Office for
Nuclear Regulation

Operating Facilities

Assessment of EDF's graphite materials properties model in NP/SC 7766 V10 SS1 (Operation of HNB R3 to a burn up of 16.425TWd) and implications for the predicted brick stresses, dimensions and overall damage tolerance assessment

Assessment Report ONR-OFD-AR-19-093
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EXECUTIVE SUMMARY

EDF Energy NGL has submitted a safety case, NP/SC 7766 SS1 V10, for the restart of Hunterston B Power Station Reactor 3 (HNB R3), which has not operated since early 2018. This new safety case contains a justification for a further period of operation up to a maximum core burn-up of 16.425TWd. It is being assessed by ONR and this assessment work will include a consideration of the overall integrity of the graphite core. Underpinning the analysis used in the safety case is a model that describes the materials properties of the irradiated graphite, in particular, how these properties are expected to vary with the degree of irradiation (fluence), weight loss and temperature. This model is termed the EDF Integrated Model (EIM), which has been developed over a period of over ten years and has been the subject of a number of reviews by NGL and independently by ONR's advisors.

Within the safety case, one particular argument (1.2) within claim 1 states that the current version of the EIM is an adequate formulation to permit modelling of the likely future behaviour of the graphite. This is important for HNB R3, as it is the 'lead' reactor in terms of cracking of the graphite bricks within the core. The assessment here includes comments on:

- The nature of the EIM and associated uncertainties,
- The use of the EIM to predict brick stresses and dimensions,
- The implication of uncertainties in the EIM predictions on the damage tolerance assessment (DTA) for the graphite core.

The conclusions from this report will be taken into account in the overall assessment of NNP/SC7766. I note that two versions of the EIM are used in NP/SC 7766. These versions are known as EIM1.1 and EIM1.2.

Prior to preparing this assessment, I have sought expert opinions on the mathematical modelling from ONR's independent advisors, particularly members of the Graphite Technical Advisory Committee (GTAC). Our advisors at the University of Manchester (UofM) and HSE's Health and Safety Laboratory have also worked together on the development of their own model (the UofM model). The predictions of the two models are compared in my assessment. This is done to illustrate the implications of particular choices of mathematical formulation and of the choices of data used to calibrate it.

This assessment deals with all the materials properties. Broadly I am content that NGL has used an adequate formulation and incorporated both the available reactor data and some 'leading' data from experiments at the Petten Materials Test Reactor. There are two areas of concern however. These are the dimensional change (DC) and the creep/CTE relationships.

For DC, the EIM and UofM models differ in their predictions. Based on the independent advice received and a comparison of the two models, I have formed the view that there is no unique method of predicting the DC beyond the level of irradiation experienced by HNB R3. Some of the advice received has taken issue with the way that the EIM has been formulated and the selection of the data for calibration. However, I can also acknowledge that NGL and their predecessor organisations have taken considerable efforts and care to obtain and consider data that can be used for predictions of the graphite behaviour.

One particular concern at the start of the assessment was that the DTA, specifically the core distortion parameters that EDF uses to describe the potential response to a seismic event, could be unduly sensitive to the DC predictions. A sensitivity study was therefore requested. The results suggest that over the period of operation for which permission is requested in the safety case, there is no overriding concern.

For the creep/CTE relationship, independent advice received is that because the relationship in EIM1.2 has been changed on a solely empirical basis from that used in EIM1.1, caution should be used, at least until there is further confirmation from analysis of reactor and Materials Test Reactor (MTR) data. The relationship is important in the prediction of future cracking. In practice though such predictions are in any case adjusted using past inspection observations. NGL has also addressed uncertainty by performing the DTA at upper bound cracking levels and providing an additional margin in time between the operational period sought and the limiting DTA cases. Therefore the uncertainty in creep/CTE is mainly in the confidence that can be ascribed to assertions that cracking will only occur as the reactor is shutdown. This has led to a recommendation below.

The EIM is also used to predict stresses and strength and the EIM is therefore used to determine if brick cracking is expected and how it may progress. There is some evidence to suggest that the existing cracking can be reasonably well explained by such analysis. Additionally, stresses predicted by the EIM and by our independent advisors show comparable predictions, again providing reassurance.

The prediction of potential failures at the brick key/keyway area, such as when subject to an external load during normal operation or limiting transients, i.e. seismic loading, requires use of the EIM for calculation of brick internal stresses and strength. It also needs EIM parameters to scale brick test results in the calculation of the capacity of the bricks to resist externally applied forces.

There is therefore a question about the sensitivity of the DTA to uncertainty in the capacity of the bricks to resist external loads. I have considered a sensitivity study and have noted that at a capacity reduction of 20%, an extra 200 loose/keyways may fail. I have though noted that a 20% reduction is a generous reduction that can be expected to cover reasonable stochastic and systematic uncertainty in those parts of the capacity determined by the EIM, such as graphite strength. Completely resolving the sensitivity of the key/keyway region is beyond the scope of this assessment, as to do so also requires assessment of the external forces that may be applied to the bricks and the potential degree of conservatism therein. The judgement of the overall adequacy of the DTA will therefore be made in the overall graphite integrity assessment, so I am providing advice in the form of a recommendation below.

I have concluded though, that given the limited period of operation for which permission is requested in the safety case, and subject to consideration of the sensitivity studies and caveats discussed above, the use of the EIM is justifiable in the safety case submitted. I am also content that the use of both EIM1.1 and EIM1.2 in the same safety case is justifiable, as for each use, NGL has chosen the version that produces the more conservative result.

I have accorded this assessment an ‘amber’ rating. This is because significant interactions have been necessary with the licensee before and after the submission of the safety case. These interactions were necessary to understand the decisions made by the licensee as they developed the EIM. Additionally, some aspects of the EIM, including those relating to the choice of calibration data have been challenged by ONR’s independent advisors. I have taken note of this advice in forming my conclusion.

I have made a total of five recommendations. The first two provide advice to the assessor dealing with the overall structural integrity of the graphite core for the safety case under consideration. The other three are of longer term relevance and do not need to be addressed as part of the assessment of the present case.

Recommendation 1:

That in assessing the overall adequacy of the licensee’s DTA work, consideration should be made on the basis that EIM values have been calculated as best estimate values. Judgements as to whether the overall analysis is sufficiently conservative should therefore consider the sensitivity studies into clearance and capacity parameters that NGL has performed.

Sensitivity studies into clearances suggest that the seismic margins remain acceptable for reasonable changes. However, it is noted that a reduction in capacity of 20% may increase the number of predicted loose key/keyway failures by 200. A 20% reduction can though be considered to be a generous allowance to encompass uncertainty.

Recommendation 2

That in assessing the overall adequacy of the graphite structural integrity aspects of the safety case, note should be taken that although cracking at shutdown is the more likely, reliance should not yet be placed on any argument that cracking can only occur at shutdown.

Recommendation 3

That NGL be advised that the apparent sensitivity of the DTA to variations in key/keyway clearances and capacity needs to be explored further for safety cases beyond SS1 i.e. beyond a burnup of 16.425TWd for HNB and for future operation of HPB.

Recommendation 4

That NGL be advised that ONR would have greater confidence in EIM predictions if recalibration was made with the most recent inspection data. This applies particularly to the DC and creep/CTE relationships. For future safety cases, either a recalibration should be performed, or a detailed justification should be provided that any conclusions would not be affected by such a recalibration.

Recommendation 5

That ONR should consider requesting further independent advice on more recent Project Blackstone data including the phase 2 results, noting that this may have more applicability to other AGRs.

LIST OF ABBREVIATIONS

ALARP	As low as is reasonably practicable
BSL	Basic Safety level (in SAPs)
BSO	Basic Safety Objective (in SAPs)
CEDTL	Currently Established Damage Tolerance Level
CTE	Coefficient of Thermal Expansion
DC	graphite dimensional change
DFR	Dounreay Fast Reactor
DTA	damage tolerance assessment
DYM	Dynamic Young’s Modulus
EIM	EDF Integrated Methodology/Model (for material properties)
FNC	Frazer-Nash Consultancy
FS	Flexural Strength
HNB	Hunterston B Power Station
HOW2	(ONR) Business Management System
HPB	Hinkley Point B Power Station
HSE	Health and Safety Executive
HSL	The Health and Safety Laboratory (part of HSE)
IAEA	International Atomic Energy Agency
KRC	Keyway Root Cracking
LC	Licence Condition
M&CS	Modeling and Computer Services
MTR	Materials Test Reactor
NGRG	Nuclear Graphite Research Group
ONR	Office for Nuclear Regulation
RGP	Relevant Good Practice
SAP	Safety Assessment Principle(s)
SFAIRP	So far as is reasonably practicable
TAG	Technical Assessment Guide(s) (ONR)
TC	Thermal Conductivity
TSC	Technical Support Contractor
UofM	University of Manchester
WCM	Whole Core Modelling

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1 INTRODUCTION

1. The Gilsocarbon graphite used in the AGR cores is well known to have materials properties that are affected by the amount of irradiation (fluence), the weight loss caused by oxidation and temperature. There are several materials properties including strength and Young's modulus that are affected. Additionally, graphite also exhibits dimensional changes as fluence increases. The extent of the property variations are considerable and need to be taken account of in a number of areas within the operational safety cases.

2. EDF NGL has dealt with the need to be able to predict the values of materials properties by creating the EDF Energy Integrated Model (EIM). This seeks to incorporate data from a number of sources, together with an understanding of graphite behaviour to produce relationships that allow prediction of materials properties, including dimensional changes, at any given time.

3. Hunterston B Reactor 3 (HNB R3) has not operated since early 2018, when inspections revealed cracking of the graphite during an inspection that was more extensive than expected. HNB R3 is believed to be the AGR reactor with the greatest amount of keyway root cracking (KRC). This is cracking that is believed to extend from the keyway roots of the fuel bricks to the bore. HNB Reactor 4 (HNB R4) and the two reactors at Hinkley Point B (HPB R3 and HPB R4) also have cracking. The KRC phenomenon is such that there is a predicted rapid rise in the proportion of bricks that have cracks, once it has commenced. This has been born out in practice at HNB and to a lesser extent at HPB. Safety cases for operation of the HNB and HPB reactors therefore include predictions of the degree of cracking. They also deal with the tolerability of the core to cracking i.e. whether the basic safety functions can be maintained in a core with extensive cracking of the fuel bricks.

4. Although the HPB reactors actually have a higher fluence and weight loss than those at HNB, the cracking appears to be more extensive at HNB R3 and it is currently considered the lead reactor in terms of cracking across HPB and HNB and indeed all the AGRs. NGL has submitted Reference 1, NP/SC 7766 SS1 V10, a safety case that seeks permission to restart HNB R3 and operate for a further period, until a burnup of 16.425TWd. An assessment is being performed by ONR that will consider the overall graphite core structural integrity aspects within that case.

5. However, Argument 1.2 deals specifically with the EIM, essentially that it allows valid prediction of properties throughout the period of currency of the case. This present assessment report deals with Argument 1.2 i.e. the EIM. It also deals with associated topics such as the use of EIM to predict stresses and dimensions. Further comment is made on the implications of uncertainty in the EIM predictions on the Damage Tolerance Assessment (DTA). This includes a discussion of a sensitivity study the licensee performed into the effect of varying the key/keyway clearances and also sensitivity studies into the effects of varying the brick capacities on key/keyway damage.

6. The latter topic i.e. the sensitivity to capacity uncertainty is not fully assessed within the present document, as the overall DTA assessment has to take account of the calculation of the external loading. I have therefore made a recommendation to the assessor carrying out the overall graphite integrity assessment to take account of the sensitivity studies in deciding whether there is sufficient overall conservatism in the DTA.

1.1 Background

7. This report presents the findings of the assessment of the use of the EIM in NP/SC 7766 SS1 V10 (Reference 1) and supporting documentation provided by NGL.

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 (Reference 2). The ONR Safety Assessment Principles (SAP) (Reference 3), together with supporting Technical Assessment Guides (TAG) (Reference 4), have been used as the basis for this assessment.

1.2 Scope

8. The scope of this report covers the use of the EIM within Reference 1. Aspects considered include:

- The nature of the EIM and associated uncertainties,
- The use of the EIM to predict brick stresses and dimensions,
- The implication of uncertainties in the EIM predictions on the damage tolerance assessment (DTA) for the graphite core.

9. The assessment does not make judgements about whether the permission for operation sought by NGL should be granted. A separate graphite integrity assessment is being produced covering the overall nuclear safety aspects of Reference 1 in terms of the graphite structural integrity.

1.3 Methodology

10. The methodology for the assessment follows HOW2 guidance on mechanics of assessment within the Office for Nuclear Regulation (ONR) (Reference 5).

2 ASSESSMENT STRATEGY

11. The intended assessment strategy is set out in this section. This identifies the scope of the assessment and the standards and criteria that have been applied.

2.1 Standards and Criteria

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

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

2.2.1 Technical Assessment Guides

14. The following Technical Assessment Guides have been used as part of this assessment (Reference. 4):

- ONR-TAST-GD-029 Graphite Reactor Cores

2.2.2 National and International Standards and Guidance

15. I am not aware of any directly relevant international standards and guidance for modelling graphite behaviour. There are graphite moderated reactors of different designs operating in several countries. Others have operated in the past. However all the AGR reactors are in the UK. Their unique design and in particular the use of Gilsocarbon within a CO_2 oxidising coolant provides challenges that are unique to the UK.

16. There are of course standards for testing and measurement, such as those produced by ASTM. ONR has held a number of meetings over the past decade that have considered the experimental difficulties in performing measurements on irradiated graphite. We have also performed inspections at the laboratories where the work takes place. However the adequacy of the experimental methods is not the focus of this assessment, but I note that a certain amount of the variability of graphite properties may be accounted for by stochastic uncertainties in the measurement processes.

17. HNB R3 is the ‘lead reactor’ in terms of cracking, i.e. it has reached an effective ‘age’ beyond that of other reactors whose condition is relevant. It is therefore likely that even if they were available, codes and standards would not provide significant reassurance about the confidence that can be ascribed to the EIM predictions in this particular safety case.

2.3 Use of Technical Support Contractors

18. Because of the limitation of the existing guidance, ONR has sought for many years to maintain sources of independent advice, using expertise from Universities and from other specialists with relevant expertise, such as the HSE’s Health and Safety Laboratory (HSL). For the work described here, significant assistance was obtained from the members of the Graphite Technical Advisory Committee (GTAC) who

produced a report on the EIM (Reference 6). Additionally a report on Dimensional Change produced under the aegis of our University of Manchester team (Reference 7) was substantially written by Modelling and Computer Services (M&CS). The conclusions of this report have been influenced by these reports and from several meetings held with these specialists.

2.4 Integration with Other Assessment Topics

This assessment report deals only with the EIM and its uses within Reference 1, together with implications of various sensitivity studies on the parameters derived from the EIM. It should not be interpreted as providing conclusions on the safety of operation of HNB R3 in isolation. However, the context of the use of the EIM relationships is important and this is referred to where necessary.

2.5 Out of Scope Items

19. As is explained above, only the EIM and its uses are addressed here. This assessment report needs to be placed in the context of ONR's overall consideration of the safety case presented in Reference 1.

2.6 Organisation of this assessment

20. Although a clear delineation between the description of the licensee's case and the ONR assessment is normally desirable in assessment reports, it has not always been possible to follow such a structure here. ONR has interacted extensively with NGL on the topic of materials property modelling. In particular, ONR has arranged for our advisors at Manchester University and HSL to develop an alternative model, generally using the same raw data. This has been done partly as a challenge to the licensee, to illustrate that different teams working with the same data may develop equally plausible but differing modelling approaches. As such, some assessment comments are more sensibly provided immediately after the explanation of the licensee's actions.

21. For convenient reference, I have put various figures from Reference 11 in Annex A, for example showing the way in which materials properties are believed to vary with oxidation and fluence, as described by the EIM.

2.7 Simplification of explanations

22. The fuel bricks in the AGRs are approximately the shape of thick section cylinders. As such there is a great deal of constraint acting on each region of the graphite from all the other graphite in the brick. Therefore a description of the whole brick behaviour needs to take account of that constraint. Thus probably no part of a brick will change its dimensions in precisely the same manner that a small unconstrained test specimen would do. The explanations provided below therefore need to be understood in the above context. A further aspect of constraint is the effect of graphite creep which will tend to act to reduce internal stresses and affect the dimensional change that occurs.

3 LICENSEE'S SAFETY CASE

3.1 Argument 1.2 in Reference 1

23. Argument 1.2 is:

Graphite material properties (including the effects of in core ageing) are adequately predicted.

24. This assessment considers the validity of the above argument.

3.2 Other arguments that refer to the EIM

25. Argument 1.3 is:

Degradation of the core over an operating period can be conservatively predicted

26. This assessment covers part of that argument i.e. that dealing with prediction of brick stresses, as these are determined largely by the internal ageing phenomena described by the EIM.

27. Argument 1.11 is:

Sensitivities to modelling assumptions are accounted for in the methods deployed

28. This argument states in evidence 1.11.2, that various sensitivities in the DTA have been explored. The present assessment only deals with the sensitivity to those parameters directly determined by the EIM e.g. brick strength and key/keyway gaps.

3.3 The functions of the EIM

29. Reference 1 states that there is confidence in the EIM prediction of materials properties up to a burnup of 17.55 TWd. There is though limited description of the EIM and its limitations in Reference 1. The salient points made within Reference 1 are that:

(i) The EIM is based on a number of data sources including Materials test Reactor (MTR) and AGR data, including MTR data that ‘leads’ the current burnup of HNB R3.

(ii) The EIM provides ‘best-estimate’ property values, with explicit representation of uncertainty and system variability, rather than being a model that includes conservatism implicitly.

(iii) The original intention was to formulate EIM using the premise that the various material properties were linked to the common graphite microstructure. However the more recent versions EIM1.1 and EIM1.2 have now included empirically driven adjustments. For example the change from EIM1.1 to EIM1.2 was driven by the desire to improve the prediction of coefficient of thermal expansion for which the analysis of trepanned data had revealed a shortfall (Section 3.4.1 gives more detail on the evolution of the EIM).

(iv) That there is sufficient sampling performed to confirm that the reactor graphite behaviour is staying within the trend indicated by the EIM

30. Because the EIM description in Reference 1 is so short, much of the following description is therefore drawn from the References and other documents and records that have emerged during interactions between ONR and NGL. Section 3.4 below is an explanation of the derivation of the EIM that is not taken directly from any NGL document. I have provided this for clarity.

3.3.1 Terms of Reference for the EIM

31. Reference 8 is a terms of reference document which identifies six principles for the EIM:

(i) That EIM can represent the evolution of properties everywhere within the bricks and over the lifetime of the AGRs.

(ii) That it is a best estimate prediction, rather than one that includes conservatism directly.

(iii) That the predictions must be a continuous function of the three field variables (fluence, weight loss and temperature), formulated for use in standard finite element packages.

(iv) Explicit statements are needed for all sources of uncertainty, separating parameter uncertainty and system variability.

(v) Where possible assumptions must be tested.

(vi) A proportionate validation should be undertaken that is consistent with best practice.

32. At this point, I note the importance of point (ii), combined with point (iv). Thus the EIM is a 'best estimate' model, with account taken of uncertainty and variability. This is of importance to the assessment of calculations that use the EIM, such as the DTA. It is perhaps inevitable and justifiable that a best estimate model is used. Of the materials properties calculated by the EIM, it is only strength where there can be any confidence that a higher value is preferable. For example, depending on the use, it is not obvious whether values higher or lower than the best estimate value of Young's modulus and dimensional change may produce the more conservative result. This generally necessitates sensitivity studies to determine the effect.

3.4 Background and the need for an EIM

33. Graphite moderated reactors were first built in the 1940s and the UK has had experience of operation of graphite moderated reactors since the 1950s. The various challenges posed by the changes in dimensions and materials properties have therefore been known for some time. The graphite for the first generation Magnox power producing reactors within the UK was made with a process that involved an extrusion. This led to an alignment of acicular particles of graphite and lead to a highly anisotropic material that grew in one direction and shrank in another.

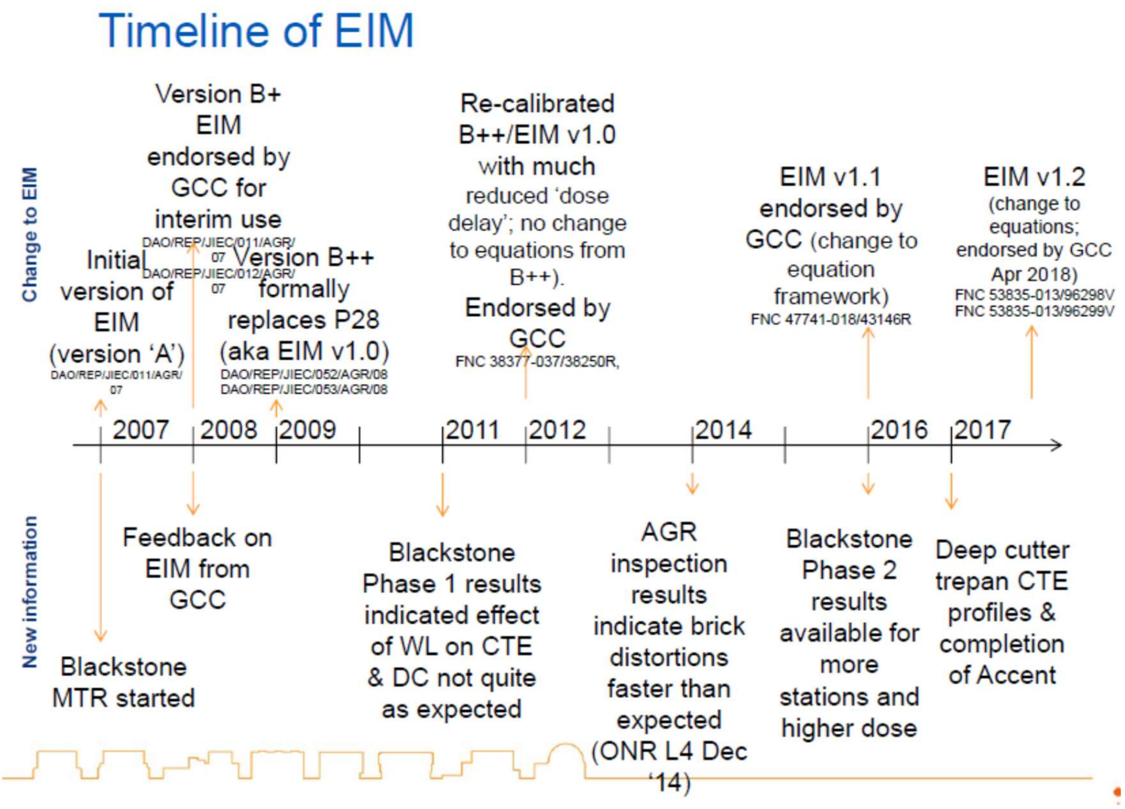
34. To avoid the engineering challenges produced by such anisotropy and also to obtain as high a density as possible, Gilsocarbon graphite was developed for use in the AGRs. Gilsocarbon is made by a complex process that includes a stage by which the raw materials are compressed in moulds. This does not lead to an entirely isotropic set of materials properties, rather it is orthotropic, such that measurements along the long axis of a brick reveal slightly different properties to the two transverse directions. The degree of orthotropy is however limited, i.e. less than 10% for all properties. Gilsocarbon is therefore sometimes described as isotropic and is generally sufficiently so that statements about graphite behaviour have a validity that applies in all directions. In particular, as it ages under the effects of irradiation, the AGR graphite initially shrinks in all directions, then reaches a point of turnaround after which it starts to grow.

