Office for Nuclear Regulation

Operating Facilities – Operating Reactors

Fault Studies Assessment of Hunterston B Power Station Reactor 3 Graphite Core Safety Case

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EXECUTIVE SUMMARY

EDF Nuclear Generation Limited has requested agreement from the Office for Nuclear Regulation under the arrangements made by the licensee under Licence Condition 22(1) to the modifications to the station safety case described in NP/SC 7766 Stage Submission 1 "*An Operational Safety Case for Hunterston B R3 to a Core Burn-up of 16.425TWd Following the 2018 Graphite Core Outage*".

Since Keyway Root Cracking was observed, the safety cases for the operation of the Hunterston B and Hinkley Point B graphite cores have been based on the principle of determining a damage tolerance level at which point the safety functions of the graphite core are demonstrated to be fulfilled. Then a lower Operational Allowance which if complied with will ensure a safety margin to the damage tolerance level. Under this safety case philosophy a Justified Period of Safe Operation is then determined from knowledge of the state of the cores informed by inspections and predictions of the rate of future cracking, demonstrating that the level of brick cracking will remain within the Operational Allowance throughout the Justified Period of Safe Operation. This approach has been accepted by the Office for Nuclear Regulation for previous safety cases.

The safety case submitted by EDF for agreement seeks to justify a Justified Period of Safe Operation for Hunterston B Power Station Reactor 3.

This assessment report has considered whether the submission adequately demonstrates that the Justified Period of Safe Operation should be Agreed. The arguments and evidence presented are largely the same as that presented for the recent graphite core safety case for Hunterston B Reactor 4, which was assessed by the Office for Nuclear Regulation. This assessment report has therefore taken account of the assessment performed on the Hunterston B Reactor 4 safety case to avoid replicating the assessment, and has focussed on determining if the conclusions of that assessment similarly apply to this assessment.

This assessment report concludes that the arguments and evidence presented in the submitted category 1 safety case NP/SC 7766 have adequately demonstrated that, from a fault studies perspective, it is acceptable for the Office for Nuclear Regulation to Agree to the Justified Period of Safe Operation for Hunterston B Reactor 3.

LIST OF ABBREVIATIONS

AGR	Advanced Gas-cooled Reactor
ALARP	As low as is reasonably practicable
BSL	Basic Safety level (in SAPs)
BSO	Basic Safety Objective (in SAPs)
CFD	Computational Fluid Dynamics
CPD	Channel Power Discrepancy
CCPD	Change in Channel Power Discrepancy
FGLT	Fuel Grab Load Trace
fpd	Failures per Demand
HNB	Hunterson B Power Station
HOSTAGE	The refuelling cooling model used to assess faults
HOW2	(ONR) Business Management System
IAEA	International Atomic Energy Agency
JPSO	Justified Period of Safe Operation
KWRC	Keyway Root Crack
LC	Licence Condition
MAP	Monitoring Assessment Panel
NGL	EDF Energy Nuclear Generation Limited
ONR	Office for Nuclear Regulation
PANTHER	PWR and AGR Neutronics and Thermal Hydraulics Evaluation Route
pry	Per Reactor Year
PSA	Probabilistic Safety Assessment
PSD	Primary Shutdown system
R#	Reactor number #
SACR	Super-Articulated Control Rod
SAP	Safety Assessment Principle(s)
SDM	Shutdown Margin
TAG	Technical Assessment Guide(s) (ONR)
WENRA	Western European Nuclear Regulators' Association

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1 INTRODUCTION

1. EDF Nuclear Generation Limited (NGL) has requested agreement from the Office for Nuclear Regulation (ONR) under the arrangements made by the licensee under Licence Condition 22(1) to the modifications to the safety case described in NP/SC 7766 Stage Submission 1 An Operational Safety Case for Hunterston B R3 to a Core Burn-up of 16.425TWd Following the 2018 Graphite Core Outage (Ref. 1).

2. This report presents the findings of the fault studies assessment of the Hunterston B Power Station (HNB) safety case for the operation of Reactor 3 to a core burn-up of 16.425TWd (Ref. 1) and the supporting documentation provided by NGL. Assessment was undertaken in accordance with the requirements of the ONR How2 Business Management System. The ONR Safety Assessment Principles (SAP) (Ref. 3), together with supporting Technical Assessment Guides (TAG) (Ref. 4) informed this report. The methodology for the assessment follows How2 guidance on mechanics of assessment within the Office for Nuclear Regulation (Ref. 7).

3. The graphite moderator core in an Advanced Gas Cooled Reactor (AGR) is made up of fuel channel bricks and interstitial bricks. The fuel channel bricks form the pathways in which the fuel stringers are inserted, and the interstitial bricks form the pathways in which the control rods are inserted (Figure 1).

4. Over the lifetime of the reactor the neutron doses to the graphite bricks lead to stresses being induced within the fuel channel bricks which can lead to cracks forming. A particular type of crack in the fuel channel bricks called Key Way Root Cracks (KWRC) are the dominant form of cracking late in reactor life, and were first observed at HNB in Reactor 3 (R3) in 2018. The reactors at HNB are periodically shutdown so that the fuel channel bricks can be inspected for cracks, giving a picture of the core condition.

5. Since KWRC was observed the safety cases for the operation of the Hunterston B (HNB) and Hinkley Point B graphite cores have been based on determining a Justified Period of Safe Operation (JPSO) expressed in core irradiation for each reactor; this approach has been accepted by ONR for previous safety cases (Ref. 14). The JPSO is determined from knowledge of the state of the cores from core inspections, and predictions of the rate of future cracking, such that the graphite cores can fulfil their safety functions at the predicted levels of cracking corresponding to the JPSO core irradiation limit with adequate margin.

6. HNB R3 remains shutdown since the graphite core inspections in March 2018 identified cracking in excess of that predicted, but within the demonstrated safety margin. NGL have now submitted a safety case (Ref. 1) seeking to justify operation of HNB R3 up to a core burn-up of 16.425TWd (roughly equivalent to 6 months further operation) at which point the reactor will be shutdown for further inspections. NGL have also presented analysis of the core degradation following ~12 months of operation in order to demonstrate the presence of a safety margin over the proposed operating period.

7. Graphite core inspections of the HPB and HNB reactors revealed that HNB R3 had the highest levels of core degradation across the four reactors. Recent safety cases for HNB R4 and the HPB reactors set JPSOs which allowed those reactors to operate up to equivalent levels of core degradation as currently found in HNB R3. Reference 1 now seeks to set a JPSO for HNB R3 (operation to 16.425TWd) which will mean that HNB R3 maintains the highest levels of core degradation amongst the four reactors. Extension to the operating periods for the HPB reactors and HNB R4 are not proposed in Ref. 1, and are outside the scope of this report.

8. As well as providing neutron moderation the graphite bricks are designed to ensure unimpeded movement of the fuel stringers and control rods, and to direct the gas flow to ensure adequate fuel cooling. This fault studies assessment report is focussed on ensuring that NGL has presented an adequate safety case to justify that the graphite core can adequately fulfil its safety functions with sufficient confidence in the presence of the predicted level of graphite brick cracking.

9. The safety case presented by EDF NGL (Ref. 1) does not propose any physical modifications to the plant, but simply seeks to justify that the aging effects of the graphite bricks does not challenge the capability of the reactor core to fulfil its nuclear safety functions.

2 ASSESSMENT STRATEGY

10. The intended assessment strategy for NP/SC 7766 Stage Submission 1 An Operational Safety Case for Hunterston B R3 to a Core Burn-up of 16.425TWd Following the 2018 Graphite Core Outage (Ref. 1) is set out in this section. This section identifies the scope of the assessment and the standards and criteria that have been applied.

11. This fault studies assessment is focussed on ensuring that NGL has presented an adequate safety case to justify that the nuclear safety functions of the graphite reactor core are maintained in the presence of graphite brick cracking over the next Justified Period of Safe Operation (JPSO).

12. The arguments and evidence presented in NGL's safety cases (Ref. 1) are largely the same – although structured differently - as those presented in NGL's recent safety case justifying operation of HNB R4; however, new evidence has been presented extending the safety case to higher levels of core degradation. I shall therefore refer to my assessment of the HNB R4 safety case (Ref. 9) where applicable and give a view on the applicability to HNB R3, rather than re-examine the same arguments and evidence. This report will therefore focus largely on the changes and developments from the HNB R4 assessment.

13. This report has considered the arguments and evidence in support of NGL's assertion that control rod entry will not be impeded during the proposed operating period (up to 16.425TWd) in fault scenarios, but consideration of control rod entry in normal operation and following a seismic event is outside the scope of this report, and is covered by a separate graphite assessment report. This report has also considered the arguments and evidence in support of NGL's assertion that the risk associated with fuel handling will not be significantly increased, and there will be no detriment to core cooling flows during the proposed operating period (up to 16.425TWd); NGL's ALARP arguments have also been considered.

2.1 Standards and Criteria

14. The relevant standards and criteria adopted within this assessment are principally the Safety Assessment Principles (SAP) (Ref. 3), internal ONR Technical Assessment Guides (TAG) (Ref. 4), 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.

2.2 Safety Assessment Principles

15. The key SAPs applied within the assessment are included within Table 1 of this report. The Fault Analysis series of SAPs has been used as a key source of relevant good practice for this fault studies assessment. The Reactor Core series of SAPs are relevant to this assessment as it is focussed on the behaviour and performance of the reactor core, and the Verification and Validation series of SAPs have been used when considering the adequacy of computer codes and mathematical models used to analyse fault transients.

2.2.1 Technical Assessment Guides

16. The following Technical Assessment Guides have informed my assessment strategy (Ref. 4):

- ONR-TAST-GD-034 Transient Analysis for DBAs in Nuclear Reactors

- ONR-TAST-GD-075 Safety of Nuclear Fuel in Power Reactors
- ONR-TAST-GD-042 Validation of Computer Codes and Calculation Methods
- ONR-TAST-GD-005 Guidance on the Demonstration of ALARP

2.2.2 National and International Standards and Guidance

17. The following international standards and guidance have been used to inform this assessment (Refs. 5 & 6):

- WENRA Safety Reference Levels for Existing Reactors
- IAEA SSG-2, Deterministic Safety Analysis for Nuclear Power Stations
- IAEA SSR-2/1 Rev 1, Safety of Nuclear Power Plants: Design

2.3 Use of Technical Support Contractors

18. No technical support contractors have been used in support of this assessment.

2.4 Integration with Other Assessment Topics

19. Assessment reports have been produced on this safety case on the topics of Fault Studies (this report), Graphite, and Civil Engineering. There is no direct overlap of scope between this report and the civil engineering report. This assessment report has interfaces with the graphite assessment as follows:

- The reliability of the Primary Shutdown System is claimed to be unaffected by the potential core distortion due to graphite brick cracking in normal operation or in seismic events as the core distortion is not significant enough to impede control rod movement. The graphite assessment report has examined the predicted levels of core distortion in normal operation and following seismic events, and its effect on the freedom of movement of the control rods, and seeks confirmation that the claim can be supported. If this claim is supported then there is no impact on the reliability of the Primary Shutdown System and thus no requirement for a fault studies assessment of the effects of a change in the reliability of the shutdown function in normal operation or following seismic events.
- The potential for graphite debris to partially obstruct the coolant flow through a fuel stringer has been considered in the safety case (Ref. 1). The graphite assessment has considered the likelihood of debris partially obstructing the coolant flow (as determined by NGL) while this fault studies assessment has considered predicted consequences, and how these, together with the likelihood, support the claims and arguments put forward by NGL.
- The potential for graphite debris to impede free movement of the fuel stringers during refuelling operations has been considered in the safety case (Ref. 1). The graphite assessment has considered the likelihood of the free movement of fuel stringers being impeded (as determined by NGL) while this fault studies assessment has considered predicted consequences, and how these, together with the likelihood, support the claims and arguments put forward by NGL.
- The potential for gaps to arise between fuel element sleeves due to core distortion or the effects of graphite debris has been considered in the safety case (Ref. 1). The assessment of the maximum size of the inter-element sleeve gap due to core distortion or graphite debris is covered in the graphite assessment report, and the assessment of the consequences of inter-element sleeve gaps is contained in this fault studies assessment report.

