Office for Nuclear Regulation

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Site:	Hinkley Point B		
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Operating Facilities Division

Hinkley Point B Reactor 4 Periodic Shutdown 2018 – Graphite Structural Integrity Assessment

Assessment Report ONR-OFP-AR-18-003
Revision 0
May 2018

EXECUTIVE SUMMARY

In March 2018, Hinkley Point B (HPB) Reactor 4 (R4) began its three-yearly periodic shutdown for examination, maintenance, inspection and testing in compliance with Licence Condition (LC) 30. One objective of the licensee, EDF Energy Nuclear Generation Limited (NGL), was to demonstrate that the condition of the graphite core is in accordance with the relevant safety cases.

During the HPB R4 2018 periodic shutdown, NGL conducted visual inspections and dimensional measurements of thirty-one graphite fuel channels and one control rod. I carried out an inspection on site while some of these inspections were being carried out. I formed the view that the work I witnessed was being performed to an adequate quality.

The licensee completed all the Maintenance Schedule requirements for the graphite core inspections during the periodic shutdown. During the core inspections carried out, the licensee observed one new fully axial bore crack and one keyway root crack in the graphite moderator bricks. This is the first observation of a keyway root crack at HPB, and is approximately 2 full power years later than the first main population keyway root cracking observed at Hunterston B (HNB). The observation of only one single keyway root crack in a 10% sample of the core suggests that the phenomenon is in its early stages of progression at HPB and is lagging HNB by some margin. Future inspections at HPB will confirm whether the rate and morphology of cracking is similar to that at HNB. However, at this stage in its progression, these findings do not challenge the limits of the safety case for the graphite core.

During the inspections, the licensee had identified an issue affecting one of the transducers measuring the distortion of the some of the core channels. The inspection tool uses two transducers for the measurements, one of which was found to be faulty as the inspections were being carried out. The licensee reviewed the data from the recent inspections and proposed a revised method for deriving the measurements affected by this fault from a single, non-faulty transducer. I reviewed the revised method as part of my assessment and concluded that the change in the methodology was relatively minor and the tilt measurements using this method were in good agreement with those obtained using the two-transducer method. I am therefore satisfied that the tilt measurements obtained during this periodic shutdown are within expectations and do not challenge the safety case assumptions. However, a number of inspections have been carried out using a faulty transducer and it is currently up to the individual to check the quality of the data. ONR therefore recommended to the licensee to implement additional steps to ensure the quality of the data before moving on to inspect the next channel. I will create a new issue on the ONR database to record progress on this action.

During the graphite inspections, the channel of a super-articulated control rod was inspected and some damage to the bore was observed. The cause for the damage was not clear from the inspection. However, the measurements of fuel channel distortion made in an adjacent fuel channel did not suggest the damage was a consequence of core distortion. Control rod drop times did not suggest any inhibition of movement of the control rod in the channel. I am therefore satisfied that the licensee took adequate action to provide evidence that control rod entry would not be impaired in this channel. NGL are committed to inspect a similar channel in Hinkley Point B Reactor 3 in 2019. However, the licensee should consider performing further inspections of channels housing control rods of a similar design and of a similar manufacturer in the HNB graphite core. These inspections would help to provide further evidence that the primary shutdown capabilities of the reactor are not affected.

To conclude, I am satisfied that the inspections undertaken during the periodic shutdown have been undertaken in line with the safety case and none of the results would preclude consent being given to return Hinkley Point B Reactor 4 back to service. I have allocated an ONR rating of ‘green’ (adequate).

Recommendations

My recommendations are as follows.

- **Recommendation 1 (to ONR Project Inspector):**
  Based on my assessment of the Hinkley Point B Reactor 4 2018 Graphite Core Inspection Results and Justification for Return to Service, I have not found any reason to prevent me recommending that consent is given to return Hinkley Point B Reactor 4 back to service.

- **Recommendation 2 (to ONR Project Inspector):**

  That the PAR should note the observation of the first keyway root crack in one of the HPB reactor cores.

- **Recommendation 3 (to ONR Project Inspector):**

  At the time of my assessment, I was provided with a verified statement by NGL justifying the graphite core inspection results in support of the licensee's request for return-to-service of HPB R4. I therefore recommend that the Project Inspector should confirm that the INSA Approved Certificate is available for the HPB R4 Return to service EC 361594.

- **Recommendation 4 (to NGL Graphite Group Head):**

  In light of the observations in control rod channel RS28, I recommend that the licensee considers performing further inspections of control rod channels at Hunterston B housing super-articulated controls, which are of similar manufacture and from the same manufacturer as those for the control rod corresponding to channel RS28.

- **Recommendation 5 (to NGL Graphite Group Head):**

  In light of the observations in control rod channel RS28; I reiterate the recommendation made in ONR's assessment of the third Hinkley Point B/Hunterston B Periodic Safety Review:

  Recommendation 1: I recommend that NGL continues to develop improved inspection and monitoring technology. In particular I consider that equipment capable of performing visual inspection and dimensional measurements of control rod channels should be developed. This is likely to be needed before either extensive cracking develops or significant distortion of fuel channels is found.

- **Recommendation 6 (to ONR Graphite Inspector):**
  To update the ONR Issues Database to capture progress on:

  i) the level of uncertainties in the graphite weight loss calculations on the long-term;

  ii) a fleetwide consideration of the graphite weight loss case;

  iii) the implementation of additional steps to ensure the quality of the data before moving on to inspect the next channel.

LIST OF ABBREVIATIONS

ACWL	Active Core Weight Loss
AGR	Advanced Gas-cooled Reactor
BMS	Business Management System
EC	Engineering Change
EMIT	Examination, Maintenance, Inspection and Testing
GAP	Graphite Assessment Panel
GWd	Gigs Watt days
GWL	Graphite Weight Loss
HNB	Hunterston B Power Station
HOW2	(ONR) Business Management System
HPB	Hinkley Point B Power Station
HSB	High-Shrinkage Brick
HSL	Health & Safety Laboratory
KRC	Keyway Root Crack
IAEA	International Atomic Energy Agency
JPSO	Justified Period of Safe Operation
LC	Licence Condition
NICIE2	New In-Core Inspection Equipment
MITS	Maintenance, Inspection, Testing Schedule
NGL	EDF Energy Nuclear Generation Ltd.
NNL	National Nuclear Laboratory
ONR	Office for Nuclear Regulation
PAR	(ONR) Project Assessment Report
PBWL	Peak Brick Weight Loss
R3	Reactor 3
R4	Reactor 4
RTS	Return-To-Service
SAP	Safety Assessment Principle(s)
SIAL	Structural Integrity Assessment Limit
TAG	Technical Assessment Guide(s) (ONR)
WCWL	Whole Core Weight Loss

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1 INTRODUCTION

1. In March 2018 Hinkley Point B (HPB) Reactor 4 (R4) began its periodic shutdown for examination, maintenance, inspection and testing in compliance with Licence Condition (LC) 30. During the periodic shutdown, the licensee, EDF Energy Nuclear Generation Limited (NGL) carried out activities according to their examination, maintenance, inspection and testing (EMIT) programme under LC28. One objective of the periodic shutdown was to demonstrate that the condition of the graphite core is in accordance with the relevant safety cases.

2. This assessment covers both the findings of the licensee's inspection programme on the graphite core and assessment of other documents that have been supplied to the Office for Nuclear Regulation (ONR) as commitments necessary for the Return-To-Service (RTS).

1.1 Background

3. HPB and Hunterston B (HNB) Advanced Gas-cooled Reactors (AGR) entered into service in 1976. They are ostensibly of the same design and the graphite cores of these reactors have the highest accumulated irradiation of all the reactors in the AGR fleet. Continued irradiation of the core in an AGR has several effects on the properties of the graphite. In particular, the graphite shrinks and then swells as a function of cumulative irradiation and the graphite loses mass as a result of radiolytic oxidation.