35. Other types of graphite exhibit this general behaviour. However, the AGRs are being operated up to and beyond the point of turnaround, which, for example, is beyond the point that any of the Magnox reactors operated to. This necessitates consideration of the behaviour of large (~150kg) bricks of graphite at a point where the outside of the bricks is still shrinking, but the inner portion has passed turnaround and is expanding.

36. Calculation of stresses to predict behaviour of individual bricks therefore has to account for these dimensional changes, along with equally important changes in other materials properties such as Young's modulus. A further application of the materials properties is in NGL's whole core modelling (WCM), as used in the DTA. This analysis seeks to predict the behaviour of the core and in particular the geometry of the control rod channels under normal operation and transient conditions.

3.4.1 Evolution of the EIM

37. For the above reasons, NGL identified the need for a materials property model, which in recent years has been termed the EIM, with the most recent version being EIM 1.2. This terminology replaced earlier formulations described as ‘Paper 28’ and the ‘B++’ model. A timeline showing the evolution of these models supplied by EDF is shown below.



38. Of the more recent versions of the EIM, EIM1.0 was the first to incorporate phase 1 of the Blackstone MTR data (Reference 9) and was introduced in 2012. The DTA analysis in Reference 1 was carried out using parameters determined using EIM1.1. This version of the EIM was introduced in 2013, although not fully adopted immediately. It was created to model observed differences in the evolution of properties not captured by EIM1.0. Most of the references relevant to the EIM in Reference 1 deal with EIM1.1 including References 10, 11, 13 and 14. Reference 12 also deals with EIM1.1, although is not referenced by Reference 1.

39. EIM1.2 (References 13, 23 and 24) was developed in 2017 to account for other observations made on trepanned data that could be best explained by altering the EIM relationship between creep strain and coefficient of thermal expansion. It is noted that EIM1.2 is used in Reference 1 in the calculation of stresses for the prediction of brick cracking and evolution, as described in Argument 1.3.

40. The significance of the changes to the EIM and the use of different versions within the same safety case is discussed in more detail below.

3.4.2 Properties modelled by the EIM

41. A number of materials properties are needed in the various analyses that NGL perform and these are therefore modelled by the EIM. The properties include Dimensional Change (DC), Flexural Strength (FS), Dynamic Young’s modulus (DYM), Coefficient of

Thermal Expansion (CTE), Thermal Conductivity (TC) and graphite irradiation creep. NGL has chosen to calculate these properties as functions of three ‘field variables’, which are fluence, weight loss and temperature. The three field variables can therefore be seen as the ‘drivers’ of different materials properties. Some materials properties appear to be predominantly affected by just one field variable, others are affected by two or three. For example, the strength of graphite declines quite rapidly with weight loss and is also affected by irradiation, but to a lesser degree. DC though is strongly affected by fluence, but that variation is at most only marginally affected by weight loss. For example, in Reference 12 (page 17), it is noted that weight loss causes a delay in turnaround, but that delay is small and comparable to the observed scatter in turnaround dose.

42. Properties are also affected by temperature, but as the AGRs operate under standard conditions, with graphite brick temperatures varying from about 380ºC to 430ºC, that variation is generally only important when seeking to use data that has been obtained elsewhere under different conditions.

3.4.3 Observations on the nature of graphite property models

43. It should be noted that this sub-section and part of sub-section 3.5 and 3.6 contain my views and are not necessarily a reflection of those of NGL. They are provided here to aid comprehension.

44. In some cases, there is an obvious mechanistic explanation for the property variation. For example, it is readily understandable that weight loss caused by oxidation, which occurs throughout the graphite, due to its open pore structure, will result in a reduction in strength. This is because there will literally be less material within a matrix to resist any applied force and a structural failure will be more likely at a lower load in a high weight loss material. However, for other properties such as DYM, the variation is much less easy to explain. Inert DYM first rises sharply with fluence, then reaches a plateau, later rising again slowly to a peak value and then declining across the range of fluence that may describe the life of AGR graphite. It seems likely that more than one physical phenomenon is occurring and would be needed to describe the behaviour in mechanistic terms. The properties are undoubtedly linked though, for example both strength and DYM experience a sharp rise with irradiation at low fluence and both decline with weight loss.

45. One factor that complicates materials property work is the variability of graphite. Thus samples, apparently manufactured in the same manner may exhibit a standard deviation of strength of ±10%, suggestive of a substantial difference in structure. Other properties vary by similar amounts. With such a large variability, the use of small numbers of test specimens to establish a relationship can be difficult and false correlations leading to erroneous conclusions have to be considered a real possibility.

46. In creating a relationship to describe a property, there is in general a number of ways to proceed. It is possible to adopt a purely statistical approach and derive equations that are essentially empirical. Thus they are not ‘mechanistic’, they are just a set of equations fitted to the available data. Alternatively, if there is a knowledge of the expected relationship, based on physical reasoning or evidence, the general form of the equation can be identified and then the parameters can be fitted to the available data. This sort of relationship is described as mechanistic.

47. ONR has normally encouraged the use of the second method, as a mechanistic approach might be seen as safer, where there is limited data and also as a better demonstration of a physical understanding of that observed data. This is reflected in the SAPs (Reference 3) and may be particularly important in the situation where an extrapolation is needed beyond the region where data is available. It will be explained below that NGL now has some relevant high fluence data, an improvement on the

situation that pertained when the EIM was being developed. However, HNB R3 is the lead reactor in terms of cracking and future operation still necessitates operation beyond where there is any AGR reactor data.

3.5 Sources of data available to NGL

48. A number of sources of data were available for NGL to develop the EIM (discussed in References 10 and 11).

1 There were several 'historic' experiments, in some cases performed before AGRs were being operated, in various materials testing reactors (MTRs) including Pluto and the Dounreay Fast Reactor (DFR). All of these experiments ceased before 1993. Although some of the experiments were performed up to fluences that exceed the expected end of life values for the AGRs, they were mainly done in inert atmospheres. Some very limited experiments were performed with 'pre-oxidised' specimens i.e. ones that had been thermally oxidised before they were irradiated. The relevance of these has been considered, but it has been widely agreed that the conditions are not entirely representative of that experienced within the AGRs. A further limitation is that not all the data was obtained using Gilsocarbon graphite and some of these experiments may have been performed under conditions that were not well recorded.

2 There is data that has been obtained from specimens removed from the AGRs using trepanning techniques. These have the advantage that they are definitely Gilsocarbon and have been irradiated in an AGR environment. Therefore, uncertainties associated with the irradiation temperature are less important. Additionally these specimens experienced simultaneous oxidation and irradiation. The most obvious disadvantage is that such specimens are only available up to the fluence at which they are extracted from the reactor. Therefore, there is a limited extent to which AGR data can predict future behaviour, particularly for the case of Reference 1, which deals with the lead reactor.

3 There is data from 'Project Blackstone'. This is a series of more recent and continuing MTR experiments performed at the Petten MTR that have allowed simultaneous irradiation and oxidation. It has played a major part in the evolution of the EIM. Although the flux (i.e. fluence rate) is higher at Petten than in an AGR, the commencement of Project Blackstone was sufficiently late in around 2008 that specimens irradiated from the as-manufactured state have not yet reached typical AGR fluences. To deal with this problem, NGL has used a number of specimens that were removed from the AGRs. These were then re-irradiated at Petten, with the additional irradiation taking them past that of the AGRs.

49. In my view, although Blackstone has been a useful exercise for NGL, the complex history of the re-irradiated specimens has proved problematical. For the first part of their lives, the specimens were part of the AGR fuel bricks and subject to the physical constraint of being in a brick. Thus they were subject to the various forces that dimensional changes impose on the bricks. For the period in the MTR, these stresses were absent. Additionally, although NGL took steps to control the temperatures, the profile of the temperatures and the uncertainties therein are different.

50. I also note a further significant difficulty that arises in the consideration of dimensional change. Although the graphite in the re-irradiated specimens was subject to dimensional change whilst in the reactor, the actual amount is not accurately known. That is not the case once these specimens reach Petten, as their dimensions were measured before and after their secondary irradiation. However this two stage

irradiation makes determination of the absolute value of dimensional change problematical and instead NGL has chosen to use the dimensional change rate i.e. the difference in dimensions measured before and after irradiation, divided by the increment in fluence.

51. Nevertheless, with the exception of dimensional change, NGL has managed to accumulate property data at fluences and weight loss values that are beyond that of HNB R3.

52. It should also be noted that although NGL has data available from the three categories itemised above, a potential fourth source has not been much used. The AGRs were constructed with various removable specimens in place, termed 'installed sets'. These were specifically designed to provide information on the ageing of the graphite and some have been removed and examined in the past. Since 1999, NGL has chosen not to remove any more of these specimens and subject them to examination. They have argued that the availability of trepanned specimens has obviated the need for data from the installed set specimens, a decision with which ONR has concurred. Trepanned specimens from the brick bores will have had the greatest fluences, although they are of limited sizes. However, examination of the installed sets would have provided samples that experienced different irradiation and oxidation conditions and have allowed the range of the overall database to be extended. Largely though, the benefits that might accrue to NGL of using the installed set specimens are not known. EDF NGL has taken a business decision not to use these specimens. ONR will therefore assess the arguments based on the data that actually is available.

3.6 Derivation of the equations used within EIM

53. Development of the model can be seen as a two stage process. In the first stage the basic equations that describe property variations are developed. In the second stage the model is calibrated i.e. numerical values of the various parameters are determined. The calibration is sometimes undertaken on a power station or reactor basis.

54. Reference 10 is a document explaining the principles of the EIM and covers the nature of graphite, the microstructure of Gilsocarbon and presents potential explanations for the material property variations that occur. I note one particular section on 'philosophy' that contains the sentence:

> 'The choice of formulation within the EIM has by necessity been rather pragmatic in order to balance the requirement for sufficient complexity (to represent physical processes within the graphite) with the requirement to maintain sufficient simplicity that calibration of the model is possible and that the model can be implemented within FE packages.'

55. In considering say the complex variation of DYM with irradiation and how it differs significantly between inert and oxidising conditions (see Annex 1), it is self-evident that any scheme of equations is going to have to be reasonably complex to describe such a variation.

56. Any modeller has to make a choice as to whether to attempt to include mathematical relationships that at least purport to represent real physical processes or whether to do so using purely statistical techniques. There is of course no reason why the relationship could not be described using a simple power series for example, albeit one that would probably need many coefficients.

57. NGL has chosen the former method with their primary EIM model, implemented using their contractors Frazer-Nash Consultancy (FNC), although I note that there is also an additional model produced by their statistical advisers Quintessa that largely follows the second method. The Quintessa method is not dealt with in this assessment report and NGL appears to regard it as a 'sanity check', rather than a model of equal weight.

58. However, a mechanistic model may be considered superior to a purely statistical one in one very important regard. That is the justifiability of using the model in an extrapolation to predict future behaviour, rather than interpolation at points between actual real data. Some years ago this was a matter of crucial importance to NGL. As will be explained, although there is data obtained in MTRs in inert atmospheres beyond the limiting AGR fluence, for a long period there was no leading data from Gilsocarbon irradiated in an oxidising atmosphere. The situation has improved somewhat, mainly by the availability of results from Project Blackstone. Additionally, analysed trepanned data now also extends through to a larger proportion of the likely life of the AGRs.

59. Nevertheless the point remains and put starkly, a purely statistical model i.e. a numerical fit to data may describe the data adequately well within the extent of that data, but may not have any validity at all when used to extrapolate.

60. Therefore perhaps influenced by ONR (for example SAP EGR.9), NGL has attempted to derive underlying equations and parameters that represent physical changes within ageing graphite and to use these as intermediate variables. A full set of equations that can describe the variation of properties with the field variables is then built up.

61. However, a second stage of the process is the actual calibration of the parameters to whatever set or sets of data are considered the most credible and relevant. Put simply therefore, the first stage sets the shape of the sometimes complex curves describing the relationship and the calibration adjusts the height and width of the various features to accord with the data. NGL sees the development of the equations as a process that largely only needs to be done once, but the calibration as a process that needs repeating as newer data becomes available e.g. from particular trepanning campaigns or Project Blackstone.

3.6.1 Derivation of the basic equations and ‘Structural Connectivity’

62. To assist with the first process described above i.e. the derivation of equations that can be considered in some way ‘mechanistic’, NGL has used an underlying variable termed ‘structural connectivity’. Structural Connectivity (Sc) purports to describe a process by which the structure becomes more interconnected with age, in fact increasing with fluence, oxidation and temperature, as shown below in a figure taken from Reference 10. I note though that Sc is not a ‘real’ or observable property.

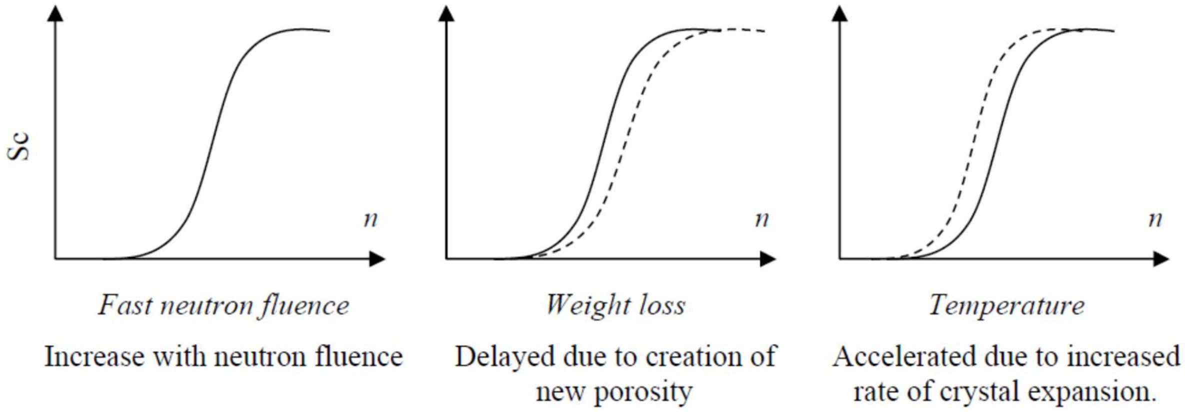


Figure 12: Dependence of structural connectivity on fast neutron fluence, weight loss and irradiation temperature

63. It is instructive to compare the shape of the Sc curves with the materials properties variation. Suitably scaled, such a term can help model for example, the rise in DYM (see Annex 1) that occurs in mid-life during the period of relevance to AGR operation.

3.6.2 Pinning

64. Several of the materials properties e.g. FS, DYM, CTE and TC experience a sharp rise shortly after irradiation commences, as shown in Annex A. This is termed ‘pinning’ and there are several potential explanations, which include the creation of inter-layer defects in the graphite crystals, which prevent the smooth sliding of the basal layers. Pinning is included in the EIM formulations. The existence of pinning perhaps has the effect that properties and effects that are measured in experiments on unirradiated materials are of limited relevance to the irradiated case. For example, the hysteresis observable in stress-strain curves for graphite under repeated loads is greatly reduced after a period of irradiation.

3.6.3 Mechanistic understanding of dimensional change

65. Reference 11 provides a potentially useful mechanistic explanation of the complex DC relationship and can be considered the licensee’s view on the matter. It observes that single crystal graphite shrinks in the in-plane a-axis and expands in the out of plane c-axis. However all bulk graphite, including Gilsocarbon, is an assemblage of crystallites with a density that is substantially less than the theoretical maximum i.e. the density of a single crystal. There is thus a certain amount of free space termed the accommodation porosity. It is surmised that the net shrinkage of graphite is explicable because the c-axis expansion is accounted for movement into the accommodation porosity and the bulk behaviour i.e. shrinkage is accounted for by the a-axis shrinkage. However according to this explanation, the accommodation porosity eventually gets used up and the c-axis expansion begins to dominate, leading to turnaround and subsequent expansion.

66. This explanation of DC behaviour easily lends itself to the prediction that DC turnaround will be delayed by oxidation. This is because there will be additional porosity in oxidised graphite. Pre-AGR MTR data using pre-oxidised graphite suggested that this was the case. However, initial Blackstone data and then AGR data cast doubt on the effect. The extent of such a delay will clearly have an impact on the time of onset of KRC. Overall, the uncertainty about this matter has been perhaps the largest unresolved question affecting the material properties and has led to continued uncertainty about onset times.

3.7 Derivation of the EIM equations

3.7.1 The EIM equation for DC

67. Using the known shape of the variations in material properties with the field variables equations were derived capable of describing the known variations. The DC relationship from Reference 11 is shown as:

$$G_i(\gamma,x,T) = \underbrace{\int_{y=0}^{\gamma} A_i(T)(1-\mathrm{e}^{-k_2(T)y})dy}_{\text{Underlying Shrinkage}} + \underbrace{\int_{y=0}^{\gamma} \overline{A}(T)B(T)S_{Cdc}(y,x,T)(1-\mathrm{e}^{-k_2(T)y})dy}_{\text{Pore Generation}} + \underbrace{\varepsilon_R\left(1-\mathrm{e}^{-k_1(T)\gamma}\right)}_{\text{Stochastic Relaxation}}$$

68. Where the Structural connectivity term Sc for DC is the first equation below.

$$S_{Cdc}(\gamma,x,T) = \frac{1}{2}\left(1+erf\left(\frac{\gamma-\mu_{dc}(x,T)}{\sqrt{2}\sigma_{dc}(x,T)}\right)\right)$$

$$S_{Ccte}(\gamma,x,T) = \frac{1}{2}\left(1+erf\left(\frac{\gamma-\mu_{cte}(x,T)}{\sqrt{2}\sigma_{cte}(x,T)}\right)\right)$$

Note that the second Sc equation is for use in the CTE equation and is discussed later below.

69. For the sake of brevity, I will not explain the above equations in detail, but the salient points are that G, the dimensional change is shown with a subscript to allow for orthotropy i.e. to indicate a different formulation in the different directions i.e. along the brick axis and perpendicular to it. G is also shown here as a function of all three field variables i.e. γ is fluence, x is weight loss and T is temperature. Most of the other terms are constants that are derived as part of the calibration including A, B, k_1 and k_2, that are functions of temperature. The stochastic relaxation term can be ignored here and is sometimes omitted anyway. A more detailed explanation of this relationship is provided in Reference 12 a paper presented to NGL's graphite core committee. I note that this paper may have proved controversial within NGL, partly because of the use of two Sc terms, taking several years for acceptance. This may be why it is not referred to directly by Reference 1.

70. Although the DC equation is very complex, it can be seen by inspection that the first term accounts for the shrinkage and the second for the growth. The swift rise in the Sc parameter, as shown in the figures above, effectively 'turns on' the second term at a point roughly equivalent to that of turnaround.

71. Further equations were derived for the other materials properties, as discussed below, again using Sc and often involving many coefficients that need to be determined as part of the calibration. There are actually over 40 parameters requiring calibration in the modelling of 7 materials properties, which is obviously a substantial task. Recalibration is performed occasionally when new data becomes available. Such recalibrations are reported and one dating from 2017 is referenced in Reference 1, this is Reference 13. In my view, the order in which the calibration is performed may be

important and there is significant ambiguity in how calibration should be performed. This point is developed further below.

3.7.2 The effect of weight loss on DC

72. The DC predictions of EIM1.1 and 1.2 differ from those of the earlier EIM1.0 in the way in which the potential delaying effect of weight loss on turnaround is dealt with. In EIM1.0 the dose delay is considered continuous. In EIM1.1, based on what was then new observations from Blackstone phase 1, the delay did not appear to be continuous for DC, although it was considered so for CTE. Consequently in the above equation for Sc the terms μ_{dc} were defined in Reference 12 (and also in Reference 11) as follows below:

$$\begin{aligned} \mu_{dc\_oxidised}(x) &= \mu_{dc\_inert}(1+\mu_{xdc}x) \qquad \gamma < \gamma_{sat} \\ \mu_{dc\_oxidised}(x) &= \mu_{dc\_inert}(1+\mu_{xdc}x_{crit}) \qquad \gamma \geq \gamma_{sat} \end{aligned} \qquad [9]$$

73. This shows how the $\mu_{dc\ oxidised}$ term is considered to saturate at a particular weight loss, but until then has increased linearly with weight loss. The use of this method is discussed further below, as a different variation of the μ terms is used between modelling of DC and CTE. Doing this was an innovation introduced with EIM1.1.

3.7.3 The EIM equations for DYM and FS

74. The closely linked equations for DYM and FS were each derived such that the property predictions are given by the unirradiated value multiplied by the product of several terms intended to account for different physical processes that affect both DYM and FS. Thus there is a pinning term, an increase modelled by the Sc term and a reduction at high dose intended to allow for additional porosity.

75. The equations are of similar complexity to those that describe DC. For simplicity I have not reproduced the equations in this assessment report, they are fully described in Reference 11, see p20. Rather than comment on the form of the equation here, I do so below in the context of the calibration, as Blackstone has provided leading data for both DYM and FS and in my view the most important factor is whether the equations developed can adequately encompass the actual data from both AGRs and Blackstone.