2.5 Out of Scope Items

20. This fault studies assessment report has focused on the potential effects of graphite cracking on the fuel including the implications in terms of fuel cooling, and free

movement of the fuel in refuelling operations. This report has also considered the free movement of control rods in fault scenarios. All other aspects of the safety case are outside the scope of this assessment report, but are considered in other ONR assessment reports, primarily the graphite assessment report.

3 LICENSEE'S SAFETY CASE

21. NP/SC 7766 Stage Submission 1 An Operational Safety Case for Hunterston B R3 to a Core Burn-up of 16.425TWd Following the 2018 Graphite Core Outage (Ref. 1) makes the following claims:

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

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

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

Claim 4: The combination of Super Articulated Control Rods (SACRs) and nitrogen is functionally capable of providing shutdown and holddown of a very distorted core.

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

22. The structure of NGL's safety case (Ref. 1) is laid out below with a summary of the supporting evidence. The level of detail I have provided for each argument below is proportionate to the relevance to this fault studies assessment report. Some topics are discussed in greater detail in Section 4 of this report where I have assessed the arguments and evidence presented.

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

24. The arguments and evidence presented under claim 1 describe the detail of the various calculation models and assessment methods which are used to provide the supporting evidence to the arguments under claims 2 & 3, and are not high level safety claims. The majority of these methods are not directly relevant to this fault studies assessment, and are relevant to the graphite specialist inspector's assessment. I list each of the arguments made under claim 1 below, but I will only expand upon those which are directly relevant to this assessment.

25. **Argument 1.1**: The state of the core can be conservatively established through sample inspections with extrapolation to the rest of the core.

26. **Argument 1.2**: Graphite material properties (including effects of in core ageing) are adequately predicted.

27. **Argument 1.3**: Degradation of the core over an operating period can be conservatively predicted.

28. **Argument 1.4**: Valid methods are available for conservatively determining control rod channel distortion in normal operation and all plant faults/hazards (excluding seismic hazard).

29. **Argument 1.5**: Valid methods are available for adequately determining control rod channel distortion in a seismic event.

30. **Argument 1.6**: The potential for core distortion to affect control rod entry or fuel movement, or cause fuel sleeve gapping, can be conservatively assessed.

31. **Argument 1.7**: Nuclear safety challenges affecting cooling of the fuel and the effects of weight loss on moderation can be reliably determined.

32. NGL states that the limit on the tolerable amount of fuel sleeve gapping has been derived using the PWR and AGR Neutronics and Thermal Hydraulics Assessment Route (PANTHER) code. NGL additionally states that the effects of sleeve gapping on the tie bar temperatures has been calculated using the HOSTAGE code.

33. NGL states that the potential effects on fuel cooling in the event of flow obstruction caused by graphite debris have been analysed using PANTHER, and validated against rig tests.

34. NGL states that the effects on the core flow pattern of fuel channel brick cracks is analysed using PANTHER.

35. **Argument 1.8**: Credible systematic degradation mechanisms not covered by the modelling have been considered.

36. **Argument 1.9**: monitoring techniques are available to identify issues between inspection outages.

37. NGL states that the condition of the graphite core can be monitored whilst the reactor is at power through analysis of several parameters (Fuel Grab Load Traces, Channel Power Discrepancies, control rod freedom of movement checks, control rod drop tests, coolant activity), and that these parameters are assessed at regular meetings of the Monitoring Assessment Panel (MAP).

38. **Argument 1.10**: Valid methods are available for determining the reliability of the Primary Shutdown system (PSD) to shutdown and holddown the reactor cores.

40. NGL describes the PANTHER based assessment route which is used to determine the amount of shutdown margin for a given core state. NGL states route demonstrates that the shutdown margin can accommodate random failures of control rods to insert.

41. **Argument 1.11**: Sensitivities to modelling assumptions are accounted for in the methods deployed.

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

43. **Argument 2.1:** The current state of the core had been conservatively established through extensive inspections and extrapolation to the rest of the core.

44. NGL states that the graphite core inspections which have taken place whilst the reactor has been shutdown (86 fuel channels total, plus 11 interstitial channels) are sufficient to determine a conservative core state to a 99.9% confidence level.

45. **Argument 2.2**: The predicted state of the core at the end of the proposed operating period has been conservatively established.

46. NGL states that the prediction models and sensitivity studies have been used to determine the levels of brick cracking expected after a further 6 months of operation, and a further 12 months of operation, and to determine the distribution of cracks with set opening ranges.

47. **Argument 2.3**: Core distortion at the end of the proposed operating period under normal operation and plant faults/hazards (excluding seismic hazard) has been conservatively predicted.

48. NGL states that there is no significant difference in core distortion between normal operation and following any plant faults, and states that the most significant core driving mechanism is that of a singly cracked fuel brick opening and thus displacing neighbouring bricks. NGL states that the effects of movement between the core, core restraint, and core support structures in faults leading to significant thermal transients has been examined as a potential core driver, and that in the most onerous scenarios the control rods have entered the core (leading to the thermal transient) prior to the transient occurring.

49. NGL gives the only other fault as having the potential to lead to core distortion prior to the control rods entering the core as an interstitial standpipe failure leading to a pressure boundary failure. NGL states that the resulting core distortion is not judged to be significant.

50. **Argument 2.4**: Graphite core degradation will not impede control rod entry within the proposed operating period, in normal operation or plant faults.

51. NGL presents the results of calculations of control rod entry margins, based on the core distortion calculations presented in argument 2.3.

52. **Argument 2.5**: Credible degradation mechanisms that are not explicitly modelled will not increase the risk of control rods being impeded.

53. NGL states that the effects of key disengagements and key failures are considered, but not explicitly modelled, and are not judged to challenge the validity of the results of the modelling.

54. **Argument 2.6**: Other nuclear safety issues related to graphite core degradation have been reviewed to confirm they do not undermine existing safety case assumptions.

55. NGL states that the effects of a loss of moderating material due to graphite weight loss have been determined and shown to be acceptable in a separate safety case.

56. NGL states that the assessments of fuel channel distortion show that there is negligible fuel sleeve gapping in normal operation and following non-seismic faults, with less than 1mm of sleeve gapping when summing the gaps across the entire fuel stringer predicted over the proposed operating period. NGL states that analysis of the thermal effects of fuel sleeve gapping has shown that up to 7mm of gapping across a stringer is tolerable, and that the assessments were done at nominal full reactor power, where the HNB reactors now operate at a maximum of 80% of nominal full power, giving a significant benefit to the fuel can temperatures.

57. NGL states that fuel sleeve gapping caused by debris stuck between the fuel stringer and the fuel channel wall is not expected, as any graphite debris would be friable and unable to impart significant force to the stringer. NGL additionally states that a geometric analysis of the fuel channel suggests that such fuel sleeve gapping if it occurred would be less than 2mm.

58. NGL states that the effects of fuel sleeve gapping on the tie bar are most onerous during a stuck fuel fault whilst fuel handling, and that analysis has shown that a 6mm gap at the most onerous location on the stringer would have a negligible impact on the risk of tie bar failure.

59. NGL states that the effects of a disruption in gas flow due to effects such as fuel brick cracking, tilting, and dished brick ends, have been assessed and shown to be insignificant.

60. NGL describes the potential for debris to become lodged in the fuel stringer, and to potentially cause high fuel clad temperatures. NGL states it is an unlikely series of events which would lead to such a fault, and also unlikely that any escalation routes would lead to significant radiological consequences.

61. NGL states that the potential for core distortion to lead to an interaction between the fuel sleeve and the fuel channel bricks is not a threat to fuel sleeve integrity due to the large load capacity of the fuel sleeve, with analysis suggesting such an interaction would only use ~4% of the capacity.

62. NGL states that the predicted core distortion over the operating period will not lead to any significant increase to the risk of fuel handling faults.

63. **Argument 2.7**: Monitoring provides diverse confidence, safeguarding against inadequate conception in the core condition and damage tolerance assessments.

64. NGL argues that significant core distortion would be detected using monitoring techniques before it threatens the capability to shutdown and holddown the reactor. And that significant fuel sleeve gapping would be detected via monitoring techniques.

65. **Argument 2.8**: The safety case legs together ensure a low level of nuclear safety risk. There are adequate margins and a lack of cliff edges (e.g. common mode failure).

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

67. **Argument 3.1**: The core state at the end of the JPSO has been conservatively established.

68. NGL states that the core state has been predicted to a 99.9% confidence.

69. **Argument 3.2**: The response of the graphite core to seismic excitation has been predicted with confidence.

70. NGL states that the seismic analysis has used core states which bound those that are predicted to develop over the operating period.

71. **Argument 3.3**: All control rods will enter the core under bottom-line seismic faults.

72. NGL states that the seismic analysis returns acceptable margins for control rod entry for all control rods during the bottom-line seismic event.

73. **Argument 3.4**: Following a bottom line seismic event, normal gas flow patterns will be maintained to ensure fuel temperatures remain acceptable.

74. NGL states that the reactor would have tripped upon a seismic event either through the actions of the protection system in response to a transient, or through operator action. Once the reactor has tripped NGL argue that the cooling requirements are reduced, and therefore the risk of elevated fuel temperatures is also reduced. NGL additionally states that the fuel sleeve integrity is not challenged by a seismic event.

75. **Argument 3.5**: Monitoring techniques will be employed within the proposed operating period to identify if core degradation is significantly outside the basis of this proposal.

76. NGL states that the monitoring techniques could detect if significant core distortion was to occur, or if there was a significant increase in brick cracking.

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

78. **Argument 4.1**: SACRs will insert into a very distorted core.

79. NGL states that finite element analysis techniques and rig tests have demonstrated that SACRs can enter into a channel at the upper conservative limit of the total bow in a control rod channel, with little impact on its insertion time.

80. **Argument 4.2**: SACRs will shutdown and holddown (short term) the reactor even if no other rods insert.

81. NGL states that the SACRs are only capable of shutdown and short-term holddown, which NGL define as a few hours following shutdown in which some limited change in xenon concentration may occur. NGL claims that the probability of the SACRs alone failing to provide short-term holddown is $2x10^{-4}$ failures per demand (fpd).

