mitigate the uncertainty associated with the 6 and 12-month core state predictions and the associated minimum control rod channel distortion margins in those core states as well as at the CEDTL. I make comment on the channel distortion margins for the intermediate core state and CEDTL in the next section.

4.8.2 The intermediate and CEDTL control rod channel distortion margins

112 At the intermediate core state, representing the 12-month core state at the 99.9% confidence level, the minimum margins for control rod channel distortion are approximately 2, but at the CEDTL the minimum margin ranges from 1 to 1.8 (Reference 14, referred to as the minimum LEWIS margin). This 1 to 1.8 range is derived from 10 separate predictions that are derived from the same seismic event and the same core state, but where each prediction is drawn from a different random distribution of the cracked bricks. This broadening of the range of minimum margins at the CEDTL is due to the larger number of DCBs and MCBs in the CEDTL core state. This is because large numbers of DCBs and MCBs introduce more degrees of freedom in the analysis leading to grater spread in the analysis results, it is indicative of the analysis methodology approaching its limit of validity.

113 There are other possible causes for the spread in minimum margins at the CEDTL, which can infer the results would not be reliable. These are associated with large numbers of loose key and integral key removals from the analysis where those components have experienced an overload during the seismic event. In those instances significantly lower m3dsfs can be predicted from the main group of results, this would indicate the analysis is no longer reliable. I find no indication in the results to suggest this is happening at the CEDTL. Given there are uncertainties in the load bearing capacity of the loose and integral keying system it is important to consider whether those uncertainties could realistically lead to the levels of loose and integral key removals to undermine the CEDTL. I consider that aspect in Section 4.8.5 where I accept there is sufficient margin in the loose and integral keying system.

114 In previous cases NGL has been able to show a CEDTL without such a range on the minimum m3dsfs and has been able to show margin beyond the CEDTL. However, given the above it is my view NGL has not been able to show margin beyond the CEDTL for this case. Whilst it is not necessary to show margin exists beyond the CEDTL, it is nonetheless important to recognise that within the conservative scope and assumptions of this case the CEDTL does represent a limiting core state. It is important then to have confidence that there is sufficient margin between the 6-month core state and the CEDTL. This is generally sought after by ensuring an adequate margin between the number of cracked bricks, especially DCBs and MCBs, at the end of the operating period and the CEDTL.

115 The CEDTL core state is larger than the 6-month core state by substantially more than a factor of 2, but in-event cracking during a seismic event could erode that margin. I consider this further in the following sections.

4.8.3 Justification for margin to the CEDTL

116 At the intermediate core state the seismic damage tolerance analysis predicts approximately 400 overloaded end-face key/keyway connections and approximately 100 radial key-keyway connections. The end-face key/keyways are features machined in to the ends of fuel bricks to ensure alignment of one fuel brick on top of the other. The radial keyways are features machined in to the sides of the fuel bricks over the full-height and they ensure relative alignment between neighbouring channels. There are thousands of these connections throughout the graphite core but clustered damage to the keying system, as might occur during a seismic event, can lead to challenges to the alignment of individual channels and the reliability of free movement of fuel and control rods. It is therefore necessary to be confident that channel distortions are not challenged by the overloads predicted to occur during a seismic event.

117 The safety case states that approximately half of the 400 end-face key/keyway overloads are in the upper layers were fuel bricks are intact, and half are in the middle layers were the majority of cracked bricks are present. Should in-event cracking occur in those upper layers then only SCBs with narrow crack openings would be generated, in terms of channel distortion these are benign and need not be considered challenging to the case. In the middle layers, however, pre-existing SCBs could transition to DCBs, and pre-existing DCBs could transition to MCBs. DCBs and MCBs introduce greater degrees of freedom to channel distortion and therefore could be a challenge to the case. On that basis then, approximately 200 additional DCBs and MCBs could be generated by the seismic event, which, when added to the pre-existing core state produces a core state similar to the CEDTL. But this does not include adequate consideration of the 100 radial key/keyway overloads that would further increase the in-event core state.

118 Qualitative judgements were made by NGL to claim this was a conservative condition, but the case did not clearly demonstrate a substantial margin between the 6-month core state and the CEDTL. I and other specialist inspectors did not consider that sufficient and NGL was required to provide further evidence detailing how a quantified margin was supported.