4. Differential shrinkage within graphite core components resulting from internal differences in accumulated irradiation gives rise to differential strains within the component. In fuel bricks, the differential strains initially generate tensile stresses at the bore. These stresses can be sufficient to crack the bricks; a phenomenon known as bore cracking.

5. The inner bore surface of a fuel brick experiences the highest dose because it is adjacent to the fuel. In the central region of the core at HPB and HNB (Layers 3 – 9) the bore of some of the fuel bricks has received sufficient dose for the graphite to cease shrinking and start swelling. This behaviour reverses the stress state within the fuel brick and generates tensile stresses at the outer circumference of the brick. The fuel bricks contain stress raising keyway passages at the outer circumference which gives rise to another cracking phenomenon known as keyway root cracking (KRC). This type of cracking can only begin to occur in fuel bricks when the graphite at the bore has begun to swell i.e. after significant cumulative irradiation.

6. At the HNB R4 periodic shutdown in 2014, two KRC's were observed in a sub-population of bricks that were shrinking at a faster rate than other bricks in the core. Therefore, despite HNB R4 having a lower cumulative core irradiation than HNB R3, HPB R4 and R3 these bricks aged at a faster rate resulting in them cracking earlier than main population bricks. These bricks were referred to as high shrinkage bricks (HSB) and NGL estimate that there are around 45 HSBs in HNB R4 and 10 in HNB R3. No HSBs have been observed in either of the HPB reactors.

7. In 2015, three KRCs were observed in the main population of graphite fuel bricks at HNB R3. This observation marked the first discovery of the onset of KRC in the main population of bricks in an AGR core. Given that the four reactors at HPB and HNB are of similar age, NGL expected to find KRC prior to the HPB R4 inspections carried out at this outage.

1.2 Scope

8. My assessment has been focussed primarily on the licensee's activities performed during the shutdown associated with the examination and inspection of HPB R4

graphite core. I have taken account of recent developments in the HPB and HNB graphite core safety cases.

1.3 Methodology

9. I have undertaken my assessment in accordance with the requirements of How2 Business Management System (BMS) guide NS-PER-GD-014 (Ref. 1). The ONR Safety Assessment Principles (SAP) (Ref. 2), together with supporting Technical Assessment Guides (TAG) (Ref. 3), have been used as the basis for this assessment.

10. The methodology for the assessment follows HOW2 guidance on mechanics of assessment within the ONR (Ref. 4).

2 ASSESSMENT STRATEGY

11. The intended assessment strategy 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

12. The relevant standards and criteria adopted within this assessment are principally the Safety Assessment Principles (SAP) (Ref. 2) and internal ONR Technical Assessment Guides (TAG) (Ref. 3). The key SAPs and any relevant TAGs are detailed within this section. National and international standards and guidance have been referenced where appropriate within the assessment report (Ref. 5). Relevant good practice, where applicable, has also been cited within the body of the assessment.

2.1.1 Safety Assessment Principles

13. I have applied the key SAPs listed in Table 2 of my report for my assessment.

2.1.2 Technical Assessment Guides

14. The following Technical Assessment Guides have been used as part of this assessment (Ref. 3):

- NS-TAST-GD-029 Revision 3 – Graphite Reactor Cores (Ref. 3)

2.1.3 National and International Standards and Guidance

15. Due to the very specific nature of graphite and its unique use in AGRs, there is a paucity of national or international standards and guidance relevant to the AGR reactor cores. Therefore, it has not been possible to utilise relevant standards and guidance in my assessment.

2.2 Use of Technical Support Contractors (TSC)

16. I have used the statistical analysis provided by Health & Safety Laboratory (HSL) in Ref. 6 to support the judgement regarding the current number of cracks in my assessment.

2.3 Integration with Other Assessment Topics

17. Aspects of this graphite assessment are related to several other technical areas such as structural integrity, fault studies and chemistry. However, there has been no integration necessary in order to complete this assessment. Assessments from other technical areas will be brought together as part of the PAR and it is advised that this assessment be read in conjunction with reports produced by other technical areas.

2.4 Out of Scope Items

18. The following items are outside the scope of the assessment.

- The thirty six graphite core trepanned samples taken from HPB R4 will be sent to National Nuclear Laboratories (NNL) at Sellafield for examination and testing. The result of this work is unlikely to be known for at least six to nine months and so I have excluded it from my assessment.

3 LICENSEE'S SAFETY CASE

3.1 Return-To-Service EC

19. At the time of my assessment of the graphite inspection findings, the licensee had not yet provided the details for the RTS EC 361594. However, the licensee provided the following verified statement as it will appear in this EC in Ref. 7:

Graphite Core Inspections

'Inspections of the graphite core were undertaken during the outage and sentenced by the Graphite Assessment Panel (GAP). The results of these inspections are out with the scope of this submission, but will be reported in EC 363401 that will define the Justified Period of Safe Operation (JPSO) for the graphite core within 60 days of return to service.'

3.2 Graphite Inspections

20. Graphite inspection takes place at each periodic shutdown of the reactor. The extent of the inspection is specified in the station Maintenance, Inspection, Testing Schedule (MITS), subject to licence condition LC28 – Maintenance, Testing, Inspection and Examination. MITS specifies the minimum graphite inspection commitment regarding the number of channels for inspection and number of graphite samples to be trepanned. Inspection of the fuel channels involves visual inspection of the channel bore and measurements of the bore diameter, ovality, and channel bow and tilt. The trepanned samples are sent to the NNL for post irradiation examination, where graphite density, strength and other material properties are measured.

21. The following graphite inspections were performed during the HPB R4 2018 periodic shutdown, as required by the Maintenance Schedule:

- Visual inspection and channel bore measurement of 31 fuel channels;
- Trepanning of 36 samples from fuel channel bricks within the core;
- Visual inspection of one control rod channel.

22. The licensee completed all the MITS requirements at this periodic shutdown.

3.3 Graphite Assessment Panel

23. The licensee considers and sentences the findings of the visual and dimensional inspections via the graphite assessment panel (GAP). This is a body with a requirement for a quorum of suitably qualified and experienced persons (SQEP), who are able to sentence the inspection findings in terms of whether they present challenges to the extant safety case. It also considers matters such as whether the inspections, dimensional measurements and trepanning have been performed adequately.

24. If significant inspection findings are identified during outages that are not within the bounds of the existing safety case, the GAP may take appropriate action such as; recommend further inspections or a changes to the safety case.

3.4 Current core burn-up for HPB R4

25. The core burn-up of HPB R4 at the time of the periodic shutdown is 15,967GWd (Ref. 8).

3.5 Pre-inspection forecasts

26. Prior to the periodic shutdown, NGL uses the results from statistical models to inform the teams in charge of the inspections on the plant about the possible outcomes (Ref. 9). According to this analysis, a total of 51 significant bore-initiated axial cracks were observed in the four HPB/HNB reactor cores, 39 of which were singly-cracked bricks and 6 doubly cracked bricks. From the statistical models, the licensee estimated that observation of up to 7 single cracks and up to 3 doubly-cracked bricks during the inspections would be in line with expectations. However, the best estimates given by the models were that one to two new singly-cracked bricks and no doubly-cracked brick would be more likely.

3.6 Route A/B/C

27. Based on the pre-inspection forecasts in Ref. 9, NGL produced a table categorising the potential extent and morphology of any observed cracking in HPB R3 and R4 (Ref. 10). The purpose of this table was to prescribe a course of action dependent on which category the observations fell within. The table contained three cracking categories A, B or C, as shown in Table 3. Following these forecasts, NGL established a route A/B/C summarising the expectations of the inspections compared to the allowances in the graphite safety case.