82. **Argument 4.3**: The seismically qualified nitrogen system will provide adequate holddown (long term).

83. NGL states that the nitrogen system has been designed to provide long term holddown to two reactors simultaneously even when a reduced number of control rods are inserted into the core, and that the system is seismically qualified. NGL states that the reliability of the nitrogen injection system is $1x10^{-2}$ fpd, and is assessed to be ~$2.73x10^{-2}$ fpd following a seismic event.

84. **Argument 4.4**: The protection is resilient to more severe levels of earthquake.

85. NGL states that the core distortion analysis has remaining margin such that a more severe seismic event could be tolerated, and that a review of the seismic qualification of the nitrogen system found no cliff edges in its capability to withstand an event beyond the bottom-line seismic event.

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

87. **Argument 5.1**: Residual risk is small.

88. NGL states that the station Probabilistic Safety Assessment (PSA) gives a probability for a radiological release leading to doses to the public of >1000mSv of ~$1x10^{-5}$ per reactor year (pry), and that if the probability of the PSD failing to shutdown or holddown the reactor was increased by an order of magnitude then the risk of a radiological release such as that discussed would increase to ~$2x10^{-5}$ pry.

89. NGL states that the reliability of the PSD only needs to be better than $1x10^{-3}$ fpd to reduce the probability of a radiological release leading doses to the public of >1000mSv following a bottom line seismic event to <$1x10^{-7}$ pry, even before the contributions of the SACRs and nitrogen system are considered.

90. NGL states that the PSA derived frequency of failure to shutdown following a bottom-line seismic event is <$1x10^{-8}$ pry, and the frequency of a failure to holddown following a bottom-line seismic event is <$4x10^{-9}$ pry.

91. **Argument 5.2**: All reasonably practicable measures to reduce risk further have been considered and implemented to this point and the future strategy is consistent with the ALARP principle.

92. NGL states that the SACRs and improvements to the nitrogen plant were implemented as risk reduction measures to address graphite core degradation. NGL state that an increase in the number of graphite inspections would have a small benefit, but with a large associated cost, and an associated risk from the additional fuel handling operations required.

93. NGL presents consideration of the potential to increase the shutdown margin (SDM) to increase the tolerance to rods failing to insert, but states that this would lead to operational difficulties. NGL also states that operation of the reactor with grey rods further withdrawn would increase the available SDM, but would also lead to operational difficulties.

94. NGL states that a graphite inspection tool has been developed to inspect control rod channels which it is stated will lead to better validation of the core state. NGL states that plans to improve the reliability of the nitrogen injection system are in place, and aim to reach a reliability of 1×10^{-3} fpd. NGL state that consideration is being given to the implementation of a boron dust injection system, which would provide additional defence in depth for long term holddown.

4 ONR ASSESSMENT

95. This fault studies assessment is focussed on determining whether NGL has presented an adequate safety case to justify that the nuclear safety functions of the graphite reactor core are maintained over the Justified Period of Safe Operation (JPSOs) for the HNB R3 (up to a core burn-up of 16.425TWd).

96. The nuclear safety functions of the graphite reactor core as stated by NGL are:

- Allow unimpeded movement of control rods and fuel,
- Direct gas flows to ensure adequate cooling of the fuel and core,
- Provide neutron moderation and thermal inertia.

I agree that these are the fundamental nuclear safety requirements on the graphite core, and thus my expectations are that NGL adequately demonstrate that these functions are fulfilled up to a core burn-up of 16.425TWd, in accordance with SAPs FA.4 & ERC.1, and that there is no cliff edge in consequences beyond this core burn-up as per SAPs FA.7 & ERC.3.

97. I will structure this report into sections focussed on each of the nuclear safety requirements on the graphite core.

98. Claim 1 of NGL's safety case (Ref. 1) presents arguments and evidence seeking to justify that the codes and methods used in analysis supporting the safety justifications presented in the other claims are acceptable. I will discuss the relevant arguments and evidence presented in Claim 1 in sections 4.2 and 4.3 of this report.

99. Claim 2 of NGL's safety case presents arguments and evidence in support of the assertion that following the proposed period of operation, control rod entry, fuel movement, and fuel cooling are acceptably ensured in normal operation or following non-seismic faults. I will discuss the arguments and evidence relevant to this fault studies assessment in sections 4.1 and 4.2 of this report.

100. Claim 3 of NGL's safety case presents arguments and evidence seeking in support of the claim that the reliability of the PSD in a seismic event will not be affected by deterioration of the graphite core over the proposed operating period. Claim 3 also presents arguments and evidence to demonstrate that fuel cooling will be adequately ensured following a seismic event over the propose operating period. I will discuss the aspects of Claim 3 relevant to this fault studies assessment in sections 4.1 and 4.2 of this report.

101. Claim 4 of NGL's safety case presents arguments and evidence in support of the assertion that the SACRs and the nitrogen injection system are capable of reactor shutdown and holddown. This claim aims to provide a demonstration of the defence in depth available in the plant design, and there are no changes to the existing plant or safety case, as such I do not discuss this claim in this report.

102. The ALARP arguments presented in Claim 5 of NGL's safety case are relevant to the topics discussed in my assessment of Claims 2 & 3, and I have therefore discussed them where appropriate in the relevant sections of this report.

103. The scope and structure of this assessment report is as follows:

- Assessment of the requirement to allow unimpeded movement of control rods and fuel (Section 4.1)
  - Control rod movement
  - Fuel movement

- Assessment of the requirement to direct gas flows to ensure adequate cooling of the fuel and core (Section 4.2)
  - The effects of changes in coolant flow paths due to cracking
  - The effects of channel distortion – eccentric annulus
  - The effects of channel distortion – sleeve gapping
  - The potential effects of debris
- Assessment of the requirement to provide neutron moderation and thermal inertia (Section 4.3)
  - The potential effects of brick cracking on the neutron flux distribution

104. Previous graphite safety cases have been assessed by ONR, and a recent fault studies assessment (Ref. 9) was undertaken on NGL's safety case for the return to service of HNB R4 following core inspection results in 2018 (Ref. 10). The HNB R4 safety case employed many of the same arguments and evidence presented in NGL's safety case for the operation of HNB R3 (Ref. 1) and thus I shall refer to the assessment of the HNB R4 safety case and its conclusions extensively within this report.

105. The ONR fault studies assessment of the HNB R4 safety case (Ref. 9) concluded that operation of HNB R4 was justified up to a core burn up corresponding to an equivalent level of core damage as HNB R3, and that further justification would be required to operate HNB R4 past a level of core damage equivalent to HNB R3 as of the 2018 inspections. The HNB R3 safety case (Ref. 1) is clearly moving the level of core damage beyond that considered in the HNB R4 assessment; I shall therefore discuss whether I consider the conclusions of the HNB R4 assessment are applicable and the reasons for this, where appropriate.

4.1 Allow unimpeded movement of control rods and fuel

106. Cracking of the graphite core bricks has the potential to increase the freedom of movement of the graphite components within the core and thus potentially lead to greater core distortion. The control rods and the fuel are inserted into the graphite core through channels in the graphite bricks and thus significant core distortion could lead to impeded movement of the control rods and the fuel as the channels become increasingly distorted.

4.1.1 Control rod movement

107. Should the freedom of movement of the control rods be significantly impeded then there is the risk that insufficient numbers of control rods enter the core on demand and that the reactor is not shutdown. This then would potentially lead to a large offsite release as a trip demand will move the plant systems into post-trip cooling configuration when the reactor hasn't shutdown such that the cooling is insufficient. My expectation is that NGL should demonstrate that no control rods are impeded due to core distortion in any operating state or fault scenario in accordance with Requirement 44 of IAEA SSR-2/1 such that the reliability of the shutdown function is not affected.

108. It should be noted that normal operating procedures for the AGRs require a demonstration that the shutdown function will be secured even in the event of the most onerous (highest reactivity worth) two control rods failing to insert. This approach has been applied throughout the operational life and graphite core ageing mechanisms will not degrade this margin.

109. Claims 2 & 3 of NGL's safety case (Ref. 1) state that core distortion will not prevent successful insertion of the control rods during normal operation, plant faults or

following a seismic event over the proposed operating period (up to a core burn-up of 16.425TWd).

110. Consideration of whether NGL's safety case has adequately demonstrated that the control rods insert in normal operation and following a seismic event is the main focus of the ONR graphite specialist inspector's assessment report. In my view the graphite specialist inspector should be satisfied that NGL have adequately demonstrated that all control rods will insert in normal operation and following a design basis seismic event prior to ONR agreeing to the modifications to the safety case described in Reference 1.

111. **Recommendation 1**: Prior to ONR agreeing to the modifications to the safety case described in Reference 1, the project inspector should confirm that the graphite specialist inspector is satisfied that NGL have adequately demonstrated that all control rods will insert in normal operation and following a design basis seismic event.

112. NGL reviewed the potential for control rod insertion to be impeded during plant faults (Ref. 11) and concluded that for all but a potential depressurisation fault due to a control rod standpipe failure the control rods would have inserted into the core by the time any core distortion occurred. The arguments and evidence presented in Ref. 1 are the same as those presented for the recent HNB R4 graphite core safety case (Ref. 10), these arguments and evidence were assessed by ONR (Ref. 9) and the assessment report concluded that NGL's arguments could be supported.

113. In my view the conclusions of Ref. 9 are applicable to this assessment report, as the justification that no control rods would be impeded in plant faults depended on the fact that the rods would have inserted into the core by the time any core distortion occurred, and this is independent of the level of core degradation.

114. NGL states that an interstitial channel standpipe failure could lead to core distortion prior to the control rods inserting, but state that the integrity of the interstitial channel graphite bricks would mean that any resulting core distortion would not be significant. The assessment of the HNB R4 safety case (Ref. 10) considered that further technical work which was being undertaken by NGL to better understand the effects on core distortion of a depressurisation fault should be included in future safety cases for the operation of HNB R4 beyond the 4 month operating period proposed in that case. Regulatory issue 7300 was raised to track the progress of the technical work.

115. In my view the above recommendation of Ref. 10 is equally applicable to HNB R3, and therefore I expected that the outcome of the technical work to better understand the impact of a depressurisation fault on core distortion would be available to support the justification of further operation of HNB R3.

116. The results of the technical work undertaken by NGL which addresses regulatory issue 7300 are presented in Ref. 12 which concludes that consideration of the flow paths within the core suggests that there would not be significant core distortion following an interstitial channel standpipe failure. The evidence presented in Ref. 12 is qualitative in nature, but relies on well-established understanding of the characteristics of chocked fluid flow, and in my view provides evidence to support NGL's arguments on the core distortion effects of a control rod standpipe failure. Ref. 12 suggests that further computational analysis of the situation would provide further confidence in the conclusions and as such I intend to leave regulatory issue 7300 open pending further discussions with NGL.