119 NGL provided the further evidence in terms of four arguments to justify a revised position (Reference 35). I have summarised those arguments as follows.

Argument 1: *The end-face key capacity used to predict the 400 overloads is conservative, and a realistic number of additional DCBs and MCBs is fewer than 50.*

Argument 2: *Overloads in the radial keying system will lead to no more than 50 additional DCBs and MCBs.*

Argument 3: *Arguments 1 and 2 represent a conservative upper bound because not all overloads will generate a full-height axial crack.*

Argument 4: *For DCBs and MCBs, Arguments 1, 2 and 3 equate to a substantial margin between the 6-month core state and the CEDTL.*

120 There are two crucial aspects to substantiating these arguments. Firstly, that the 400 overloads are claimed to be associated with a conservative end-face key capacity.

Secondly, other significant conservatisms provide confidence in the revised positon. I outline these areas in the following sections.

4.8.4 Use of a revised end-face key capacity

121 For the current core age of HNB R3 SS1 defined the end-face key capacity to be approximately 10kN, from this value ~400 end-face key/keyway overloads were predicted. Although the capacity is varied between layers to account for the relative ageing effects, the quoted 10kN value is for layer 5 and serves as a good reference point for the purpose of the commentary I make here.

122 NGLs derivation of that 10kN includes the ageing effect on graphite from irradiation and weight loss which varies between layers but there is also significant variation throughout any given fuel brick. Therefore, when ageing the capacity the level of irradiation and weight loss should be taken from the same location in the brick as the crack initiation site, in other words, the ageing effect should be co-located with the crack initiation site. Co-location was not accounted for in NGL's methodology for SS1, instead NGL aged the capacity conservatively using an approximate method.

123 The ageing effects of irradiation also generate stresses in the fuel bricks that will reduce the capacity of the end-face key/keyways to carry seismic loads, thereby offsetting the effect of co-location. When the effect of co-location and irradiation-induced stresses are combined together, NGL showed a 30% increase in the end-face key/keyway capacity over that used in SS1.

124 NGL also noted that the capacity was based on the lowest value of a series of feature tests (Reference 36), and the use of a mid-range value would be more appropriate. Use of the mid-range value in combination with co-location and irradiation-induced stresses results in a revised capacity approximately 50% greater than that used in SS1.

125 A 50% increase in the end-face key/keyway capacity does not equate to a 50% reduction in the number of overloads. For instance, if the seismically induced forces associated with the overloaded end-face key/keyways were many times greater than the capacity, a 50% increase in the capacity would not change the number of overloads. NGL therefore made a sensitivity study to identify the magnitude of forces associated with the overloaded end-face key/keyways so the effect of varying the end-face key/keyway capacity could be understood. The sensitivity study reinforced the existing evidence that the vast majority of the end-face key/keyway forces during a seismic event are substantially smaller than the capacity, but showed the majority of the overloads are at a similar level to the end-face key/keyway capacity. Using the revised capacity NGL were able to demonstrate a margin of 2 for the numbers of DCBs/MCBs between the 6-month core state and the CEDTL using the revised capacity.

126 I have already described in Section 4.2 that the intermediate core state effectively acts as an OA, providing margin to uncertainty in the core state predictions. Whilst it may seem inappropriate that NGL demonstrates margin between the 6-month core state and the CEDTL instead of between the intermediate core state and the CEDTL, I am nonetheless content with this approach for two reasons. Firstly, whilst channel distortion margins are not predicted at the 6-month core state, they will be similar or better than quoted at the more onerous intermediate core state. Secondly, the number of DCBs+MCBs at the 6-month and 12-month core states (49 and 68 respectively, see table 4) is relatively small, therefore NGL's margin of 2 would not be substantially reduced if determined at the 12-month core state.

127 I have reviewed NGLs methods for deploying the co-location effect and the inclusion of irradiation induced stresses into a revised end-face key/keyway capacity, and I am content that they are based on sound principles. I consider however that there is reasonable room for improvement in the analyses supporting co-location and the inclusion of irradiation-induced stresses should the revised capacity methodology be deployed in future cases. I therefore make the following recommendation to the project inspector.