28. Inspection results that return either a B or C outcome would require revision to the Justified Period of Safe Operation (JPSO) and possibly the safety case. NGL defines the A/B/C routes as follows:

- Route A: The observations lie within or below expectations and will not adversely affect the pre-defined JPSO, i.e. 18-month JPSO and within safety case NP/SC 7716;
- Route B: The observations lie broadly within expectation but could result in a potentially reduced JPSO under NP/SC 7716 (Operation covered up to 60 day EC);
- Route C: The observations lie sufficiently outside of expectation that the underlying models or assumptions would be challenged therefore a new safety case is required to support RTS.

4 ONR ASSESSMENT

29. This assessment has been carried out in accordance with HOW2 guide NS-PER-GD-014, “Purpose and Scope of Permissioning” (Ref. 1).

4.1 Scope of Assessment Undertaken

30. The scope of the assessment is limited to the findings from the graphite inspections undertaken during the 2018 HPB R4 periodic shutdown, which are summarised in the licensee’s GAP sheets (Refs. 11, 12, 13, 14 and 15). I also considered the safety limits to help me form a view on the adequacy of the inspection findings.

4.2 Interventions undertaken during periodic shutdown

31. [redacted] ([redacted]), [redacted] ([redacted]) and I carried out an intervention of NGL’s graphite core inspection activities which took place during the 2018 periodic shutdown of HPB R4 (Ref. 16). Our inspection specifically focused on arrangements for graphite core examination, inspection and testing. However, following previous errors being made during 2017 HNB graphite inspections, we also focussed our attention on the quality control of the measurements.

32. At the time of our visit, the licensee had completed 14 visual inspections and bore measurements, out of a target requirement of 31. Overall, I was satisfied with the quality of the inspections and that the staff performing the inspections had been adequately trained. However, NGL identified some issues with the inspection tool measuring the tilt of the channels. I discuss this issue further in Section 4.3.4. On the basis of this inspection, I had allocated an ONR rating of ‘green’ – adequate.

4.3 Results of the graphite inspections

4.3.1 Bore cracking

33. When a defect has been identified, the licensee produces an image of the brick containing the defect from the data collected during the inspection. This image is then collated along with other measurements in a ‘GAP sheet’ and sentenced by graphite inspection SQEPs during the subsequent GAP meeting. During the inspections, only one new full height axial bore crack was found in Channel J29 (Ref. 14). This channel had not been inspected previously. The defect is shown in Figure 1.

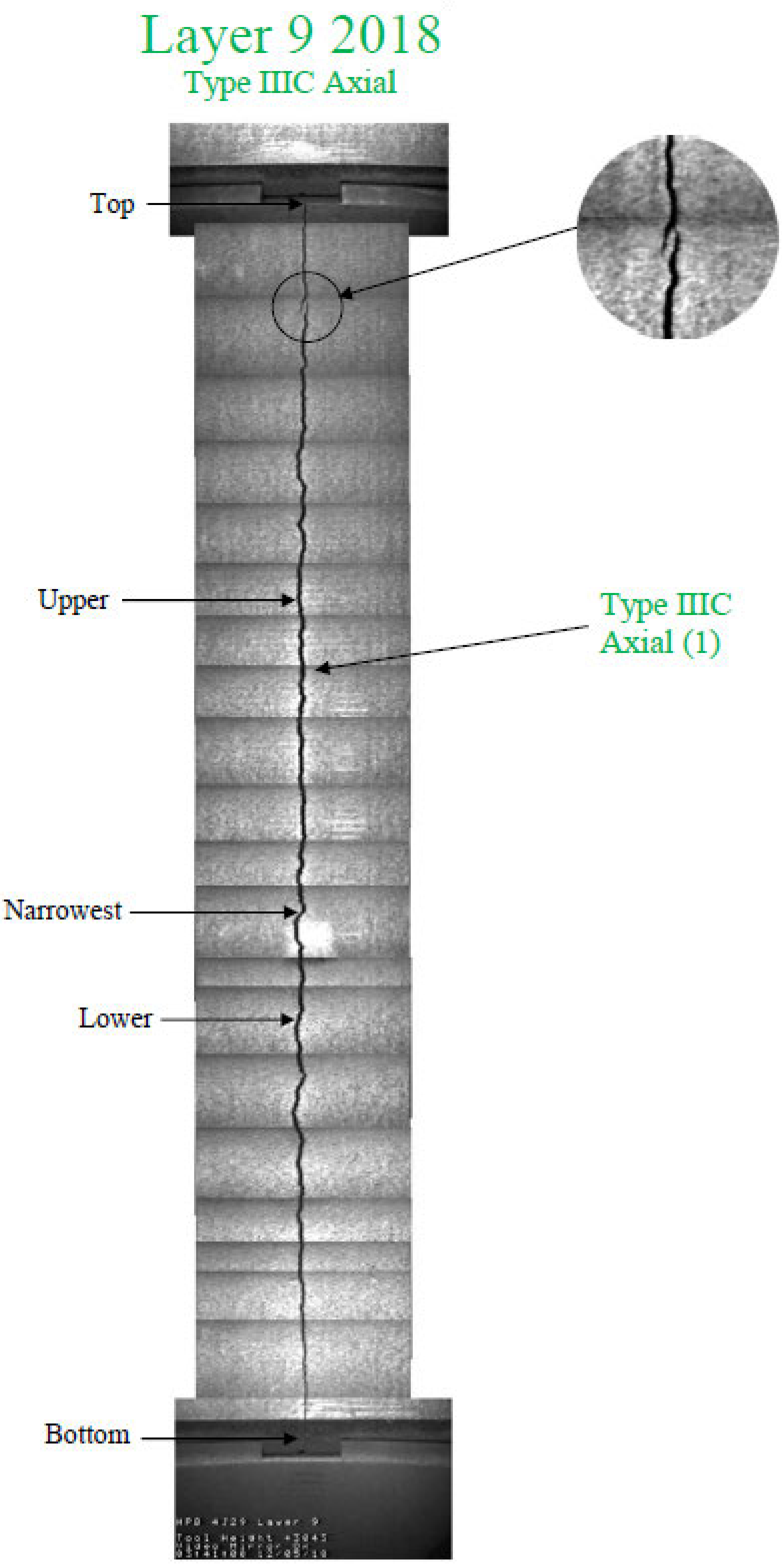
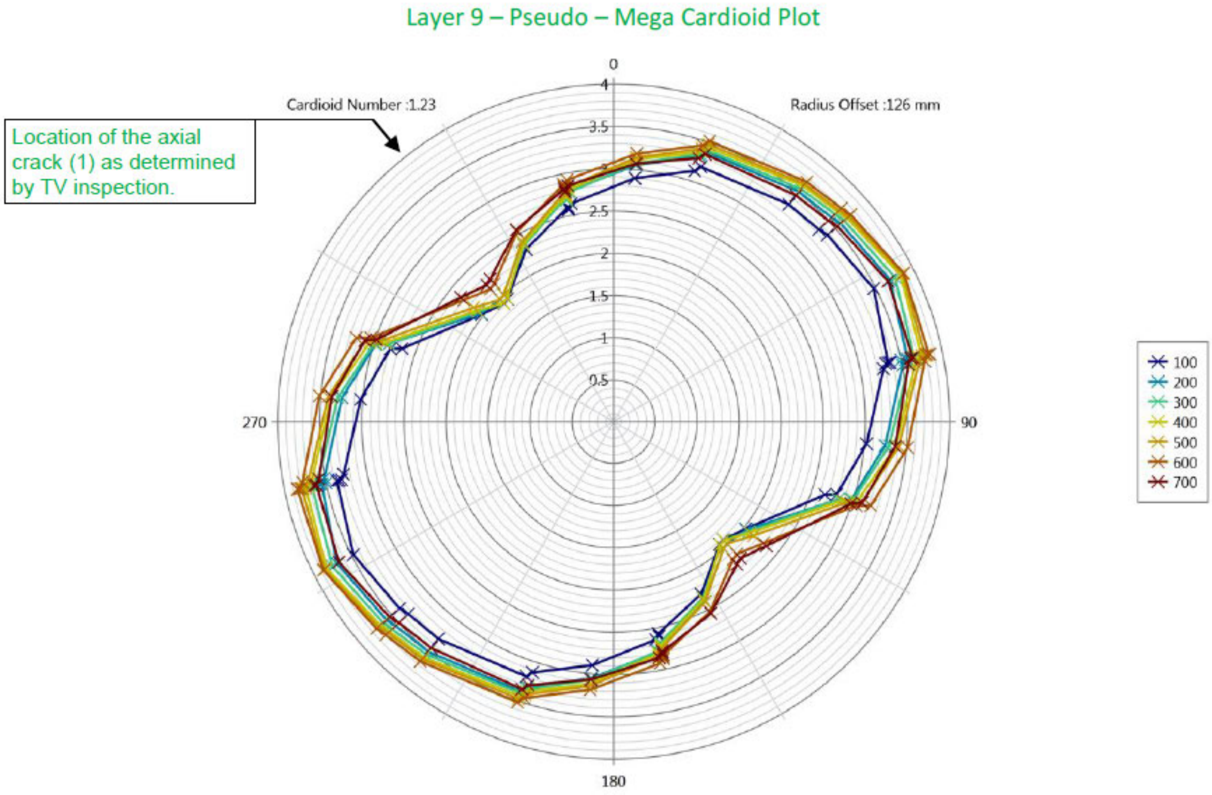


