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Operating Facilities Division

Hinkley Point B Reactor 3 Periodic Shutdown 2019 – Graphite Structural Integrity Assessment

Assessment Report ONR-OFD-AR-19-016
Revision 0
23 May 2019

EXECUTIVE SUMMARY

This report presents the findings of the ONR assessment of the 2019 graphite core inspections at Hinkley Point B Reactor 3 (HPB R3) and the justification for its restart as presented in EC 365309 for a three month period of operation.

HPB R3 entered a statutory outage in March 2019. As part of its commitments under Licence Condition 30, EDF Energy Nuclear Generation Limited (NGL) carried out an inspection programme on the graphite core. I carried out a number of interventions during the outage and I witnessed inspection of one of the fuel channels. Based on my assessment of the inspection procedure and findings, I consider that both the quality and the extent of the inspection to be adequate to allow proper assessment of the core state.

It is worth noting that NGL deployed a new inspection tool capable of collecting, for the first time, dimensional measurements in addition to the visual scans from control rod channels. The capability of collecting dimensional measurements was only available for the fuel channel inspections. I consider the deployment of the new tool as an important development which will provide valuable information about the core state as the graphite cores age.

I note the observations of keyway root cracks at HPB R3 in this outage for the first time. Previously a keyway root crack was observed at HPB R4 in 2018. The extent of cracking observed in HPB R3 is lower than that observed in Hunterston B (HNB) reactors, although HPB R3 is ahead in terms of core burn-up. This indicates that the onset of keyway root cracking in HPB lags that of HNB reactors despite the higher burn-up.

I also note that the inspection findings were within the expectations that were set out by NGL prior to the outage (less than 10% cracked bricks).

Based on the inspection findings, NGL produced forecasts of the numbers of cracked bricks within the core at the current time and after certain periods of operation. NGL carried out sensitivity studies on key process parameters assumed in the forecasting models to account for uncertainty. The current core state was found to be within the operational allowance (OA) of the current safety case NP/SC 7716. It was also found that the core state would remain within the OA of NP/SC 7716 for at least three months of further operation according to the most onerous case of the sensitivity studies. Based on the best estimate case, the core state would remain within the OA of NP/SC 7716 for more than six months of further operation.

I consider NGL's forecasts to be appropriate and able to demonstrate the core state adequately over the proposed period of operation of three months. Therefore, I consider NGL's judgement that the core state would remain within the OA set in the current safety case NP/SC 7716 for at least three months of further operation to be reasonable.

I note there is a small difference between the core burn-up modelled in the damage tolerance assessments (DTA) of NP/SC 7716 (ie, 16.7 TWd) and the core burn-up proposed in EC 365309 (ie, 16.742 TWd). The difference is 0.042TWd, and I consider such a small difference to be within the uncertainties in the models underpinning the OA of NP/SC 7716. There is no known cliff edge effect on the graphite material properties due to such a small change in irradiation dose at the current level of core burn-up. I also note that operation beyond the core burn-up limit of NP/SC 7716 is subject to approval by the Independent Nuclear Safety Assurance (INSA). I consider that NGL's arguments on the validity of its core damage tolerance assessments in NP/SC 7716 and the arrangements made for operation up to the proposed core burn-up of 16.742 TWd to be adequate.

To conclude, I am satisfied with the claim, arguments and evidence laid down within EC 365309 and I have no objection to consent being given to return Hinkley Point B Reactor 3 back to service for the proposed period of operation of three months (up to a core burn-up of 16.742 TWd). Operation beyond the proposed period would require a new safety case.

I made a number of recommendations and list them below:

- **Recommendation 1 (to ONR Graphite Structural Integrity Inspector):** to update Regulatory Issue 5101 related to control rod channel inspection tool. The new tool was deployed to inspect four control rod channels at HPB R3 during the 2019 outage. NGL judges the deployment as successful, but inspection data is yet to be assessed.
- **Recommendation 2 (to NGL Graphite Branch Head):** NGL should consider including brick cracking in ring 10 of the core in its damage tolerance assessments. These damage tolerance assessments may benefit from consideration of the effects of the asymmetrical dose (and possibly temperature and weight loss) distributions on the cracking behaviour in ring 10 through stress analysis.
- **Recommendation 3 (to ONR Project Inspector):** based on the graphite core inspection findings and the assessment of the return to service EC 365309, I see no reason to object retuning HPB R3 to power for the proposed operating period of three months (up to a core burn-up of 16.742 TWd). I also note that operation beyond the burn-up limit of NP/SC 7716 is subject to approval by the Independent Nuclear Safety Assurance (INSA).

LIST OF ABBREVIATIONS

ALARP	As low as is reasonably practicable
BSL	Basic Safety level (in SAPs)
BSO	Basic Safety Objective (in SAPs)
BMS	Business Management System
CEDTL	Currently established damage tolerance level
CO	Crack opening
DTA	Damage tolerance assessment
GAP	Graphite Assessment Panel
HOW2	(ONR) Business Management System
HNB	Hunterston B
HPB	Hinkley Point B
HSE	Health and Safety Executive
HSL	Health and Safety Laboratory
IAEA	International Atomic Energy Agency
INSA	Independent nuclear safety assurance
KWRC	Keyway root crack / keyway root cracking / keyway root cracked
LC	Licence Condition
NGL	EDF Energy Nuclear Generation Ltd
OA	Operational allowance
ONR	Office for Nuclear Regulation
PECIT	Prototype Eddy Current inspection tool
PAR	Project assessment report
PSR	Period Safety Review
R	Reactor
RGP	Relevant Good Practice
RtS	Return to service
SABRE	Statistical Assessment of Bricks using @Risk in Excel)
SAP	Safety Assessment Principle(s)
SCAP	Safety case anomaly process
SSC	Structure, System and Component
TAG	Technical Assessment Guide(s) (ONR)
TSC	Technical Support Contractor

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1 INTRODUCTION

1. EDF Energy Nuclear Generation Limited (NGL) has shutdown Hinkley Point B (HPB) Reactor 3 (R3) in March 2019 for its periodic shutdown in compliance with Licence Condition (LC) 30 of its Nuclear Site Licence. During the periodic shutdown, the licensee, 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 the findings of the licensee's inspection programme on the graphite core and the supporting documentation submitted by NGL to support return to service (RtS).

1.1 Background

3. The reactor cores at Hunterston B (HNB) and Hinkley Point B (HPB) have been subjected to the greatest irradiation of the AGR fleet. Some of the fuel bricks in these reactors have reached the keyway root cracking (KWRC) stage.

4. KWRC was first observed in HNB R4 in 2014 in a sub-population of bricks known for its higher shrinkage (as indicated by measurements of the brick bore diameters). In 2015 KWRC was observed in HNB R3 in the main population of fuel bricks. Inspections of HNB R3 in 2018 revealed a significant increase in the number of cracked fuel bricks.

5. Continued inspection of the cores at HNB has revealed a related cracking phenomenon to KWRC. It appears that axial cracking and subsequent crack opening can generate additional stresses in both the cracked brick and adjacent bricks due to the interaction by means of the keying system.

6. There are now several classes of full height axial cracks; bore cracks, keyway root cracks, secondary cracks and induced cracks. Of these, only bore cracks appear to be showing no significant increase in number in the central region of the core. Due to crack opening, some damage to the end-face keys/keyways (eg, a short crack emanating from the root of an end-face key/keyway and joining the main full height axial crack) may occur and this is termed as secondary damage.

7. Inspections on both reactors at HPB have continued and the first keyway root crack was discovered in HPB R4 in March 2018. Based on the inspection of HPB and HNB reactors, it appears that there is a delay in the onset timing of KWRC in HPB reactors compared to HNB reactors.