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

128 I have also reviewed the origins of the revised capacity value and found some initial cause for concern. The mid-range value comes from a set of feature tests (Reference 36) that show a range of virgin end-face key capacities. One might consider then that the mid-range value is reflective of a best estimate of that range. The range does not however reflect a stochastic variation of material properties; it reflects several sets of particular geometric configurations of the keying system. One of those configurations is clearly associated with the low end of the range, potentially challenging the appropriateness of using a mid-range value. It is reasonable however, to assume some degree of randomness on the location of overloaded end-face key/keyways relative to those particular configurations, so I am still content that a mid-range value can reasonably be argued as appropriate. It is also informative to recognise that even if the lower value of the range is used instead of the mid-range value the margin of 2 is not substantially reduced.

129 Further confidence can be gained in the margin of 2 when it is also considered in terms of the conservatisms put in place by NGL. I outline those conservatisms next.

4.8.5 Conservatisms in the in-event cracking methodology.

130 Using the mid-range capacity, NGL have reasoned an additional 100 DCBs/MCBs would occur during the 1 in 10,000 year seismic event, when accounting for both EFK and radial-key/keyway (RKW) overloads. NGL added this to the revised prediction of 49 DCBs/MCBs (see Section 4.3 paragraph 68 above, Reference 22 and Table 2). This gives an approximate in-event core state of 150 DCBs/MCBs at the end of the 6-month core state, and thus the margin of 2 when compared to the 300 DCBs/MCBs at the CEDTL. NGL's reasoning chose to ignore a number of factors that taken together, or some merely alone, would in my opinion significantly reduce the 100 additional DCBs/MCBs. These are as follows.

- Small-scale feature tests showed column-weight would increase the capacity thereby reducing the number of additional DCBs/MCBs. Column-weight was not included in the full-scale tests that have derived the mid-range value.
- The capacity of an EFK to carry seismic loads is reduced by the presence of irradiation-induced stresses. These stresses are relived to some degree when an intact brick cracks to become a SCB. NGL has not accounted for stress relief and is therefore using a lower capacity than is strictly necessary. The size of the stress relief is inherently uncertainty, but not accounting for it is nonetheless a conservative approach.
- The seismic ground motion is applied in the most onerous direction relative to the graphite core.

- The absence of friction in the seismic model that predicts the EFK forces is a substantial conservatism. The effect of friction would be to reduce the acceleration of the bricks within their clearances thereby reducing the forces, therefore neglecting friction means more overloaded key/keyway connections are being predicted than need to be.

- NGL assume all the SCBs with an overloaded EFK generate a DCB/MCB. Given reactor observations of the variability of brick cracking, it is reasonable to expect that not all the overloads will generate a full-height axial crack.

- The DTA uses a core age of 17TWd, this sets the clearances and keying system capacities to be approximately twelve months more degraded than at the end of the 6-month operating period.

131 Given the above conservatisms, it seems reasonable to accept that although there is uncertainty in NGLs reasoning of 100 additional DCBs/MCBs, there is also substantial cause to consider NGLs reasoning is conservative.

132 I am therefore content that NGL has adequately demonstrated a sufficient core state margin to the CEDTL, and that within the 6-month operating period sufficient margin exists on control-rod channel-distortion.

4.9 Graphite material model assessment

133 At the root of the DTA is NGL's graphite material model, referred to as the EIM. The EIM is a complex theoretically based material model that is calibrated to reactor graphite properties. Those properties are determined from samples trepanned from the graphite fuel bricks, dimensional measurement of fuel channel bores, and from materials test reactor data. In this way, past ageing of the graphite is captured and future ageing predicted.

134 The EIM feeds two crucial inputs to the DTA, the clearances in the keying system and the load bearing capacity of the keying system. With continued operation being sought at increasingly damaged core states, and the seismic load case showing more damage to the keying system in those states, the EIM has been subjected to formal assessment by a specialist inspector, Reference 11. The specialist inspector has concluded the following.