Figure 1: Full axial bore crack observed in Layer 9 of Channel J29.

34. This crack presents some features common to KRCs, close to a keyway, relative straightness. However, its cardioid plot shows the 'lipping-in' which is characteristics of bore cracks and is associated with the tensile stresses increasing at the bore in early life of the graphite; see Figure 2.



The axial crack is not evident on the diameter plot or on the ovality plot. The axial crack can be observed on the cardioid plot above.

Figure 2: Cardioid plot derived from the bore measurements in Channel J29.

35. In Figure 2, the ‘100’ location corresponds to the top brick in the channel and ‘700’ corresponds to the lowest brick. It follows from these measurements that the crack observed is a bore crack and was sentenced as such by the GAP.

36. Since bore cracking is considered to be an early-life phenomenon, the total number of such cracks in the reactor is unlikely to change and newly observed bore cracks only highlight the fact that the channels had not been previously inspected. The estimates for the number of single axially cracked bricks are below the safety case allowance. I expect that this level of bore cracking will not significantly progress as the core ages. NGL considers circumferential cracks to be relatively benign for the structural integrity of the core because of their relatively low instance. This judgement was considered to be reasonable in ONR’s assessment of NP/SC 7662 (Ref. 17).

37. Including the results of the current periodic shutdown, NGL’s statistical model estimates that up to 99 bore cracks (99th percentile confidence level) could be present in the HPB R4 reactor core (based on Tables 9 and 10 of Ref. 9). Based on a best estimate, the number of cracks in HPB R4’s reactor core is likely to be around 23. I therefore consider that the level of bore cracking observed to date does not challenge the structural integrity of the graphite core for the next operating period.

4.3.2 Keyway root crack

38. Due to the core age being similar to that of the HNB cores, NGL expected there to be a reasonable likelihood of observing KRCs during this shutdown. NGL state that layers 4 to 6 in the central region of the core are currently most likely to contain KRCs since these layers receive the highest irradiation. The licensee also defines ‘lambda factors’

which are derived from the deformation, or bow, of the brick resulting from irradiation. Although no clear relationship was found between these factors and cracking, the licensee uses these factors as potential leading indicators to inform the decision made on the inspections.

39. According to route A/B/C in Ref. 10, NGL considered that up to 2 KRC would be consistent with the early observation of keyway root cracking at HNB R3. On this basis, observation of more than 2 KRCs would suggest either an earlier time of onset at HPB R4 or a faster than expected rate of progression. During the current graphite inspections, NGL found only one KRC in channel E25, layer 4 (see Figure 3) which is within route A; the observations lie within or below expectations and will not adversely affect the pre-defined JPSO, i.e. 18-month JPSO and within safety case NP/SC 7716.

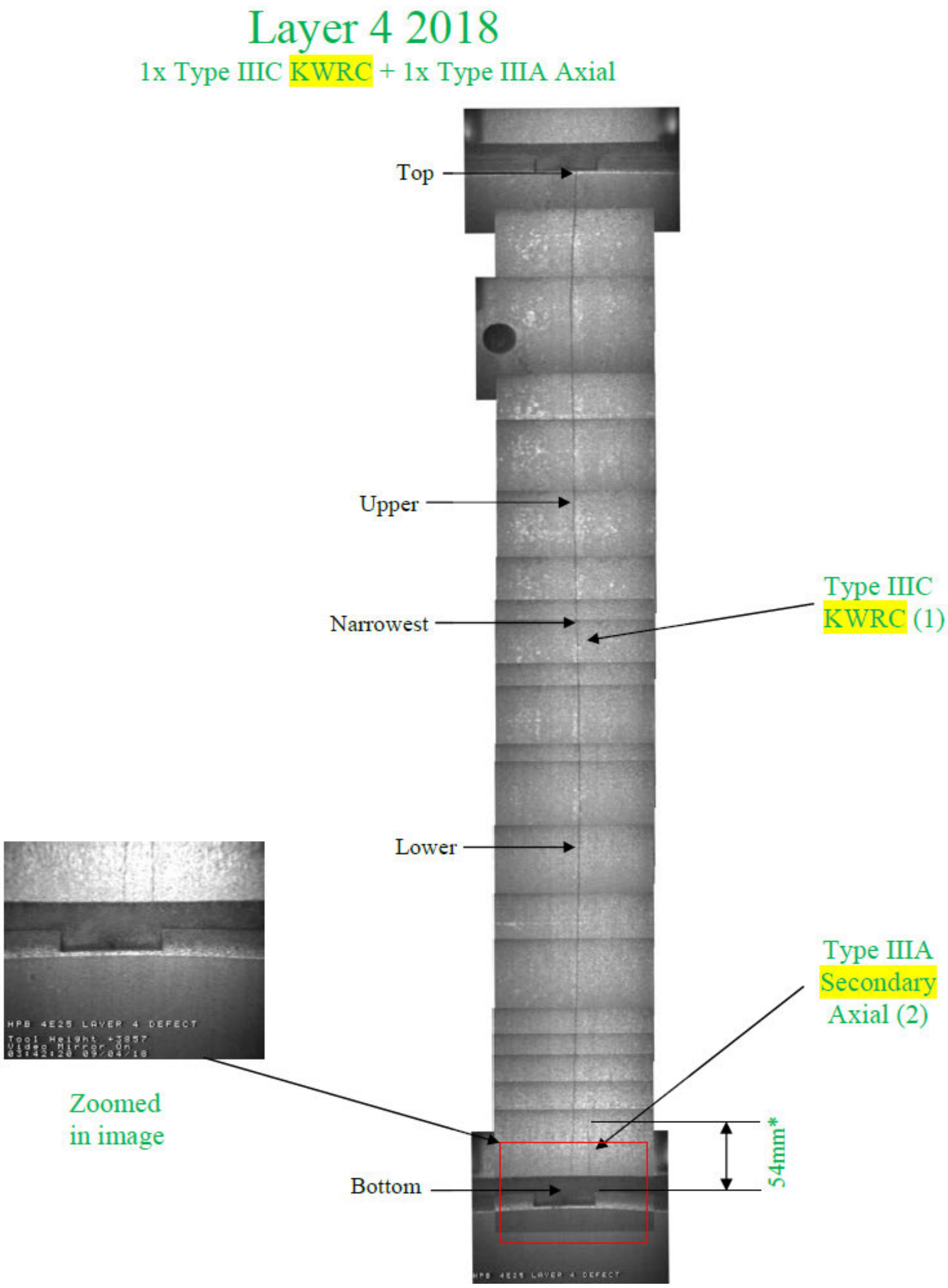


Figure 3: KRC in Channel E25, layer 4.