8. In March 2019 HPB R3 was shut down for a statuary outage to carry out a periodic inspection. Further inspection of the graphite core was part of the schedule.

9. This report presents the findings of the assessment of the HPB R3 graphite core inspections as presented in the Graphite Assessment Panel's (GAP) minutes [1] and supporting documentation provided by NGL [**Error! Reference source not found.**] to support RtS. Assessment was undertaken in accordance with the requirements of the Office for Nuclear Regulation (ONR) How2 Business Management System (BMS) guide NS-PER-GD-014 [2]. The ONR Safety Assessment Principles (SAP) [4], together with supporting Technical Assessment Guides (TAG) [5], have been used as the basis for this assessment.

1.2 Scope

10. The scope of this report covers the assessment of the findings of the graphite core inspections at HPB R3 2019 and the justification for its restart as presented in EC 365309.

1.3 Methodology

11. The methodology for the assessment follows HOW2 guidance on mechanics of assessment within the Office for Nuclear Regulation (ONR) [6].

12. This assessment has been focussed primarily on the results of the graphite inspections of HPB R3 and the predicted core state during the proposed period of operation under the current safety case NP/SC 7716 [7].

2 ASSESSMENT STRATEGY

13. The intended assessment strategy for HPB R3 outage 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

14. The relevant standards and criteria adopted within this assessment are principally the Safety Assessment Principles (SAP) [4], internal ONR Technical Assessment Guides (TAG) [5], relevant national and international standards and relevant good practice informed from existing practices adopted on UK nuclear licensed sites. 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. Relevant good practice, where applicable, has also been cited within the body of the assessment.

2.1.1 Safety Assessment Principles

15. The key SAPs applied within the assessment are included within Table 1 of this report.

2.1.2 Technical Assessment Guides

16. The following Technical Assessment Guides have been used as part of this assessment [5]:

- ONR-TAST- GD-029 Revision 3 – Graphite Reactor Cores.

2.2 Use of Technical Support Contractors

17. In my judgement on the adequacy of NGL’s predictions of the current and future core states, I considered independent predictions and advice provided by statisticians from the Health and Safety Laboratory (HSL) made under graphite research contract ONR271.

2.3 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 R3 will be sent to National Nuclear Laboratories (NNL) at Sellafield for examination and testing. The result of this work will take at least six to nine months to be known. This will be taken into account in future core assessments and so it is excluded from my assessment.

3 LICENSEE'S SAFETY CASE

3.1 Background

19. In March 2019 HPB R3 was shut down for the purpose of a periodic inspection of its graphite core, which I and another inspector attended [8]. NGL's inspection of the graphite core was to consist of [9]:

- the visual inspection and dimensional measurement of 31 fuel channels
- visual inspection of one control rod channel
- Deployment of Prototype Eddy Current Inspection Tool (PECIT) to inspect 13 fuel channels
- Deployment of a new control rod channel inspection tool (capable of obtaining visual inspection and dimensional measurements) to four control rod channels
- Trepanning 36 graphite samples

20. The 31 fuel channels were selected to include 13 channels that were edge or near edge channels to demonstrate the core restraint integrity, nine channels were targeted to achieve this requirement. The representative 22 channels were selected using NGL's code CHANSELA, a statistical code for representative channel selection.

21. NGL's Maintenance Schedule included the commitment to inspect a minimum of 26 fuel channels, inspect one control rod channel and trepan a minimum of 30 graphite samples.

22. Prior to the outage NGL informed myself and other ONR inspectors of the expected numbers of KWRCs [10] and provided the strategy that would be adopted following different potential outcomes from the March 2019 outage. These outcomes were categorised as Routes A, B and C [11].

23. The proposed structure of Routes A, B and C consisted of many different criteria, related to the number of observations of keyway root cracked bricks, to judge the inspection findings. The criteria of Routes A, B and C are shown in Table 2 [11].

24. It is therefore the purpose of the assessment summarised in this report to assess the inspection findings and determine whether the return to service EC 365309 provides sufficient justification that it is safe for HPB R3 to return to service for a three month period of operation.

3.2 Activities performed during the outage

25. During the outage, NGL carried out visual inspections and dimensional measurements of 31 fuel channels, visually inspected one control rod channel and trepanned 36 graphite samples from six fuel channels; a list of the channels is provided in Table 3. The inspection findings were consequently sentenced by the Graphite Assessment Panel (GAP) according to NGL's arrangements. I note therefore that both the NGL's Maintenance Schedule commitments and the target amounts of inspection and trepanning have been met.

26. NGL used a Prototype Eddy Current Inspection Tool (PECIT) to inspect 13 fuel channels [12]. PECIT equipment gives information about the graphite surface density and may reveal sub-surface cracks.

27. NGL deployed a new prototype tool, a modified version of the fuel channel inspection tool, to inspect four control rod channels. The new tool is capable of measuring channel distortion and bore diameters in addition to the visual inspection. The development of such tool was an ONR recommendation from the third periodic review (PSR3) and the subject of Regulatory Issue 5101. I recommend updating this

regulatory issue to reflect the tool deployment which was judged by NGL as successful (Recommendation 1).

28. During this outage, trepanned samples were obtained from cracked bricks. Samples were successfully taken from three bricks containing cracks. Visual inspection post trepanning did not reveal further damage.

29. In summary, the inspection findings were as follow [13]:

- Ten new singly Keyway Root Cracked (KWRC) bricks were observed (including three induced full height axial cracks).
- There were no doubly or multiply KWRC bricks observed.
- Two new doubly bore cracked bricks were observed.
- The crack opening at the bore of any new single KWRC Bricks was less than 5 mm.
- The measured maximum channel bows were less than 6 mm.
- The change in channel bow for repeat inspected channels was less than 3 mm.

30. NGL found the inspection findings, as sentenced by the GAP, to be within the criteria for Route A. A list of the inspection observations is provided in Table 4.

31. In light of the inspection findings, and in line with Route A, NGL has produced EC 365309 [2] to justify that it is safe for HPB R3 to be returned to service (under current safety case NP/SC 7716) up to a core burn-up of 16.742 TWd which is estimated to be reached after a three month period of operation. During this operating period, NGL intend to submit an updated safety case to ONR justifying a longer period of operation (up to about 12 months from RtS).

3.3 The return to service EC 365309 [2]

32. EC 365309 [2] proposes a justified period of safe operation (JPSO) up to a core burn-up of 16.742 TWd (equivalent to about 3 months of operation after return to service) for HPB R3 under the operational allowance (OA) set in the current safety case NP/SC 7716. The proposal:

- *"Summarises the inspection findings and reports any significant observations which may challenge the safety case.*
- *Demonstrates that the core state remains acceptable throughout the proposed JPSO. The extent of cracking is shown to remain within the OA.*
- *Demonstrates that risks remain ALARP, considering the extent of inspection that has been performed. This includes a reconfirmation of the judgement made in the SCAP assessment of the seismic DTA, and confirmation that there is no significant extent of cracking in ring 10 or layers 8 to 11, to confirm that there is no challenge upon full insertion of any control rod at any time.*
- *Provides the necessary updates to station operational service documents (e.g. for control of permitted core burn-up)."*

33. The EC contains one claim and several arguments with evidence in support of the return to service of HPB R3. The claim is:

> *"**Claim 1:** A JPSO of 16.742 TWd is demonstrated for the HPB R3 graphite core."*

34. The main purpose of this EC is to demonstrate that for the proposed operating period the core state, in terms of the number of cracked bricks, remains within the OA of NP/SC 7716 which was set out as:

- No more than 350 axially cracked bricks of which:

- no more than 100 are singly axially cracked bricks open by more than 12mm,
- no more than 20 are singly cracked bricks open by more than 18mm,
- and, no more than 180 are doubly axially cracked bricks.