> *That in assessing the overall adequacy of the licensee's DTA work, consideration should be made on the basis that EIM values have been calculated as best estimate values. Judgements as to whether the overall analysis is sufficiently conservative should therefore consider the sensitivity studies into clearance and capacity parameters that NGL has performed.*
>
> *Sensitivity studies into clearances suggest that the seismic margins remain acceptable for reasonable changes. However, it is noted that a reduction in capacity of 20% may increase the number of predicted loose key/keyway failures by 200. A 20% reduction can though be considered to be a generous allowance to encompass uncertainty.*

135 I therefore consider the effects of the uncertainty in clearances and capacity in the following sections.

4.9.1 Clearances

136 As the graphite core ages, the dimensions of the graphite bricks change due to irradiation effects. This ‘dimensional change’ causes the clearances in the keying system to change in a non-linear manner with increasing core age. The clearances influence the DTA by changing the amount of free movement a single brick has relative to its neighbours, this can therefore influence channel distortions but could also affect the number of failures predicted in the keying system during a seismic event.

137 The clearances cannot be measured directly and are therefore predicted via numerical models utilising the EIM, where the EIM is calibrated to dimensional changes of the fuel brick bores. Because the approach is not straightforward and there is no industry-established code to support NGL’s methods, ONR has sought an independently derived material model from experts at the University of Manchester (UoM).

138 NGL provided the specialist inspector with a DTA comparison when using either the EIM or UoM derived clearances. I have considered the comparison and it is my view that the UoM model predicts the same DTA outcome as the EIM. Although the UoM model appears to generate larger numbers of keying system failures and larger channel distortions, the differences are in my view negligible.

139 The comparison provided by NGL also offers additional comparisons by doubling and tripling the difference between the EIM and the UoM clearance predictions. A doubling and tripling of the difference is entirely arbitrary, having no physically meaningful interpretation of the uncertainties, but it is useful to explore trends. In my view the trends illustrated that uncertainty in clearances could lead the current safety case methodology to an untenable DTA at core ages substantially beyond those proposed by SS1. I do not consider a recommendation is necessary to cover this point, as it will be part of usual assessment practice by specialist inspectors.

140 I am therefore content that NGL has adequately addressed the uncertainties on clearances and that they do not undermine the SS1 claims.

4.9.2 Capacity

141 In Section 4.8 I have outlined my view of the effects of uncertainty in the EFK capacity, but this does not account for uncertainty in the capacities of the radial keying system, i.e. the loose and integral keys.

142 When a key/keyway interaction is predicted to overload during a seismic event, established practice is to remove the associated EFK, integral key or loose key from the whole core model. It has become clear from various studies by NGL that removal of certain quantities of integral keys and loose keys can reduce the reliability of the whole core model to predict the distortions of control rod channels in a seismic event. It is important then to take account of the levels of integral and loose key failures when evaluating NGLs claims on the damage tolerance of the graphite core.

143 Reference 14 details the predictions of control rod channel distortions, it also details the numbers of loose and integral keys that are predicted to overload during the seismic event. NGL has illustrated this in terms of histograms of the key capacity utilisation, which I have repeated for reference in figures 3 and 4 below.