117. In my view, the conclusions of Ref. 12 are approximately independent of the core condition as long as the interstitial channel bricks in the affected channel remain intact; as there is no systematic cracking predicted in interstitial channels, and currently no cracks have been observed in interstitial channels, I judge that there is a demonstrated

lack of a cliff edge in the expected progression of core degradation for core distortion following plant faults, and that the expectations of SAP ERC.3 have been met. I note however that there is a potential cliff edge in consequences from a standpipe blowout fault if the interstitial channel integrity was compromised, and have confirmed with the graphite specialist inspector that there is confidence that interstitial channel integrity is very unlikely to be compromised by core degradation over the proposed ~6 month operating period (Ref 13).

118. In my view NGL have provided sufficient evidence to demonstrate that the expectation that there be no impediment to the free movement of control rods as per IAEA SSR-2/1 Rev 1 Requirement 44 (Ref. 6) has been met for all plant faults.

119. As NGL have demonstrated that there would be no impediment to the free movement of control rods, there is also no change to the capability of the control rods to fulfil the shutdown function, and no change to the level of shutdown margin. The second line of protection provided by the super-articulated control rods and the nitrogen injection system is also secure; I therefore judge that the expectations of SAP ERC.2 - that two diverse systems should be provided for shutting down a reactor, and that a suitable shutdown margin should be maintained - have been met.

120. The arguments and evidence presented in the HNB R3 safety case (Ref. 1) in order to justify that there are no further ALARP improvements to be made with respect to improving the shutdown function reliability are the same as those presented in the recent HNB R4 safety case (Ref. 10). The ONR assessment of the HNB R4 safety case (Ref. 9) concurred with NGL's judgement that there are no reasonably practicable improvements which could be made to reduce the risks associated with failure to shutdown. I therefore conclude that, since the primary shutdown reliability is not affected, the same applies to HNB R3.

4.1.2 Fuel movement

121. Graphite brick cracking has the potential to increase the core distortion which may impede the movement of fuel. Additionally debris produced due to graphite brick cracking could cause an obstruction and lead to fuel snags or ledges. If fuel were to become stuck during fuel movement then there is an increased probability of the fuel being dropped which would likely lead to fuel damage, and a release of radioactive isotopes into the primary circuit. The consequences of a fuel movement fault are much lower than the potential consequences of failing to shutdown the reactor (which is the largest potential consequence of graphite brick cracking in NGL's safety case, Ref. 1). However the risks are still significant and need to be demonstrated to be ALARP.

122. The HNB R3 safety case presents evidence seeking to demonstrate that fuel movements would not be significantly impeded up to levels of core damage significantly in excess of that predicted over the proposed ~6 month operating period. In my view this is an adequate demonstration that there is a lack of cliff edge in the consequences in proximity to the operating envelope, and meets the expectations of SAP ERC.3.

123. The ONR assessment of the HNB R4 safety case (Ref. 9) concluded that NGL had demonstrated that a hypothetical 10 fold increase in fuel snag frequency was still tolerable when assessed against the SAPs Numerical Targets (NT.1 Target 8); in my view this is equally applicable to HNB R3 as the fuel route risk is comparable across the two reactors and was calculated as risk per reactor year (i.e. based on the risk of refuelling operations over a year, not over the four month period justified in the case). This gives a large margin to accommodate any increase in fuel handling risk due to debris. NGL states that any increase in fuel snag frequency from core distortion or graphite debris would be small. In my view the graphite specialist inspector should be satisfied that NGL have adequately demonstrated that there would not be a significant

increase in fuel snag frequency from core distortion or graphite debris over the proposed ~6 month operating period prior to ONR agreeing to the modifications to the safety case described in Reference 1.

124. **Recommendation 2**: Prior to ONR agreeing to the modifications to the safety case described in Reference 1, the project inspector should confirm that the graphite specialist inspector is satisfied that NGL have adequately demonstrated that there will be no significant increase in fuel snag frequency from core distortion or graphite debris (compared to that presented in the most recent HNB R4 safety case) over the proposed JPSO up to 16.425TWd.

125. For the HNB R4 case, NGL judged that suspending low power refuelling and moving to offload refuelling was not reasonably practicable (Ref. 10). This was based on the decrease in risk relating to the removal of “failure to trip” and “failure of post trip cooling” fault sequences being comparable with the increase in risk from increased demands on the reactor protection systems. NGL judges that this argument is equally valid for HNB R3 as they claim that an increase in fuel snag frequency is unlikely over the ~6 month period of operation. This sensitivity study for HNB R4 was carried out considering risk per reactor year and not specifically relating to the four month period. Therefore, assuming that an increase in fuel snag frequency is very unlikely (and this is supported by the graphite inspector), I support the judgement that moving to offload refuelling is not reasonably practicable over the ~6 month period.

126. In addition, EDF NGL has now implemented improvements to fuel grab load trace trending. A digital overlay has been produced which will potentially highlight any load traces which fall outside of normal observation in a manner which might indicate core distortion. This could provide capability to detect instances of potential or likely impedance of fuel due to core distortion. There is no guarantee that this modification will improve the reliability of fuel grab load trace trending but I judge this to be a worthwhile ALARP modification. I therefore judge that the evidence presented adequately demonstrates that the risks associated with fuel handling are acceptable.

127. Other considerations with respect to fuel handling are:

- The effect of debris on sub veto height faults
- Increased fast neutron dose to fuel sleeves potentially resulting in an increase to hangman’s drop distances in a ledge and release fault
- The potential for the tie bar guide tube to become blocked due to the effects of graphite dust

128. The above considerations were assessed in ONR’s assessment of the HNB R4 safety case (Ref. 9), which concluded that the risks were acceptable and ALARP. For sub veto height faults, the arguments made by NGL are insensitive to core degradation and therefore the conclusions of the ONR assessment of the recent HNB R4 safety case (Ref. 9) are applicable.

129. In relation to increased fast neutron dose, NGL had written a safety case to reduce the irradiation limit for fuel shuffling. For the assessment of HNB R4 return to service (Ref. 9) I confirmed with EDF NGL that this safety case, and associated technical specification change, had been implemented (Ref. 10). This change equally applies to Reactor 3; I have therefore not considered this any further.

130. With regards to graphite dust, Ref. 9 concluded that it is extremely conservative to assume that all of the stringers in the core have blocked tie bar guide tubes as no blocked guide tubes have been observed in the AGR fleet and analysis of the consequences of tie bar guide blockage for other sites should bound the position at Hunterston B due to its lower refuelling power and lower levels of carbon deposition. The risk for the conservative scenario of all the tie bar guide tubes being blocked was

estimated to be of the order of the Target 8 BSL. I have received advice from the graphite specialist inspector that the increase in the amount of dust in the primary circuit of R3 during this operating period is expected to be small compared to the existing dust load (Ref. 13), and therefore I judge that that the limited increased potential for blockage of the tie bar guide tubes does not invalidate the fuel handling safety case over the proposed operating period (consistent with the conclusion reached in Ref. 9 for R4).

131. The approach taken in the HNB R3 safety case (Ref. 1) is consistent with the approach taken for the recent HNB R4 safety case (Ref. 10). I have considered above the effect of the more advanced core state for HNB R3 and I consider EDF NGL's judgement that the risks associated with fuel handling have been reduced ALARP to be valid. This judgement is conditional on the project inspector confirming with the graphite inspector that a significant increase in fuel snag frequency is very unlikely over the ~6 month operating period up to 16.425TWd (Recommendation 2).

4.2 Direct gas flows to ensure adequate cooling of the fuel and core

132. Increased cracking of the graphite bricks has the potential to change the gas flow paths within the core; this has the potential to reduce the cooling of core components and fuel. My expectations in this regard are that the safety case should demonstrate that sufficient coolant flow should be maintained to ensure that fuel and core component temperatures remain within their operational limits in accordance with SAP EHT.2, and that in the event of a fault there are sufficient barriers to a radiological release remaining, in accordance with SAP FA.7.

4.2.1 Arrow head to annulus flow

133. The gas flow paths within the graphite core are complex, and a large part of the total gas flow takes a route through the gaps between graphite bricks in order to keep the graphite bricks cool, this is called re-entrant flow. One aspect of the re-entrant flow is that it flows from the area called the arrow-head passage on the outside of the fuel channel bricks (graphite bricks which form the channels through the graphite core into which the fuel stringers are inserted) to the inside of the fuel channel bricks, in to an area between the bore of the fuel channel brick and the outside of the fuel stringer's graphite sleeve, called the annulus (Figure 6).

134. Cracking in the fuel channel bricks has the potential to lead to an increase in the flow from the arrow-head passage to the annulus as it may create new flow paths to pass through the fuel channel brick. I expect that NGL should demonstrate that the fuel clad temperatures are maintained within the operational limit in normal operation and that fuel clad integrity and fuel sleeve integrity are maintained in all fault scenarios in accordance with SAPs FA.7 & EHT.2.

135. If fuel sleeve integrity were not maintained then the coolant gas flow path in the stringer would be disrupted which could potentially lead to overheating of the fuel clad. If fuel clad integrity were to be lost then radioactive contamination would be released into the primary coolant, this would not lead to any significant off-site radiological consequences if only a small number of fuel pins were to fail.

136. The arguments and evidence presented in the HNB R3 safety case (Ref. 1) are the same as those presented in the recent HNB R4 safety case (Ref. 10). ONR's assessment (Ref. 9) of the recent HNB R4 graphite core safety case examined the arguments and evidence relating to the effects of brick cracking on the arrow head to annulus flow, and concluded that NGL adequately demonstrated that the effects of increased arrow-head to annulus flow due to brick cracking are acceptable and are independent of the number of brick cracks. I therefore conclude that the expectations of SAPs FA.7 & EHT.2 have been met in NGL's safety case for HNB R3 (Ref. 1), and

that the effects of arrow-head to annulus flow do not present an impediment to the operation of HNB R3 for the proposed ~6 month period (up to a core burn-up of 16.425TWd).

4.2.2 Channel distortion

137. Increased cracking of the graphite core has the potential to increase the freedom of movement of the graphite components within the core and thus potentially lead to greater core distortion. The fuel sits within the graphite core in channels in the graphite bricks and thus distortion of these fuel channels could lead to changes in the shape of the annulus (the gap between the fuel channel bore and the outside of the fuel sleeve), and thus changes to the flow paths around the fuel sleeve.

138. The design intent is that the fuel elements form a rectilinear free-standing column supported from below and sited concentrically within the fuel channel (see Figure 3 for a depiction of the column of elements). Figure 5 shows how elements are held in alignment by their lower sleeve ends fitting into the sleeve of the element below. If the fuel channel walls distort there would be changes to the shape of the annulus and to flow paths. If the degree of distortion was large, it is possible that that fuel channel bricks could touch an element pushing the column out of the intended alignment. This could open up gaps between fuel elements with the potential to impair cooling of the fuel.

Eccentric Annulus

139. If the annulus was perfectly concentric then the gas flows down the annulus would be approximately symmetric, and thus the cooling of the fuel sleeve would be approximately even around the circumference of the sleeve. The effects of fuel channel distortion could be to make the annulus eccentric such that the size of the flow path on one side of the annulus is larger than the other, and thus the cooling of one side of the fuel sleeve would be reduced, and the other increased.