40. This figure also shows evidence of secondary damage from the primary keyway root crack at the corner of the end face. This channel had been inspected in 2002, 2005, 2011 and 2015 and was targeted due to previous low 'lambdas'.

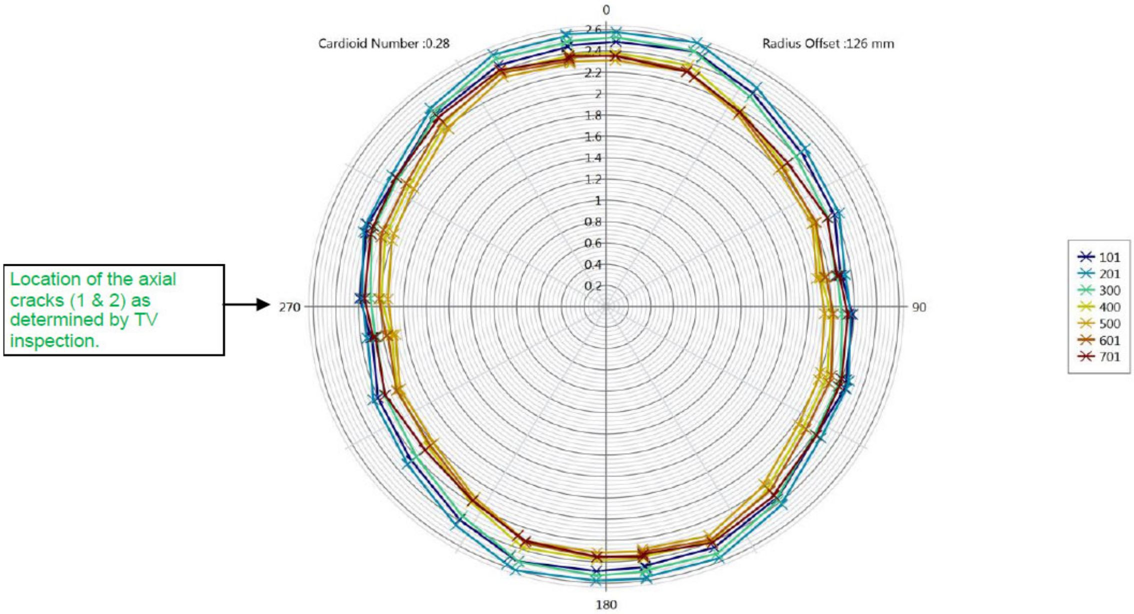


Figure 4: Cardioid plot derived from the bore measurements in Channel E25.

41. Figure 4 shows the cardioid plot for channel E25 which confirms the absence of lipping-in and the sentencing as a KRC. From a structural integrity point of view, KRCs are more significant than bore-initiated cracks since NGL expects their number and the crack opening to increase over time. NGL has developed some models to predict the number of cracks expected during the inspections and make an estimate on the total number of cracks in the core. This observation is therefore consistent with NGL's expectations.

42. The licensee will produce an EC within 60 days of restart of HPB R4. This EC will consider the likely extent of cracking in R4 and R3 at the end of the JPSO. In advance of this NGL has estimated that, at the 99.9% confidence level, currently, no more than approximately 65 and 85 cracked bricks are present in the HPB R4 and R3 reactor cores respectively (Ref. 18). I also note that no KRC had been observed in the graphite core of HPB R3 during the last graphite inspections of 26 channels in February 2018. HPB R3 is only six months ahead of R4 in terms of core burn-up. It is therefore unlikely that either reactor will exceed their current limit of 20% fully axial cracked bricks, i.e. 350 cracked bricks, before the 60-day EC is produced and before ONR has considered the JPSO for R3 and R4.

43. On this basis, I am satisfied that the level of cracking observed during the current inspections should not prevent return to service of HPB R4.

4.3.3 Independent forecast analysis

44. To advise ONR on the licensee's crack predictions, HSL provided an independent report in Ref. 6 to evaluate the number of cracks in the core and validate the current models. HSL's most likely scenario for HPB R4 was to observe two new full height axial bore cracks and one KRC during these inspections. Although HSL did not provide future projections, their results are consistent with Quintessa's best estimates (up to two new singly cracked bricks). These estimates are in good agreement with the results from the graphite inspections which revealed one newly observed bore crack and one KRC. Therefore, this provides some confidence that the statistical model best

estimates provides reasonable estimates of the number of cracks in the core and projections over the next operating period and that the number of cracks in the reactor is below the safety case allowance of 20% (~350 bricks).

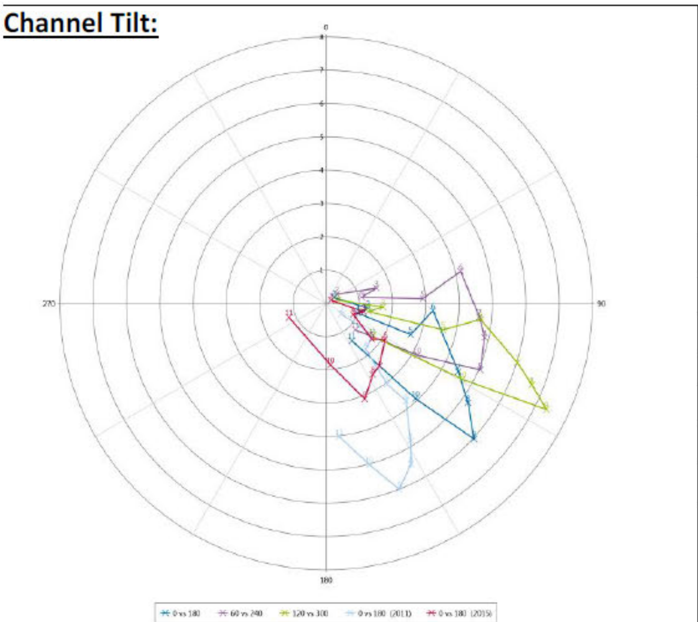
4.3.4 Core distortion

45. Visual inspections and bore measurements are made using an inspection tool referred to as 'NICIE2' (New In-Core Inspection Equipment). The angle of the channel is determined by its 'tilt' and gives a measure of the overall distortion of the core. This measurement is usually determined using two transducers measuring the angle of the tool as it moves through the channel. The brick bow, channel bow and channel tilt are derived from these readings and are shown in the GAP sheets (Refs. 11, 12, 13 and 14). During the outage, the bore and tilt measurements are reviewed and confirmed by the GAP. I attended several of these GAP meetings and consider that the level of the technical discussion is adequate and it considered the main aspects of the graphite inspections.

46. The bore, channel tilt and channel bow measurements are within expectations and are consistent with previous data for the channels which had already been inspected. On this basis, I am satisfied that there is currently no adverse trend that might indicate distortion of the channels or of the core. With regards to the tilt measurements, the licensee identified an error in the measurements due to a failing transducer. I consider this issue further in Section 4.3.5 below.

4.3.5 Tilt measurement issues

47. During the inspections, NGL notified ONR that one of the transducers, T1-3, was faulty and gave an artificial rotation of the measurements compared to historic data. This is illustrated in Figure 5 below. The licensee also reported that additional twisting the NICIE2 tool could occur during inspections. This twisting was previously accounted for by using an additional factor to represent the difference in average tool twist between the two scan pairs.