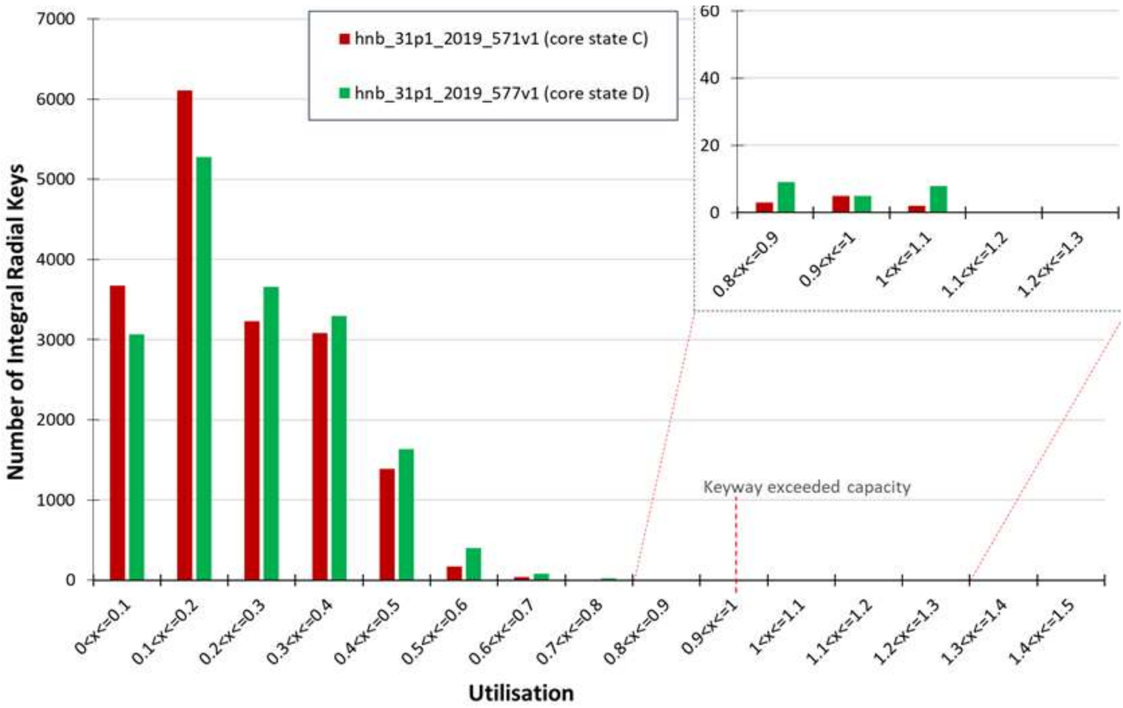


Figure 3: Distribution of the utilisation of the integral key capacity, Reference 14.
(*Utilisations greater than 1 equate to keys that are overloaded.*)
(*Core state C = intermediate core state, core state D = CEDTL.*)

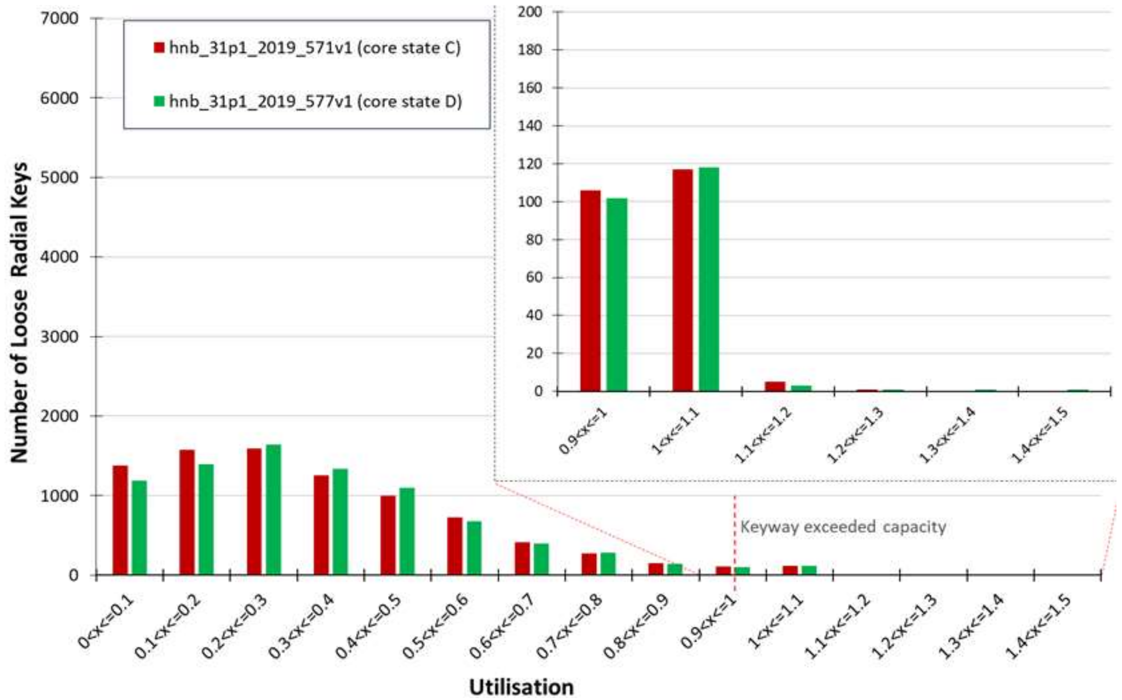


Figure 4: Distribution of the utilisation of the loose key capacity, Reference 14.
(*Utilisations greater than 1 equate to keys that are overloaded.*)
(*Core state C = intermediate core state, core state D = CEDTL.*)