140. Failure of the fuel sleeve would lead to a disruption to the coolant flow paths similar to that for gaps between the fuel sleeves as discussed later, however failure of the fuel sleeve may have a greater effect than sleeve gaps. It is also plausible that failure of the fuel sleeve could produce graphite debris which could cause disruption to the coolant flow, the consequences of which would be similar to those discussed in Section 4.2.3. I therefore expect that NGL's submission should demonstrate that there are large margins to the failure of the fuel sleeve, and that the expectations of SAP EHT.2 that coolant flow should maintained within limits, are met.

141. The most limiting case for annulus eccentricity is if the fuel stringer sleeve were to be touching the fuel channel bore on one side for the entire length of the channel. Reference 15 presents the results of NGL's analysis of the effects of annulus eccentricity on fuel channel brick temperature, fuel sleeve temperature and fuel clad temperature.

142. The arguments and evidence presented in the HNB R3 safety case (Ref. 1) are the same as those presented in the recent HNB R4 safety case (Ref. 10) and seek to demonstrate that the peak fuel temperature and peak fuel channel brick temperature are within acceptable limits, and that the fuel sleeve temperature does not reach a point at which the sleeve integrity would be threatened.

143. ONR's assessment (Ref. 9) of the recent HNB R4 graphite core safety case examined the arguments and evidence relating to the effects of an eccentric annulus on fuel clad and fuel sleeve temperatures and judged that the effects of annulus eccentricity were acceptable, and that NGL had taken adequate account of the effects of annulus eccentricity in fault conditions. I therefore conclude that NGL's safety case for HNB R3

(Ref. 1) has demonstrated that the effects of an eccentric annulus on fuel sleeve and fuel clad temperatures are acceptable, and that the expectations of SAP EHT.2 have been met. My conclusions in this regard are largely independent of the condition of the graphite core as the consequence assessment has considered a bounding condition.

<u>Sleeve Gapping</u>

144. The fuel stringer sleeve directs the coolant gas flow over the fuel pins in order to ensure adequate fuel cooling. The fuel elements consist of 36 fuel pins within a graphite sleeve (Figure 2 **-** The fuel design has changed from this diagram, but the main components are the same for the purposes of this discussion). Eight fuel elements are joined together by a metal bar (tiebar) running through the centre of each element which holds the weight of the fuel stringers when the fuel is moved, but is unloaded when the fuel is in situ.

145. The element sleeves form a pipe from the bottom of the reactor core to the top where it joins to the upper reflector and the rest of the fuel assembly (Figure 3), the gas flow continues up through the assembly to the outlet ports which form the other end of the pipe and release the coolant above the gas baffle dome (Figure 4).

146. The gas flow through the reactor is at the highest pressure at the outlet of the gas circulators, from here between 40% and 60% of the flow goes up the side of the graphite core and in through the gaps and channels in the core, this is the re-entrant flow (Figure 4). The re-entrant flow passes down the arrow head passages and the fuel channel annulus (among other channels) to the bottom of the core. The remainder of the gas flow goes to the bottom of the core directly from the gas circulators where it mixes with the re-entrant flow and goes into the fuel stringers.

147. The pressure is reducing along the gas path due to the flow resistance of the core components, and thus the gas pressure on the outside of the fuel stringer sleeves (the re-entrant flow) is higher than the gas pressure within the fuel sleeve.

148. Core distortion has the potential to lead to fuel stringer distortion; if the fuel channel distortion is large enough then the channel may begin to impinge upon the fuel stringer and distort the fuel stringer. When the fuel stringer begins to become distorted gaps will begin to open between the sections of the fuel stringer sleeve. There is tolerance to some fuel stringer distortion as the interface between fuel element sleeves is lipped to provide some degree of gas seal (Figure 2).

149. If the gaps between fuel element sleeves becomes large enough then gas will flow from the outside of the sleeve into the stringer, this will increase the pressure within the stringer at the point of the sleeve gap. The pressure gradient up the channel will then have changed, with the pressure gradient from the bottom of the channel to the gap being reduced; this will reduce the coolant flow over the fuel between the bottom of the channel and the gap leading to increased temperatures.

150. The pressure gradient between the gap and the top of the stringer will have increased potentially increasing the flow of coolant over the fuel elements above the gap; additionally the gas flowing into the stringer through the gap will be cooler than the gas that has travelled up through the stringer over the lower fuel pins and thus the fuel channel gas outlet temperature (CGOT) will be reduced. There is then the possibility that the operator or the auto-control system could try to increase the power in the channel in order to raise the temperature as indicated by the CGOT thermocouple further increasing the temperatures in the fuel pins below the gap.

151. My assessment approach was to gain confidence that NGL's submission demonstrated that the effects of sleeve gapping on fuel clad temperatures are such

that the operating limit on fuel clad temperature is not breached, and that adequate account has been taken of uncertainties in accordance with SAPs SC.5 & AV.2.

152. NGL states that the maximum sleeve gap that will occur over the proposed ~6 month operating period is <1mm in normal operation. It is acknowledged that scenarios could arise in which fuel sleeve gaps of up to 2mm could occur due to the effects of graphite debris, or shuffling of bowed fuel stringers but it is argued that gaps up to 7mm can be tolerated. The arguments and evidence submitted in support of this are the same as those presented in the recent HNB R4 safety case (Ref. 10).

153. NGL's damage tolerance analysis for HNB R3 has been assessed for this permission by ONR graphite specialists who have concluded that there are no core distortion differences between R3 and R4 in the normal operation condition over the proposed 6 month operating period (Ref. 13). NGL's analysis of the effects of graphite debris and shuffling are interpreted from the normal operation (non-seismic) analysis and therefore I judge it reasonable to assume the assertions made in the HNB R4 safety case for the size of fuel sleeve gaps that can occur also apply to HNB R3. As a result, I am satisfied that the supporting demonstration presented by NGL for the HNB R4 safety case (Ref. 10) and ONR's assessment of it (Ref. 9) can be can be applied to the HNB R3 safety case (Ref. 1).

154. The ONR assessment (Ref. 9) of the HNB R4 safety case (Ref. 10) examined that methodology employed by NGL to determine the effects of sleeve gapping on the fuel clad temperatures, and concluded that the methodology was appropriate and that adequate verification and validation of the methodology had been demonstrated along with sensitivity studies, such that the expectations of SAPs AV.4 & AV.6 had been met.

155. The ONR assessment of the HNB R4 safety case (Ref. 10) concluded that the validation of the sleeve gap flow resistances introduced significant uncertainty such that it highlighted that further validation of the sleeve gap flow resistances would be required should sleeve gapping in excess of 4mm be predicted. I judge that this conclusion applies to HNB R3 also.

156. In conclusion I judge that, since sleeve gapping is not predicted in excess of 4mm, NGL has adequately demonstrated that the effects of sleeve gapping are acceptable over the proposed ~6 month operating period (up to a core burn-up of 16.425TWd).

4.2.3 Debris

157. As the graphite bricks in the reactor core crack, there is the potential for debris to be produced. Once debris is loose in the gas circuit, it is possible that it could make its way into the inside of the fuel sleeve and create an obstruction to the cooling gas flow.

158. The ONR fault studies assessment (Ref. 9) of the recent HNB R4 safety case (Ref. 10) recommended that further work would be required to reduce the uncertainty on the amount of blockage that would be required to lead to fuel clad melt before operation of HNB R4 could be justified beyond the current HNB R3 core state, and regulatory issue 7291 was raised to track the work and progress on the issue. I judge that the recommendation equally applies to HNB R3, and as such I expect that NGL should provide further evidence to reduce the uncertainty on the thermal effects of a coolant flow blockage.

159. Consideration of the thermal effects of a fuel element blockage at the time of ONR's HNB R4 assessment was based on extrapolation of the results of rig test experiments (Ref. 17) and suggested that blockages of ~17% of the fuel element flow area could lead to fuel clad melt. There were two significant sources of uncertainty associated with the consideration of the thermal effects of a blockage in this manner; firstly, the

uncertainty associated with extrapolation of the rig test results, and secondly, the uncertainty associated with the application of the rig test results to reactor conditions.

160. In order to address the recommendation from ONR's HNB R4 assessment (Ref. 10) NGL commissioned two independent studies aimed at reducing the uncertainties associated with the thermal effects of a fuel element blockage (Refs. 15 & 16).

161. Refs. 15 & 16 both used Computational Fluid Dynamics (CFD) modelling to examine the thermal effects of a fuel element blockage at blockage sizes beyond that examined in the rig tests (Ref. 17) and were validated against the results of the rig tests. These studies are aimed at reducing the first source of uncertainty discussed above - that due to extrapolation of the rig test data.

162. Refs. 15 & 16 were independent studies performed by separate organisations with CFD modelling expertise, and using different CFD codes to study the same problem. Refs. 15 & 16 made several different modelling assumptions and choices. In my opinion NGL's strategy in using two independent studies in this manner was a good way of ensuring that diverse methods were employed and that the potential for modelling errors or 'group think' was minimised. In my view the expectations of SAP AV.2 have been met in this regard.

163. In general CFD modelling is known to be sensitive to the turbulence model employed, and whilst both Ref. 15 and Ref. 16 employed the same turbulence model in the different CFD codes this was a modelling decision reached by both studies independently on the best choice of turbulence model for the application. Both Refs. 15 & 16 additionally considered the impact of using different turbulence models and present the results of sensitivity studies done for other turbulence models. The results of the sensitivity studies in Refs. 15 & 16 demonstrate that the turbulence model used by both studies gives the best agreement with the experimental data, and also that the results are relatively insensitive to the turbulence model used. In my view NGL have met the expectations of SAP AV.6 on the use of sensitivity studies, and also of SAP AV.2 on validation of computer models.

164. The results of Refs. 15 & 16 suggest that fuel element blockages of ~17% of the flow area would not lead to fuel clad melt as was assumed from the linear extrapolation of the rig test data presented in Ref. 17, and would in fact not even lead to fuel clad temperatures in excess of the station operating limits. Ref. 15 also examined the effects of a fuel element blockage of ~24%, and concluded that the resulting heat transfer impairment would only be marginally worse than that at ~17% blockage, suggesting the presence of a significant margin to fuel clad melt.

165. I note that the work presented in Refs. 15 & 16 does not address the second source of uncertainty discussed above – the application of the rig test data to reactor conditions – however I judge that the large margins to fuel clad melt demonstrated in the studies are likely to bound such uncertainties. Regulatory issue 7291 was raised during the course of ONR's assessment of the recent HNB R4 safety case to track the work in quantifying and reducing these uncertainties, and I shall keep it open pending further discussions with NGL on addressing the residual sources of uncertainty; however, in my opinion NGL has adequately addressed the recommendation from ONR's assessment of the recent HNB R4 safety case - to quantify and reduce the uncertainties associated with the point at which fuel clad melt would occur following a fuel element blockage.

166. From discussions with the ONR graphite specialist inspector I understand that the assessed probability of graphite debris causing a flow obstruction in a fuel element is not considered to be significantly increased during the proposed operating period of HNB R3 compared to that of the recent HNB R4 period of operation justified in Ref. 10.

I recommend that the project inspector confirms that the graphite inspector supports this understanding.