- In addition, a core burn-up of no more than 16.7 TWd.

35. The OA was set with margin against the currently established damage tolerance level (CEDTL). The damage tolerance assessment (DTA) leg of the safety case demonstrated tolerance to cracking levels set by the CEDTL. The CEDTL cracking levels are roughly double those of the OA.

36. NGL judge that the graphite core inspection findings indicated that cracking behaviour is consistent with expectations.

37. NGL judge that the current core state and the future core state after ~ 3 month operating period would remain within the OA of NP/SC 7716 detailed above.

38. NGL propose to increase the core burn-up limit of NP/SC 7716 from 16.7 TWd to 16.742 TWd.

39. NGL provide arguments in support of the validity of the DTA at a core burn-up of 16.7 TWd to a slightly higher core burn-up of 16.742 TWd.

40. NGL also provide arguments in support of the validity of the outcome of the safety case anomaly process [14] related to the seismic CEDTL of NP/SC 7716.

41. NGL state that there are significant margins on the weight loss limits and the core restraint limits beyond the proposed operation period of three months.

4 ONR ASSESSMENT

42. This assessment has been carried out in accordance with HOW2 guide NS-PER-GD-014, “Purpose and Scope of Permissioning” [2].

4.1 Scope of Assessment Undertaken

43. The scope of the assessment is limited to the graphite core inspection findings and the claim and arguments presented in EC 365309 “Justification for the Return to Service and Continued Operation of HPB R3 to a Core Burn-Up of 16.742 TWd following the Graphite Core Inspections in March / April 2019”.

4.2 Interventions undertaken during periodic shutdown

44. I visited HPB during the outage and met with NGL’s staff to discuss the inspection activities, arrangements and some of the results that were available at the time of the intervention [8]. At the time of my visit, NGL had performed eight fuel channel inspections. I made no significant adverse observations during this intervention that would lead me to doubt the quality of the data that had been obtained or the competence of those involved in the process. I allocated an ONR rating of ‘Green’.

45. I observed a number of GAP meetings where the inspection findings were discussed and the cracks sentenced according to NGL’s arrangements.

46. I attended a Level 4 meeting [15] on 02 May 2019 to discuss the graphite core inspection findings of HPB R3. During the meeting, NGL also presented current and future predictions of the core state and its approach for returning the reactor to service.

4.3 Assessment of the inspection findings

47. I have reviewed the GAP minutes and GAP sheets which contained details of the defects found during the inspection. I consider that NGL have followed structured arrangements for carrying out the inspections and for sentencing the findings. I consider these arrangements to be adequate. I also consider the quality of the data collected to be adequate to allow proper analysis and sentencing.

48. I note that KWRC was observed for the first time in HPB R3 during this outage. Also, induced and secondary cracking damage were observed.

49. The observation of KWRC is not surprising, given that a KWRC was observed in HPB R4 in March 2018 and the observations of more prevalent cracking in HNB reactors. However, I note that the amount of cracking in HPB R3 is less than that observed in HNB reactors, although HPB R3 is ahead in terms of core burn-up.

50. The inspection findings indicated that the onset of KWRC in HPB R3 lags behind that of HNB R3 and R4. However, there remains uncertainty related to the rate of cracking progression in HPB reactors.

51. I am content that the inspection results are within Route A criteria (which were defined prior to the inspections) as judged by NGL.

52. I highlight some of the inspection observations in Annex 8.1.

53. The number of bore cracks found was ‘in line with expectations’, but slightly in excess of ‘the most likely outcome’ according to the Quintessa pre-inspection predictions report for bore cracking [16]. Although HPB reactors appear to contain a larger number of bore cracks compared to HNB reactors, there appears to be an increase in the number of bore cracks in the edge and near edge channels.

54. Currently, NGL does not account for cracking in ring 10 in its whole core models supporting the DTA leg of the safety case. Based on the current observations of an increased number of bore cracks and the likelihood of onset of KWRC in ring 10, I recommend that NGL should consider including cracking in ring 10 in the DTA leg. These damage tolerance assessments may benefit from consideration of the effects of the asymmetrical dose (and possibly temperature and weight loss) distributions on the cracking behaviour in ring 10 through stress analysis (Recommendation 2).

55. Bore and channel measurements of the 31 fuel channels appear to be within expectations. Some low lambda factors (ie, a comparison of brick diameters at brick ends to at mid-height) were observed in bricks that did not contain cracks. NGL expects that low lambda factors to be an indicator of post-turnaround behaviour and the proximity to KWRC.

56. The Eddy Current results of the 13 channels inspected using the Prototype Eddy Current Inspection Tool (PECIT) do not appear to challenge the visual findings. In one case, additional support had been provided by PECIT to sentence what appeared to be a minor crack in channel H31 layer 4 shown in Figure 1. As PECIT indicated that the crack did not extend or open, it was sentenced as a surface scratch.

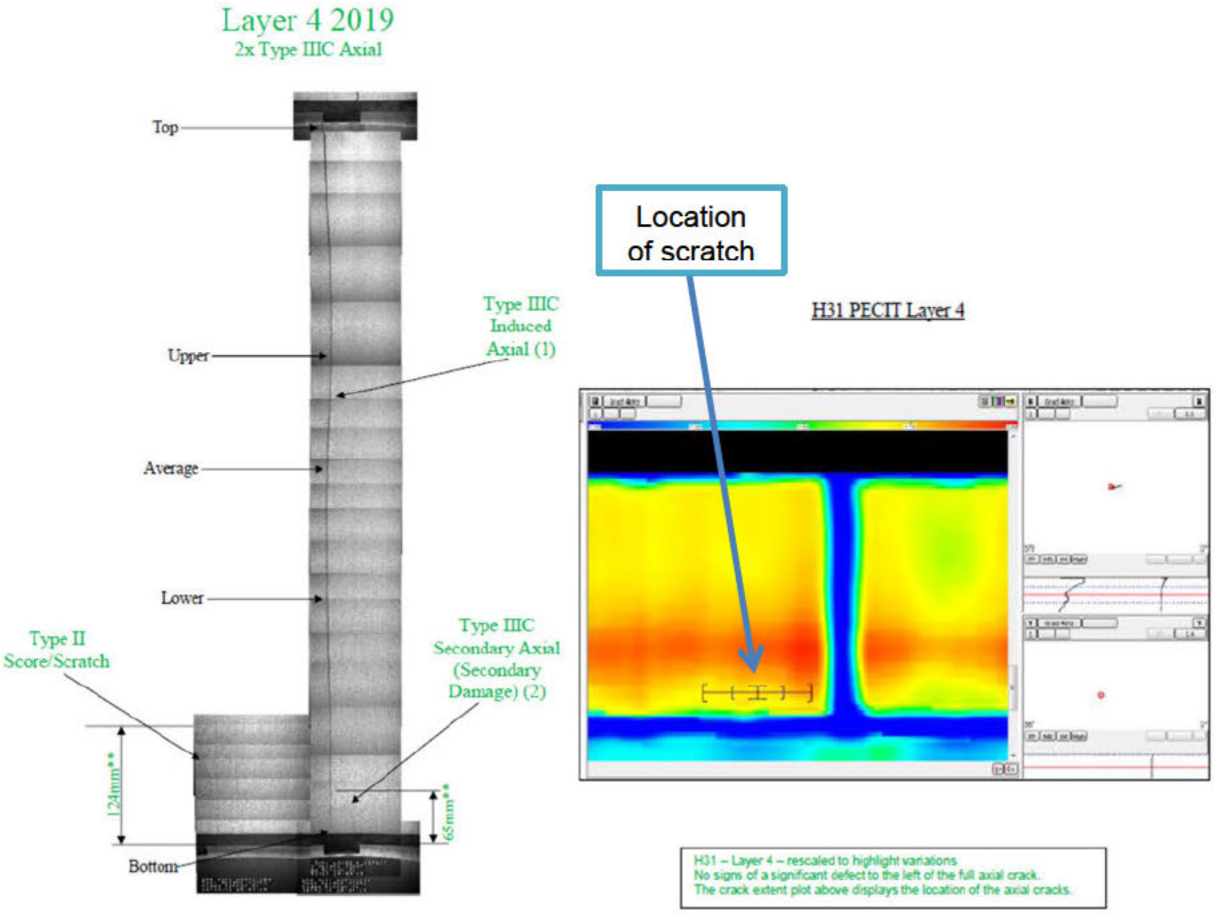

Figure 1. H31 layer 4 brick visual and PECIT scans (2019)