Taken From N+120 - N+300	
Layer	**Channel Tilt (mm)**
2	0
3	2
4	1
5	4
6	5
7	6
8	7
9	7
10	5
11	2

Figure 5: Tilt measurement plot for Channel L15 (Ref. 19).

48. NGL subsequently repaired the faulty transducer and analysed the data recorded using the faulty transducer. The licensee subsequently reviewed the recent inspection data produced in a short note in Ref. 20. This note identified that the fault occurred in

the 5th channel in the inspection sequence (channel U35) and suggested that these measurements could be corrected using the reading from a single transducers.

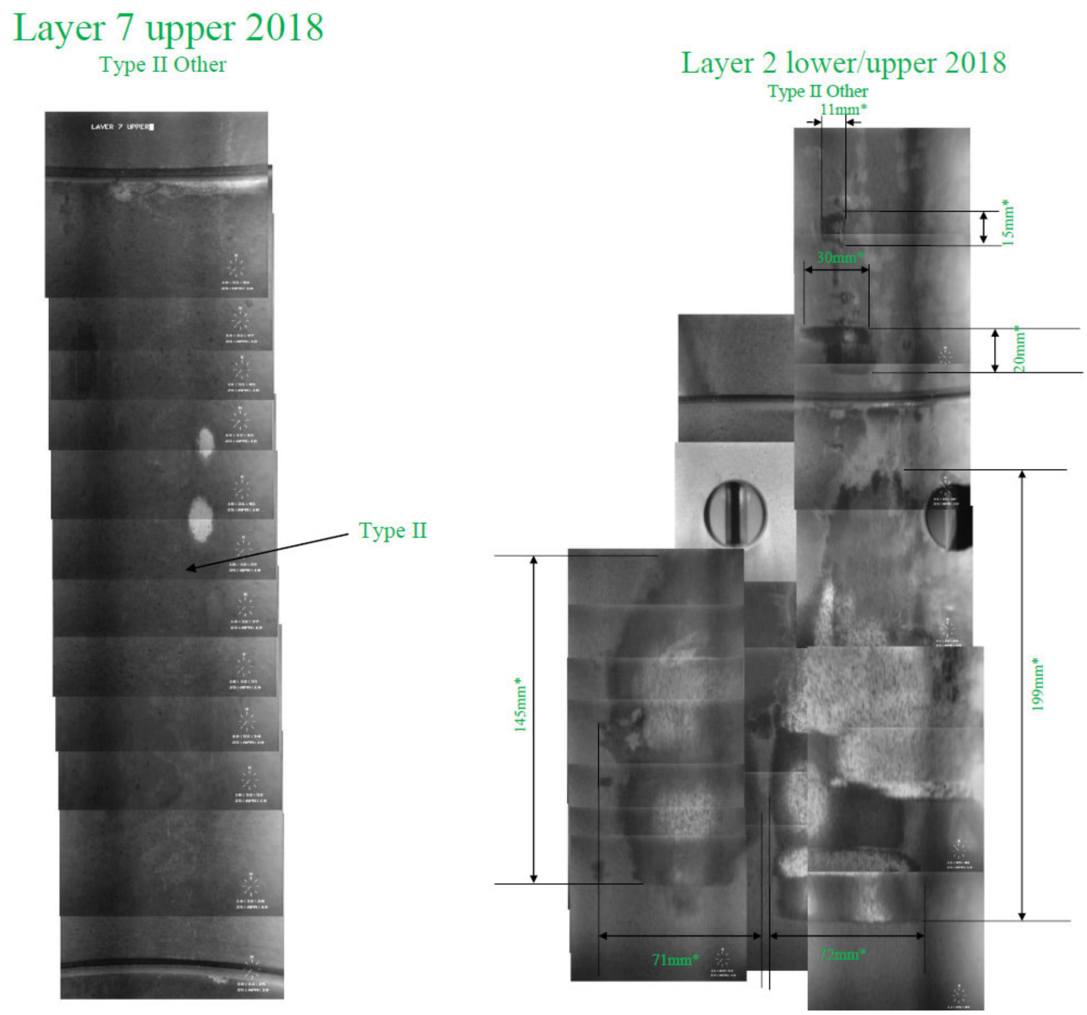
49. NGL subsequently proposed a new method in Ref. 21 to derive the tilt measurements from the data retrieved from the valid transducer. The main change concerns a trigonometric formula and is relatively minor. The impact of this change was also reviewed considering 440 historical data, including data from HNB. The changes in the tilt calculations were within 0.1mm of the original calculations, which therefore validates the adequacy of the single transducer method.

50. I am satisfied that this issue was promptly identified by the licensee and that appropriate action was taken to repair the faulty transducer. I am also satisfied that the method proposed to calculate the channel tilt from a single transducer showed a good agreement with the previous method. I therefore consider that the licensee adequately addressed this issue. I also consider that the measured core distortions are within expectations and do not challenge the safety case assumptions.

51. However, although the licensee was able to detect this fault relatively early this time, there are insufficient checks of the quality of the inspection data when it is being collected from the channel to identify the fault during the inspection. This meant that several channels were inspected before the fault was realised by the GAP's interrogation of the tilt results. ONR has therefore recommended to the licensee (at HNB) in Ref. 22 that further improvements should be made to confirm the quality of the data collected from a channel before moving to inspect the next channel. I am adding this as a recommendation to the licensee to reinforce this expectation.

4.3.6 Control Rod channel observations

52. One of the EMIT's requirements is to perform the visual inspection of a control rod channel during every periodic shutdown and the licensee chose to inspect channel RS 28. This channel houses a 'contract' super-articulated bulk control rod manufactured by IMI. During inspection of channel RS28, unusual markings were found on the channel wall, including damage in the form of chipping at the top and bottom of the Layer 7 brick and contact marks on the Layer 2 brick as shown in Figure 6 below:



(a) (b)

Figure 6: Marks in (a) Layer 7 and (b) Layer 2 of Control Rod Channel RS28.

53. These defects were considered by the GAP who classed these defects as 'Type II – Features that could grow into cracks if stresses are sufficient, and cracks of a length that implies existence prior to irradiation non-propagating defect' (Ref. 23).

54. After observing the damage in the control rod channel, the licensee decided to change the scope of the inspections to inspect a fuel channel R27 adjacent to control rod channel RS28 where damage had been observed. The licensee performed some bore measurements in fuel channels R27 and confirmed that there was negligible channel distortion and that measurements were similar to the previous inspection in 2015. The licensee reported that no defect and no damage to the bricks had been observed in fuel channel R27. The maximum channel bow was 4mm and the maximum channel tilt was also 4mm. There is therefore no adverse indication in this fuel channel that could explain the damage in control rod channel RS28. In addition, the inspections in fuel channel R27 provide confidence that the damage in channel RS28 is localised and is not the result of excessive core distortion.

55. Following ONR's request, the licensee provided some possible explanation for the damage observed in Ref. 24. According to the licensee, the markings observed may have been caused by contact by the control rod during drops, original defects, inspection equipment or the removal of the control rod shock absorbers to allow sub-diagrid viewing. The licensee also mentions that this type of damage had not been observed before, but that similar scuff marks have been observed in fuel channels where the stabilising brushes interact with the channel walls. According to NGL, the

control rod drop times are all within specification and it would appear unlikely the current damage would challenge the integrity of the brick or cause blockage. NGL will consider the observed damage in more detail within the 60 day EC. NGL has also committed to inspect a channel housing a super-articulated control rod of the same manufacturer as the control rod in HPB R4 channel RS28 in the HPB R3 reactor core in 2019 (Ref. 24).