167. **Recommendation 3**: Prior to ONR agreeing to the modifications to the safety case described in Reference 1, the project inspector should confirm that the graphite specialist inspector is satisfied that NGL have adequately demonstrated that there will be no significant increase in the probability of fuel element flow obstruction from graphite debris (compared to that presented in the most recent HNB R4 safety case) over the proposed JPSO up to 16.425TWd.

168. Based on the assumption that the probability of a fuel element flow obstruction will not significantly increase over the proposed operating period, and NGL's demonstration that the consequences of a fuel element flow obstruction are significantly reduced from that considered previously, I judge that NGL have adequately demonstrated that the risks from graphite debris have been reduced so far as is reasonably practicable for the proposed operating period (up to 16.425TWd).

4.3 Provide neutron moderation and thermal inertia

169. There is no plausible effect on the thermal inertia of the graphite core due to graphite brick cracking. Graphite weight loss does affect the mass of the graphite core, and thus its thermal inertia, however the effects of graphite weight loss are outside of the scope of this report, and there is no change to the limit on graphite weight loss proposed in NGL's safety case (Ref. 1). The effects of graphite weight loss are considered by ONR through a separate work stream (Reference 20).

170. Other plausible effects on the neutron flux distribution from graphite brick cracking were examined in the ONR assessment (Ref. 9) of the recent HNB R4 graphite core safety case (Ref. 10), but ONR's assessment concluded that NGL had adequately demonstrated that the safety function of the graphite core to provide neutron moderation and thermal inertia was unaffected by the presence of graphite brick cracking. I therefore conclude that the safety function of the graphite core to provide neutron moderation and thermal inertia has been adequately demonstrated to be fulfilled over the proposed operating period (up to a core burn-up of 16.425TWd).

4.4 Recommendations from ONR's previous assessments

171. Regulatory Issue 7292 was raised following ONR's assessment (Ref. 9) of the recent HNB R4 safety case (Ref. 10). This issue was raised to track the work to examine whether the coolant activity monitoring systems (BCD and GAM) could differentiate between a typical minor fuel failure at a high power location in the fuel stringer and a more significant fuel clad melt at a low power location. Ref. 9 saw this as an ALARP measure.

172. NGL produced Ref. 19 which examined the detectability of fuel clad failures at the element 1 location. Ref. 19 concluded that the uncovering of a single fuel pellet at the element 1 location would be detectable by the BCD, although the increase in coolant activity would not be likely to trigger a response from the operators as the operator action levels would not be reached. Ref. 19 also concluded that it would not be possible to identify the location and magnitude of the fuel failure from the BCD signal. Ref. 19 did identify that should a fuel pellet become loose in the gas stream and become lodged at a higher rated location in the fuel stringer this would generate a BCD signal in excess of the operator action and alarm levels which would allow the operators to prevent further fault escalation.

173. In my view the investigation reported in Ref. 19 was an ALARP improvement in the understanding of the potential fault progression and protection following a hypothetical fuel clad melt at the element 1 location. I will leave regulatory issue 7292 open

pending further discussions with NGL on any further work which might be ALARP. This does not present an impediment to permissioning of Ref. 1.

174. Regulatory issue 7300 was raised following ONR's assessment (Ref. 9) of the recent HNB R4 safety case (Ref. 10). This issue was raise to track the work to examine the effects on core distortion of a control rod channel closure unit failure leading to a depressurisation fault. I have discussed this topic in section 4.1.1, and although some work on the topic has been delivered and the understanding of the topic has progressed adequately to date the regulatory issue will remain open pending further discussion with NGL on potential further work. This does not present an impediment to permissioning of Ref. 1.

175. Recommendation 1 of ONR's fault studies assessment (Ref. 9) of the recent HNB R4 safety case (Ref. 10) was "*For inclusion in future safety cases justifying the operation of the Hunterston B Reactor 4 graphite core, NGL should perform further analysis of the effects of a blockage at the element 1 support grid in order to establish the point at which fuel clad melt temperatures would be reached*." And regulatory issue 7291 was also raised to track the work on the topic. I have discussed this topic in section 4.2.3, and I judge that the recommendation has been adequately fulfilled, as NGL have taken all reasonably practicable steps to reduce the uncertainties in the time since the recommendation was made. The regulatory issue will remain open pending further discussion with NGL on potential further work that would be reasonably practicable in the future. This does not present an impediment to permissioning of Ref. 1.

176. Recommendation 2 of ONR's fault studies assessment (Ref. 9) of the recent HNB R4 safety case (Ref. 10) was "*The changes to Technical Specification 8.1.3 proposed in NP/SC 7653 should be implemented at Hunterston B prior to restart of Reactor 4*." This recommendation was fulfilled prior to the restart of HNB R4, and the Technical Specification change applies to both HNB reactors.

177. Recommendation 3 of ONR's fault studies assessment (Ref. 9) of the recent HNB R4 safety case (Ref. 10) was also a continuation of a recommendation from Ref. 14 and stated "*NGL should include consideration of fuel channel distortions following a seismic event and its effect on fuel sleeve gapping in future graphite safety cases*." Consideration of fuel channel distortions following a seismic event was not included in Reference 1, and thus the recommendation was not fulfilled, however NGL have provided an extract of a report in development which makes some arguments related to this topic (Ref. 18). I have not assessed these arguments in detail as they are not presented in any verified or published reports or safety cases, but they appear to be a reasonable basis upon which to fulfil the recommendation.

178. As NGL are clearly working on fulfilling recommendation 3 from Ref. 9 and as this was not judged to be a significant shortfall in Ref. 9 when the recommendation was made, I judge that the fact that NGL has not fulfilled this recommendation should not represent an impediment to permissioning. I will make the same recommendation in this report to ensure that the issue retains focus.

179. **Recommendation 4**: NGL should include consideration of fuel channel distortions following a seismic event and its effect on fuel sleeve gapping in future graphite safety cases.

4.5 ONR Assessment Rating

180. I identified no significant shortfalls against relevant good practice, and the technical quality of the evidence presented by NGL was good. There was no requirement for significant regulatory intervention to manage technical issues, and NGL have made good progress on addressing the outstanding technical issues raised by the recent HNB R4 assessment. I therefore judge that Reference 1 should be rated Green.

5 CONCLUSIONS AND RECOMMENDATIONS

181. This report presents the findings of the fault studies assessment of the Hunterston B Power Station (HNB) safety case for the operation of Reactor 3 to a core burn-up of 16.425TWd (Ref. 1) and the supporting documentation provided by NGL.

182. I have focussed my assessment on determining whether EDF NGL have adequately demonstrated that the safety functions of the graphite core will be fulfilled over the proposed ~6 month Justified Period of Safe Operation (JPSO) up to 16.435TWd, and I have made extensive use of a recent ONR fault studies assessment of the HNB R4 graphite core safety case (Ref. 10). I have concluded for each of the faults assessed that the safety case arguments and evidence are not sensitive to the increase in core degradation, and that the evidence presented by NGL adequately demonstrated that the increase in core degradation over the HNB R4 safety case position was acceptable.

183. I conclude – conditional on the satisfactory fulfilment of my recommendations - that NGL has adequately demonstrated that the nuclear safety functions of the graphite core to:

- allow unimpeded movement of control rods and fuel,
- to direct gas flows to ensure adequate cooling of the fuel and core,
- to provide neutron moderation and thermal inertia,

will be fulfilled over the proposed period of operation up to 16.425TWd, and that, from a fault studies perspective, ONR should agree to the modifications to the safety case described in NP/SC 7766 SS1 (Ref. 1).

184. This assessment has proceeded in parallel with a graphite specialist assessment, and has operated under the assumption that the graphite inspector is satisfied that:

- NGL has adequately demonstrated that there is no effect on the reliability of the Primary Shutdown System from a design basis seismic event.
- NGL has adequately demonstrated that it is very unlikely for there to be a significant increase in fuel handling risk from core distortion or graphite debris.
- NGL has adequately demonstrated that it is very unlikely for there to be a significant increase in the probability of fuel element flow obstruction due to graphite debris.

185. This report therefore recommends that the project inspector confirms that the graphite specialist inspector is satisfied with the above points.

- **Recommendation 1**: Prior to ONR agreeing to the modifications to the safety case described in Reference 1, the project inspector should confirm that the graphite specialist inspector is satisfied that NGL have adequately demonstrated that all control rods will insert in normal operation and following a design basis seismic event.
- **Recommendation 2**: Prior to ONR agreeing to the modifications to the safety case described in Reference 1, the project inspector should confirm that the graphite specialist inspector is satisfied that NGL have adequately demonstrated that there will be no significant increase in fuel snag frequency from core distortion or graphite debris (compared to that presented in the most recent HNB R4 safety case) over the proposed JPSO up to 16.425TWd.
- **Recommendation 3**: Prior to ONR agreeing to the modifications to the safety case described in Reference 1, the project inspector should confirm that the graphite specialist inspector is satisfied that NGL have adequately demonstrated that there will be no significant increase in the probability of fuel element flow obstruction from graphite debris (compared to that presented in

the most recent HNB R4 safety case) over the proposed JPSO up to 16.425TWd.

- **Recommendation 4**: NGL should include consideration of fuel channel distortions following a seismic event and its effect on fuel sleeve gapping in future graphite safety cases.

6 REFERENCES

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2. NOT USED

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4. ONR TAGs http://www.onr.org.uk/operational/tech_asst_guides/index.htm

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   ONR-TAST-GD-075 Safety of Nuclear Fuel in Power Reactors
   ONR-TAST-GD-042 Validation of Computer Codes and Calculation Methods
   ONR-TAST-GD-005 Guidance on the Demonstration of ALARP

5. Western European Nuclear Regulators' Association. Reactor Harmonization Group. WENRA Reactor Reference Safety Levels. WENRA. September 2014. www.wenra.org.