57. The visual inspection of the five control rod channels did not reveal any significant damage.

58. The new control rod inspection tool was deployed to inspect four of the five control rod channels inspected in this outage. NGL collected dimensional measurements in addition to the visual scans. The dimensional measurements will be subsequently analysed by NGL and will contribute to the safety cases in the future. NGL judged the deployment of the tool as successful in terms of collecting the measurement data.

59. I consider the deployment of the new tool as an important development which will provide valuable information about the core state as the AGR cores age.

4.4 Assessment of the return to service EC 365309 [2]

4.4.1 Core state forecasts

60. I have reviewed EC 365309 and some of its references. I focus on the central claim that the current core state and the future core state after about three months operation remain within the OA set in NP/SC 7716 with regard to the number of cracked bricks.

61. NGL used a statistical tool, referred to as CrackSim which was developed by Quintessa, to forecast the numbers of singly cracked bricks, doubly cracked bricks and multiply cracked bricks before returning to power and following certain periods of operations. The forecasts are provided at different calculational confidence levels (ie, 50% or best estimate and 99.9%).

62. CrackSim statistical calculations take account of the ageing processes which are defined as parameters. These parameters were set based on inspection data, numerical modelling and judgements made by suitably qualified and experienced persons (SQEPs).

63. The core forecasts are sensitive to some of the process parameters, such as the inclusion of an early cracking fraction and an offset in the onset of KWRC between HPB R3 and R4 reactors.

64. Reference [17], which was produced by Quintessa based on process parameters produced by NGL, provides the core forecasts used in EC 365309. The baseline case analysed used the SABRE 2019 HPB cracking rates for HPB R3 and R4 (SABRE refers to NGL's Statistical Assessment of Bricks using @Risk in Excel)), which gives a fixed R3-R4 offset; an assumption that an early cracking fraction exists; historical inspection results for both HPB R3 and R4 included in conditioning; and a baseline prior for scaling the cracking rates based on HNB posterior uncertainty distributions.

65. NGL also provided sensitivity studies to cover the uncertainty in the process parameters. Sensitivity studies looked at variants to the key process parameters, such as the use of the SABRE 2019 HPB R3 rates for both reactors, giving no R3-R4 offset; assuming that no early cracking fraction exists; excluding the R4 historical inspection results, so there is no R4 conditioning; and taking a wider prior uncertainty distribution for scaling the cracking rates.

66. The forecasts of the numbers of cracked bricks at the current state of the core and after four-month operation for the different cases considered are shown in Tables 5 and 6 [17]. These tables show that at the 99.9% confidence level, the core state remains within the operational allowance (OA) of NP/SC 7716 up to a three month operating period for the most onerous case considered.

67. It is worth noting that for the baseline case, the operational allowance was not predicted to be reached for more than six month of further operation even at the 99.9% confidence level.

68. I asked our Technical Support Contractor (TSC), HSL, to independently forecast the current and future core states based on the inspection findings. The forecasts are shown in Table 7 [18]. Some assumptions and inputs used by HSL are different to those made by NGL but HSL's assumptions are most similar to the more onerous case considered by NGL. HSL predictions indicate that the operational allowance set in the current safety case NP/SC 7716 of 350 singly cracked bricks will not be reached within the proposed operating period of three months.

69. Based on the sensitivity studies and the independent predictions, I consider that NGL has provided adequate evidence to support the core state forecasts. Those forecasts support the argument that the core state would remain within the OA set in NP/SC 7716 after a further three month operation.

4.4.2 Validity of NP/SC 7716 DTA

70. NGL acknowledges that there are mainly two issues relating to the NP/SC 7716 DTA validity:

- The DTA in NP/SC 7716 was performed for a core age of 16.7 TWd (not 16.742 TWd).
- The potential challenge upon the OA for DCBs associated with the in-event damage (also termed run-time damage) in the seismic assessment.

71. NGL states that *"The DTA assessments supporting NP/SC 7716 are performed for a core age of 16.7 TWd. The JPSO is 16.742 TWd which is beyond the assessed age, such that graphite core component strengths will be marginally lower than assessed and component clearances will tend be marginally higher than assessed. However, it can be judged (from the DTA assessments supporting NP/SC 7716 and its predecessors, performed for a range of core ages) that there is low sensitivity of the DTA results to such a modest exceedance of the assessed age. There is considered to be sufficient margin in the 16.7 TWd DTA assessments to easily accommodate any small degradation in results that would be associated with exceedance of the assessed age of 16.7 TWd. In addition, the longer term safety case being produced under NP/SC 7792 reports DTA for much higher extents of cracked fuel bricks and at a core age of 17.2TWd. The key DTA references have already completed due process. Therefore it is judged acceptable to operate to 16.742TWd."*

72. NGL also states "*Progress on the production of the longer term safety case NP/SC 7792 will be reviewed before the existing R3 core burn-up limit of 16.7 TWd is reached and the DI updated to Rev 003 with the new core burn-up limit of 16.742 TWd*"

73. The age of the core is one of the factors affecting the margins on the control rod entry. Other factors include numbers and distributions of cracks, crack opening and external forces such as seismic forces. I consider a small change in the core age alone, of the magnitude that is proposed, would not have a significant effect on the DTA results and would fall within the uncertainty associated with the modelling. Moreover, there is no known cliff edge effect on the material properties due to such a small change in irradiation dose at the current level of core burn-up.

74. Furthermore, the operation beyond the burn-up limit of NP/SC 7716 is subject to approval of the longer term CAT1 safety case by the Independent Nuclear Safety Assurance [19].

75. I consider NGL's arguments of the validity of the DTA presented in NP/SC 7716 and the arrangements made for operating beyond the core burn-up limit of NP/SC 7716 for HPB R3 to be adequate, as long as the number of cracked bricks remains within the OA of NP/SC 7716 (which was assessed in §4.4.1).

76. With regards to the potential challenge upon the OA for DCBs associated with the in-event damage (also termed run-time damage) in the seismic assessment, NGL states that *"the OA of 180 DCBs is supported by seismic DTA studies which do not adequately account for the effects of in-event damage to the keying system. This issue has been addressed through the SCAP, whereby it was judged that update to the core boundary input motion would remove the potential for significant in-event keying system failures (noting that NP/SC 7716 returns acceptable control rod insertion margins when there is no in-event keying system damage). The update to the GCORE*

seismic assessments to account for the updated core boundary motion is still in progress, but with all indications that the outcome of the SCAP (which was supported by SQEP judgement) remains unchanged."