3.7.4 The EIM equation for CTE

76. CTE is modelled differently to both DYM and FS, as modelling by the use of several product terms was considered inappropriate. This was for several reasons, including that CTE appears to reach a saturated value irrespective of the unirradiated value. CTE is considered to have a degree of orthotropy, hence slightly different parameters are used for each direction. However, the variation of CTE with irradiation and oxidation is comparatively simple, see Annex 1. This simplicity is reflected in the equation used to model CTE. Thus there is an initial rise and then a steady fall with irradiation, slightly decreased by the effects of oxidation.

77. Three further matters affect the modelling of CTE. These are firstly the effect of oxidation. In contrast to DC, the effect of oxidation is considered to be a continuous effect i.e. one that does not saturate. Secondly CTE is itself a function of temperature and this is modelled as a linear dependence. Thirdly, CTE is affected by the material strain and a separate equation exists for the modification of CTE according to imposed strain. These factors are considered further below.

78. Again Blackstone has provided leading data for CTE and the same considerations apply as for DYM and FS.

3.7.5 The EIM equations for TC

79. TC falls initially with irradiation and then falls more slowly under oxidising conditions. The modelling is therefore comparatively simple. Reference 11 notes though that because of limited measurement from AGRs the modelling is performed largely using historic MTR and Blackstone data. In my view, TC is perhaps the material property of least importance in the analyses performed.

3.7.6 Irradiation Creep within the EIM

80. It is not my intention here to provide a full explanation of NGL's modelling of irradiation creep. Creep can be understood at a simple level as movements of atoms within the graphite under load that will result in strain and in many cases lead to a reduction in stress. Quantifying the phenomenon and providing more detailed mechanistic explanations has proved difficult for NGL and all other workers.

81. Creep does have an importance to the assessment of Reference 1 however because the formulation of the creep/CTE relationship was changed between EIM1.1 and EIM1.2. The explanation here is intended mainly to deal with those changes. Creep is dealt with in more detail in Reference 11, 23 and 24 by NGL and by GTAC in Reference 22.

82. The figure below is taken from Reference 11 and shows the creep strain as a function of fluence, presumably under constant load, expressed as a function of three terms primary, recoverable and secondary creep strain. The three terms are summed to obtain the overall creep strain value.

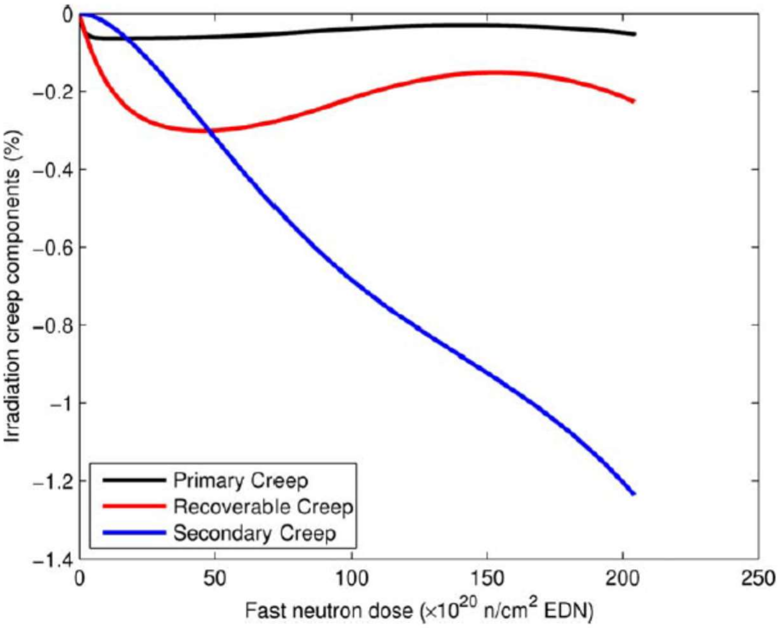


Figure 18: Components of proposed irradiation creep expression. These are summed in order to obtain the predicted irradiation creep trend.

83. Within EIM1.1, CTE is considered to be dependent just on primary creep strain according to the equation below (equation 20 from Reference 11).

$$\begin{aligned} CTEs_{20-120}/CTEu_{20-120} &= -1.34\varepsilon_p + 1 \quad \text{Compression} \\ CTEs_{20-120}/CTEu_{20-120} &= -2.38\varepsilon_p + 1 \quad \text{Tension} \end{aligned} \qquad [20]$$

Where, $CTEs_{20\text{-}120}$ is the stressed CTE, $CTEu_{20\text{-}120}$ is the underlying unstressed value and ε_p is the primary creep strain as a percentage.

84. Within EIM1.2 CTE is instead considered to be dependent upon recoverable creep strain, as shown in equation 20 from Reference 23 reproduced below

$$\begin{aligned} CTEs_{20-120}/CTEu_{20-120} &= G_c\varepsilon_{rec} + 1 \quad \text{Compression} \\ CTEs_{20-120}/CTEu_{20-120} &= G_t\varepsilon_{rec} + 1 \quad \text{Tension} \end{aligned} \qquad [20]$$

Where, $CTEs_{20\text{-}120}$ is the stressed CTE, $CTEu_{20\text{-}120}$ is the underlying unstressed value and ε_{rec} is the recoverable creep strain as a percentage. The parameters G_c and G_t are empirical and fitted to the available data.

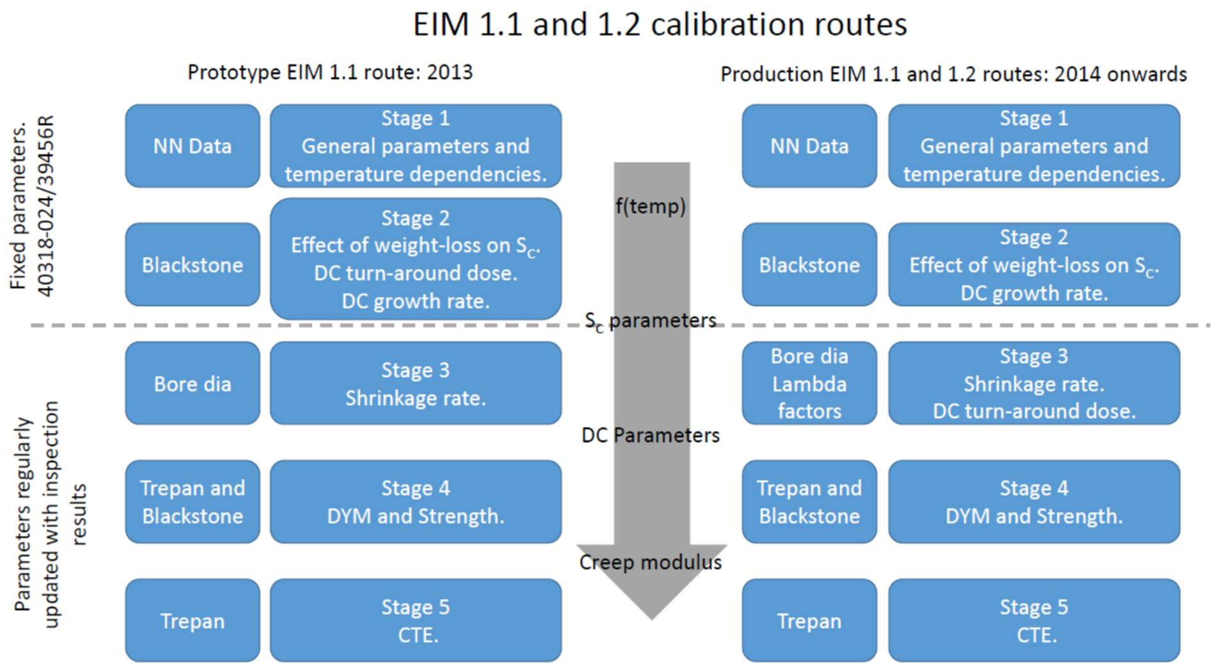
85. The motivation for the change in the CTE/creep relationship is explained in References 23 and 24 as a necessity to better explain observed CTE data from samples removed from AGRs using the deep cutter tool. This had not been used in early trepanning campaigns. Comment on the justification for this change is made below, as well as discussion on the implications of the change for predicted cracking.

86. Creep data has also become available from experiments performed at Petten during Project Accent, as discussed in the above References. I note that the irradiation increment achieved during Accent was comparatively small at approximately 50×10^{20} n/cm^2 EDND (see Annex 1 for an explanation of fluence units).

3.8 Calibration of the EIM

87. EDF/FNC considers the derivation of the EIM framework and its subsequent calibration to be separate processes. Thus separate reports are published on the EIM calibration (References 13, 14 and 15). To understand the calibration process, I held a series of meetings with EDF/FNC (References 16, 17 and 18). The figure below (Reference 17) illustrates the calibration process, including how it has evolved as further reactor data has become available, particularly on the DC turnaround dose.

88. In this section, I will explain the calibration process and I will concentrate on DC, as in my view, the DC calibration has required EDF/FNC to make the more significant decisions involving choice of data. In contrast, for the other material properties, where there is leading data from Blackstone, the calibration is conceptually simpler and necessitates finding the best ‘fit’ of the equations to the data.



89. It can be seen that the initial calibration is performed with the set of data described as ‘NN’ (discussed below), with Blackstone data being used to describe the effect of weight loss on Sc and the post turnaround DC growth rate. From 2014 onwards reactor measurements i.e. lambda factor and bore diameter measurements are used to determine the pre-turnaround shrinkage rate and the DC turnaround dose. This is an improvement on the earlier situation when the DC turnaround dose had to be taken from Blackstone data. Note that Lambda factors are geometrical parameters that NGL uses to describe the altered profile of a brick bore. These changes arise due to the combined effects of DC driven by fluence and the constraint provided by the graphite in the brick itself.

3.8.1 The NN data

90. The designation NN refers to a single block of production HPB graphite that was used to make MTR test specimens in the pre-AGR period. The following figure (Figure 2 from Reference 12) shows a subset of the NN data obtained at 390ºC. The top left figure shows the EIM1.1 DC curve for the two orthogonal directions. Data from the NN experiments seems to have been instrumental in characterising the orthotropy of Gilsocarbon and this is reflected in the DC equation above that describes DC in the two orthogonal directions.

91. It will be seen below, that although the orthotropy is not in dispute, the selection of a subset of the NN data by EDF/FNC has been challenged by our independent advisors, particularly since the subset used excluded higher fluence data at and beyond turnaround.

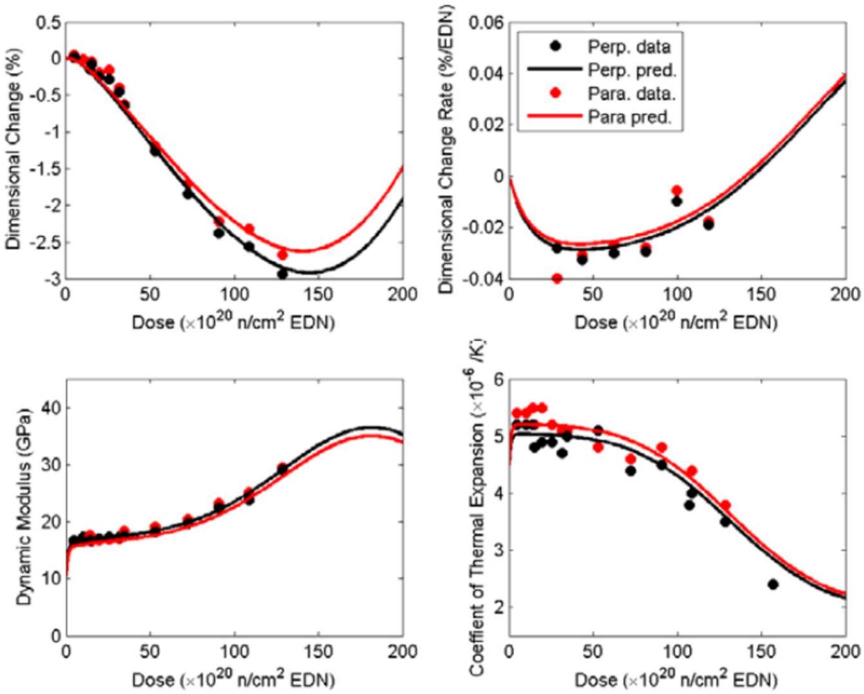


Figure 2: Material properties from samples irradiated at 390°C and corresponding EIM v1.1 fit. Perp. and Para represent measurements made perpendicular to and parallel to the long axis of the parent brick.

3.8.2 The ATR-2E data

92. A set of data from an experiment using a non-Gilsocarbon graphite known as ATR-2E was also helpful in the development of the EIM. The figure below is taken from Reference 12.

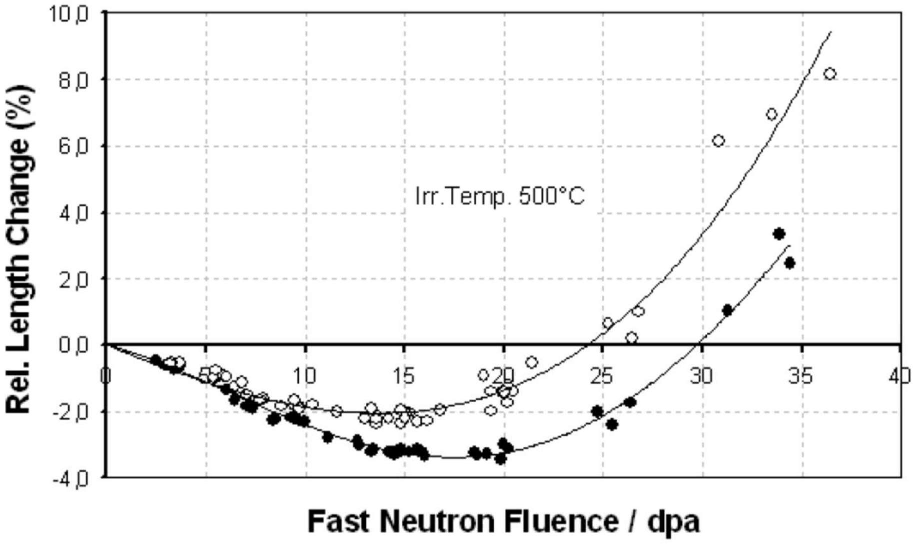


Figure 1: Dimensional change behaviour of ATR-2E graphite samples irradiated at 500°C in an inert environment (after Reference 9). (Open symbols are measurements made perpendicular to the extrusion direction, whilst black symbols are measurements made parallel to the extrusion direction).

93. The reference states that the ATR-2E graphite is more anisotropic than Gilsocarbon. The authors note the anisotropy at pre-turnaround fluences, but observe that post

turnaround, the curves appear to have similar gradients. For this reason the EIM DC equations consider the post turnaround gradient to be isotropic.

94. Reference 12 therefore describes the use of the NN data and the interpretation of the ATR-2E data as providing an ‘underlying calibration’ i.e. that it describes the behaviour of Gilsocarbon in an inert atmosphere over a limited range of fluences and identifies the orthotropy of the pre turnaround DC shrinkage and the likely isotropic post turnaround DC growth.

95. I note here though that ONR’s GTAC advisors (Reference 6) have challenged the influence of the ATR-2E data, on the basis that the type of graphite was substantially different to Gilsocarbon, in particular that it is more anisotropic.

3.8.3 Further calibration of the EIM DC relationship to account for weight loss induced delay to turnaround

96. Reference 12 then describes the calibration of the terms that represent the effect of weight loss in delaying turnaround. The figure below shows the available data.

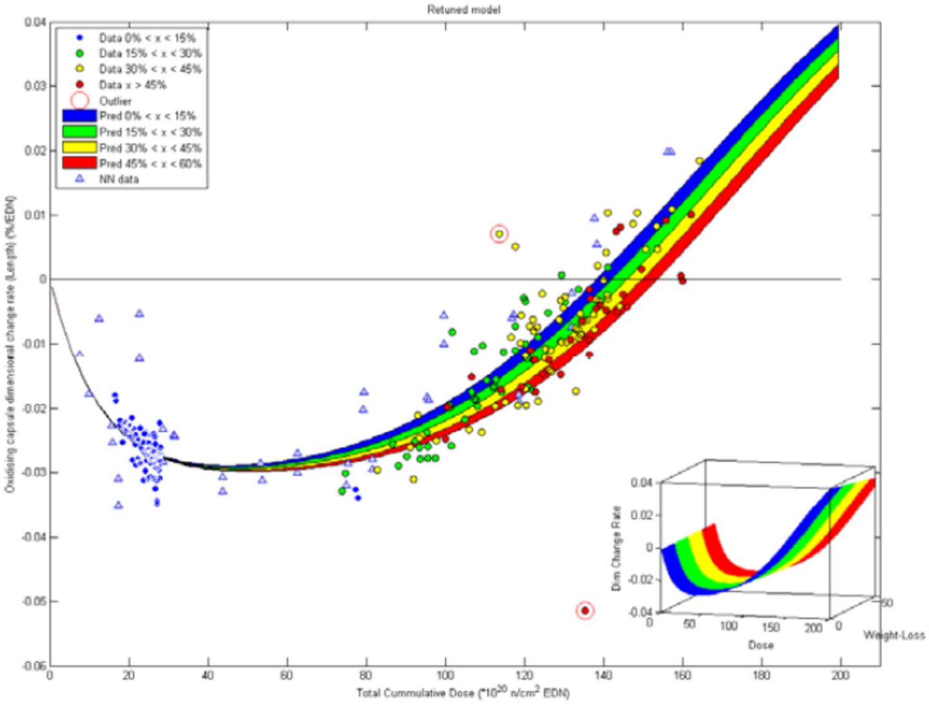


Figure 9: Blackstone Phase 1 oxidising capsule dimensional change rates measured along the sample length and predictions from EIM v1.0 employed in 43% weight-loss safety case (after Reference 6).

97. Note that because of the difficulty in determining absolute DC discussed above, the vertical axis is dimensional change rate, not absolute DC. The data points are ones derived from the Blackstone phase 1 oxidising capsule. It is possible to discern a trend by which the higher weight loss data points are slightly delayed with respect to the lower ones. Statistical analysis of this trend is used to calibrate the parameters that describe the dose-delay.

98. The data is overlaid on the coloured bands that represent the predictions of EIM1.0. The notable scatter of the data points is taken by Reference 12 to be indicative that as

well as there being a dose delay, that the turnaround fluence is itself ‘intrinsically scattered’.

99. Calibration of the various terms needed to account for a dose delay was nevertheless achieved. The dose delay term μ_{xdc} as used in the Sc calculation is considered fixed but the turnaround dose term μ_{dc} is considered to be normally distributed and the breadth of this distribution is obtained from AGR data.

100. It may be useful to observe at this point that the magnitude and nature of the ‘dose delay’ is highly influential on the results of the analyses that subsequently use the EIM. However the precise nature of that delay has changed between EIM versions, particularly EIM1.0 to 1.1. In my view, the dose delay is small and not easy to quantify. Additionally other phenomena might produce the same effect within the data, for example an unrecognised temperature error in the Blackstone irradiation temperatures.

3.8.4 Calibration to AGR inspection data

101. As increasing amounts of data have been obtained from AGR measurements directly, it has been possible to use that data to calibrate some of the EIM parameters. In particular, bore diameter data from inspection campaigns have allowed parameters such as the A_{perp} and μ_{dc} terms in the main DC and Sc equations respectively to be derived. These parameters contribute to the determination of the pre-turnaround gradient and point of turnaround.

102. There are of course advantages in the use of AGR data, rather than parameters derived from separate MTR experiments. For example the calculation of the bore diameter of an aged brick requires the use of the DC relationship, a function of all three field variables, together with other parameters including creep. If the EIM calibration had been performed purely using MTR data, then any systematic and unrecognised differences between the MTR and AGR conditions e.g. due to uncertainties in irradiation temperature, could result in erroneous diameter calculations. By calibrating directly to AGR data, such sources of systematic uncertainty are removed.

3.8.5 Limits of the AGR calibration data

103. Use of actual AGR data has considerable advantages for the reasons described above and others. For example there may be systematic uncertainties in the field variable parameters such as temperature and fluence between the MTR and AGR conditions. Use of AGR data largely removes such sources of uncertainty. However the AGR data will normally lag the actual reactor condition and extrapolation beyond that point will be necessary using one of the leading sources of data.

104. There is then a question as to what the maximum reasonable extent of the extrapolation should be and I will return to that topic in the ONR assessment below.

3.8.6 Calibration of the EIM post turnaround DC curve

105. The post turnaround DC curve is obtained partly from the original NN data, as there were some data points that remained after the majority of the post turnaround data was excluded for reasons discussed below. However it was then noticed that the Blackstone data suggested that a slightly (8%) steeper post turnaround curve should be used. Such a curve was then joined on to the DC curve just after turnaround. The post turnaround gradient is essentially described by the parameter B in the equation above.

3.9 Other materials properties including creep

106. The majority of this section deals with the DC calibration. Properties including FS, CTE, TC and DYM are measured using samples removed from the reactor by trepanning, some of which were re-irradiated in the Blackstone experiments to gain leading data. Creep can only be measured directly in experiments in which a loaded specimen is irradiated and is perhaps the most difficult to measure. A separate series of irradiation creep experiments 'Project Accent' have been carried out. Consideration of the Accent results and of trepanned data led to the EIM1.2 changes, which mainly affect the creep/CTE relationship.

107. I will refer to the modelling of these other materials properties in my assessment below.

4 ONR ASSESSMENT (1) – THE EIM AND ITS CALIBRATION

108. This assessment has been carried out in accordance with HOW2 guide NS-PER-GD-014, “Purpose and Scope of Permissioning” (Reference 2).

4.1 Scope of Assessment Undertaken

109. The scope of the assessment is limited to aspects of Reference 1 that concern or use the EIM. This includes in particular argument 1.2, the topic of the rest of section 4. Section 5 deals with the use of EIM to predict stresses and section 6 deals with the sensitivity of the DTA results to variations in EIM derived parameters.

110. It will be seen that the assessment draws heavily on advice received from our independent advisors particularly GTAC and the UofM/HSL team that has developed an alternative model with the aid of M&CS. After describing the UofM/HSL model and showing how the predictions differ from those of the EIM, I contrast the approaches and consider the merits of each.