6. IAEA guidance www.iaea.org.

   IAEA SSR-2/1 Rev 1, Safety of Nuclear Power Plants: Design
   IAEA SSG-2, Deterministic Safety Analysis for Nuclear Power Stations

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

8. ONR Assessment Rating Guide Table. CM9: 2016/118638

9. ONR Assessment Report: ONR-OFD-AR-19-029 Rev 00, Fault Studies Assessment of the Hunterston B R4 Return to Service Safety Case Following Core Inspection Results in 2018. CM9: 2019/176010

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12. Frazer-Nash Report: FNC 60433-018/110016V, HNB Graphite Core Safety Case Flows and Pressures Following a Control Rod Closure Failure, Issue 1, September 2019. CM9: 2020/36780

13. ONR Email: L Easterbrook to R Le Grove 22/06/2020, RE: HNB R3: SS1 assessment interface between fault studies and structural integrity. CM9: 2020/0189277

14. ONR Assessment Report: ONR-OFD-AR-16-053, Assessment of the NP/SC 7716 Keyway Root Cracking Onset Safety Case for the Hunterston B and Hinkley Point B Graphite Cores, November 2016. CM9 2016/228144

15. Frazer Nash Report: FNC 61760/49465R Issue 1, Graphite Debris: Partial Fuel Element Blockage Validation of CFD Model against Test Rig Data and Predictions for 17% and 24% Blockage, January 2020. CM9: 2020/130103

16. EDF R&D Report: UKC-R-2019-012 V1.0, CFD Analysis of Debris in an AGR Fuel Channel, April 2020. CM9: 2020/130076

17. EDF NGL Report (CEBG): RD/B/N3611, The Effects of Debris on the Heat Transfer Performance of CAGR Fuel Clusters, March 1976. CM9: 2019/0174226

18. EDF NGL Email: [redacted] 20/04/2020 FW: Letter on ONR Recommendations on HNB R4 graphite safety case. CM9: 2020/130125

19. EDF NGL Report: E/REP/BCBB/0118/AGR/19 Rev 000, The AGR Burst Can Detection System Response to Fuel Debris, December 2019. CM9: 2020/136013

20. ONR Assessment Report: ONR CNRP Assessment Note - Hinkley Point B & Hunterston B, safety case for graphite weight loss (NP/SC 7574) - reactor physics and fault analysis. CM9: 2011/501530

Table 1

Relevant Safety Assessment Principles Considered During the Assessment

SAP No	SAP Title	Description
FA.4	Fault tolerance	DBA should be carried out to provide a robust demonstration of the fault tolerance of the engineering design and the effectiveness of the safety measures.
FA.7	Consequences	Analysis of design basis fault sequences should use appropriate tools and techniques, and be performed on a conservative basis to demonstrate that consequences are ALARP.
ERC.1	Design and operation of reactors	The design and operation of the reactor should ensure the fundamental safety functions are delivered with an appropriate degree of confidence for permitted operating modes of the reactor.
ERC.2	Shutdown systems	At least two diverse systems should be provided for shutting down a civil reactor.
ERC.3	Stability in normal operation	The core should be stable in normal operation and should not undergo sudden changes of condition when operating parameters go outside their permitted range.
EHT.2	Coolant inventory and flow	Sufficient coolant inventory and flow should be provided to maintain cooling within the limits (operating rules) derived for normal operational and design basis fault conditions.
SC.5	Optimism, uncertainty and conservatism	Safety cases should identify areas of optimism and uncertainty, together with their significance, in addition to strengths and any claimed conservatism.
AV.2	Calculation methods	Calculation methods used for the analyses should adequately represent the physical and chemical processes taking place.

AV.4	Computer models	Computer models and datasets used in support of the safety analysis should be developed, maintained and applied in accordance with quality management procedures.
AV.6	Sensitivity studies	Studies should be carried out to determine the sensitivity of the analysis (and the conclusions drawn from it) to the assumptions made, the data used and the methods of calculation.
NT.1 Target 8	Frequency dose targets for accidents on an individual facility – any person off the site	The targets for the total predicted frequencies of accidents on an individual facility, which could give doses to a person off the site are: **Effective dose, mSv** / **Total predicted frequency per annum** (**BSL** / **BSO**) 0.1–1: 1 / 1×10^{-2} 1–10: 1×10^{-1} / 1×10^{-3} 10–100: 1×10^{-2} / 1×10^{-4} 100–1000: 1×10^{-3} / 1×10^{-5} >1000: 1×10^{-4} / 1×10^{-6}

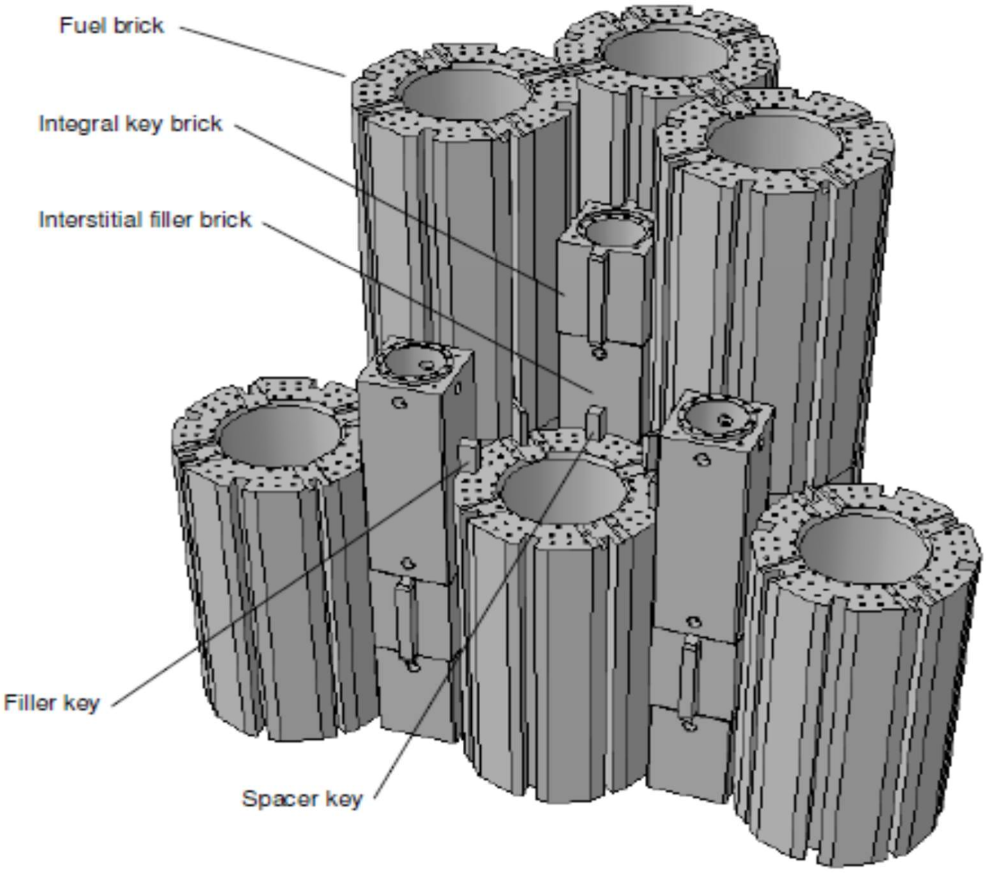

Figure 1 – Illustration of the fuel and interstitial bricks and the keying system at Hinkley Point B and Hunterston B