77. Furthermore, NGL argues that *"The significant margin between the forecasted core state within the JPSO and the OA is also considered to support the judgement that control rods will not be impeded by the graphite core. Even at 6 months, only 20 DCBs are forecast at 99.9% calculational confidence, which is far below the OA for DCBs of 180. Hence, even in the unexpected situation that the updated seismic DTA does not support an OA of 180 for DCBs, there remains no significant challenge to the NP/SC 7716 safety case basis that the graphite core does not impede control rod entry."*

78. The seismic input has a significant effect on the margins of control rod entry, and the reduction in the seismic forces anticipated as a result of the new seismic buildings model would be expected to increase the control rod entry margins.

79. NGL's forecasts of low numbers of doubly cracked bricks to exist over the proposed period of operation add another level of assurance that the DTA anomaly will not be reached within three months of further operation.

80. As the improvements to the seismic buildings model will be incorporated in the updated longer term safety case, I consider NGL's arguments of no significant increase in risk to control rod insertion from the position presented in NP/SC 7716 to be adequate, as long as HPB R3 remains within the OA of NP/SC 7716 (the current safety case it has been operating under alongside the SCAP).

4.5 Other matters

81. NGL had installed flux stringers in HPB R3 and HNB R4 reactors in the side-core regions to validate the irradiation dose calculations used for the assessment of the structural integrity of the core restraint components.

82. The flux stringers retrieval from HPB R3 was deferred from the 2016 statutory outage to the planned vessel entry during the current statutory outage. ONR inspectors agreed to this deferral, because it was not proportional to carry out a vessel entry for only retrieving the flux stringers. In addition, the current core restraint safety case was still to be valid by time of the planned vessel entry during the 2019 statutory outage, giving enough time for retrieval and analysis before a new safety case was needed.

83. NGL successfully retrieved some of the flux stringers from HNB, but opted to not retrieve the flux stringers from the HPB R3 during the current outage. This decision was not communicated to ONR in a timely manner.

84. NGL is of the opinion that the flux stringers retrieved from HNB were enough to validate the dosimetry calculations and that no additional value would be gained from the HPB flux stringers.

85. Despite the similar design between HPB and HNB, the graphite material properties including weight loss are different and this may lead to different dosimetry results. Also, the flux stringers in HPB were placed further away from the central core than the ones installed in HNB to reduce the uncertainty in the depth effects on dosimetry.

86. I consider that the uncertainties in the core restraint dose calculations especially those affecting the shorter two lengths of puller rods will remain and will need to be addressed in the update to the core restraint safety case. However, I do not consider this to have a significant effect with regards to the return to service following the current outage as the current core restraint safety case remains valid.

4.6 ONR Assessment Rating

87. Based on the findings of this assessment, I consider that the safety case to be adequate. I therefore allocate an ONR overall rating of ‘Green’ according to ONR Assessment Rating Guide [20].

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

88. This report presents the findings of the ONR assessment of the graphite core inspections findings at HPB R3 2019 and the justification for its restart as presented in EC 365309.

89. I judge the graphite core inspection procedure and findings are of adequate quality. I consider the findings to be within expectations.

90. I consider the core state forecasts conducted by NGL to be adequate and that they fall within the OA set in the current safety case NP/SC 7716.

91. I also consider it reasonable that NGL judges that the core state would remain within the OA set in the current safety case NP/SC 7716 for at least three months of further operation.

92. I note there is a small difference between the core burn-up modelled in the damage tolerance assessments (DTA) of NP/SC 7716 (ie, 16.7 TWd) and the core burn-up proposed in EC 365309 (ie, 16.742 TWd). The difference is 0.042TWd, and I consider such a small difference to be within the uncertainties in the models underpinning the OA of NP/SC 7716. There is no known cliff edge effect on the graphite material properties due to such a small change in irradiation dose at the current level of core burn-up. I also note that operation beyond the core burn-up limit of NP/SC 7716 is subject to approval by the Independent Nuclear Safety Assurance (INSA). I consider that NGL's arguments on the validity of its core damage tolerance assessments in NP/SC 7716 and the arrangements made for operation up to the proposed core burn-up of 16.742 TWd to be adequate.

93. To conclude, I am broadly satisfied with the claim, arguments and evidence laid down within EC 365309 and I have no objection to consent being given to return Hinkley Point B Reactor 3 back to service for the proposed period of operation of three months(up to a core burn-up of 16.742 TWd). Operation beyond the proposed period would require a new safety case.

5.2 Recommendations

94. My recommendations are as follows.

- **Recommendation 1 (to ONR Graphite Structural Integrity Inspector):** to update Regulatory Issue 5101 related to control rod channel inspection tool. The new tool was deployed to inspect four control rod channels at HPB R3 during the 2019 outage. NGL judges the deployment as successful, but inspection data is yet to be assessed.
- **Recommendation 2 (to NGL Graphite Branch Head):** NGL should consider including cracking in ring 10 in the damage tolerance assessments. These damage tolerance assessments may benefit from consideration of the effects of the asymmetrical dose (and possibly temperature and weight loss) distributions on the cracking behaviour in ring 10 through stress analysis.
- **Recommendation 3 (to ONR Project Inspector):** based on the graphite core inspection findings and the assessment of the return to service EC 365309, I see no reason to object retuning HPB R3 to power for the proposed operating period of three months (up to a core burn-up of 16.742 TWd). I also note that operation beyond the burn-up limit of NP/SC 7716 is subject to approval by the Independent Nuclear Safety Assurance (INSA).

6 REFERENCES

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2. EC 365309 Proposal Version 01 Verified 15-05-19, Justification for the Return to Service and Continued Operation of HPB R3 to a Core Burn-Up of 16.742 TWd following the Graphite Core Inspections in March / April 2019, (CM9 2019/141017).

3. ONR HOW2 Guide NS-PER-GD-014 Revision 4 - Purpose and Scope of Permissioning. July 2014. http://www.onr.org.uk/operational/assessment/index.htm.

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

5. Technical Assessment Guide (TAG) 29: Graphite Reactor Cores. November 2018. http://www.onr.org.uk/operational/tech_asst_guides/ns-tast-gd-029.pdf.

6. Guidance on Mechanics of Assessment within the Office for Nuclear Regulation (CM9 2013/204124).

7. NP/SC 7716 Proposal Version 04 (EC 353779 Rev 000), Safety Case for the Graphite Core and Core Restraint: Operation after the Onset of Keyway Root Cracking, March 2016 (CM9 2019/141889).

8. Inspection of the Hinkley Point B Reactor 3 Graphite Core Inspection Arrangements during its March 2019 Statutory Outage, ONR Intervention Report, March 2019 (CM9 2019/98878).

9. NGL, Proposed Inspections at HPB R3 in March 2019 (CM9 2019/140201).

10. [redacted], Quintessa, Initial Scoping Estimates of the Expected Numbers of Cracked Bricks at the HPB R3 2019 Statutory Outage, February 2019 QRS-3031I-TN3 Version 1.0, (CM9 2019/140259).

11. NGL, HPB R3 march 2019 Graphite Core Inspections: Routes A / B / C, (CM9 2019/140463).

12. NGL, HNB R3 2019 Eddy Current Raw Data of 13 Channels (CM9 2019/140491).

13. Summary of Graphite Core Inspections at the Hinkley Point B R3 Statutory Outage in 2019, DAO/REP/JIEC/364/HPB/19, Revision 000, May 2019 (CM9 2019/141016).

14. NGL, NP/SC 7716 DCBs anomaly – 01108470 (CM9 2019/142571).

15. ONR-OFD-CR-19-075 Revision 0, Level 4 meeting on HPB R3 2019 graphite inspection results, safety case strategy for return to service and HNB R4 analysis progress held in Birmingham 2 May 2019 , (CM9 2019/135795).

16. QRS-3007O-4 Version 1.0, Application of Statistical Models to Bore Cracking at Hinkley Point B R3 Inspections in March 2019 (CM9 2019/141019).