56. I therefore consider that the licensee's commitment to inspect a similar channel in HPB R3 in 2019 is sufficient. However, the licensee could consider performing further inspections of channels housing control rods of a similar design and of a similar manufacturer in the HNB R3 graphite core which may shortly be subject to further inspections. These inspections would help to provide further evidence that the primary shutdown capabilities of the reactor are not affected.

57. I note that there is an existing ONR recommendation in the assessment of HPB/HNB PSR3 (Recommendation 1 in Ref. 25) to develop an inspection tool to improve the monitoring capabilities of the core, in particular in relation to dimensional measurement within the control rod channels. In my opinion, the findings of this inspection reinforce the need for such a consideration to be made. I therefore re-iterate ONR's original recommendation below:

'Recommendation 1: I recommend that NGL continues to develop improved inspection and monitoring technology. In particular I consider that equipment capable of performing visual inspection and dimensional measurements of control rod channels should be developed. This is likely to be needed before either extensive cracking develops or significant distortion of fuel channels is found.'

58. Given that damage of the type observed has not previously been observed in other control rod, I recommend that control rod channels housing super-articulated control rods of similar manufacture and from the same manufacturer (IMI 'contract' rods) should be considered for further inspection, both at HPB and HNB.

4.4 Graphite weight loss

4.4.1 Safety case limits

59. Graphite Weight Loss (GWL) is caused by radiolytic oxidation of the graphite in a carbon dioxide atmosphere. This causes a number of material changes in the graphite which may potentially challenge the safety functions of the core. NGL uses a thermofluids software, FEAT-DIFFUSE, which they develop specifically to assess GWL and relate it to the core burn-up. At HPB, the following limits are associated with GWL (Ref. 26):

(i) Active Core Weight Loss (ACWL) limit of 17% associated with the risk of fuel failures during faults, other than steam ingress, at shutdown: reached at 18,850GWd;

(ii) Structural Integrity Assessment Limit (SIAL) of 43%, confidence in the ability to assess brick integrity: reached with a burn-up of 19,350GWd;

(iii) Peak Brick Weight Loss (PBWL) limit of 25%: reached with a core burn-up of 20,950GWd;

(iv) Whole Core Weight Loss (WCWL) limit of 10.3%: predicted to be reached with a core burn-up of 20,700GWd.

60. The SIAL limit corresponds to '10% of bricks with 5% of their volume > SIAL and 5% of bricks with 10% of their volume > SIAL' (Ref. 27).

4.4.2 Licensee's estimates for graphite weight loss

61. Table 1 shows my own estimates on GWL based on NGL's GWL calculations in Ref. 26. I simply derived these estimates by interpolation from the information presented in Table 7 of Ref. 26.

Table 1: Best estimates GWL projections at the time of current shutdown and for the next operating period (based on Table 7 of Ref. 26).

	Current estimate at 2018	Projection at the end of the next operating period[§]	Current Limit
Core burn-up, GWd	15967	17341	N/A
ACWL, %	14.2	15.5	17
SIAL	0.3% > 10% 1.8% > 5%	1.1% > 10% 4.3% > 5%	5% > 10% 10% > 5%
PBWL, %	18.6	20.5	25
WCWL, %	8.1	8.5	10.3

62. Table 1 shows that all of the GWL projections are all predicted to remain within the safety case limits in the next three-year period, with adequate margins. I note that these are based on best estimates rather than conservative estimates as required by NS-TAST-GD-029 Revision 3 – Graphite Reactor Cores (Ref. 3). On my request, the licensee committed to provide further justification to support these forecasts (Ref. 28). I will consider this justification and follow up on this concern as a long-term development plan for a fleet-wide graphite weight loss intervention. I am adding this as an action in the recommendations.

63. However, notwithstanding this issue on the level of conservatism in the GWL forecasts, I consider that there is a considerable margin between the calculation and the 17% limit so as not to prevent the RTS of the reactor.

4.5 ONR rating

64. To conclude, I am satisfied that the inspection of the graphite core has been undertaken in line with the safety case and I allocated an ONR rating of 'green' (adequate) – see Ref. 29.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

65. In March 2018, HPB R4 began its three-yearly periodic shutdown for examination, maintenance, inspection and testing in compliance with LC 30. One objective of the licensee, NGL, was to demonstrate that the condition of the graphite core is in accordance with the relevant safety cases.

66. My assessment report deals with the graphite core and covers the licensee's activities during the outage, together with other work that they have performed to demonstrate that the graphite core is fit for purpose. During the HPB R4 2018 periodic shutdown, NGL conducted visual inspections and dimensional measurements of thirty-one graphite fuel channels and one control rod. I carried out an inspection on site while

[§] *Assuming a core burn-up increase of 458GWd per year.*

some of these inspections were being carried out. I formed the view that the work I witnessed was being performed to an adequate quality.

67. As required by the licensee's inspection schedule, thirty-six graphite samples were trepanned from the core for property measurements such as density and strength. Due to the complexity of these measurements, these trepanned samples will be analysed at the NNL after the outage. The licensee completed all the Maintenance Schedule requirements for the graphite core inspections during the periodic shutdown. In addition, although these are not a Maintenance Schedule requirement, ten fuel channels were inspected using eddy currents. These inspections may help the licensee to identify sub-surface cracks and determine variations in graphite density close to the channel bore.

68. During the core inspections carried out, the licensee observed one new fully axial bore crack and one keyway root crack in the graphite moderator bricks. The licensee has previously demonstrated that bore cracking is a consequence of early life ageing behaviour and does not expect this type of damage to progress significantly with core age. This judgement is consistent with inspections. Keyway root cracks are more significant as this damage mechanism is predicted to increase as the core ages. The licensee considers that this may be potentially life limiting for the reactor. NGL observed the first keyway root crack in the HPB reactors during this periodic shutdown, but similar cracks have been already been observed in the HNB reactor cores.

69. Since the HPB reactor cores are of similar design and core age as those at HNB, the keyway root crack observed during this shutdown was expected prior to the shutdown. However, the Hinkley Point B reactor cores are lagging the Hunterston B cores in terms of the numbers of KRC as its onset date was approximately 1.5 to 2 full power years later. NGL will justify the JPSO for HPB R3 and R4 in an EC produced 60 days after restart of R4. In advance of this NGL has estimated that, at the 99.9% confidence level, currently, no more than approximately 65 and 85 cracked bricks are present in the HPB R3 and R3 reactor cores respectively. It is therefore unlikely that either reactor will exceed their current limit of 20% fully axial cracked bricks, i.e. 350 cracked bricks, before the 60-day EC is produced and before ONR has considered the JPSO for R3 and R4. I am therefore satisfied that the current inspection findings do not challenge the safety of the graphite core.

70. During the inspections, the licensee had identified an issue affecting one of the transducers measuring the distortion of the some of the core channels. The inspection tool uses two transducers for the measurements, one of which was found to be faulty as the inspections were being carried out. The licensee reviewed the data from the recent inspections and proposed a revised method for deriving the measurements affected by this fault from a single, non-faulty transducer. I reviewed the revised method as part of my assessment and concluded that the change in the methodology was relatively minor and the tilt measurements using this method were in good agreement with those obtained using the two-transducer method. I am therefore satisfied that the tilt measurements obtained during this periodic shutdown are within expectations and do not challenge the safety case assumptions. However, a number of inspections have been carried out using a faulty transducer and it is currently up to the individual to check the quality of the data. ONR therefore recommended to the licensee to implement additional steps to ensure the quality of the data before moving on to inspect the next channel. I re-iterate this recommendation below.