111. It is hopefully useful for me to state here though that I have decided not to judge one of these models superior to the other. They have both been developed by experienced teams. The predictions that emerge for post turnaround DC differ notably though. Rather than attempt to decide which is more likely to represent the future behaviour of AGR graphite, I prefer to consider both plausible and to conclude that there is uncertainty in future behaviour.

112. Within section 4, I have dealt with DC and the Creep/CTE relationship in the most detail, as it these areas where there is some contention and also where uncertainty may have a significant impact on predictions within the DTA and for cracking behaviour.

113. For the other material properties, where in my view, NGL can reasonably claim to have leading data, I consider that there is likely to be less difficulty and ambiguity in modelling the behaviour. In principle, given that the EIM equations have been produced to model the observed variations, it should just be a question of calibrating them against the data. The actual situation is surely more complex, as the variability of graphite has to be accounted for and also there are uncertainties in the field variables.

114. This complexity is perhaps reflected in the changes that have occurred within the EIM. In Reference 1, EIM1.1 is used for the DTA and EIM1.2 is used elsewhere, such as in the prediction of future cracking. I therefore also consider the differences between the two versions and whether the use of two versions within one safety case is reasonable.

4.2 Comparison with Standards, Guidance and Relevant Good Practice

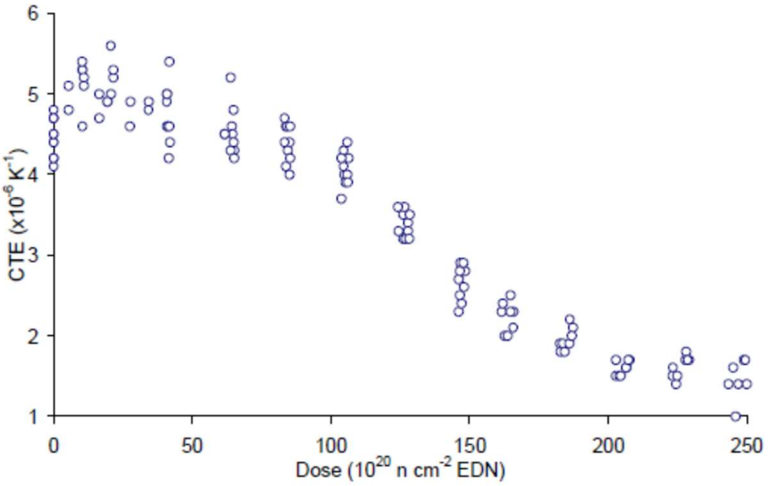
115. I am not aware of any directly applicable standards and guidance to the mathematical modelling of graphite behaviour. This sub-section identifies some aspects relevant to what I understand to be good practice and applies to section 4, 5 and 6.

116. I note that any activity to develop a materials property model of such a complex material has to deal with a number of difficulties. These have been faced by both the developers of the EIM i.e. EDF and FNC and also by the Nuclear Graphite Research Group (NGRG) at the UofM and HSL. These difficulties include that:

(i) There are a number of datasets available to use. These are from different types of experiment, and from the reactor itself, as described above. The data cannot necessarily be easily compared. With data from diverse sources, judgements about the levels of quality control that applied during particular experiments and uncertainties may differ, as may the extent of the data.

(ii) Graphite has a variability. Thus even if an equation is derived that is a claimed description of the particular parameter, not all the data will ‘fit on the line’. Indeed this variability may serve to reduce confidence that the form of the relationship derived is adequate.

(iii) There appears to be no infallible method of identifying the mathematical ‘form’ of a relationship that best describes a set of data. By ‘form’ I mean the basic equations which will have associated uncalibrated parameters when first derived. Purely as an example here, the figure below that shows a set of CTE data discussed in Reference 6 on page 7, could perhaps be approximated by a linear relationship, a quadratic or a cubic. Although the cubic relationship might best describe the two points of inflexion, the residuals that would emerge from such a fit to a dataset with such a large apparent variability, would not necessarily imply that the cubic was a better fit.



117. A statistical method does exist that can be used to indicate the relative quality of statistical models for a given set of data. This is the Akaike Information Criterion (AIC). However, it is only a criterion and may have limited utility in comparing the EIM with the UofM model, as one of the main points of issue is which data to use, not purely the mathematical relationship. Application of the AIC seems mainly to be intended for cases where very similar data are used (Reference 19). Use of AIC is therefore not advocated as a method of deciding whether one model is superior to the other when the difference between them also involves the use of different data. Later though, I refer to a use of AIC by NGL/FNC to compare EIM1.1 and EIM1.2 where the same data is used and I have been advised that this is a reasonable use of AIC (Reference 39).

118. In the absence of a method of determining the best form of relationship, my own view is that:

(i) Extrapolation beyond the range of AGR data has to be treated cautiously, noting that, in my example above, the linear, quadratic or cubic fits would behave very differently outside the range of the data.

(ii) That there is nothing inherently better or worse about the different basic equations used by either EDF or UofM/HSL. All views on such a topic should in any case be informed by the data. It is the decisions about the choices of data that are likely to matter the most in the resulting relationships.

119. I note that in this context, the main point of contention between the EIM and UofM/HSL models is in which datasets to use.

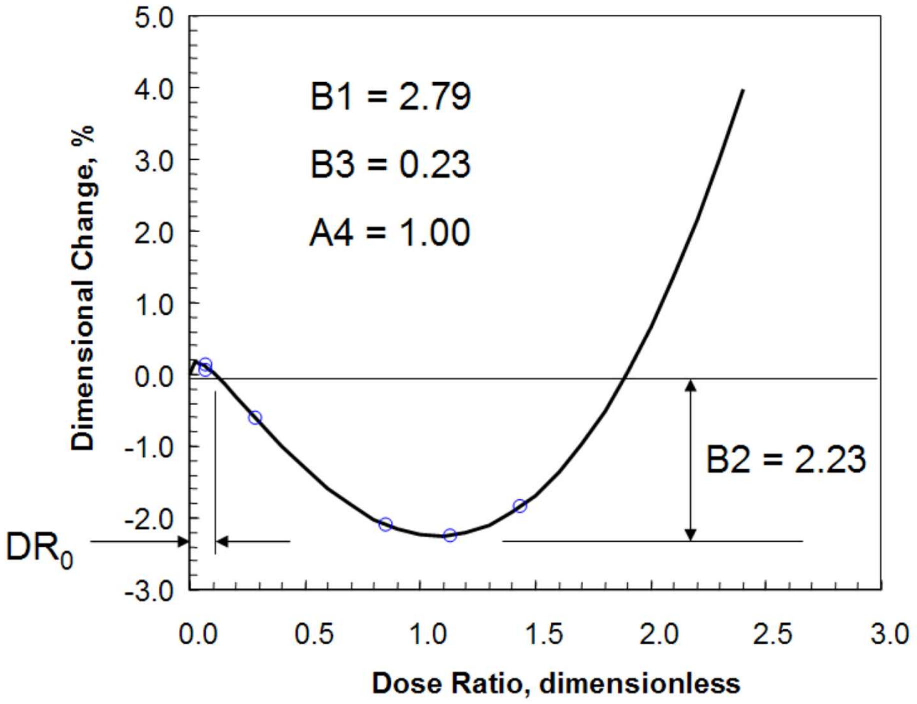
4.3 The University of Manchester model of DC and other materials properties

120. ONR commissioned the University of Manchester, HSL at Buxton and M&CS to provide analyses of graphite data. Such analyses have proved useful to ONR over a period of years as they allow an independent view to be presented that is not associated with that of the licensee. In particular, an entirely separate set of relationships has been derived. These do not purport to be mechanistically based, they are derived from a data-led approach. It would be reasonable to describe the equations used as significantly simpler than those used in the EIM, a difference that may have both positive and negative aspects. The original M&CS model is described in References 26 and 27, with more recent developments described in Reference 7.

121. The first equation is shown in the figure below (from Reference 26) and describes the model developed by M&CS by considering inert MTR data. It can be seen that the general form of the equation is that of a parabola i.e. a quadratic, slightly distorted by the term DR^{B3}. I note that the value of B3 is 0.23, a sufficiently small number that the general parabolic form is not greatly changed, as the term increases slowly and is near unity, when DR is >0.5. M&CS also uses a dimensionless parameter DR which is the dose ratio i.e. the fluence divided by the fluence at turnaround of the particular dataset.

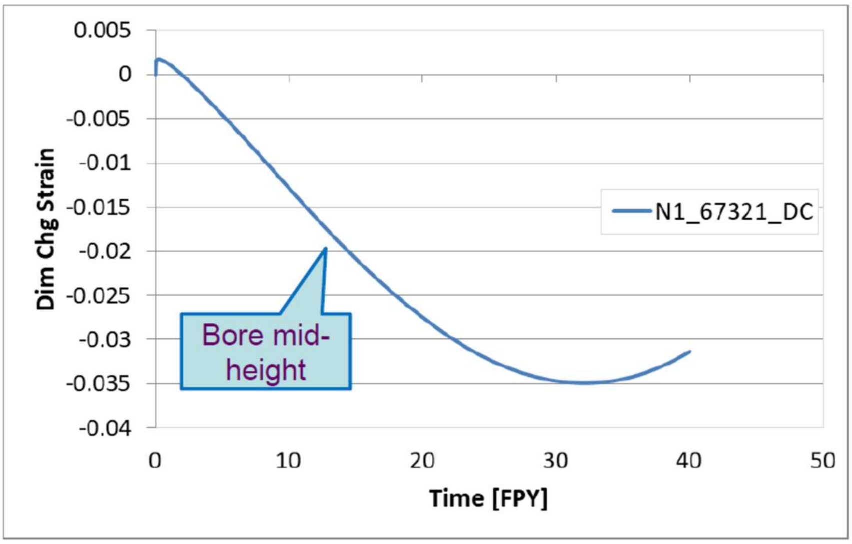
122. By using a dose ratio, M&CS has in effect provided a ‘master curve’ approach i.e. a way of analysing a number of different sets of MTR data, all of which can be normalised to a common point of turnaround of unity in his dimensionless scheme.

$$DimChg = DR^{B3}[B1(DR - A4)^2 - B2] \tag{3-3}$$



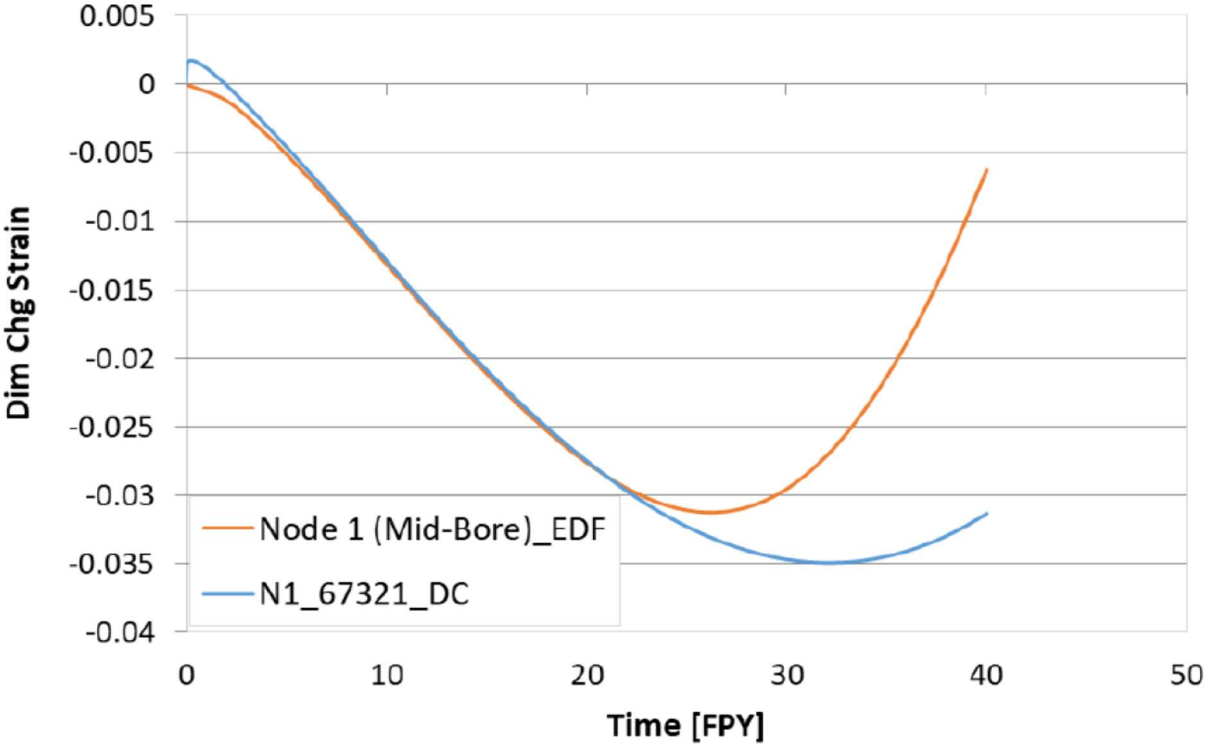
123. M&CS’s model does not directly permit comparison with the AGR data, which is obtained under oxidising conditions. Therefore the University of Manchester team added terms to M&CS’s equation that permits it to be adjusted to allow for a potential delay in DC turnaround due to oxidation. The resulting equation is shown below, together with a graph showing a particular calibration to a set of AGR data.

$$DimChg_{effective} = DimChg + \left(\frac{S_0}{0.07} DR^2 - S_0 DR \right) - \left(\frac{S_0}{0.07} DR_{effective}^2 - S_0 DR_{effective} \right)$$



124. Although this model adds a complexity, the small size of the coefficients such as S_0 is such that the equation still basically describes a parabolic shape over the range of interest.

125. ONR also asked the graphite technical advisory committee (GTAC) to comment on the EIM, including the differences between the EIM and UofM models. It will be useful to explain these differences here. The two DC curves have been plotted out in the figure below taken from the GTAG report Reference 6.



126. The features that can be noted from the comparison figure above are firstly that there is agreement over most of the pre-turnaround range and that secondly that there is a significant difference both in the point of turnaround and also the post turnaround gradient.

4.4 An initial comment on the differences between the two models and the way in which they are calibrated

127. Consideration of the EIM DC and UofM equations shows a significant difference, apart from the inherent complexity of the EIM form. The EIM equation is essentially two main terms, one of which describes the shrinkage and the other, which includes the region where the structural connectivity term increases from zero to unity, describes the turnaround and post turnaround behaviour. In contrast, the UofM equation is simpler and being a ‘slightly distorted’ parabola, will have a similar pre and post turnaround gradient, almost symmetrically disposed about the point of turnaround.

128. There are significant consequences of the above when it comes to calibration. The development of both equations was highly influenced by pre-AGR MTR data, with both equations treating the effects of weight loss as a ‘distortion’ of an unirradiated relationship.

129. As there is now both trepanned data and dimensional measurements from reactor channel inspections from HPB and HNB that go up to the point of turnaround, it has been possible for both models to be calibrated against the reactor data. Thus it is in no sense surprising that both curves agree with each other in the pre-turnaround region. Reactor inspection data also permits allowance to be made for the orthotropy of Gilsocarbon, as the forces that act in the direction of the brick axis affect the brick profile by means of the ‘lambda factors. These are parameters developed by EDF which represent the departure of the bore shape from the purely cylindrical towards a ‘double wheatsheaf’ type of shape. In the horizontal plane i.e. the one where hoop stresses act, the bore diameter at different heights conveys the more useful information.

130. The majority of data currently available is descriptive of the reactor behaviour in the pre-turnaround region up to a point slightly, but not significantly after turnaround. I note that the EIM places turnaround to be at approximately 135x10^{20} n/cm^2 EDND, whereas the present fluence is about 160x10^{20} n/cm^2 EDND, but that the most recent calibration may not have extended that far. It is therefore also evident that the pre-turnaround calibration does not have any great influence on the post turnaround region. It is the latter region that is in contention and which may play an important part in both the rate of cracking and in dimensions that affect the DTA. To understand the differences in the two models, it is necessary to consider the ways in which they have been calibrated in that region and this will now be explained.

4.5 Calibration of the UofM model and differences in calibration approach to that used in the EIM

131. Reference 6 is a report produced by GTAC, commissioned to address the validity of the EIM approach. Reference 7 is a report written by ONR’s advisors at the University of Manchester and M&CS that was commissioned specifically to address questions about the use of particular data sets for calibration of the EIM. Many of the observations below are points made within those reports. It will become evident that there are some disagreements about the selection of data between the M&CS/UofM/HSL team advising ONR and the EDF/FNC team.

132. The M&CS approach was to use as much as possible of the available pre-AGR MTR inert data. In total there are about 2100 data points in the full MTR database, which reduce to 1581 data points that are relevant graphite types and for which dimensional measurements were made. Of these, only 24 were considered to be statistical outliers by M&CS such that they needed to be excluded on the basis that they might have a disproportionate effect on the calibration of the model. M&CS only excluded data that were considered to be Chauvenet outliers. This is a standard statistical technique designed to exclude points so far from a mean trend that they are unlikely to occur by

chance. M&CS then randomly chose 1400 of these remaining points, setting aside 10% to use as a calibration check. His model is therefore based upon 1400 points.

133. As an example of the data used and of the use of dose ratio, which also allows for a temperature correction, the figure below shows HPB type NN data from a range of irradiation temperatures. It can be seen that there is data above turnaround and that the ‘with’ and ‘against’ grain directions exhibit slightly different dimensional changes.

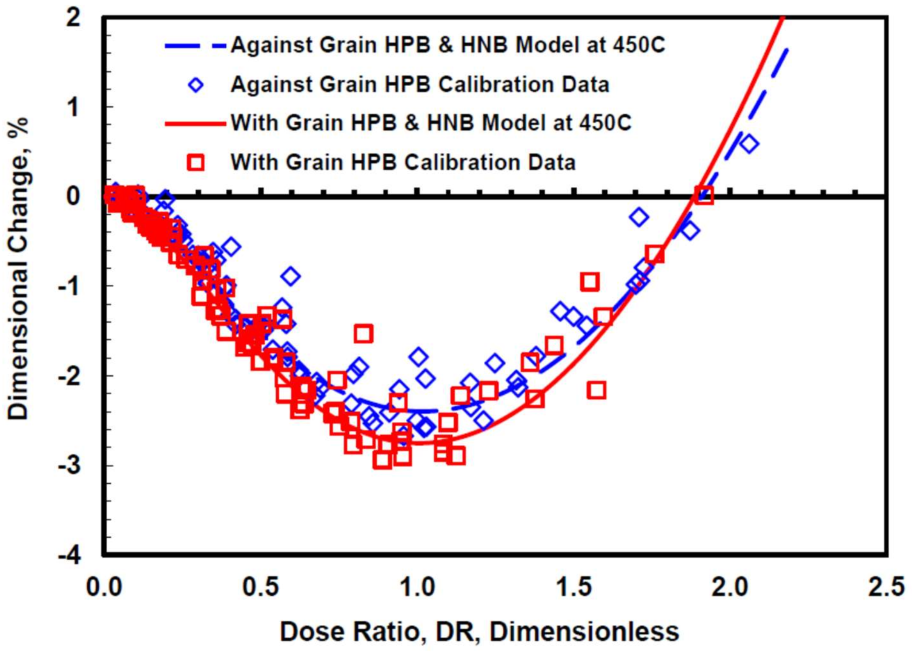


Figure 3. Hinkley Point B (AGL, NN code) Data at 295 ≤ T_{irr} ≤ 620°C, NGRG Model at 450°C (assumed typical of Hunterston B) See also Figure 9, same calibration data plus validation and outlier data

134. The temperature correction that M&CS applies is shown in the equation below and allows substantially more data to be used in the same analysis than if sets only from a particular experimental temperature were used. Note that not all the 1400 points are shown in the above figure, just the HPB NN data.

$$DR = (dose)/(estimated\ turnaround\ dose) = (dose)/\left(f(direction)(2211 - T_{irr})^{3.17}\right) \quad (1)$$

135. The M&CS relationship only uses four fitting constants i.e. maximum DC amplitude, turnaround dose and the difference between with and against grain amplitudes i.e. B1, B2, B3 and A4 in the equation above. A subsequent check with the 157 points not used in the calibration produced similar standard deviation to the calibration set, indicating that the model was not over fitted to the data.

4.5.1 Calibration of the UofM model to AGR data i.e. allowing for the oxidation induced dose delay

136. The subsequent adjustment of the M&CS relationship to account for the potential dose delay was performed at the UofM, using analyses performed by HSL derived from AGR bore diameter at different heights within the brick (Reference 17). In principle this process involves using the relationship in a finite element stress analysis to calculate the resulting brick shape, then comparing the brick dimensions with those measured in inspection campaigns and iteratively adjusting the parameters until the best fit is found.

In practice the number of finite element analyses needed is reduced by means of an emulator methodology developed by HSL as part of the BCN project (see Reference 25). Fundamentally this process has the effect of slightly stretching the curve along the DR (horizontal) axis, so that the dose delay is accounted for.

4.5.2 The EIM choice of data for the first stage of calibration using the inert MTR specimens

137. In contrast to the M&CS approach, the EIM was originally calibrated against a far more restricted set of the inert MTR data. It appears that a choice was made to use only the 181 NN graphite data points i.e. those from only one HPB production brick. Of the available NN data, some was further excluded on the basis that it was obtained outside the temperature range said to be relevant to AGRs i.e. between 390ºC and 600ºC. This removes 21 points that are between 295ºC and 390ºC.

138. M&CS is therefore very critical of the choice of data used to calibrate the EIM, noting that the remaining 160 points result in quite a small set to calibrate such a complex multivariate model such as EIM, whereas M&CS has managed to use 1400 for a model that is simpler anyway.

139. There is a further criticism in that the data available were reduced still further by taking out 18 points, leaving only 142. The reasons given include the samples being ‘out of trend’, samples having been re-irradiated and samples ‘having been lapped’, the latter presumably to square off ends for measurement purposes. M&CS considered each data point and the reasons for its inclusion or exclusion from the EIM calibration process. M&CS disagrees with the choices made by EDF/FNC in a number of cases. In particular M&CS notes that only 5 of the 18 points excluded would have been removed as Chauvenet outliers. The most important consequence of the data exclusion is though that much of the NN data at higher fluence has been excluded, leaving only 24 points above turnaround. Of these 24 remaining, there are at least two that M&CS would have excluded as Chauvenet outliers and which may have biased the EIM post turnaround curve in a steeper direction.

