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VARIATION OF INTERNAL STRESSES IN A NUCLEAR GRAPHITE BRICK IN ADVANCED GAS-COOLED REACTORS

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ABSTRACT

Nuclear graphite in advanced gas cooled reactors is subjected to fast neutron irradiation, which causes changes in the dimensions and material properties of the graphite. These changes are further altered by radiolytic oxidation and the combined changes can affect the structural integrity of the graphite components. Much work has been conducted on the structural integrity of graphite bricks, but confidence in the numerical analyses is constrained due to the uncertainties in the stress predictions. This paper focuses primarily on the study of predicted internal stresses within a graphite moderator brick, and describes the methodology devised to identify and calibrate the relevant model parameters. A combined finite element and statistical modelling approach has been conducted. The outcome of this paper will provide further understanding of the stress system in nuclear graphite moderator bricks and increase confidence in future predictions of internal stress.

INTRODUCTION

The majority of the civil nuclear power reactors operating in the United Kingdom are Advanced Gas-cooled Reactors (AGRs). In an AGR, graphite is an essential component as it forms channels for the fuel and control rods and also acts as a moderator. Therefore, the structural integrity of graphite components is of prime importance. During operating conditions, reactor components, specifically the fuel channels, are subject to fast neutron irradiation and radiolytic oxidation (Neighbour, 2000). Fast neutron irradiation causes internal stresses which are high enough to crack graphite fuel bricks. However, irradiation induced creep relieves these stresses (Chang, 1974), and this is the reason why most of the AGRs are still in operation. The stress pattern during the life of the AGR graphite brick shows complex behaviour. During its lifetime, a graphite brick undergoes two different phases of stress (i.e. tensile and compressive) at the bore and periphery. The tensile stresses are believed to have a detrimental effect on the integrity of the nuclear graphite bricks. The bore surface experiences tensile stress during a particular time frame early in its life, while the periphery of the brick undergoes compressive stress. After this time period the behaviour of the stresses is reversed, and during the later time the bore is subjected to compressive stresses while the periphery of the brick experiences tensile stresses. The time when the stresses are reversed is called stress reversal. Before stress reversal there is a high possibility of bore initiated cracks or cracks initiated from coolant access hole drilled axially through the brick (known as methane holes); and post stress reversal it is believed that the possibility of cracks stems from the corners of keyways machined into the periphery of the brick (known as keyway roots).

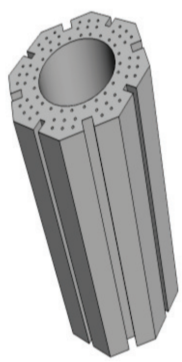
The objective of this research is to present an effort to improve finite element modelling (FEM) predictions of nuclear graphite in both irradiated and oxidised environments. This is carried out by conducting sensitivity studies through varying parameters associated with the material properties and their effect on the stress behaviour of nuclear graphite bricks before stress reversal. This work will help to understand the stress behaviour in initiating cracking, which has been observed in AGR graphite bricks.

The focus of this study is on the stresses generated along methane holes. Four sensitivity studies, on the basis of maximum hoop stress to strength ratios (SSR) have been conducted in the present work.

FE MESH AND MODELLING TECHNIQUE

A industry-standard FEM code (ABAQUS Standard) was used to model the Hinkley Point 'B' (HPB) nuclear graphite brick. Due to the symmetry in the geometry and loading of the brick [Figure 1 (a)] only an octant of the brick cross-section along the full axial height was modelled [Figure 1 (b)]. A 3D stress, 20 node, quadratic brick element (C3D20R) was used with reduced integration for the graphite brick. Nuclear graphite is subjected to fast neutron irradiation and radiolytic oxidation during the reactor operation, and these affect material properties. The user-defined material subroutine ManUMAT (Tsang and Marsden, 2008; and Eason et al., 2005 & 2008) was used to include the constitutive relationships and the above mentioned effects.

(a)

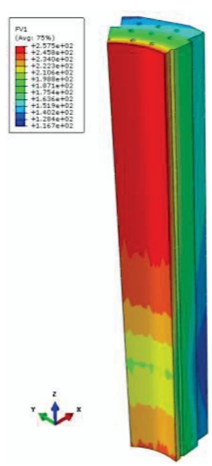


(b)

Figure 1 (a) Nuclear graphite brick HPB (b) Finite element mesh of octant of a brick

The temporal and spatial distributions of the loads for the brick in FEM are used in the form of field variables that describe the distribution of fast neutron fluence, irradiation temperature, and weight loss (Fahad et al., 2013; and McNally et al., 2014). Examples of the field variables are shown in Figure 2.