17. QRS-3031I-11 Version 1.0, Forecasts for HPB R3 following the 2019 Statutory Outage (CM9 2019/141020).

18. Email communication, HSL predictions of the number of cracked bricks (CM9 2019/141021).

19. Email communication from HPB Station (CM9 2019/145965).

20. ONR Assessment Rating Guide Table (CM9 2016/118638).

7 TABLES

Table 1. 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 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	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.
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 2. Routes A, B and C criteria [11]

HPB R3 march 2019 Graphite Core Inspections: Routes A / B / C

Version 05 for HPB R3 2019 GAP

The Inspection findings will be assessed against
Route A: The observations lie within or below expectations and additional inspection will not provide evidence to support an improved confidence of the JPSO
Route B: The observations lie slightly above expectation but the return to service can be supported with a defined JPSO. Additional inspection of 14 targeted channels will provide information to support subsequent period of operation defined by JPSO
Route C: The observations lie sufficiently outside of expectation that the underlying models or assumptions would be challenged and inspection beyond 14 target channels will provide benefit to support safe operation.

	Parameter	Reason	Safety Issue	Route A	Route B	Route C
1) KWRC of MAIN POPULATION BRICKS	**Number of New Single KWRC Bricks (including induced full length axial cracks)**	KWRC progression faster than predicted	Overall progression of HPB quicker than anticipated compared to HNB	0 - 20 new single KWRC bricks observed	21-30 new single KWRC bricks observed	More than 30 new single KWRC bricks observed n
2) KWRC of MAIN POPULATION BRICKS	**Number of Double KWRC Bricks (main population)** **Distinction will need to be made between Prompt and Delayed Double Cracking where possible in the post-outage assessment**	Incomplete knowledge of stress state / brick strength. To determine whether "conversion" rate of single cracking to double cracking is consistent with supporting assessments	Damage progression may be different to HNB	0 - 1 double KWRC bricks observed	2-3 double KWRC bricks observed	4 or more doubly cracked bricks observed
3) KWRC of MAIN POPULATION BRICKS	**Number of Multiple KWRC Bricks (full length cracks)**	Incomplete knowledge of stress state / brick strength	Damage progression may be different to HNB	0 multiply KWRC bricks observed	1-2 of the observed KWRC bricks are multiply cracked	3 or more multiply cracked
4) 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]
5) CHANNEL DISTORTION	**Channel Distortion - uncracked channel - and cracked channel with allowance for cracked brick - excluding edge channels**	Incomplete knowledge of whole core behaviour	Fuel movement / cooling or control rod entry could be impeded if channel distortions are large or there are large kinks / steps in the channels	Measured maximum channel bow is < 6 mm *(the current maximum observed)*	Measured maximum channel bow is up to 10 mm *(up to 2x current maximum)*	Measured maximum channel bow is > 10 mm
6) CHANNEL DISTORTION	**Change in Channel Distortion (repeat inspected channels)**	Incomplete knowledge of whole core behaviour	Fuel movement / cooling or control rod entry could be impeded if channel distortions are large or there are large kinks / steps in the channels	Change in channel bow of < 3 mm for repeat inspected channel	Change in channel bow between 3 mm and 5 mm for repeat inspected channel	Change in channel bow of > 5 mm for repeat inspected channel

Table 3. List of inspected channels [13]

Channel	Ring	Previous Inspection	Cracks Observed	Table
D19	9		0	
D27	9	2016	0	
E33	9		7	3
H31	6		4	4
J11	8		0	
J19	4	2014	3	5
J25	4		2	6
K37	7		0	
L07	9		5	7
L19	3	2018, 2003, 2000	0	
L29	3		0	
P11	7		1	8
P23	2		0	
P33	5	2009	1	9
P41	9	2016	1	10
Q15	5		0	
S13	7		6	11
S31	6	2017	1	12
S37	8		0	
T23	6	2009	0	
U17	8		0	
V27	8	2016	1	13
E35	10		0	
F15	8	1976 (TV only)	1	14
G09	10	2014, 2008	3	15
K43	10		0	
R41	10	2009	6	16
S09	9	2009, 2006	0	
T09	10	2009, 2006	6	17
V33	9		1	18
W23	9	2012	0	

Table 4. Summary of the 2019 inspection observations [13]

During the Hinkley Point B R3 2019 statutory outage inspections thirty one fuel channels (310 bricks) were inspected and measured. Thirteen fuel channels were repeat inspections. Sixteen fuel channels contained forty nine Type III defects in thirty two bricks. Five control rod channels (115 bricks) were TV inspected. The control rod channels contained no defects.

Inspection Summary			
Number of Fuel Channels Inspected	31		
Number of Fuel Channel Bricks Inspected	310		
Number of Fuel Channel Bricks with Defects	32		
Number of Control Rod Channels Inspected	5		
Number of Control Rod Channel Bricks Inspected	115		
Number of Control Rod Channel Defects	0		
Expected New Bore Cracks[1]	Most Likely	Range	
Expected New Type IIIC Axial Defects	1-2	7	
Expected New Double Full Height Axial Defects	0	3	
Expected New Type IIIC Circumferential Defects	6	2-12	
Numbers of Defects	Previous	New	Total[2]
Number of Type IIIA Axial Defects (Bore initiated)	6[2]	5	10
Number of Type IIIC Axial Defects (Bore initiated)	4	6[2]	10
Number of Type IIIA Circumferential Defects	2[2]	1	1
Number of Type IIIC Circumferential Defects	5	8[2]	13
Number of Type IIIA Secondary Defects	0	0	0
Number of Type IIIC Secondary Axial Defects	0	4	4
Number of Type IIIA Induced Axial Defects	0	1	1
Number of Type IIIC Induced Axial Defects	0	3	3
Number of Type IIIC Keyway Root Crack Defects	0	7	7
Number of Double Type IIIC Full Height Axial Defects[3]	1	2	3
Additional Inspections			
Number of Trepanned Samples Retrieved	36		
Number of Fuel Channels Inspected with PECIT	13		

[1] Quintessa Pre-inspection report QRS-3007O-4
[2] One Type IIIA axial crack was reclassified as a Type IIIC axial crack. Two Type IIIA circumferential cracks were reclassified as Type IIIC circumferential cracks.
[3] Double full height axial defects are included in the total number of Type IIIC axial defects.

Table 5. Best estimate and 99.9% confidence level CrackSim current forecasts at return to service (core burn-up 16621GWd) [17]

Case	*SCB*	*DCB*	*MCB*	*CO > 6mm outside*	*CO > 12mm outside*
Baseline	69 (191)	3 (12)	0 (2)	8 (33)	0 (1)
Fixed R3-R4 offset, No early cracking	93 (229)	3 (10)	0 (1)	6 (27)	0 (1)
No R3-R4 offset, Early cracking fraction	81 (239)	4 (15)	0 (2)	11 (41)	0 (2)
No R3-R4 offset, No early cracking fraction	108 (261)	3 (11)	0 (1)	8 (32)	0 (1)
No R4 conditioning	81 (239)	4 (15)	0 (2)	11 (40)	0 (2)
Wider prior	69 (192)	3 (12)	0 (2)	8 (33)	0 (1)

Table 6. Best estimate and 99.9% confidence level CrackSim forecasts at core burn-up of 16782GWd (~4 months operating period) [17]

Case	*SCB*	*DCB*	*MCB*	*CO > 6mm outside*	*CO > 12mm outside*
Baseline	98 (278)	4 (17)	0 (2)	15 (48)	0 (2)
Fixed R3-R4 offset, No early cracking	146 (339)	4 (12)	0 (1)	13 (48)	0 (2)
No R3-R4 offset, Early cracking fraction	118 (342)	5 (21)	0 (3)	18 (59)	0 (2)
No R3-R4 offset, No early cracking fraction	167 (380)	4 (13)	0 (1)	17 (57)	0 (2)
No R4 conditioning	118 (342)	5 (21)	0 (3)	18 (59)	0 (2)
Wider prior	98 (283)	4 (17)	0 (2)	15 (47)	0 (2)