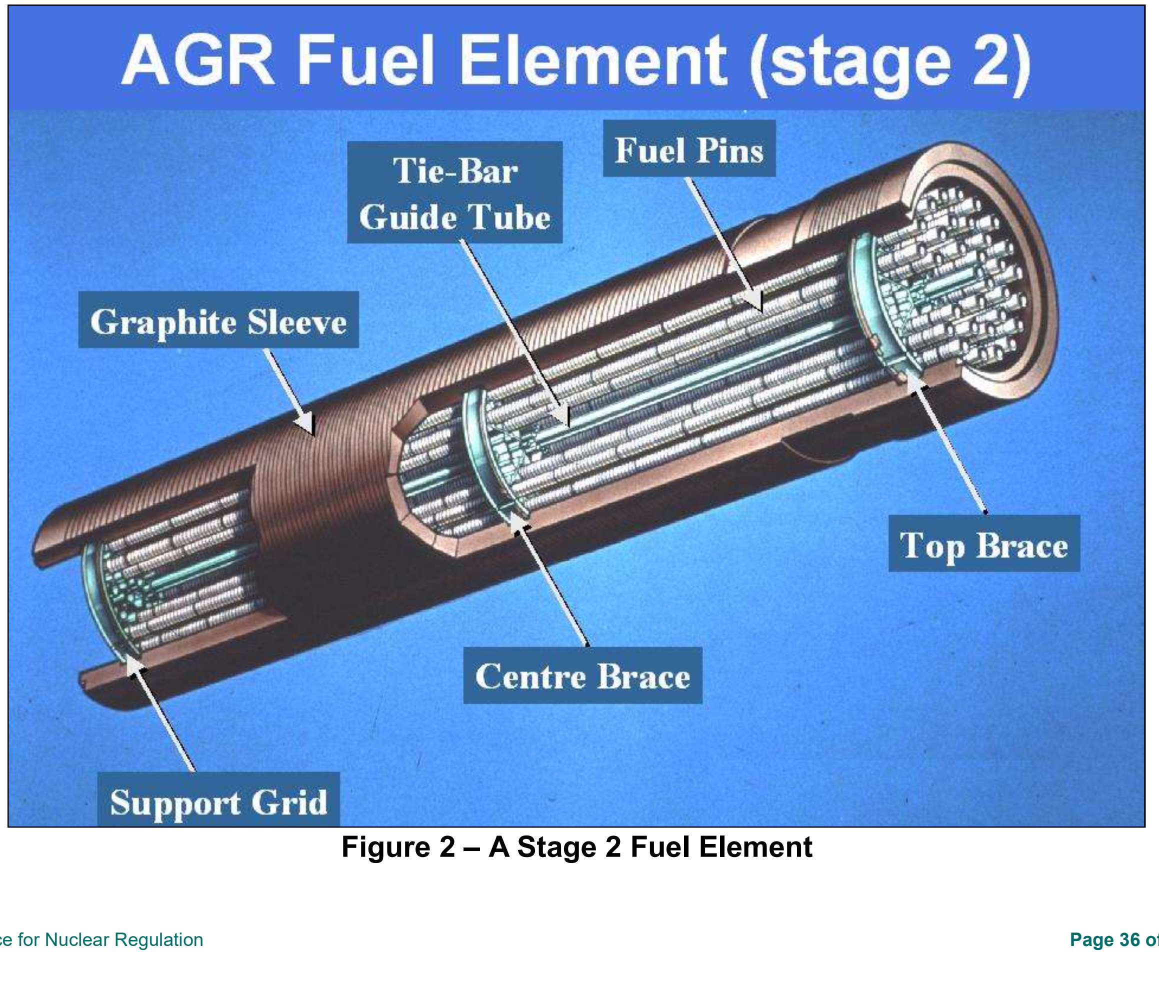

Figure 2 – A Stage 2 Fuel Element

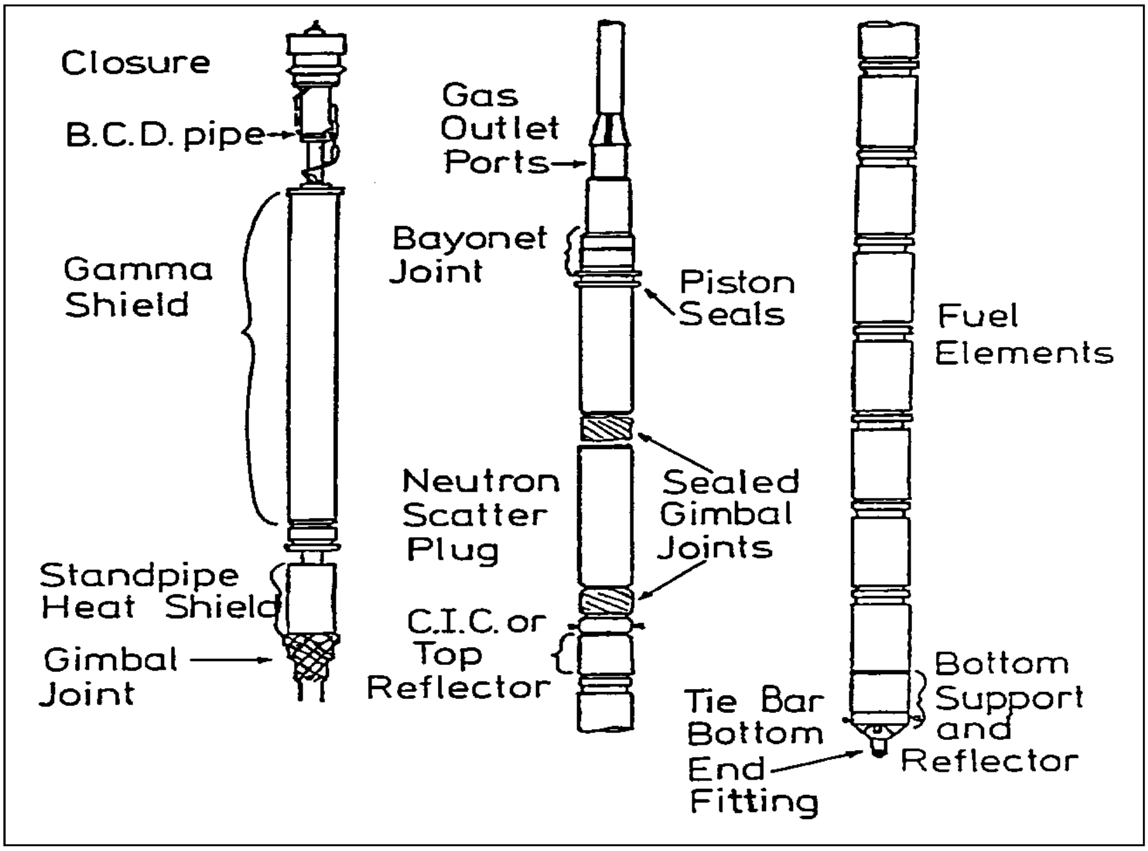

Figure 3 – Fuel Stringer

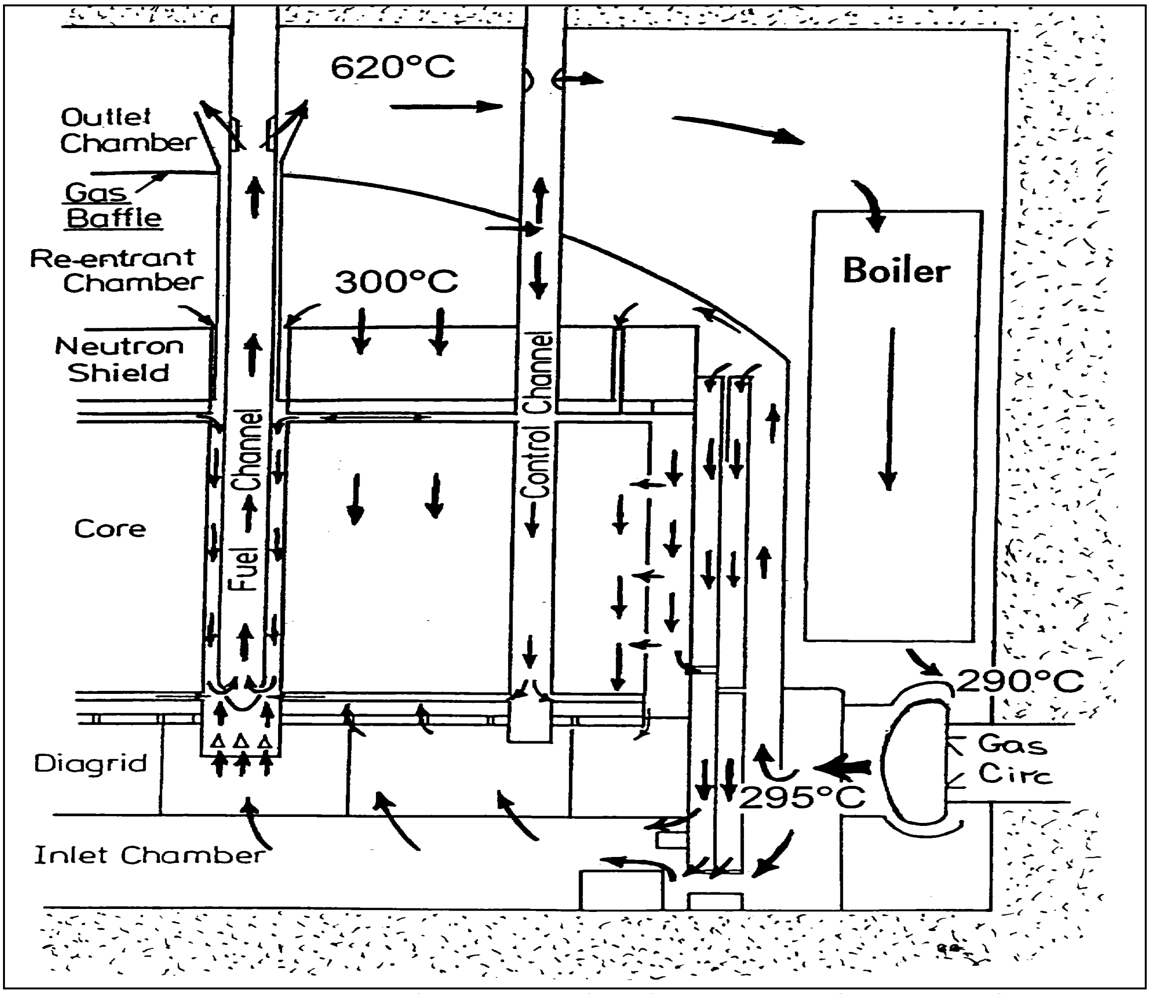

Figure 4 - Typical AGR Reactor Gas Coolant Flow (whole core)

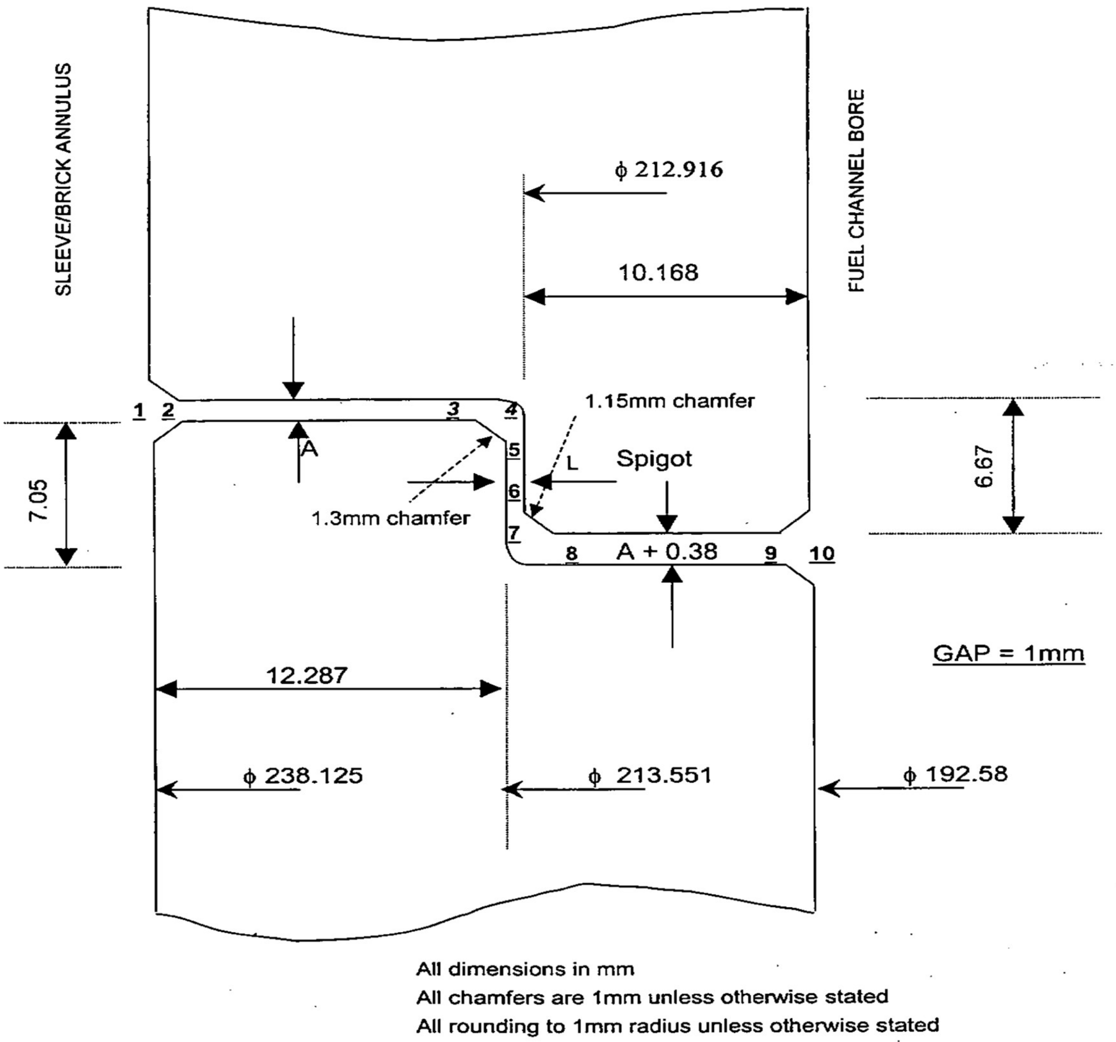

Figure 5 – Fuel sleeve end geometry

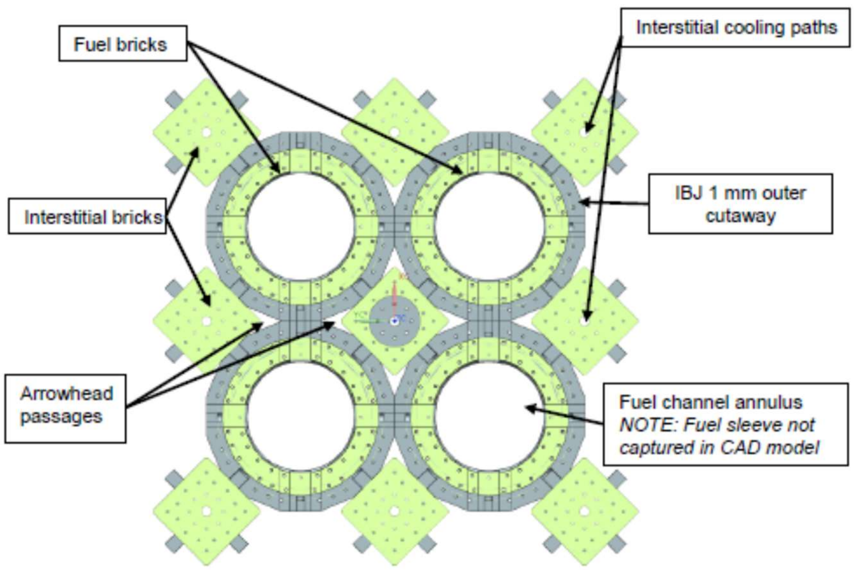

Figure 6 – Plan view of graphite core showing arrowhead passages, and annulus with no fuel stringer in-situ