4.5.3 Effect of choice of calibration data on other materials properties

140. M&CS notes that the data used in the DC calibration is also used in the derivation of parameters that describe other materials properties e.g. through terms such as Sc. They note (Reference 7 p16) that the use of what they consider to be biased data in the DC model will also affect the other material properties. In my view, such an effect may be mitigated because for all other material properties, the Blackstone data can be said to be leading of the conditions in HNB R3. It is only for DC that there is a contention about the use of the Blackstone data. I discuss the confidence of the modelling of other material properties further below.

4.6 Discussion of model differences

141. As is evident above, in forming my own views I have had to take note of the fact that our independent advisors, including GTAC, the UofM/HSL teams, together with M&CS have challenged some aspects of the licensee’s EIM. Additionally the UofM model makes significantly different predictions for DC post turnaround. I summarise the situation as follows:

    (i) NGL has expended a large effort in developing the EIM. Their systematic approach required a measure of foresight and investment over a long period, particularly with the implementation of Project Blackstone and Project Accent. Credit is due for their approach. The analysis teams have made careful choices and their strategy was undoubtedly influenced by ONR, for example in their attempts to produce a mechanistic, rather than purely statistically based model.

(ii) NGL has though not been entirely successful in producing a mechanistic model. Concepts such as structural connectivity (Sc) have been criticised by GTAC as not having any real physical basis. Furthermore, the apparent difference in the way in which weight loss affects DC and CTE have of necessity led to the modification of Sc purely on an empirical basis.

(iii) In contrast, the M&CS/UofM/HSL model started out using a 'data led' approach i.e. it is purely a statistical model, albeit one that both they and ONR consider physically reasonable. As a statistically derived model, there would generally be a greater concern about its use for extrapolation, although the different calibration strategy may obviate this as a concern as explained below.

(iv) Given the significantly different predictions of the two models, there does therefore remain a considerable uncertainty in the behaviour of graphite beyond the point that HNB R3 has reached. This concern is greatest for DC, but the concern is mitigated for the other properties by the existence of the leading Blackstone data.

(v) The EIM is a more complex model than the M&CS one. The EIM DC relationship appears to have at least 12 parameters. Additionally, many more are needed for the other material properties. In contrast, the M&CS model is far simpler, requiring only six for DC, including allowing for the conversion of fluence to dose ratio.

(vi) The greater number of parameters in the EIM DC model allows greater flexibility. In particular it allows the post turnaround gradient to differ from that of the pre-turnaround gradient. In contrast, the M&CS model does not, apart from the slow varying DR^{B3} term, which only slightly distorts what would otherwise be a parabola i.e. derived from a quadratic form. M&CS's equations are derived from pattern recognition algorithms to provide an insight on the functional form of the relationship. From these, they select suitable equations to model the data (References 26, 27). They have selected what would appear to be the simplest equation that provides an adequate fit to the data. I should add though, that as the pre and post turnaround behaviour represents graphite in a substantially different state, it seems physically plausible that the gradient should be different.

(vii) There are a number of different datasets potentially available for calibration, albeit many of these were obtained under inert conditions. Some limited 'pre-oxidised' experiments were performed, but there is concern that these do not describe behaviour under simultaneous oxidation and irradiation conditions.

(viii) Project Blackstone has proved invaluable to NGL for all material properties, particularly in obtaining leading data i.e. data that is ahead of HNB R3 in terms of both weight loss and irradiation. However there is considerable difficulty in using the DC data, as part of the fluence for each specimen was obtained while it was still in an AGR brick and part when it was further irradiated at Petten. As such, the constraint changed through life, affecting the creep strain. Also the shrinkage before it was trepanned can only be estimated, not directly measured. It is therefore only possible to measure the change in dimensions, over a substantial increase in fluence obtained in the second irradiation. Thus even though a nominal dimensional change gradient can be calculated, it may have been obtained over a period where the specimen was shrinking, turned around and then began to grow. Thus it is not a mathematically rigorously defined gradient. A gradient that could be held in greater regard would have required more frequent measurements of the specimens' dimensions.

142. I therefore make the following observations about the two methods.

(i) I do not see it as inherently undesirable that the EIM DC formulation is so complex. The equations describe known graphite behaviour and allow flexibility. The M&CS approach is though simpler and as modified by the UofM, can also describe the change in DC with irradiation. It seems to be the calibration where the main potential area of contention lies.

(ii) M&CS has made a significant advance in analysis by creating and using the dose ratio method. It has allowed nearly all the historic inert Gilsocarbon data to be shown as relevant. However, the choice of data for the EIM had been made by the time M&CS's work became available.

(iii) EDF/FNC had taken a different approach to the one M&CS subsequently developed, selectively choosing data that they considered relevant. M&CS has a valid criticism of the way in which some of the data available for use in the EIM calibration was excluded. It is an important observation that most of the post turnaround NN data was excluded from the EIM calibration. This necessitates the use of other data to define that region.

(iv) In contrast though, the allowance for the weight loss delay to DC turnaround is an 'add-on' for the M&CS model, whereas it is perhaps more carefully considered for the EIM. Both the UofM model and the EIM are tuned to the AGR data over the range that it is available. Hence it is not surprising that they agree with each other and with the reactor observations in this region.

(v) The M&CS model cannot easily use the Blackstone DC data anyway. M&CS maintains that it would result in a loss of rigour to do so, as that data has ambiguities because only the gradient of the DC curve can be calculated. In contrast, the EIM uses the Blackstone DC data to define the post turnaround DC gradient. A related observation was that the post turnaround curve does not exhibit noticeable orthotropy and the equations were adjusted to accommodate this when EIM1.1 was created. This decision seems to have been based on the observations on the ATR-2E data, which our advisors consider unrepresentative of Gilsocarbon.

4.7 Conclusion on the nature of the EIM DC relationship

143. In forming a conclusion on the applicability of the EIM DC relationship to the licensee's safety case (Reference 1), I have attempted to take a full account of their considered views expressed in the various references mentioned here and at a number of meetings. I have also taken note of the advice from independent sources. Overall, I have concluded that both representations of DC are credible. That it is possible for two widely disagreeing relationships to have been derived is mainly a result that the choice of data to use is not obvious. Expert judgement has been used by both parties, but as in other areas, experts may disagree.

144. Because of this apparently irreconcilable difference, I consider that the most productive way forward is for the licensee to show that the various predictions made using the EIM should be shown to be mainly insensitive to the nature of the post turnaround DC gradient. As EIM predicts a steeper gradient than the UofM model, I consider it is self-evident that the former will predict both earlier onset of keyway root cracking and that the rate of cracking, derived from the variability of properties will also be higher. Thus the EIM will provide a conservative prediction in so far that the onset times of KRC are

no longer in question for HPB and HNB, although there are still unknowns about the rate.

145. However it is less obvious to me that the EIM makes predictions that are conservative for the DTA leg of the safety case in Reference 1. There are apparent sensitivities of the DTA to dimensions such as the gap between bricks and the gap between the key and keyway. These parameters will in any case differ in each layer and between the centre of the core and the periphery. I note that the sensitivity of the DTA to the predictions of the key/keyway gap is not well established. A series of technical questions (TQ) has been developed to contribute to the exchange of information relevant to the assessment of Reference 1. I discuss these further below.

4.8 Other materials properties including creep

146. I have already noted that I have not considered the other material properties in as much detail as for DC. I consider this proportionate, given the current concerns which centre on the DTA, which was considered potentially highly dependent upon DC predictions.

147. In support of the statements in the above paragraph, I note that the most recent GTAC Q56 report on the EIM (Reference 6) did not raise specific difficulties with the modelling of the other material properties. Additionally an older GTAC report Q44 (Reference 28) which considered Project Blackstone was supportive of that project and positive about the prospects of using the results obtained as leading data. Over the past 10 years, ONR has also had numerous level 4 meetings with NGL and performed inspections where the quality of the materials property data measurements have been considered. I will, however, make a recommendation that ONR considers whether further independent advice in this area is needed, as currently there is no GTAC review of later Blackstone phases.

148. I do though consider the creep/CTE relationship in some detail below, as this is important in the prediction of stresses for both the DTA and for cracking predictions. GTAC Q56 did not cover the creep/CTE relationship. That is the subject of a separate report (Q62) (Reference 22).

4.8.1 Strength

149. Strength of graphite is obviously of importance. A number of safety cases are in development that are expected to advance NGL's arguments about graphite strength e.g. the forthcoming Hartlepool/Heysham 1 case, which will seek to increase the structural integrity assessment limit to 50%. Assessment of these cases will undoubtedly contain comments on the EIM relationship.

150. I note though that one of the most positive aspects to emerge from the Blackstone results is that the graphite appears to retain strength up to high weight losses i.e. at least 50%. This is discussed in Reference 28 and ONR has generally been less concerned about the possibility of a sudden reduction in strength at high weight loss since the Blackstone phase 1 results became available.

151. Noting that strength is a strong function of weight loss and that weight loss is one of the field variables, I consider that the greater uncertainty in strength possibly resides in the uncertainty in the weight loss. I therefore do not wish to comment further on the EIM modelling of strength, apart from saying that I consider that the modelling of the weight loss will dominate the uncertainty, not the relationship within EIM that expresses strength as a function of the three field variables.

152. Some differences in the values of strength near the keyways predicted using EIM1.1 and 1.2 have been noted. It is believed that these are associated with a change in the

prediction of fluence that occurred separately to, but at the same time as the change in EIM version. I have not assessed these changes, although NGL has stated that they are comparatively small for HPB/HNB, making less than 5% difference (Reference 29 and associated presentation). I deal with the implications of uncertainty in strength further below.

4.8.2 Young's modulus

153. The GTAC report (Reference 6) briefly discusses the modelling of DYM in EIM1.1, noting the complexity of the DYM equation evolved out of the original formulation in EIM1.0 to a new version for EIM1.1. This was developed, based on evidence from Blackstone from paired samples irradiated in oxidising and inert atmospheres and is alleged to account for the observed weight loss effects.

154. EIM is a best estimate model and unlike strength, it is not self-evident whether higher or lower values of DYM, or shifts in the fluence at which the changes occur produce more or less conservative results in analyses. Consequently uncertainties in DYM will generally need to be addressed by sensitivity studies. Apart from that and the complexity of the DYM variation with irradiation, I have no great concern about the EIM relationship for DYM, which is fitted to data including that from Blackstone. In principle, it seems reasonable to take the available Blackstone data as 'leading' of that likely to be observed in the AGRs.

4.8.3 Thermal Conductivity

155. TC is perhaps of lesser importance than DYM anyway, but similar comments would apply as for DYM.

4.8.4 CTE and graphite irradiation creep

156. CTE and creep are dealt with in the same section here as there is expected to be a dependence. Both properties are comparatively difficult to measure. Thermal expansion produces only small strains in graphite, only about 30% of those which occur in steel. Creep measurement requires an irradiation experiment in which samples have been placed under a known load. Inevitably, this is difficult to implement and NGL deserves credit for managing to obtain even the limited data that they have got so far.

157. ONR has previously requested advice from GTAC on creep and earlier reports are available, i.e. Question 22 in 2006 and Question 36 in 2010 (Reference 20). More recently, ONR requested a report on the experimental aspects of the then proposed ACCENT experiment in Question 51 (Reference 21 in 2019) and on the materials modelling concerning creep and CTE i.e. essentially the differences between EIM1.1 and 1.2 in Question 62. This latter GTAC report is still in production (Reference 22).

158. Creep can be considered to be important in two areas. Firstly, it alters the dimensional change that would otherwise occur in an unconstrained situation. Creep is a stress relaxation mechanism and will generally act to reduce any internal stresses.

159. Secondly, CTE and its variation with irradiation plays an important role in the prediction of stress both at power and at shutdown. When the reactor is at power, there is a temperature gradient across the bricks, but there is also a CTE variation because of the difference in fluence and oxidation across the brick. The stress state that develops is reduced by the effects of creep, a continuous process that occurs whilst the reactor is critical. When the reactor is shutdown, e.g. for inspection, that stress state will change, as the temperature gradient across the bricks reduces and further creep is assumed not to occur. Depending on the nature of the creep/CTE relationship it may be that the predicted stresses are either higher at power or higher at shutdown, for

particular points in life. Notably, the use of EIM1.2 equations suggests that it is more likely that cracking will occur at shutdown, rather than at power over the next proposed period of operation. I compare the EIM1.1 and EIM1.2 stress predictions below.

160. However, although the influence of creep on CTE is a matter of empirical observation, it is not one for which a credible mechanistic explanation is yet available. The change between EIM1.1 and 1.2 is in which element of creep strain is used as the determinant of change in CTE. In EIM1.2, the change in CTE is described as a function of the recoverable creep strain, as opposed to the primary creep strain that was used in EIM1.1. This appears to demonstrate a better correlation, but the draft GTAC report urges caution, making the following comments:

161. *Thus, it is the opinion of GTAC that the change of the EIM from v 1.1 to v 1.2, being a result of the change to the CTE-creep strain relationship, is not mechanistically based. The model is based on limited CTE data with significant scatter and therefore the margin of error must be taken into account in carrying out any predictions. Thus, GTAC considers that EIM v1.2 can only be supported as an empirical improvement in the EIM methodology as long as it can be used successfully to model the accumulating experimental data from trepanned samples and other reactor data, such as lambda factors, and in core component predictions*.

and later:

GTAC considers that whilst it has little confidence in the modelling of irradiation induced creep and its associated effect on properties, it recognises that the empirical methodology EIM v.1.2 has been shown to improve property predictions of trepanned samples and predictions of reactor data and is supported as long as it can do so. Given that there are still some areas for improvement GTAC considers that EDF Energy should continue to review and update the methodology as data are accumulated in future.

162. Although Reference 22 is still in draft, the above statements can be taken as the opinions of the authors. I also noted that the empirical justification for the change in creep/CTE relationship is justified statistically in Reference 13 and 24 in part by use of the Akaike Information Criterion. I have referred to this technique already to obtain advice on the limitations and applicability of the technique (Reference 19). I sought further statistical advice. In Reference 39, I was advised that in the above context, it appears to be a reasonable use of AIC. Thus there is a valid statistical basis for concluding that the use of recoverable creep strain, as opposed to primary creep strain produces a better correlation with the trepanned data.

4.9 Use of EIM1.2 to predict cracking will occur at shutdown

163. At least up to 16.425TWd, for periods of normal operation, which include six-monthly inspections, the use of EIM1.2 will lead to a prediction of higher rates of cracking, as the shutdown stresses are larger than those predicted with EIM1.1. The shutdown stresses are larger than the at-power stresses because of the contribution from thermally induced stress, the magnitude of which is affected by the predicted values of CTE. This also leads to the prediction that cracking will occur at shutdown.

164. Although ‘cracking at shutdown’ is not a major part of NGL’s overall safety case, it perhaps does have a value and is discussed by NGL in argument 1.3. This is because it suggests that the degree of cracking found during any inspection was not present during the preceding period of operation and that cracking predicted in a subsequent operational period will not actually occur until the following shutdown. However at higher burnups than 16.425TWd, the difference between the shutdown and at-power stresses is narrower for EIM1.1 compared to EIM1.2. In this sense, the potentially different predictions of EIM1.1 and EIM1.2 would suggest some caution is needed in the consideration of cracking at shutdown arguments, because they are so sensitive to the predicted values of CTE.

165. It may be that NGL is able to present more convincing arguments about the influence of creep on CTE in the future. In my view, at present though, ONR should not accept an argument that cracking would only occur at shutdown, although there is certainly empirical inspection evidence that some cracking does occur then. I have made a recommendation to this effect

166. Otherwise, it does though seem conservative for NGL to use EIM1.2 for the prediction of future cracking rates and I consider the evidence as to whether EIM1.2 produces a reasonable prediction of brick stresses in the next section.

5 ONR ASSESSMENT – (2) OVERALL CONFIDENCE IN EIM VALUES, FIELD VARIABLES AND CALCULATED BRICK STRESSES

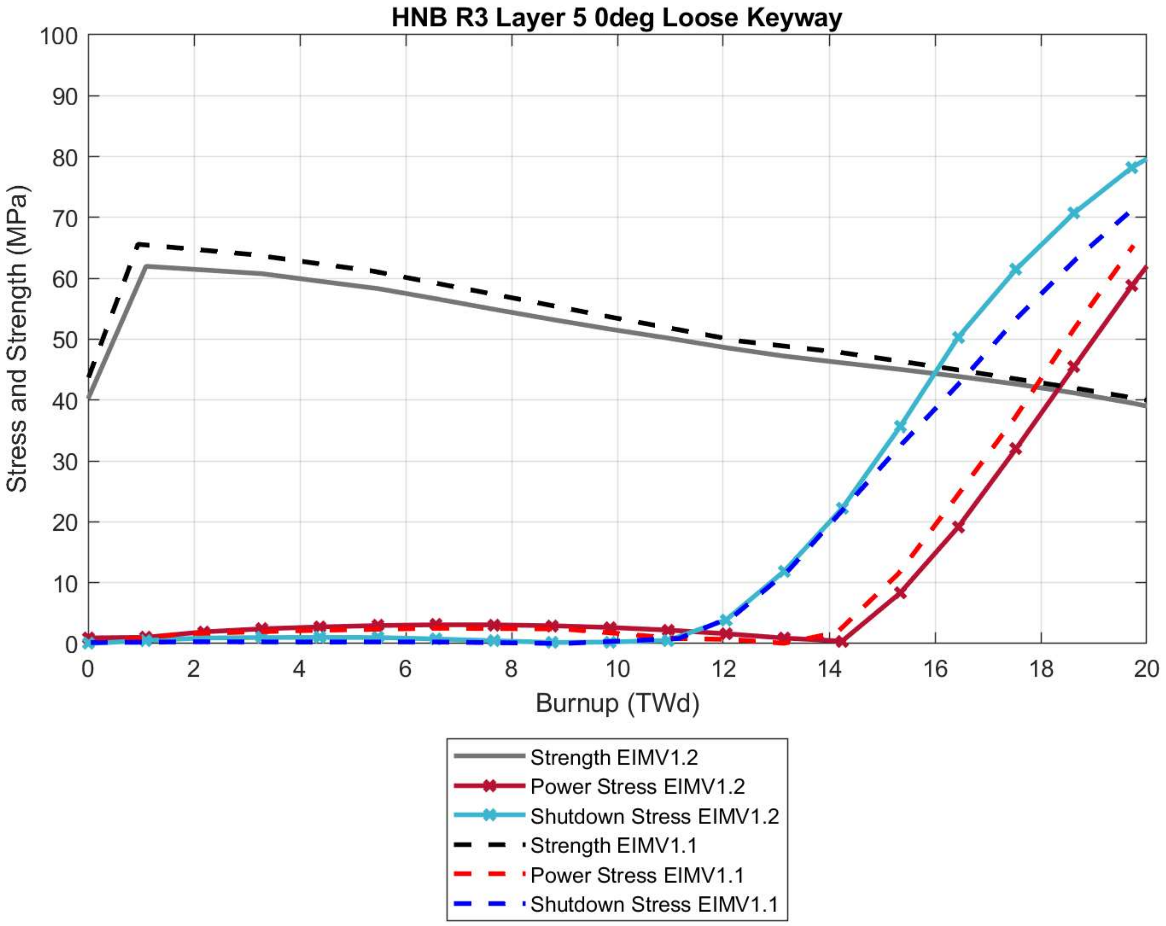
167. The EIM has been used in several different parts of SS1:

- It is used to provide inputs to the DTA, with both the dimensions and brick internal stresses and strengths being used. In section 6 below, I assess the effect of uncertainty in the EIM predictions, by considering NGL's sensitivity studies into the effects of varying the dimensional clearances and brick capacities to resist external forces.
- It is used in the prediction of cracking and crack evolution. Thus both the rate of formation of new cracks and their evolution e.g. crack opening rate are informed by the use of the EIM.

168. Both cracking rate and crack opening rate are observable parameters and the predictions for them are partly based on the EIM, with a degree of correction based on the empirical observations. Cracking observations therefore offer a route by which a measure of confidence in stress calculations can potentially be gained. Prediction is though also complicated by the interaction of bricks, with forces being transmitted via the keying system. This leads to phenomena such as induced cracking, where forces appear to be transferred via the end-face keys. However the first KRC to crack in a channel, 'the primary' KRC, can often be identified and in many cases it appears that this first crack has not been greatly influenced by its neighbours. Thus the primary KRC will have occurred when the internal stress at the keyway in that brick reaches the strength.

5.1 Evidence to support NGL's stress predictions – relative conservatism in EIM1.1 and 1.2

169. In the figure below from Reference 36, the EIM1.1 and 1.2 stress and strength predictions are shown for a loose keyway in layer 5. It can be seen that there is a slight difference in the EIM1.1 and 1.2 derived strengths, with EIM1.2 predicting them to be slightly lower. This is accounted for by the incorporation of new data and a change in the field variables. It appears to be a marginal effect at the burnups relevant to Reference 1.



170. The ‘at-power’ stresses are the more relevant for the DTA, as the concern would predominantly be for a seismic transient during operation. These stresses are higher with EIM1.1. As EIM1.1 stresses are used in the DTA, I am content that NGL has used the more conservative of their two available models.

171. I note also that the ‘at-shutdown’ stress is higher than the at-power stress for both models, suggesting that cracking in layer 5 at loose keyways would be more likely to occur at shutdown for both models, particularly since periods of operation are unlikely to exceed 6 months.

172. I note also that the shutdown stresses are higher for EIM1.2 than EIM1.1, indicating that it is more conservative to use EIM1.2 for cracking prediction, as it brings forward the time at which any particular level of cracking would be reached.

5.2 Evidence to support NGL’s stress predictions - Evidence from analysis of Keyway Root Cracking at HNB

173. In Reference 38, an analysis of KRCs known of in HNB by 2017 in re-inspected channels is described, i.e. a total of 11 cracks. They use a brick specific analysis i.e. taking account of the layer and individual channel parameters. Using this technique a prediction is made using both EIM1.1 and 1.2 of the expected time of cracking. This is then compared with the observed ‘time window’ in which cracking could or would have occurred i.e. as set by the last inspection where the crack was not present and the first where it was. In the figure below i.e. figure 4 from Reference 38, the green bars represent the time window for cracking and the dots represent cracking at-power and at-shutdown predictions for both EIM1.1 and 1.2. It is noted that the at-power

predictions are very similar for both EIM1.1 and EIM1.2 and ahead of both of the shutdown predictions. The blue dots represent the EIM1.2 at-shutdown predictions. These are earlier than those for EIM1.1. Also 7 out of 11 of them overlap with the time window.