71. As part of the Maintenance Schedule requirements, the licensee performs the visual inspection of a control rod channel. During this inspection, damage in two of the bricks was observed in layer 2 and in layer 7 of the channel. The cause for the damage was not clear from the inspection. The licensee performed core distortion measurements in an adjacent fuel channel and confirmed that these were within expectations. Control rod drop times did not suggest any inhibition of movement of the control rod in the

channel. NGL are committed to inspect a similar channel in HPB R3 in 2019. I am therefore satisfied that the licensee took adequate action to provide evidence that control rod entry would not be impaired in this channel. However, the licensee could consider performing further inspections of channels housing control rods of a similar design and of a similar manufacturer in the HNB R3 graphite core. These inspections would help to provide further evidence that the primary shutdown capabilities of the reactor are not affected.

72. To conclude, I am satisfied that the inspections undertaken during the periodic shutdown have been undertaken in line with the safety case and none of the results would preclude consent being given to return Hinkley Point B Reactor 4 back to service.

5.2 Recommendations

73. My recommendations are as follows.

- **Recommendation 1 (to ONR Project Inspector):**
  Based on my assessment of the Hinkley Point B Reactor 4 2018 Graphite Core Inspection Results and Justification for Return to Service, I have not found any reason to prevent me recommending that consent is given to return Hinkley Point B Reactor 4 back to service.

- **Recommendation 2 (to ONR Project Inspector):**

  That the PAR should note the observation of the first keyway root crack in one of the HPB reactor cores.

- **Recommendation 3 (to ONR Project Inspector):**

  At the time of my assessment, I was provided with a verified statement by NGL justifying the graphite core inspection results in support of the licensee's request for return-to-service of HPB R4. I therefore recommend that the Project Inspector should confirm that the INSA Approved Certificate is available for the HPB R4 Return to service EC 361594.

- **Recommendation 4 (to NGL Graphite Group Head):**

  In light of the observations in control rod channel RS28, I recommend that the licensee considers performing further inspections of control rod channels at Hunterston B housing super-articulated controls, which are of similar manufacture and from the same manufacturer as those for the control rod corresponding to channel RS28.

- **Recommendation 5 (to NGL Graphite Group Head):**

  In light of the observations in control rod channel RS28; I reiterate the recommendation made in ONR's assessment of the third Hinkley Point B/Hunterston B Periodic Safety Review:

  Recommendation 1: I recommend that NGL continues to develop improved inspection and monitoring technology. In particular I consider that equipment capable of performing visual inspection and dimensional measurements of control rod channels should be developed. This is likely to be needed before either extensive cracking develops or significant distortion of fuel channels is found.

- **Recommendation 6 (to ONR Graphite Inspector):**
  To update the ONR Issues Database to capture progress on:

  i) the level of uncertainties in the graphite weight loss calculations on the long-term;

  ii) a fleetwide consideration of the graphite weight loss case;

iii) the implementation of additional steps to ensure the quality of the data before moving on to inspect the next channel.

6 REFERENCES

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20. HPB R4 2018: NICIE2 Tilt Measurements – Description of Issue. [redacted]. 16th April 2018. TRIM 2018/135012.

21. HPB R4 2018: Calculation of Channel Tilt and Channel Bow using Data from only one Tilt Inclinometer. [redacted]. DAO/EAN/JIEC/265/AGR/18. Revision 000. May 2018. TRIM 2018/152526.

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28. RE: RE: HPB R4 2018 Periodic Shutdown - Questions. Active Core Weight Loss Forecasts. 14 May 2018. TRIM 2018/163211.

29. ONR Assessment Rating Guide Table – TRIM Ref. 2016/118638.

Table 2: Relevant Safety Assessment Principles Considered During the Assessment.

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 Tolerances	The design should demonstrate tolerance of graphite reactor core safety functions to: (a) the aging 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: (a) facilitate inspection during manufacture and service; and (b) permit the inclusion of surveillance samples for monitoring of materials behaviour.
EGR.7	Material Properties	Analytical models should be developed to enable the prediction of graphite reactor core material properties, displacements, stresses, loads and condition.
EGR.8	Predictive Models	Predictive models should be shown to be valid for the particular application and circumstances by reference to established physical data, experiment or other means.
EGR.9	Material Property Data	Extrapolation and interpolation from available materials properties data should be undertaken with care, and data and model validity beyond the limits of current knowledge should be robustly justified.
EGR.10	Effects 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	Operational Limits	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.

Table 2 (Continued): Relevant Safety Assessment Principles Considered During the Assessment.

SAP No	SAP Title	Description
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.14	Monitoring System	The design, manufacture, operation, maintenance, inspection and testing of monitoring systems should be commensurate with the duties and reliabilities claimed in the safety case.
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 3: Excerpt of NGL’s Graphite Core Inspection Routes A/B/C Showing the Expectations for Keyway Root Crack Inspections (TRIM 2018/137106).

	Parameter	Reason	Safety Issue	Route A	Route B	Route C
1a) KWRC of MAIN POPULATION BRICKS	**Number of Single KWRC Bricks (main population, representative channels)**	KWRC progression faster than predicted	NP/SC 7716 operational allowance of 20% singly axially cracked bricks. Potential impact on graphite core safety case for HNB R3 / HPB R3 & R4.	0 - 2 KWRC bricks observed in main population (representative channels)	3 - 6 KWRC bricks observed in main population (representative channels)	More than 6 KWRC bricks observed in main population (representative channels)
1b) KWRC of MAIN POPULATION BRICKS	**Number of Newly Observed Single KWRC Bricks (main population, targeted channels)**	KWRC progression faster than predicted	NP/SC 7716 operational allowance of 20% singly axially cracked bricks. Potential impact on graphite core safety case for HNB R3 / HPB R3 & R4.	0 - 2 newly observed KWRC bricks observed in main population (targeted channels)	3 or 4 newly observed KWRC bricks observed in main population (targeted channels)	More than 4 newly observed KWRC bricks observed in main population (targeted channels)
2a) KWRC of MAIN POPULATION BRICKS	**KWRC Outside of Peak Rated Layers (4-6) / Central Core Region (rings 1-9) (representative channels)**	Incomplete knowledge of stress state / brick strength leading to uncertainty in cracking rate	Core condition not clear. Potential impact on graphite core safety case for HNB R3 / HPB R3 & R4.	0 or 1 KWRC brick outside this region (representative channels)	2 KWRC bricks outside this region (representative channels)	More than 2 KWRC bricks outside this region (representative channels)
3) KWRC of MAIN POPULATION BRICKS	**Number of Multiple KWRC Bricks (full length cracks; includes secondary axial cracking) (all 26 central fuel channels)**	Incomplete knowledge of stress state / brick strength	Shear / separation of multiply cracked bricks gives increased potential for core distortion	0-1 multiply KWRC bricks observed in the main population	2 or 3 of the observed KWRC bricks in the main population are multiply cracked	More than 3 of the observed KWRC bricks in the main population are multiply cracked
4) KWRC of MAIN POPULATION BRICKS	**Number of Main Population Bricks with induced axial cracking from opening of a KWRC Brick**	Damage to bricks adjacent to KWR cracked bricks is a realistic expectation	Safety case limit of 20% axially cracked bricks. Increased potential for channel distortion	≤ two thirds of primary KWRCs have initiated an induced crack	> two thirds of the primary KWRCs have initiated an induced crack	N/A
5) KWRC of MAIN POPULATION BRICKS	**Crack Opening of any new single KWRC bricks [the maximum value of the minimum measured crack opening over the bearing key height]**	To determine whether measured crack opening rates are consistent with rates used in supporting assessments	Axial crack opening leads to greater 'slackness' in the core and potential for core distortion. The safety case has limits on axial crack opening.	Crack opening at the bore < 5 mm [the maximum value of the minimum measured crack opening over the bearing key height]	Crack opening at the bore between 5 mm and 8 mm [the maximum value of the minimum measured crack opening over the bearing key height]	Crack opening at the bore > 8 mm [the maximum value of the minimum measured crack opening over the bearing key height]