Table 7. HSL predictions of the number of singly cracked bricks at different confidence levels and different operating periods [18]

			Time after restart (months)					
reactor	***percentile***	***at restart***	***3***	***6***	***9***	***12***	***18***	***24***
HPBR3	50	101	144	195	256	322	461	599
HPBR3	90	153	212	281	357	436	596	740
HPBR3	99	202	273	355	441	528	698	842
HPBR3	99.9	240	312	406	500	594	759	900

8 ANNEX(ES)

8.1 Annex 1: Highlight of some of the inspection observations

1. **S13**: the first KWRC was observed in this central fuel channel in brick layer 5. The channel had not been previously inspected. In this outage, it was found to contain:

    - A circumferential crack and a full height axial crack in brick layer 6.
    - A full height axial crack in brick layer 5.
    - A full height axial crack in brick layer 4.
    - A partial axial crack in brick layer 3.
    - Secondary damage to some end-face features.

    Figure A1.1 shows those defects. NGL sentenced the full height axial crack in brick layer 5 as a KWRC which has induced the other axial cracks. The circumferential crack in brick layer 6 was sentenced as a bore crack. I consider the sentencing to be in line with NGL's sentencing tree. However, in my opinion, the axial crack in brick layer 6 may not have conclusively been induced by the KWRC in brick layer 5 due to the cracks locations and the secondary damage to the end-face key at the bottom of the crack in brick layer 6. This highlights the potential difficulties in the classification of some cracks (because the timing of cracking is not known for some bricks) and hence there is some inevitable uncertainty in sentencing.

    I note that similar chains of interactions have been observed in HNB R3 and R4, but such chains were more widespread in HNB reactors compared to the current observations in HPB R3, indicating that KWRC in HPB R3 lags that of HNB reactors.

2. **E33**: this is a near edge (ie, ring 9) channel which had not been previously inspected. This channel contained the following defects:

    - A partial axial crack in layer 11.
    - A circumferential and a partial axial crack in layer 9.
    - A KWRC in layer 7 shown in Figure A1.2.
    - Two full axial bore cracks in layer 5 as shown in Figure A1.3 (this is a doubly bore cracked brick).

    Edge and near edge channels are expected to receive lower irradiation dose as opposed to the central channels as the flux is lower towards the boundaries of the core. The combination of a KWRC brick in layer 7 and a doubly bore cracked brick in layer 5 is surprising, because the layer 5 brick would be expected to have received a higher irradiation dose than the layer 7 brick. However, because this channel had not been inspected previously, it is not possible to know the age of the cracks. However, the cardioid plot of the doubly cracked brick in layer 5, illustrated in Figure A1.3, shows a distinctive lipping indicative of bore cracking. This distinctive shape is missing from the cardioid plot of the layer 7 brick, as shown in Figure 2, which was sentenced as a KWRC. I consider the sentencing of those cracks to be reasonable and aligned with NGL's sentencing tree.

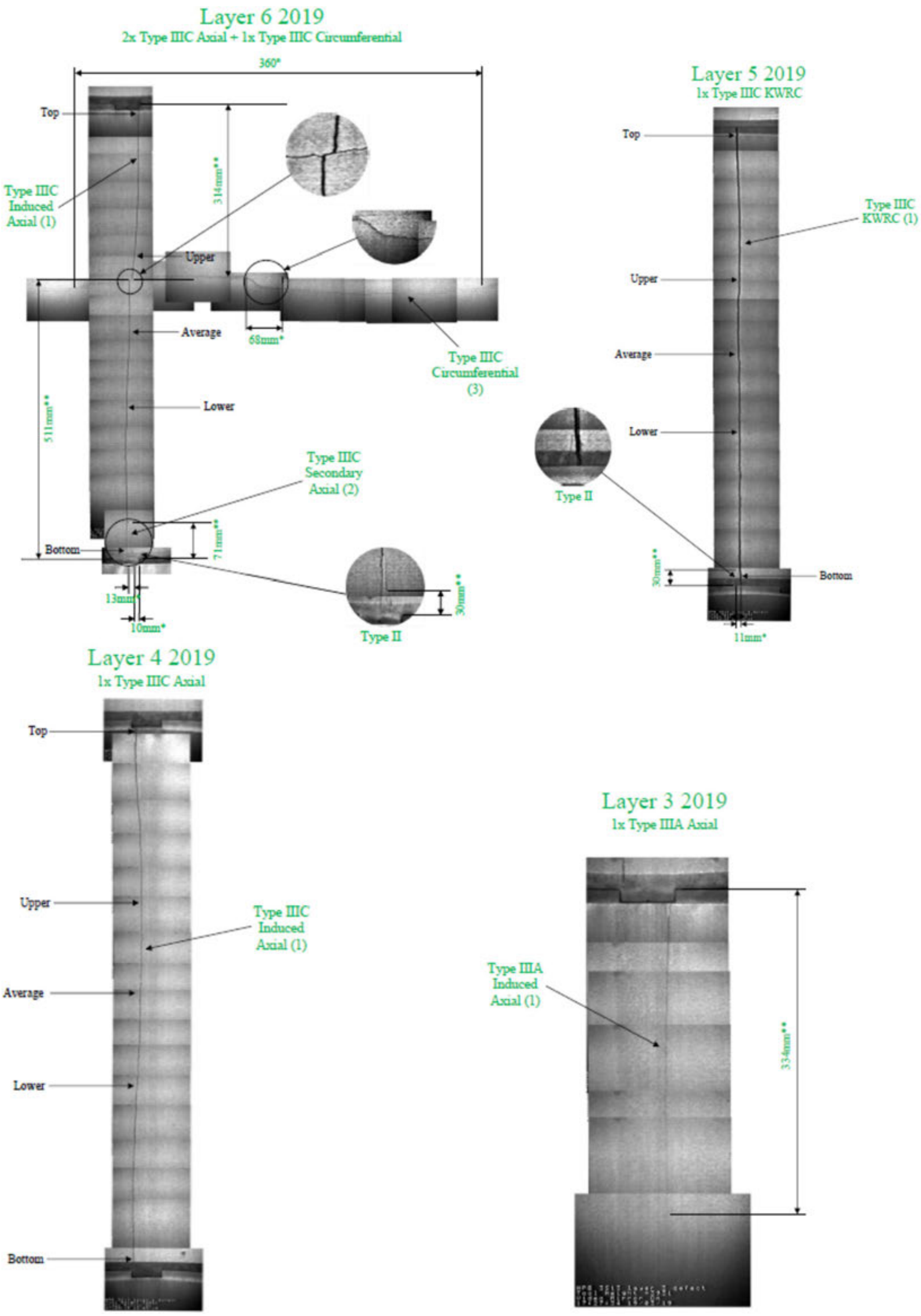

Figure A1.1. Observed defects in fuel channel S13 (HPB R3 2019)