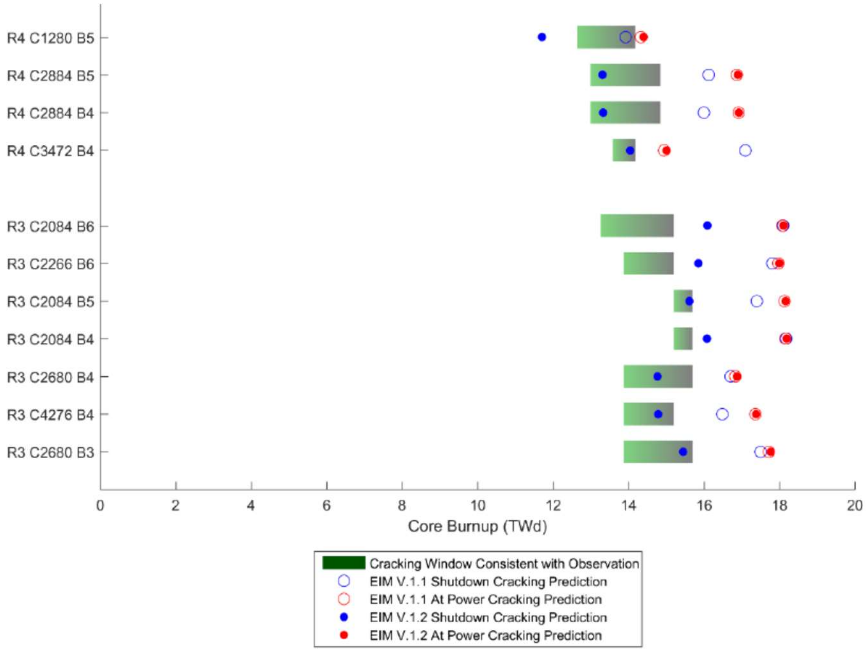


Figure 4: Visualisation of keyway root cracking windows consistent with observations and predictions using EIM V.1.1 and EIM V.1.2. The bars represent the range of cracking burnups consistent with observations. The window consistent with observation ranges from the burnup at which the brick was last observed intact (green) to the burnup at which the brick was observed cracked (grey).

174. Further analysis was performed using the EIM calibrated values that describe uncertainty, to provide uncertainty at 2σ for both EIM1.1 and EIM1.2. Figures 7 and 8 from Reference 38 shown below show the uncertainty bars for EIM1.1 and EIM1.2 respectively.

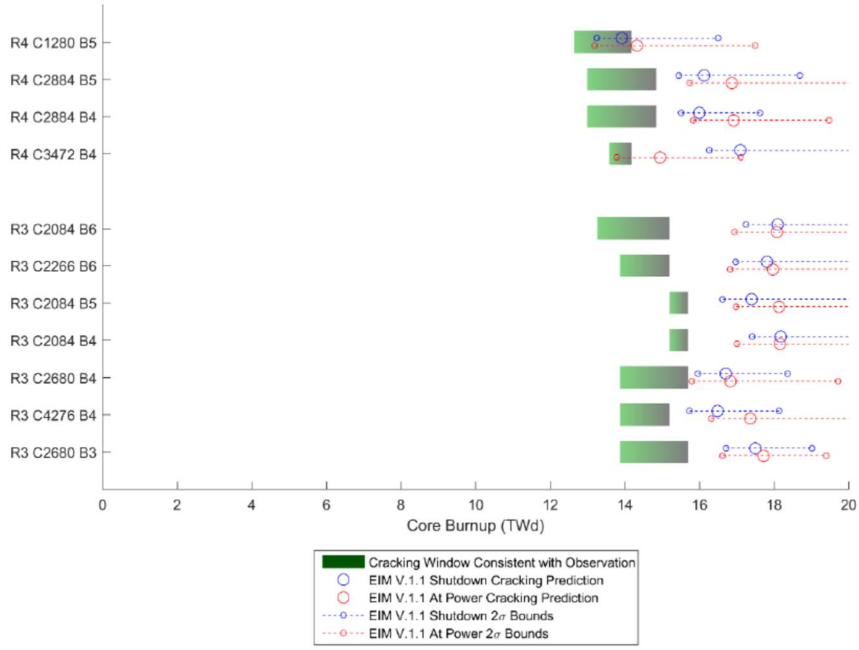


Figure 7: Visualisation of keyway root cracking windows consistent with observations, predictions and uncertainty bounds using EIM V.1.1. The bars represent the range of cracking burnups consistent with observations. The window consistent with observation ranges from the burnup at which the brick was last observed intact (green) to the burnup at which the brick was observed cracked (grey).

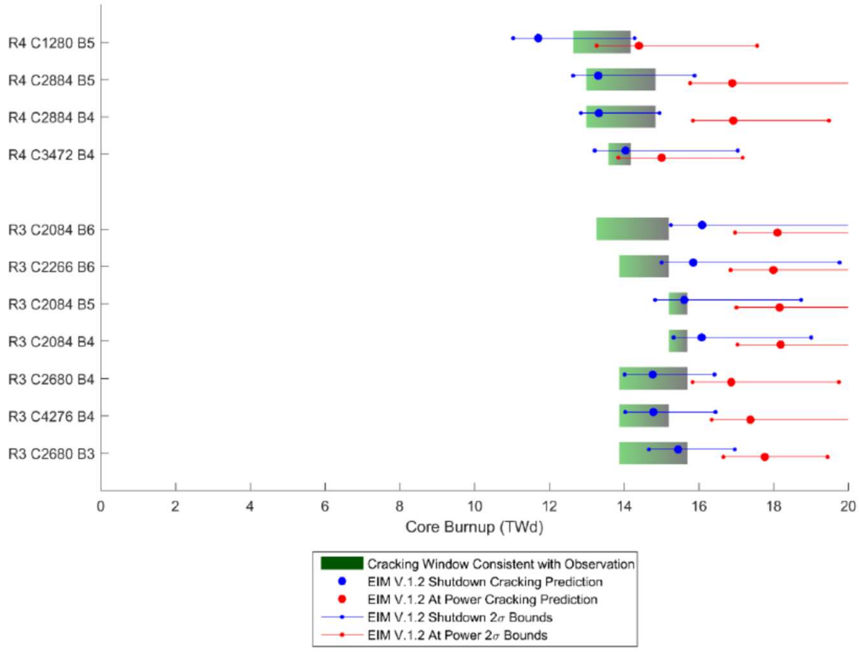


Figure 8: Visualisation of keyway root cracking windows consistent with observations, predictions and uncertainty bounds using EIM V.1.2. The bars represent the range of cracking burnups consistent with observations. The window consistent with observation ranges from the burnup at which the brick was last observed intact (green) to the burnup at which the brick was observed cracked (grey).

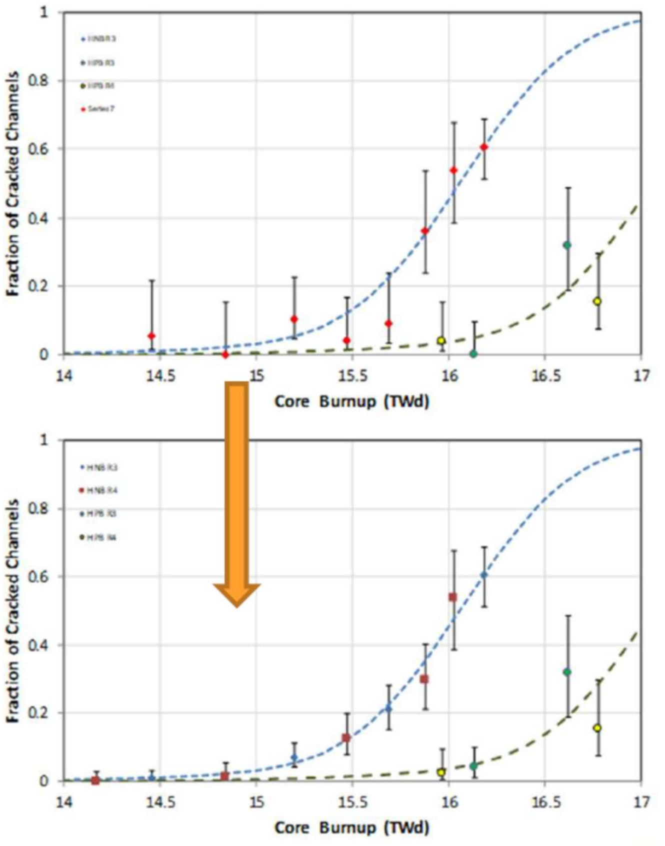
175. It can be seen from Figure 8 that the EIM1.2 cracking at-shutdown prediction overlaps in most cases with the observation window. The authors of Reference 38 comment that, with EIM1.2, overlap occurs for 10 out of 11 bricks, whereas with EIM1.1, overlap only occurs for 2 out of 11.

176. The authors of the GTAC Q62 report (Reference 22) note that the change from EIM1.1 to 1.2 produces a good agreement with the timing window, although caution that this may not be purely due to the change in the CTE/creep relationship, as updated calibrations and dosimetry changes are also involved.

5.3 Evidence to support NGL’s stress predictions - Further use of EIM1.2 to explain observed cracking

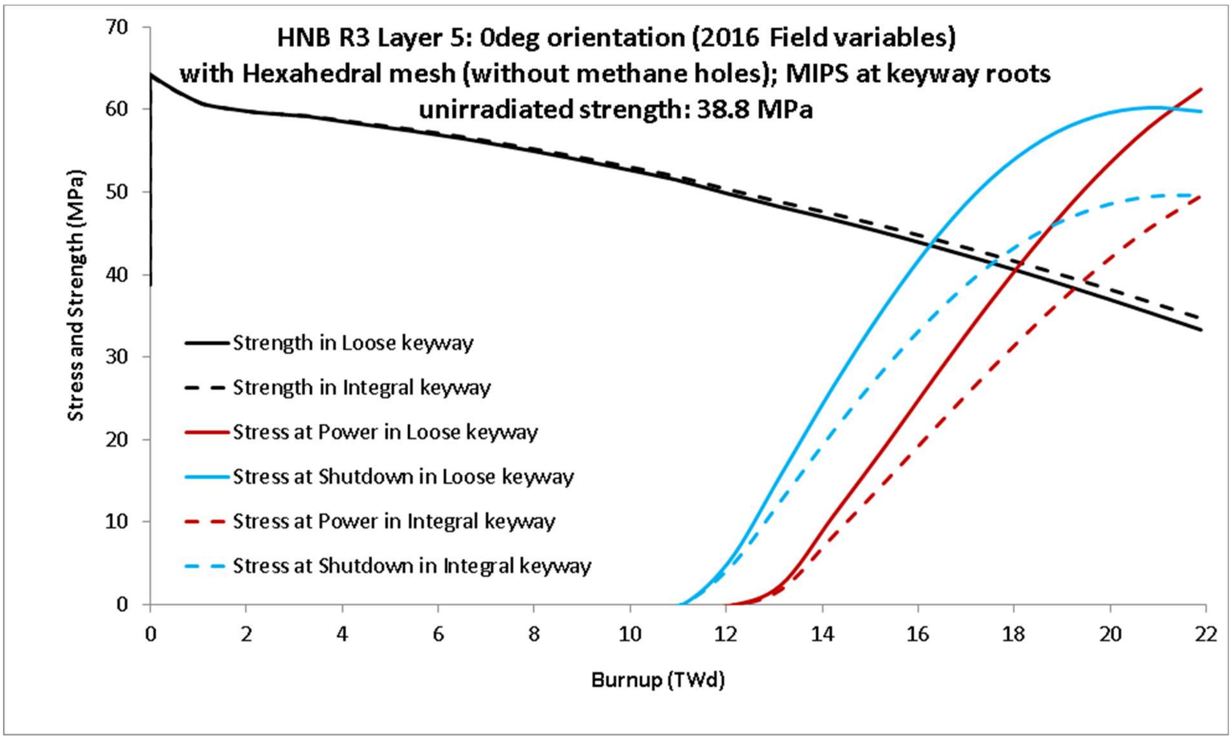
177. Recent analysis suggests that at least for HNB, the previous inspection findings can be reasonably explained. For example in Reference 35, I note that by making allowance for the degree of crack opening found when cracks were inspected, a back-calculation can be made to determine when the cracking occurred. This seems to allow a consistent explanation of the past HNB R3 and R4 inspection results.

178. The figure below shows the inspection observation of fraction of cracked channels for each inspection. The above back-calculation is shown in the lower graph. This appears to fit the HNB observations onto a smooth progression curve and is rather better at doing so than in the higher graph, where the data is just plotted using time of inspection. The HPB results are less well explained however and NGL is currently considering whether materials property differences between HPB R3 and R4 may be responsible.



5.4 Evidence to support NGL’s stress predictions - Comparison with stress predictions from the UofM model

179. Using the UofM independent model (Reference 37), stresses were also predicted and are shown in the figure below. These were calculated using the field variables used for EIM1.1 and are therefore perhaps best compared with EIM1.1.



180. The stress predictions between the UofM and EIM1.1 model are comparable, although the stress at power appears slightly higher for the UofM model. Thus in the above figure, the stress at power in the more vulnerable loose keyway is approximately 28MPa at 16.425TWd. This can be compared with the figure in section 5.1, where the equivalent EIM1.1 stress is approximately 26MPa. This should not be seen as a complete validation of the EIM predictions as, for example, there are common field variables used, so any error in those calculations would carry through into the stress predictions. Nevertheless, the materials property models are significantly different and it is reassuring that the results are comparable.

5.5 Evidence to support NGL's stress predictions - Interim conclusions as to stress predictions using EIM

181. I have identified some areas above, where the EIM predictions are shown to be consistent with observations and independent calculations. It appears that EIM1.2 allows somewhat better explanations of cracking than EIM1.1, although EIM1.1 is the most conservative in terms of at-power stresses and that is used in the DTA.

182. It is reassuring that the EIM appears able to explain past behaviour, but that does not prove that it can predict future behaviour. Cautiously though I conclude that the stresses and strengths predicted by the more conservative EIM1.1 appear reasonable. Consequently, the DTA analysis can be regarded in a positive light with respect to the EIM inputs, provided that sensitivity studies are performed to account for uncertainty. The results of such studies are discussed below.

183. I am not wholly confident that future cracking or other aspects of brick cracking behaviour can be predicted accurately, but note that NGL has addressed that task by calculating upper bound values that appear significantly worse than the expected level of cracking. As such, I do not consider that full confidence in EIM predictions is essential to come to a positive conclusion in the assessment of the predicted future core state. My overall conclusions below reflect this and form part of the

recommendation to the assessor dealing with the overall graphite integrity (Reference 30).

184. There may be other evidence available, such as from the prediction of brick shape parameters and comparison with measured data. This was referred to in the answer to the TQ in Reference 32, but I have not considered these in detail here.

6 ONR ASSESSMENT (3) SENSITIVITY STUDIES - IMPLICATION OF UNCERTAINTIES IN THE EIM PREDICTIONS ON THE DTA

185. The seismic analysis is being considered in detail in Reference 30, the overall graphite structural integrity analysis. Comment here is only intended to deal with the possible sensitivity of the seismic margins to parameters derived from the EIM, particularly the brick clearances and the capacity of the keying system.

186. Some parameters are used in calculations that lead ultimately to predictions that can be tested. For example predictions of stress and strength lead to brick cracking predictions that are compared to the cracking observed in inspections. However in the AGRs, the outside of the bricks is not inspectable. The clearances and capacity of the key/keyway regions are therefore only known from EIM predictions, with no direct observation available to confirm them. As such, confidence is needed in those predictions. Although evidence that the keying system is functioning correctly is available from observations on the core, using both monitoring and inspection technologies, this confidence only applies to the normal operating conditions. Infrequent transients such as seismic events would place greater loads on the keying system. For this reason the DTA analysis is dependent upon the predictions of the EIM for seismic transients, particularly for the parameters that describe the clearances, such as the key/keyway clearances and the capacity of the bricks to resist external forces without failing. I address the potential sensitivity of the DTA to these two factors below.

6.1 Effect of EIM uncertainties on key/keyway clearances and seismic margins

187. As discussed above, there is an uncertainty in the DC relationship and in particular the post turnaround DC curve is predicted to be steeper in the EIM than the corresponding UofM one. As it is not obvious which would provide the more conservative analysis and in any case to explore the sensitivity of the EIM prediction to uncertainty, A TQ was asked and responses were received (Reference 32). For convenience I have put the wording of TQ G8 below.

We note that use of EDF's EIM is explicitly claimed in argument 1.2 in NP/SC 7766, although reference 35 (NP/SC 7623) identifying EIM's validity up to the end of 2020 dates from 2013. We also note the various discussions and reports (e.g. at GTAC on 2 October 2019, GTAC Q56 and NGRG-R288) addressing the EIM and comparisons with the independently derived 'University of Manchester' (UofM) model. ONR's provisional view is that both models provide credible predictions of materials properties, but we note that these predictions differ significantly beyond the point where AGR data has been used to calibrate the models, particularly for dimensional change (DC). Thereby, the UoM model provides some potential indication of the uncertainty in the EIM model beyond the point of calibration.

For instance, the EIM predicts a steeper post turnaround DC curve than the UofM model, intuitively it seems likely that the EIM would predict a higher cracking rate than the UofM model and thus that EIM would be conservative compared to the UofM model in that respect at least.

However, it seems less obvious that the same can be said for the DTA i.e. that use of the EIM will produce a more conservative result.

It would considerably aid confidence in the DTA predictions if EDF could demonstrate that the DTA results are not unduly sensitive to brick dimensions as affected by the DC relationship and that the period of extrapolation is appropriately limited. In particular, it would increase ONR's confidence if it could be shown that for the DTA results, the EIM produces a more conservative assessment than would occur if for instance the UofM curves were used.

The following ancillary questions also arise:

1. As used in HPB and HNB safety cases, how recent is the data used to calibrate the DC curve in EIM1.2?
2. Is there a limit to the extrapolation i.e. what is the greatest time allowed between the latest DC calibration and the end of any future operational period? It is assumed here that the DC calibration is most influenced by data derived from bore profile measurements rather than the Blackstone data.
3. Are there any current safety cases, where an older EIM calibration is used in the DTA, compared to SABRE/Cracksim calculations presented in the same case.
4. For DTA sensitivity studies, why is it a valid technique to perform these by looking at results at different reactor ages or should parameters be varied separately? In particular say, the DC curve?
5. How does DC affect the DTA? Thus what layers have keys ‘gripped’ at present, when are other layers gripped and what affects the DTA margins i.e. is it higher layers being gripped or is it the ‘release’ of central layers that has most effect on the margin? Is there any general understanding of the more important parameters (key/keyway gap, inter brick gap etc)?

Overall therefore, can we be confident that the DTA results would not be greatly affected by reasonable changes in the EIM predictions, over the period of extrapolation implicit in the safety case?

188. NGL addressed the TQ in its Reference 32 responses by calculating a parameter relating to the key/keyway gap and then performing seismic analysis at different values of that gap. Dimensional change in the graphite bricks will affect the DTA in a number of ways. The gap between the bricks will slowly and continuously increase throughout the AGR lifetimes, as there is a net brick shrinkage. The graphite at the outside of the bricks does not pass turnaround. However the graphite nearer to the bore of the fuel bricks does pass turnaround and this leads to complicated brick shape changes. These affect the key/keyway gap. In the central higher fluence layers of the core, the predicted gap is predicted to have decreased until the keys were gripped by the keyway. Some years later the key will have been released and for those layers, the key/keyway gap then started to increase. At layers at the top and bottom of the core, the point of contact may never be reached. Thus over the period of currency of Reference 1, it is possible that the key/keyway gaps in the central layers are increasing, but decreasing above and below.

189. It was considered that the core distortion parameters could be unduly sensitive to the key/keyway gap, as this changes proportionately more than the gap between the bricks. To address this concern, FNC therefore calculated the key/keyway gap using EIM1.1 and a ‘surrogate’ version of the UofM model. A comparison is shown in the figure below, which is figure 6 from the FNC document embedded in the first response to TQ G8 in Reference 32.

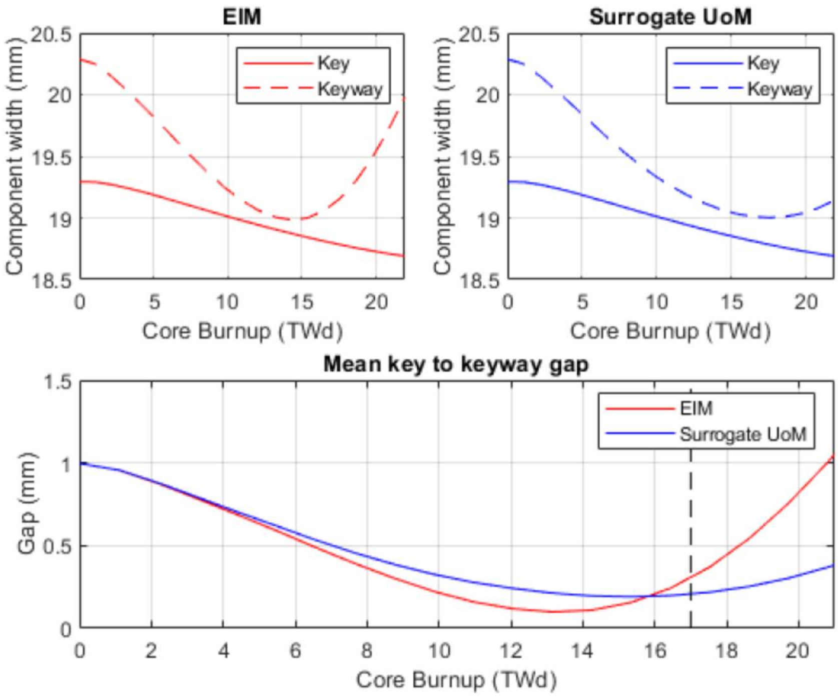
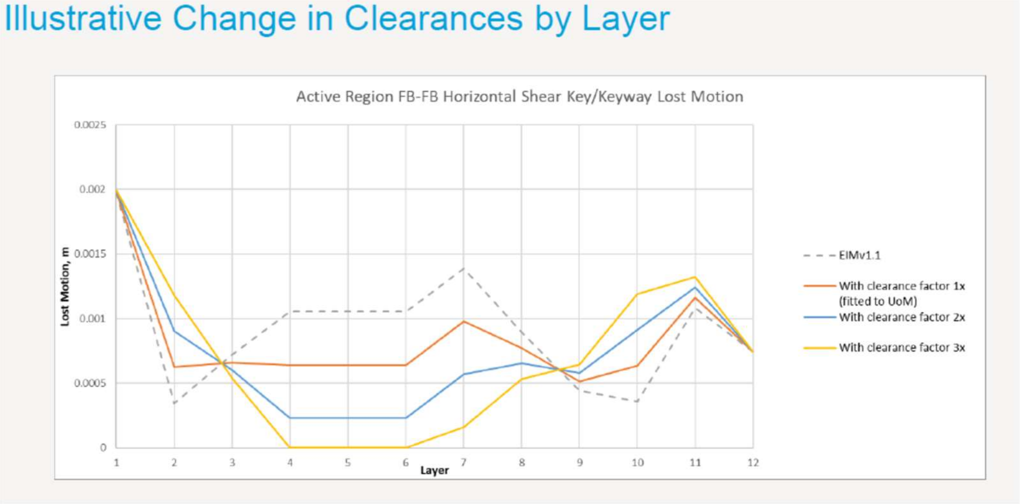


Figure 6: Predicted distortions of the loose bearing key and keyway at brick mid-height.