144 In figures 3 and 4 NGL show that the high utilisations are part of a long and shallow tail. This is because the seismic event causes the highest loaded keys/keyways to cluster in particular locations in the core, to increase the size of those clusters needs a substantially more severe seismic event or a substantial reduction in the key/keyway load bearing capacity. Subsequently there is a long shallow tail, and that indicates a

degree of insensitivity to the DTA capacity value. For instance, figure 3 shows the integral key/keyway DTA capacity value would need to be reduced by 20-30% for there to be a sizeable increase in the number of overloaded integral key/keyways. Similarly, figure 4 indicates the loose key/keyway DTA capacity would need to be reduced by 10% before there was a sizeable change in the number of overloaded loose keys.

145 Systematic uncertainty in capacity is challenging to the safety case as it could lead to a global over prediction. For instance, potentially as a result of scarce data a systematic over prediction of what is referred to as graphite creep could lead to an over prediction of capacity. Stochastic variations in the keying system capacity should be expected, but are not as significant a concern as systematic uncertainty because when applied across the graphite core those stochastic variations will broadly cancel each other out. This is consistent with the specialist inspector's assessment of NGL's graphite material model (Reference 11) which considers a 20% systematic reduction in capacity can be considered a generous allowance to encompass uncertainty.

146 Given figures 3 and 4 above, it is my view that a 20% reduction in capacity would lead to the removal of enough key/keyway interactions to approach the limits of reliability in the whole core model as observed to date. When considered in isolation from all other uncertainties and conservatisms a 20% reduction appears unpalatable to the case arguments. However, it must be noted that the stated 20% reduction is effectively arbitrary; it does not carry any specific statistical meaning. A number of important conservatisms and uncertainties weigh against each other, for instance, figures 3 and 4 above are determined using capacities at 17TWd, whereas operation is proposed only to 16.425TWd. This means figures 3 and 4 already include a systematic reduction in capacity of approximately 10% (Reference11).

147 It is my view an isolated consideration of the potential systematic reduction in capacity when clearly there are other conservatisms and uncertainties at work would be an unreasonable basis to decline SS1. Overall, I consider SS1 has demonstrated sufficient margin and conservatism to offset the uncertainties. I am of the view however, that the robustness of the existing safety case methodology is approaching its limit of viability in SS1 due to the assumptions and conservatism that constrain it. I outline the consequences of this view in the following section, taking account of Recommendation 3 in the specialist inspector's assessment of the EIM (Reference 11).

4.10 Future cases

148 Since the onset of keyway root cracking NGL has been able to demonstrate robust safety case arguments for continued safe operation of the HNB graphite cores via SS1 and its predecessor's. That robustness is made possible by the inherent conservatisms in the safety case methodology and the demonstrated margins in the DTA, but there are also inherent uncertainties in describing the graphite core ageing phenomena and its response to them. Those uncertainties are weighed against the conservatisms and the demonstrated margins, but it has become clear through my assessment of SS1 that the conservatisms that have added robustness to the case to date will become a weakness to future cases. As core ageing advances, future cases will very likely have to erode those conservatisms, some of which I have outlined in Section 4.8.5, to maintain a viable DTA. In those circumstances, it will be necessary to counter the erosion of those conservatisms with a clearer quantified view of the uncertainties. Usual practice to address this would be via a probabilistic assessment but, given the complexity of the DTA, a broad ranging probabilistic assessment may not be feasible.

149 It is my view then that to maintain a clear degree of conservatism in the DTA, a case for operation beyond SS1 should ultimately identify the major conservatisms and

uncertainties and should seek to quantify their combined effect on the DTA. I therefore make the following recommendation to the project inspector.

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

4.11 ONR Assessment Rating

150 NGL had to provide significant additional evidence to support the seismic damage tolerance arguments (Section 4.8). It was my view this matter had to be resolved before my assessment could progress beyond it.

151 ONR guidance is to rate the assessment against the licensee's original submission, and in accordance with the ONR assessment rating guide (Appendix 1 of Reference 8), I have assigned an amber rating to NP/SC 7766 SS1 due to the significant additional evidence required. 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

152 NGL has submitted NP/SC 7766 SS1 proposing a further 6-months of operation for HNB R3 to a core burn-up of 16.425TWd.