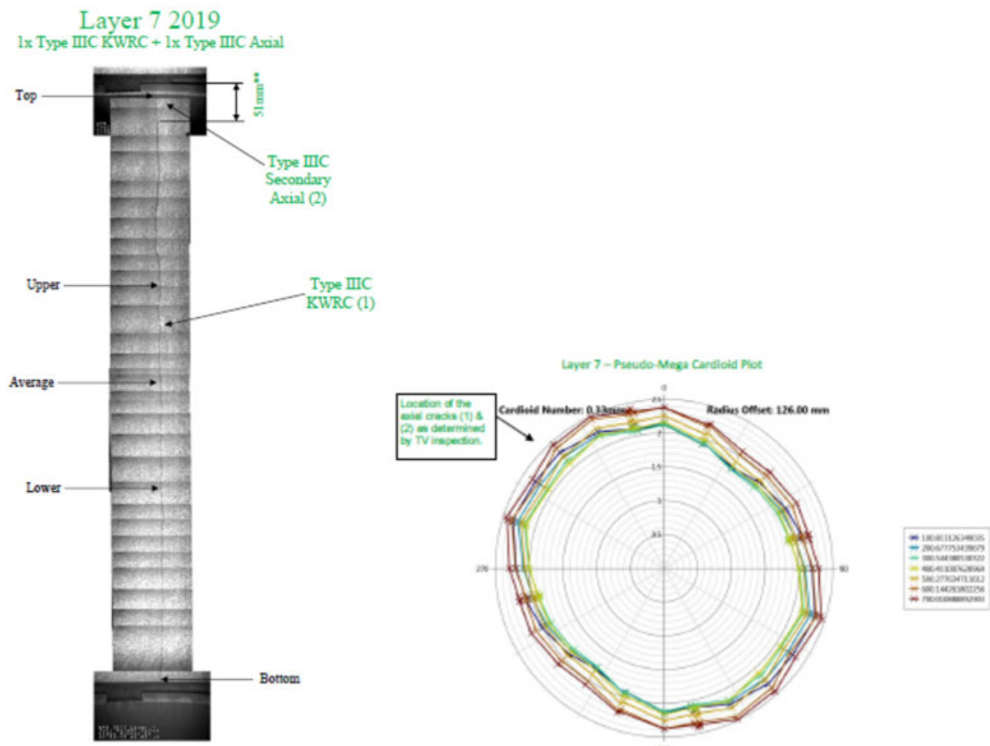

Figure A1.2. E33 KWRC in layer 7 and its cardioid plot

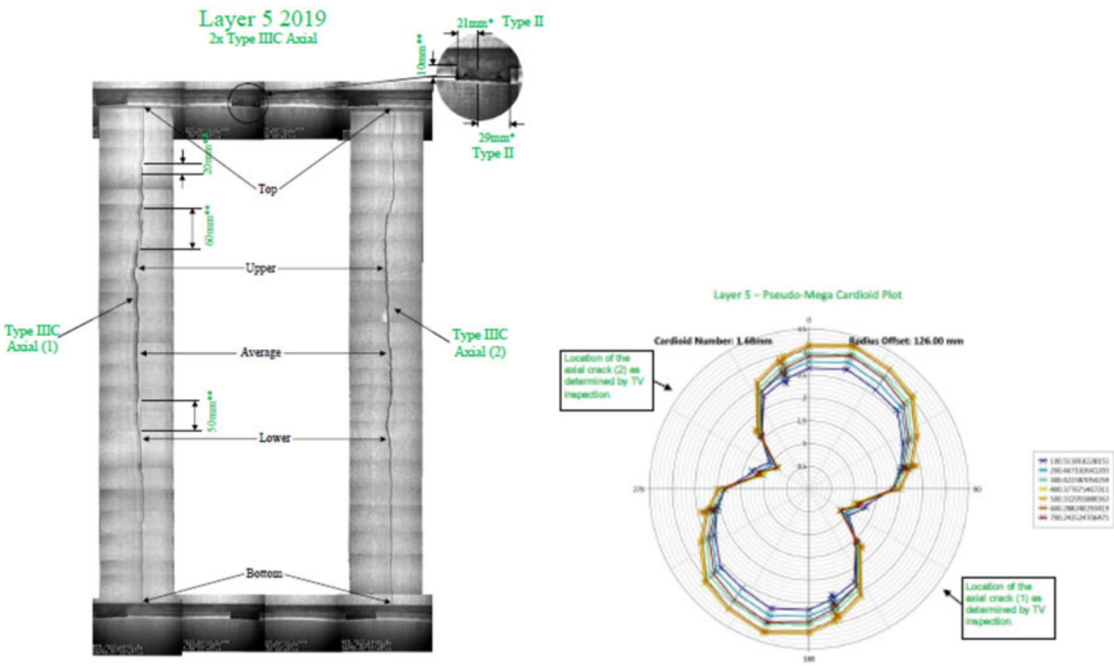

Figure A1.3. E33 doubly cracked brick in layer 5 and its cardioid plot

3. **T09:** This is a ring 10 double edge channel which had been inspected previously in 2009. In 2019 inspection, it was found to contain cracking in layers 4, 6, 7 and 9. At the time of the 2009 inspection, it had a single crack in layer 6. This is now accompanied by another full height axial crack approximately 135º away from the first crack in addition to secondary damage of the end-face key at the bottom of the original crack as shown in Figure A1.4. The other cracks in the other layers appear similar to those observed in 2009. Based on its bore shape and in line with its sentencing tree, NGL sentenced the cracks in layer 6 as bore cracks, making this brick a doubly bore cracked brick. However, this observation of a doubly bore cracked brick where the

cracks are not diametrically opposite each other is unusual, as most double bore cracks are diametrically imposed.

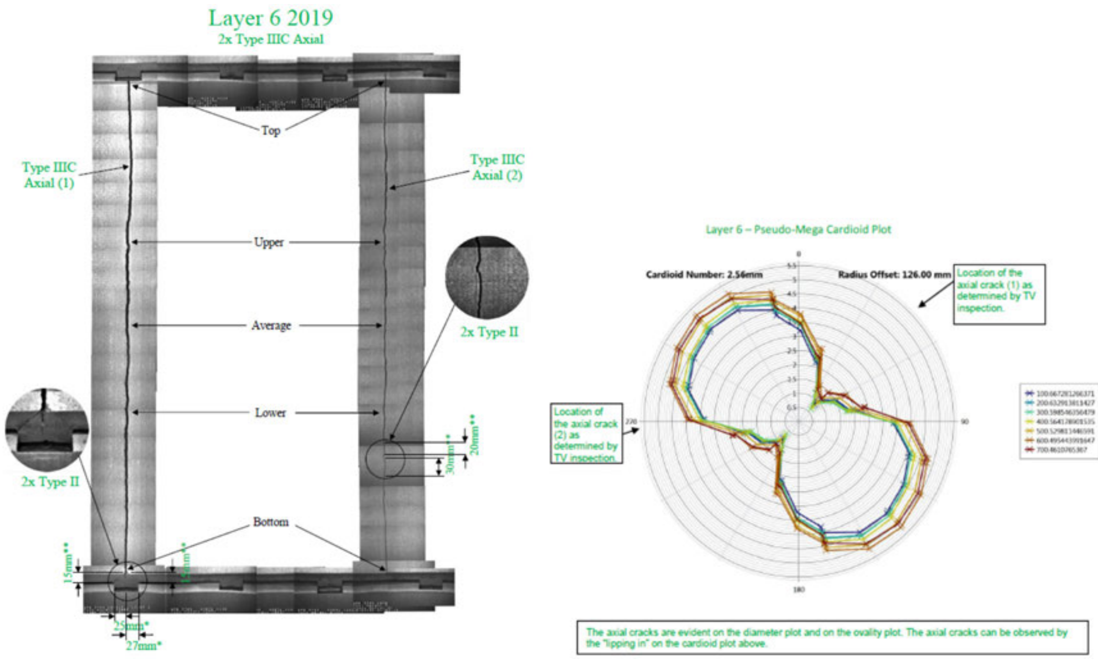

Figure A1.4. T09 doubly cracked brick in layer 6 and its cardioid plot (2019)