190. It can be seen that the mean key/keyway gap at 16.425TWd, slightly to the left of the dotted line would differ little between the models, perhaps by less than 200µm. This small value is reassuring in itself. However there is a caveat in that FNC have calculated a mean gap, not the minimum gap that is used in GCORE. The minimum gap decreased to zero as explained above and the behaviour thereafter may have been slightly different because of the pinching of the keys by the keyways and the associated constraint. FNC's finite element analysis program FEAT cannot address contact between surfaces and NGL normally uses a further stage of analysis performed elsewhere before determining the GCORE parameters.

191. A further caveat is that just adjusting the clearances would probably not quite represent the situation that would occur if the UofM DC curve had been used completely, as the clearances at different layers would probably not be in the same proportion. The comparison between the models is therefore limited in these two ways and the judgements made here have allowed for an associated uncertainty in how a more detailed analysis might have differed.

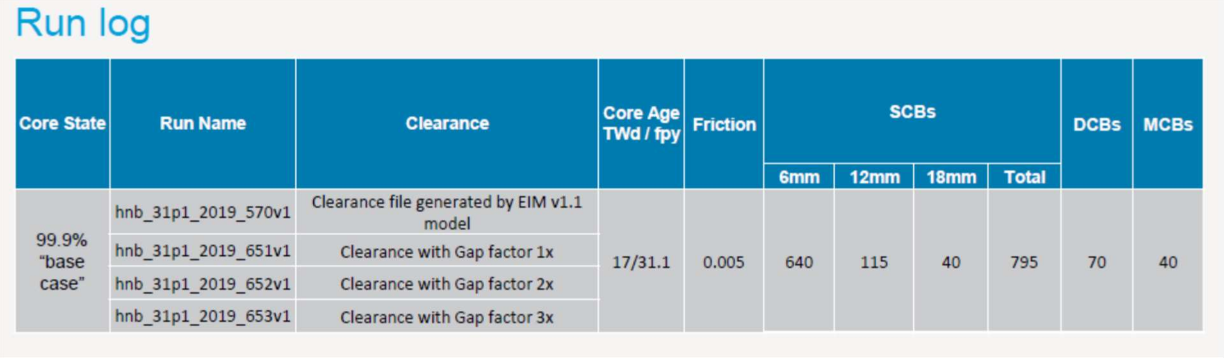
192. FNC's calculated gaps have therefore been converted to values required by GCORE, the analysis was performed and the results described in the TQ response to TQ G8 as follows. The figure below illustrates the gaps input for the clearances for each core layer. Here the vertical axis is 'lost motion', a parameter comparable to the key/keyway gap. It describes the relative motion permitted by the geometry which has to allow for possible rotation of the key and keyways with respect to each other as well as the key/keyway gap.



Illustrative Change in Clearances by Layer

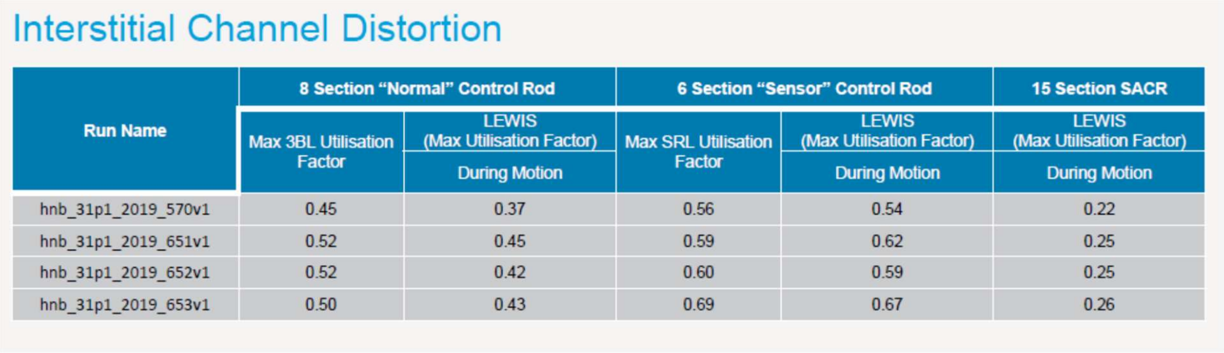
193. The ‘lost motion’, for the EIM is greater than the UofM prediction for layers 4 to 8, reflecting the higher fluence, whereas for the higher and lower layers it is similar or smaller. I discuss the implications of this below.

194. Four GCORE runs were performed, as described in the ‘run log’ table below. These are for EIM1.1 parameters, and UofM surrogate key/keyway gap values multiplied by 1, 2 and 3. In each case, the cracking state is stated at the 99.9% level i.e. allowing for uncertainty in the cracking predictions after a period of operation. Although the degree of cracking is less than the CEDTL, I consider that it is an adequate level for the purposes of a sensitivity study. The other two tables show the calculated interstitial channel distortion and the extent of keying system damage. All three tables are from the TQ G8 response.



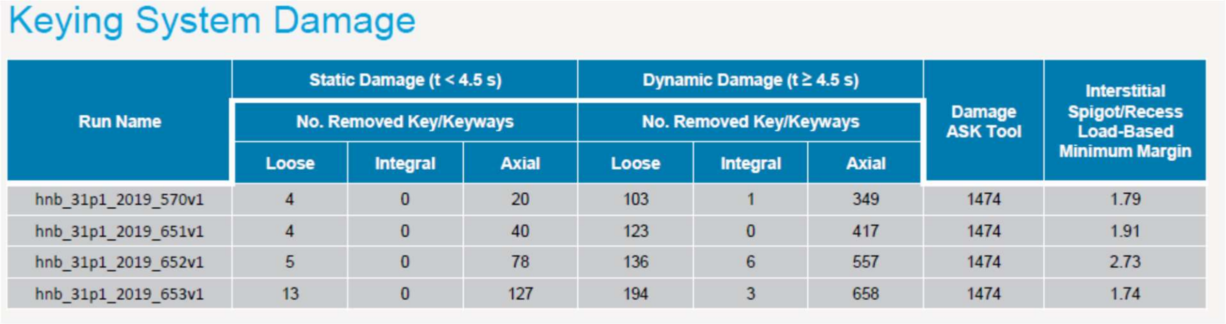
Run log

Core State	Run Name	Clearance	Core Age TWd / fpy	Friction	SCBs				DCBs	MCBs
					6mm	12mm	18mm	Total		
99.9% “base case”	hnb_31p1_2019_570v1	Clearance file generated by EIM v1.1 model	17/31.1	0.005	640	115	40	795	70	40
	hnb_31p1_2019_651v1	Clearance with Gap factor 1x								
	hnb_31p1_2019_652v1	Clearance with Gap factor 2x								
	hnb_31p1_2019_653v1	Clearance with Gap factor 3x								



Interstitial Channel Distortion

Run Name	8 Section “Normal” Control Rod		6 Section “Sensor” Control Rod		15 Section SACR
	Max 3BL Utilisation Factor	LEWIS (Max Utilisation Factor)	Max SRL Utilisation Factor	LEWIS (Max Utilisation Factor)	LEWIS (Max Utilisation Factor)
		During Motion		During Motion	During Motion
hnb_31p1_2019_570v1	0.45	0.37	0.56	0.54	0.22
hnb_31p1_2019_651v1	0.52	0.45	0.59	0.62	0.25
hnb_31p1_2019_652v1	0.52	0.42	0.60	0.59	0.25
hnb_31p1_2019_653v1	0.50	0.43	0.69	0.67	0.26



Keying System Damage

Run Name	Static Damage (t < 4.5 s)			Dynamic Damage (t ≥ 4.5 s)			Damage ASK Tool	Interstitial Spigot/Recess Load-Based Minimum Margin
	No. Removed Key/Keyways			No. Removed Key/Keyways				
	Loose	Integral	Axial	Loose	Integral	Axial		
hnb_31p1_2019_570v1	4	0	20	103	1	349	1474	1.79
hnb_31p1_2019_651v1	4	0	40	123	0	417	1474	1.91
hnb_31p1_2019_652v1	5	0	78	136	6	557	1474	2.73
hnb_31p1_2019_653v1	13	0	127	194	3	658	1474	1.74

195. For the more challenging sensor control rods, the utilisation does increase, although not dramatically and it remains below unity. It is noted that each set of clearances is only described by the results from a single GCORE run, the trend might be more consistent if an average of say 10 runs had been performed. Nevertheless for all three types of control rod a consistent picture emerges.

196. When the keying system damage is considered, it can be seen that there is an increase between the EIM1.1 and UofM models, although not dramatically, being less than doubled for loose and axial keys, even for the worst i.e. x3 clearances.

197. It is though notable that the utilisations worsen i.e. distortions get greater when moving from the EIM1.1 clearances to the UofM ones. This may be because with smaller clearances in the peak rated layers, seismic motion brings bricks and their keys into contact sooner and allows the forces to increase.

198. An alternative explanation might be that the greater clearances in the UofM model in the higher layers i.e. 9-11 plays a role in the worse GCORE margins that result. One of the reasons that I have limited my conclusions below to the period covered by Reference 1 i.e. to 16.425TWd is because it is not clear which factor is worsening the margins. This has led to a recommendation that will need to be addressed in subsequent safety cases.

199. However whatever the reason, it appears that the UofM model is the more conservative for the DTA in terms of predicted clearances.

200. Following a consideration involving other ONR inspectors, I have therefore made a judgement. It is that the seismic analysis is not so sensitive to uncertainty in the key/keyway gap that the adoption of, for example, a DC curve similar to that proposed by the UofM as opposed to that derived from EIM1.1, would produce a significantly different conclusion about the acceptability of the seismic margins. I have reflected this judgement in a recommendation to the assessor of the overall graphite integrity aspects of the safety case below.

201. I note though that this judgement does depend on the change in key/keyway gaps being limited. Reference to the figure above shows that the difference in gap is low at the limits of the safety case i.e. 16.425TWd, but is increasing thereafter. Therefore the conclusion I have reached above does not necessarily apply to future safety cases, which may require a more detailed analysis. As discussed above, I have made the need for further analysis for successor safety cases an additional recommendation.

6.2 Effect of EIM Uncertainties on Capacities and seismic margins

202. The capacity of the keying system is accounted for by analysis that includes the internal stress that occurs from brick ageing, the brick strength, the external force applied to the bricks and the limiting load that the external keys and keyways can withstand. The first two of these parameters are entirely set by the EIM. The third is

calculated in the GCORE program using EIM parameters and other inputs e.g. the magnitude and nature of the seismic transient.

203. The fourth parameter uses EIM and field variable values in scaling test data obtained from unirradiated feature tests. The scaling is complex. There may also be an additional sensitivity to assumptions that has not been well explored by NGL, such as the differences between unirradiated and irradiated graphite in its resistance to fracture at a stress concentration. This has been discussed by GTAC in Reference 31 and termed ‘notch strengthening effects’. It remains an additional source of concern, albeit one that may be limited, perhaps amounting to an additional uncertainty of 10-15% (see Reference 34). As there are several other uncertainties in the overall analysis, a further 10-15% additional uncertainty in capacity may not be significant.

204. It can be seen therefore that the capacity of the keying system is determined in part by EIM derived parameters.

205. An understanding of the factors affecting the core distortion has emerged that highlights the importance of key/keyway damage (Reference 30). In regions where damage is avoided, the core distortion margin is comparatively ‘well-behaved’, declining in an understandable manner as, for example, the degree of cracking increases. However if the inputs are such that significant key/keyway damage occurs, the core distortion margins both worsen and become less well-behaved, in that they are more sensitive to the precise configuration of cracking analysed.

206. As such, NGL has proposed that it is reasonable to address the sensitivity to capacity by making a judgement on the degree of key/keyway damage, rather than purely looking for a sensitivity to a particular EIM parameter such as graphite strength. In my view, attempting to do the latter may be problematical anyway, as strength and DYM are linked. Both are used in NGL’s capacity calculations. Consequently, it may be that only a full probabilistic study with all EIM materials properties treated as distributed parameters would resolve the sensitivity to capacity fully.

207. In response to a question on the sensitivity to capacity (Reference 32 the TQ G8 spreadsheet tab, email of 9 July 2020), NGL states that the sensitivity to capacity can be understood by consideration of the utilisation of the key/keyways, as illustrated in Reference 33. The figure below is figure 10 from that reference and shows histograms of the number of keys as a function of the key/keyway utilisation.

208. Utilisation is defined as the potential seismic external load divided by the capacity i.e. failure is possible when utilisation is greater than unity. NGL contends that only a small proportion of integral radial and loose radial key/keyways have utilisation greater than 0.8. This is certainly true for the integral keys, where less than a further 20 key/keyways would be predicted to fail. For the loose key/keyways there may be more than 200 additional failures. It should be noted that these analyses are at a cracking level described as states ’C’ and ‘D’; i.e. the intermediate core state and the CEDTL, respectively. However the numbers of failures do not include any progressive effects i.e. ‘in event damage’, the process by which a key/keyway failure causes load to be redistributed elsewhere such that further failures occur during the potential seismic event.

209. NGL does though point out two conservatisms in the above analysis. These are firstly that the analysis is performed at 17TWd, beyond the 16.425TWd covered by Reference 1. In Reference 32 (TQ G8 third response), the effect on the capacity is said to be a conservatism at 16.425TWd of 10% for the loose key/keyways, 2% for the integral and 4% for the axial key/keyways. The second is that GCORE uses the original brick masses, ignoring graphite weight loss, which is said to be up to 20% in the central layers. Some 2015 analysis suggested that this would result in a reduction in the peak loads of 5 to 8%, reducing the number of overloaded key/keyways by about

20% for the loose key/keyways and 50% for the integral ones. This analysis does not appear to have been updated though. A third conservatism is that the utilisation histograms are for the GCORE runs performed that provided the worst margins.

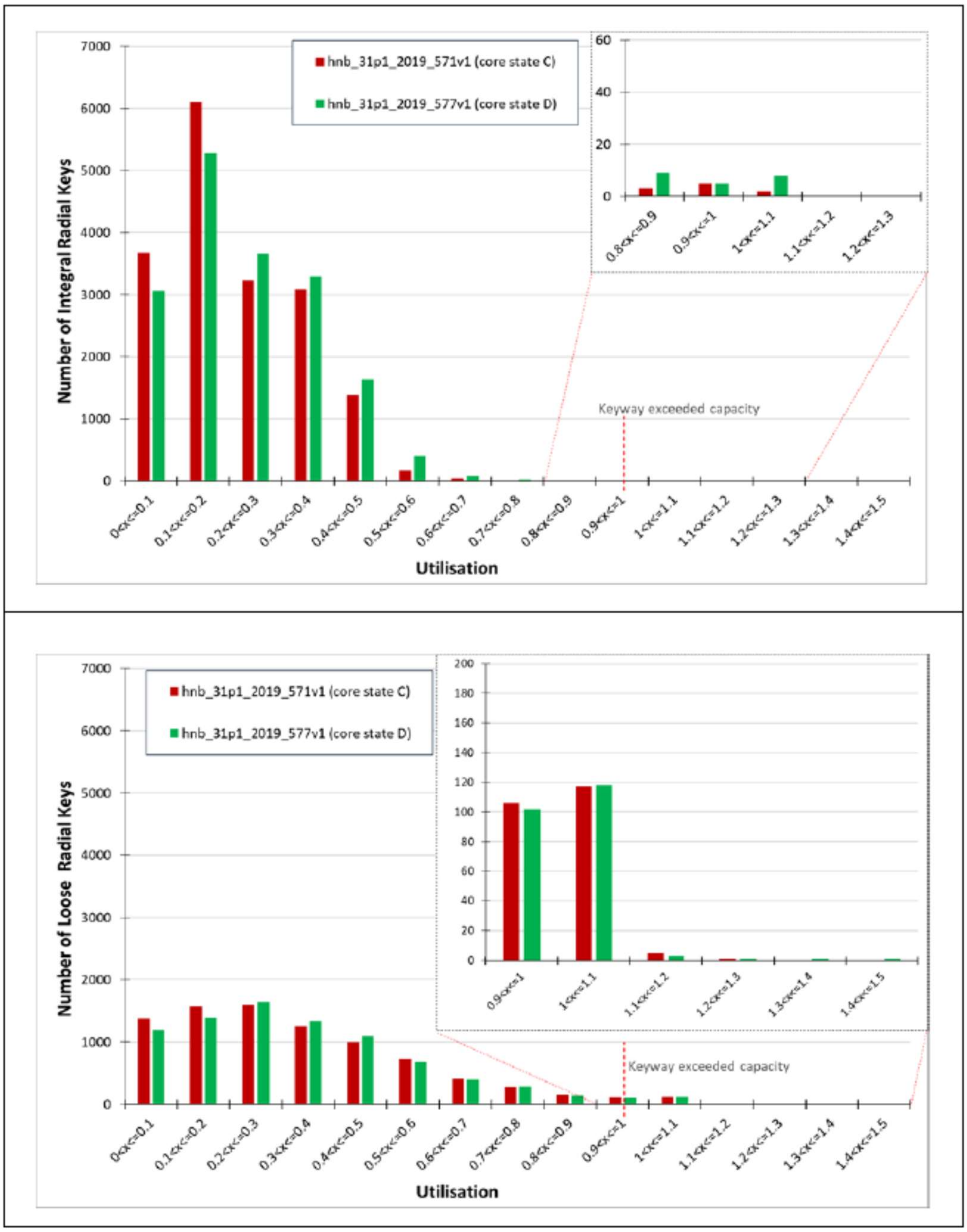


Figure 10 – Integral and loose key/keyway utilisation histograms for most onerous runs from cracking conditions C and D.

210. Whilst I acknowledge these conservatisms, it is not immediately obvious whether NGL has provided an adequate argument that a reduction in capacity of up to 20% will be sufficient allow for potential systematic errors in the materials properties calculated by the EIM and whether it significantly worsen the seismic margins.

211. It does appear to be the case that the extra key/keyways that would fail are limited to perhaps 200 loose keys and a few integral ones. The studies do not reveal how many extra axial/end-face keys might fail. I can though see that there are potential optimisms in the analysis, such the absence for allowance for the scaling of notch

strengthening effects, that are balanced by potential conservatisms, such as that the analysis is performed at 17TWd, not 16.425TWd.

212. A further point is that a distinction should be made between the variability of graphite and potential systematic uncertainty in the EIM predictions. In the former case it is to be expected that there is a natural variation in properties, such as strength, throughout the volume of a brick. In some cases this may mean a key/keyway may fail earlier than predictions made using ‘expectation value’ properties would indicate. In other cases a key/keyway may fail later, or not at all. Overall the effect may balance out. What would be more concerning to me would be the possibility of a systematic effect such that all bricks failed at a lower load than that predicted.

213. The above concern is exacerbated by the fact that no observation of the state of the key/keyways has been or is possible. Trepanning is carried out to a depth comparable to the position of the keyways, although circumferentially offset to avoid breaking into the keyways. Although subsequent analysis may allow reasonable prediction of the bulk properties, it does not help to predict any aspect relating to potential fracture behaviour, such as stress concentration effects.

214. I have already explained that it is not a trivial task to equate a reduction in graphite strength to a particular level of capacity reduction, where capacity is a measure of the ability of the key/keyway to resist an external load without failing. Apart from the complex variation in properties with irradiation, there is the likelihood that some properties are correlated. For example DYM and strength are often associated, although the precise nature of a correlation has been disputed.

215. Nevertheless it does appear to me to be reasonable to state that a 20% reduction in capacity is a sufficient sensitivity study. From my assessment above, the predictions of stresses and strength using EIM1.1 appear slightly conservative compared to the EIM1.2 and it is EIM1.1 values that are used for the DTA. Although no physical validation of the capacity is possible, comparisons I have made above with our independent analysis do not suggest additional large systematic uncertainties in stress are likely.

216. In any case, sensitivity studies should not deny that the best-estimate value is by definition more likely to represent a typical value of any parameter than one at the extreme of a sensitivity study. Part of the intention of sensitivity studies is generally to show the absence of swift changes in behaviour i.e. ‘cliff-edge’ effects, not to deny that the behaviour is unaffected by variation in the inputs. This is recognised in the SAPs e.g. EGR.7 (Reference 3 para 380). There does not appear to be any ‘cliff edge’ in behaviour, just a steady increase in predicted key/keyway failures as capacity is reduced.

217. There are of course several inputs to the DTA that need to be considered, such as the magnitude of the potential seismic event. These are being considered elsewhere. In terms of the EIM, in noting that a 20% capacity reduction is a sufficient sensitivity study, I would not wish to exclude the possibility that with further work, NGL could justify a smaller reduction, perhaps by quantifying more precisely some of the optimisms and conservatisms I have discussed.