153 NGL has moved away from previous safety case methodologies by removing the OA in favour of showing tolerance to an intermediate core state, representative of the 12-month core state, as well as a CEDTL. In terms of the extant DTA methodologies, I am content that NGL has shown tolerance to the intermediate core state. In a change from previous cases however, SS1 has not shown margin beyond the CEDTL. Given the conservatism present in the DTA I do not consider the SS1 CEDTL to represent a hard limit of tolerability, only a limit to the methodology implemented in the SS1 case.

154 To ensure the SS1 case was assessed in the light of the latest information available, the specialist inspector requested that NGL update the HNB R3 SS1 core state predictions with the January 2020 R4 observations. Subsequently, where core state predictions were needed in this assessment, the revised predictions have been used. A good comparison to core state prediction by ONR independent advisors offers further confidence in the core state predictions. Based on this, I am content that appropriate core states have been predicted by NGL with sufficient confidence and are bounded by the damage tolerance assessments.

155 I have explained my view that the DTA for the normal operating condition presented under NP/SC 7785 (HNB R4) is equally applicable to R3. Since I have accepted the adequacy of that DTA in my previous assessment of NP/SC 7785 I have made no further comment on it here.

156 Since NP/SC 7785, NGL has revised the seismic DTA with a corrected seismic building response, corrected end-face key capacities, and upper bound building properties. These changes significantly increased the damage to the graphite core keying system during the seismic event to a level that the existing safety case methods no longer easily account for. An alternative approach to evaluating seismic tolerance to keying system failures, referred to as in-event cracking, was subsequently introduced.

157 In-event cracking assumes the outcome of an overloaded key or keyway is additional brick cracking instead of the previously assumed keying system failure. With the in-event cracking assumption, it is plausible that a 1 in 10,000 year seismic event during the 6-month operating period could lead to a core state exceeding the intermediate core state. This could undermine the channel distortions margins that SS1 quotes at the intermediate core state. It was necessary then to confirm that the in-event core state did not substantially exceed the intermediate core state and was not approaching the CEDTL. This was confirmed through additional interactions with NGL and I am subsequently content that the 6-month core state has adequate margin to the CEDTL.

158 Graphite fragments and debris pose a risk to unimpeded fuel movement and cooling. To support the continued applicability of the arguments made under the previously permissioned NP/SC 7785, NGL has made a more detailed evaluation of graphite fragment and debris observations. It is my view the review has provided a more robust evaluation of graphite debris production. I have found no reason to change the existing position determined by the assessment of NP/SC 7785 that the graphite debris risk should be considered a design basis event during the validity of SS1.

159 I am therefore satisfied that NGL has provided sufficient evidence to support continued operation of HNB R3 for a further 6-month period, i.e. up to 16.425TWd.

5.2 Recommendations

160 To address in-event cracking, NGL refined the determination of end-face key capacities. Whilst I am content the refinement is based on sound principles, should the revised capacity methodology be deployed in future cases I consider there is reasonable room for improvement in the analyses supporting co-location of stress and strength and the inclusion of irradiation-induced stresses. I therefore make the following recommendation to the project inspector.

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

161 It is my view that the current safety case methodology, as applied to SS1, is reaching a limit of viability due to the conservatisms embedded within it. Any proposal for continued operation beyond SS1 is therefore likely to argue reductions to those conservatisms in some way. In those circumstances, it is my view to maintain a clear degree of conservatism in the DTA, a case for operation beyond SS1 should ultimately identify the major conservatisms and uncertainties and should seek to quantify their combined effect on the DTA. I therefore make the following recommendation to the project inspector.

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

6 REFERENCES

1 NP/SC 7766 (EC 363560) version 10, Hunterston B Power Station, Graphite Core Safety Case NP/SC 7766 Stage Submission 1, An operational safety case for Hunterston B R3 to a core burn-up of 16.425TWd following the 2018 graphite core inspection outage. *CM9 reference 2020/124498.*

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. *CM9 Reference 2016/168297*.

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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 5: Relevant Safety Assessment Principles considered during the assessment.