218. Cautiously therefore, I conclude that there does not appear to be an undue sensitivity to reasonable variation in capacity, such as may be engendered by possible uncertainties in the predictions of the EIM or the associated stress analysis.

219. I understand that should 200 loose key/keyway connections fail, there would be concerns that with associated integral and end-face key/keyway damage, the overall DTA may be on the limit of what might be considered tolerable. I should emphasise though that a 20% reduction in capacity is a level that, in my view, encompasses EIM

uncertainties. It may not be necessary to consider that other parameters are at limiting values, whether they be from the EIM i.e. the clearances, or from other DTA inputs.

220. I consider that the arguments in the safety case could be more effectively and more clearly made and that this should be done in successor safety cases. I will include a recommendation to that effect in my conclusions. In terms of advice to the assessor dealing with overall graphite integrity, I make a recommendation that he should note that the predictions of EIM are made on a best estimate basis and that at worst this suggests that should capacity have been overestimated, approximately 200 extra loose key/keyways might be at risk. I note therefore that this appears to be a greater sensitivity than that revealed in the sensitivity study to clearance.

6.3 Other responses to questions in TQ G8

221. In TQ G8 (Reference 32), I asked a number of ancillary questions. It emerged in one response that the EIM calibration has only been performed using inspection data from inspections at HNB performed up to 2014, even though the latest calibration report was written in 2017. In my view, NGL is therefore failing to make use of inspection data that they have available. This is important data, as it is from the most recent operational periods where the greater amount of post turnaround DC data is available. The TQ response shows some of the more recent data and NGL has argued that it is still within the expected trend. Nevertheless this is not as good as having incorporated the data into a revised calibration. I do not consider that using a calibration that fails to take account of the 2015-2018 operational period for HNB R3 is within the original intentions of the EIM philosophy. I therefore make a recommendation that for future safety cases, the EIM is either recalibrated or a detailed justification is made that conclusions would be unaltered should the recent data be included.

7 ONR ASSESSMENT RATING

222. Having considered ONR’s assessment rating guide (Reference 40), I believe that an assessment rating of ‘Amber’ is appropriate. The reason for this is that significant interaction with the licensee has been necessary, before and after the submission of the safety case, to obtain adequate explanation of the reasoning that has led to the licensee’s argument about EIM in Reference 1. Additionally, I have received independent advice that challenges the choice of data that the licensee has used in formulating their EIM DC relationship.

223. I have already sought improvements in the information and explanations provided. Most importantly I consider that the recommendation that I make in this AR will need to be addressed by the inspector assessing the overall graphite integrity aspects of Reference 1 and the project inspector, before acceptance of the safety case. In view of the above recommendation, I do not consider that additional ONR issues need to be created or existing ones modified.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

224. This report presents the findings of the ONR assessment of aspects of Reference 1 that involve the materials property model termed the EIM. It includes:

- the adequacy of the EIM formulation, with particular reference to the DC and creep/CTE relationships,
- the use of EIM to predict stresses and,
- the sensitivity of the DTA margins to variations in parameters that are derived using the EIM, namely the key/keyway clearance and the capacity of the keying system to resist external loads.

225. I support NGL's work to create the EIM. It is essential that they have a materials property model available for use in safety cases. For several materials properties NGL has calibrated the equations using data from AGRs. This currently covers the period up to 2014. They also have Project Blackstone data available that allows a reasonable claim that they have leading materials property data that extends beyond the planned operational lifetime.

226. However there are complications in the case of DC that make the Blackstone data difficult to use. This is why my assessment report has considered the DC equations and calibration in detail. There have been a considerable number of interactions between ONR, our advisors and EDF NGL and their advisors on these topics. It has not been possible to reach agreement between the various experts as to the adequacy of the EIM DC relationship. Nevertheless it is important to acknowledge the careful work carried out by NGL and their various contractors, over a period of over ten years. ONR's independent advisors have been similarly diligent and have proposed an alternative model that differs in terms of the DC predictions in the post turnaround region.

227. Rather than reject one of the methods, I prefer therefore to conclude that there may be sufficient overall uncertainty, encompassing choice of data, the natural variability of graphite and the interpretation of trends, that both models present credible explanations of likely future DC. As such, it was important to determine the sensitivity of NGL's claims in Reference 1 to the EIM DC predictions and other uncertainties that exist. This is particularly important in the case of the DTA work presented in Reference 1 and has led to the recommendation that emerges from this assessment.

228. For the creep/CTE relationship it is noted that this is the main difference between EIM1.1 and EIM1.2. There is some evidence that the newer EIM1.2 creep/CTE relationship leads to stress predictions that can best explain the observed cracking at HNB. However our independent GTAC advisors have advised caution, due to the empirical nature of the change.

229. The creep/CTE relationship is important in the prediction of future cracking. However NGL has addressed uncertainty here by calculating an upper bound prediction of number of cracks. Additionally there is a margin between the predicted core state after the requested period of operation and the CEDTL. Furthermore, predictions of future cracking are also only partly based on the EIM, they are adjusted according to recent inspection results.

230. Therefore I am not unduly concerned about NGL's use of EIM1.2 as part of the prediction of cracking rates. ONR will always be very cautious about such predictions, particularly at HNB which is the leading reactor in terms of cracking.

231. However, the use of EIM1.2 would also lead to a conclusion that cracking would occur at shutdown, due to the extra thermal stress, rather than at power. Although this is also predicted using EIM1.1 during the current operational period, the matter is less clear-cut. I therefore make an additional recommendation that any claims and arguments relating to the inevitability of cracking at shutdown should be regarded with caution. I do though consider it likely that the existing cracking has mostly occurred at shutdowns.

232. In terms of the sensitivity studies performed into seismic response, the clearance study indicates that the UofM model produces a worse predicted core distortion and an increased number of predicted key failures. However the core distortion parameters are still in the acceptable region, even if more limiting clearances are used i.e. beyond even the region between the predictions of the EIM and UofM models. The increased number of predicted key/keyway failures is though perhaps marginal between the two models.

233. However the capacity sensitivity study indicates that this parameter affects the DTA considerably. Should the capacity be 20% lower, there may be an extra 200 loose key/keyways that fail. However I consider a 20% reduction in capacity is a generous allowance for uncertainty that shows that there is no ‘cliff-edge’ increase in key/keyway failures. Also, in the case of the clearances, our independent analysis gives cause for concern that they may be different from that proposed by NGL. There is no such concern that the capacity has been greatly overestimated, which is not balanced by as-yet unquantified conservatisms. I note that the stresses used in the determination of capacity would be similar using EIM1.1 and EIM1.2. The UofM model does predict slightly higher at-power stresses, although these are comparable with those from the EIM. My recommendation is therefore formulated to make the assessor aware of these considerations.

234. In summary therefore, I have concluded that Argument 1.2 in Reference 1 is supportable i.e. it is reasonable for the EIM to be used. In saying this I note that EIM1.1 has been used in the DTA and EIM1.2 has been used in the other analyses. NGL’s decision to do so is understandable and apparently conservative. Related arguments involving stress predictions and use of the EIM in DTA work are also supported, with the caveats mentioned above. I have made two recommendations relevant to the overall assessment of the graphite integrity aspects of Reference 1 and three others that are relevant to any future safety cases.

235. It should be noted that the support for the arguments stated above applies only to the period of currency of Reference 1, although it can be assumed that it will also apply to a forthcoming safety case for operation of HNB R4 for a similar operational period.

8.2 Recommendations

236. Recommendation 1

237. That in assessing the overall adequacy of the licensee’s DTA work, consideration should be made on the basis that EIM values have been calculated as best estimate values. Judgements as to whether the overall analysis is sufficiently conservative should therefore consider the sensitivity studies into clearance and capacity parameters that NGL has performed.

238. Sensitivity studies into clearances suggest that the seismic margins remain acceptable for reasonable changes. However, it is noted that a reduction in capacity of 20% may increase the number of predicted loose key/keyway failures by 200. A 20% reduction can though be considered to be a generous allowance to encompass uncertainty.

239. Recommendation 2

240. That in assessing the overall adequacy of the graphite structural integrity aspects of the safety case, note should be taken that although cracking at shutdown is the more likely, reliance should not yet be placed on any argument that cracking can only occur at shutdown.

241. Recommendation 3 (Not needed for assessment of Reference 1)

242. That NGL be advised that the apparent sensitivity of the DTA to variations in key/keyway clearances and capacity needs to be explored further for safety cases beyond SS1 i.e. beyond a burnup of 16.425TWd for HNB and for future operation of HPB.

243. Recommendation 4 (Not needed for assessment of Reference 1)

244. That NGL be advised that ONR would have greater confidence in EIM predictions if recalibration was made with the most recent inspection data. This applies particularly to the DC and creep/CTE relationships. For future safety cases, either a recalibration should be performed, or a detailed justification should be provided that any conclusions would not be affected by such a recalibration.

245. Recommendation 5 (Not needed for assessment of Reference 1)

246. That ONR should consider requesting further independent advice on more recent Project Blackstone data including the phase 2 results, noting that this may have more applicability to other AGRs.

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Annex 1: variation of materials properties with irradiation and oxidation as predicted by the EIM

It should be noted that a number of units are used to measure fluence. That used mainly in NGL's documents about EIM is (x 10^{20} neutrons/cm^2 EDN) where EDN (or EDND) is 'equivalent DIDO neutron dose' a factor that takes into account the power spectrum of that reactor compared to another. This is important when comparing fluences from different types of reactor i.e. thermal and fast, as the different spectra of neutrons will affect the graphite material differently. The figures below are taken from Reference 11 and it can be noted that the maximum fluence expected in an AGR lifetime is around 230x10^{20} neutrons/cm^2 EDN.

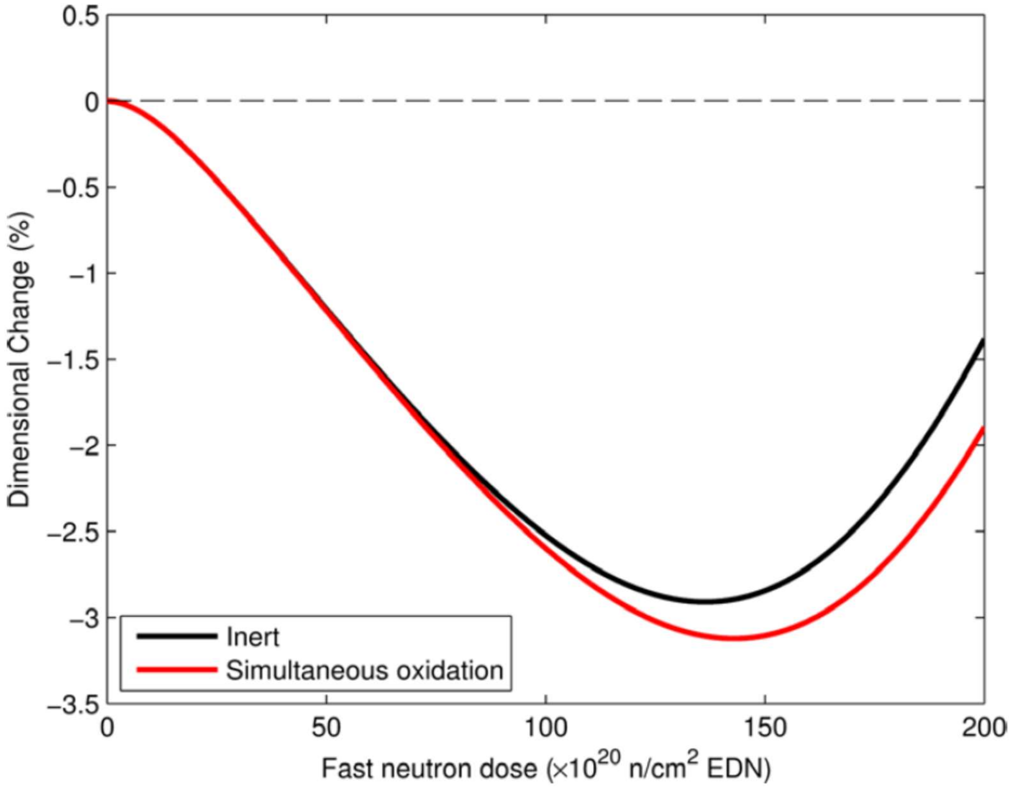

Figure 3: Schematic of the evolution of DC under fast neutron irradiation in either inert conditions of combined with a linearly increasing weight loss up to 50%.

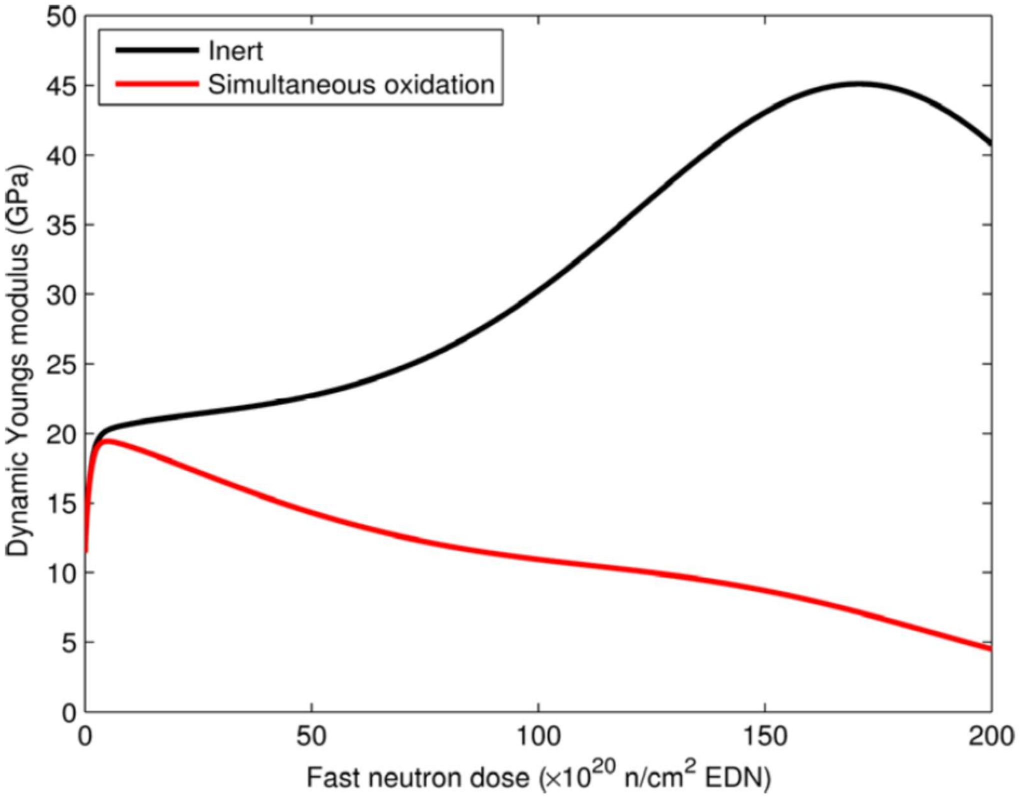

Figure 4: Schematic of the evolution of DYM under fast neutron irradiation in either inert conditions of combined with a linearly increasing weight loss up to 50%.

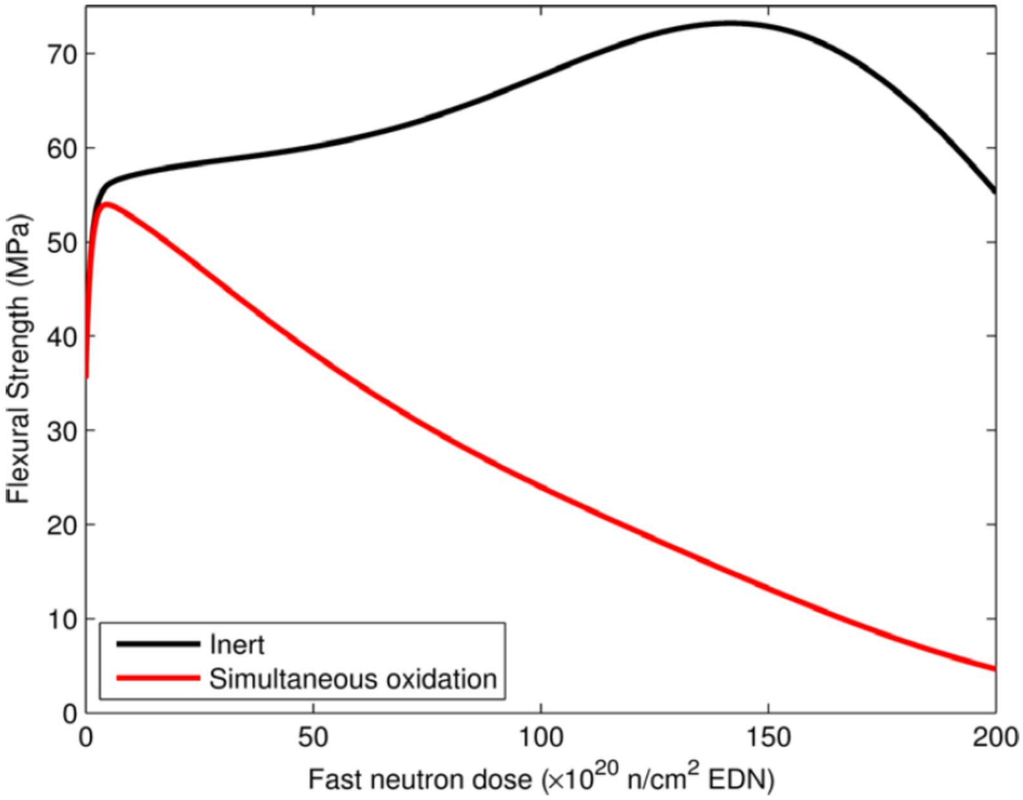

Figure 5: Schematic of the evolution of FS under fast neutron irradiation in either inert conditions of combined with a linearly increasing weight loss up to 50%.

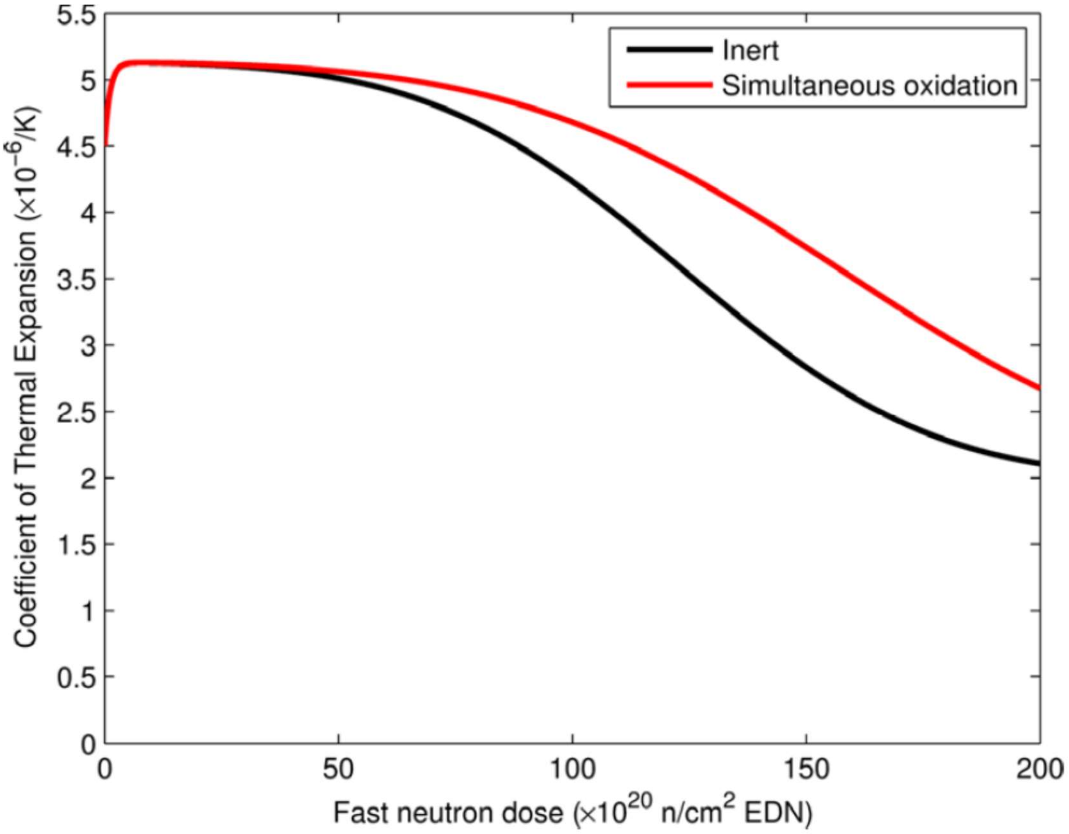

Figure 6: Schematic of the evolution of CTE under fast neutron irradiation in either inert conditions of combined with a linearly increasing weight loss up to 50%.

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.5	Manufacturing Records	A record should be made of the manufacturing case histories.
EGR.6	Location Records	A record should be made of the position of individual components in the structure during construction

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.8	Predictive Models	Predictive models should be shown to be valid for the particular application and circumstances by reference to established physical data, experiment or other means.
EGR.9	Materials Property Data	Extrapolation and Interpolation from available materials properties data should be undertaken with care, and data an model validity beyond the limits of current knowledge should be robustly justified
EGR.10	Effect of defects	An assessment of the effects of defects in graphite reactor cores should be undertaken to establish the tolerance of their safety functions during normal operation, faults and accidents. The assessment should include plant transients and tests, together with internal and external hazards.
EGR.11	Safe working life	The safe working life of graphite reactor cores should be evaluated.
EGR.12	Margins	Operational limits (operating rules) should be established on the degree of graphite brick ageing, including the amounts of cracking, dimensional change and weight loss. To take account of uncertainties in measurement and analysis, there should be an adequate margin between these operational limits and the maximum tolerable amount of any calculated brick ageing.
EGR.13	Use of data	Data used in the analysis should be soundly based and demonstrably conservative. Studies should be undertaken to establish the sensitivity to analysis parameters.
EGR.15	Extent and frequency	In-service examination, inspection, surveillance and sampling should be of sufficient extent and frequency to give confidence that degradation of graphite reactor cores will be detected well in advance of any defects affecting a safety function.