(a)



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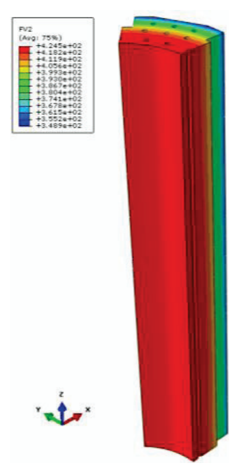

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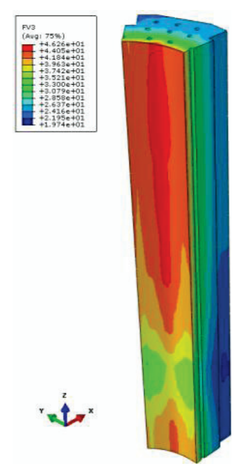


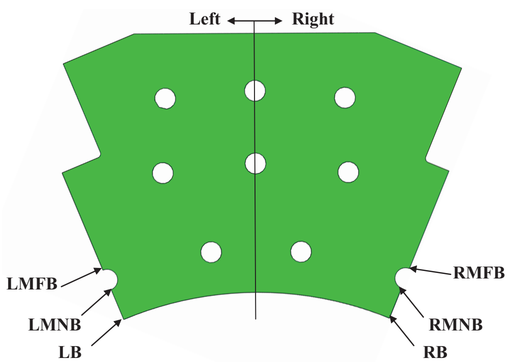
Figure 2: Examples of field variables (a) Fluence (b) Irradiation temperature (c) Weight loss

SELECTION OF CRITICAL LOCATION IN THE FE MESH

In this section location of maximum SSR is identified. An octant of a brick consisted of eight complete methane holes and two semi-holes (due to symmetry), as shown in Figure 3 and for the sensitivity studies all of these could not be analysed simultaneously. Therefore, it was important to choose a methane hole having maximum SSR. For this purpose the following steps were taken:

Step 1:

Maximum SSR for the entire mesh was analysed to find the time period for higher stress to strength ratios. It can be seen from Figure 4 that the region between the 2 full power years (fpy) and 24 fpy (as expected) may be taken into consideration. Although after 24 fpy the values are constantly increasing, there is a stress reversal and the higher values after 24 fpy are at the keyway roots, which was not the focus of the current research (Note that the spikes in Figure 4 show reactor stresses caused by thermal stress relieved by irradiation creep during operation coming back in the reverse direction on shut down). On this basis it was decided to focus between 2 and 24 fpy during which time the stresses near the bore are larger.



where, LMFB and RMFB are Left and right methane far bore resp., LMNB and RMNB are left and right methane near bore resp., LB and RB are left and right bore, resp.

Figure 3: Labels of the methane holes for the comparison of stress to strength ratios

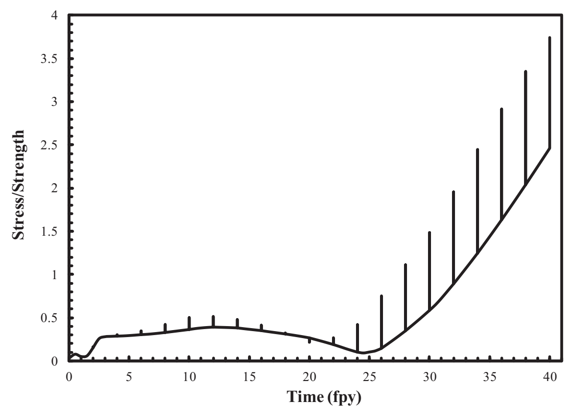


Figure 4: FE results of maximum hoop stress to strength ratio for the whole mesh (octant)

Step 2:

Visual observations were conducted to find the methane hole with higher SSR in the brick (an example is shown in Figure 5). With careful visual analysis it was concluded that the higher ratios were along the methane holes which are along the narrow section of the brick, as shown in Figure 3. Further analyses were conducted by comparing the SSR along the methane holes (in axial direction). The brick bore was also included in the comparison as it showed values comparable to the methane holes. Figure 6 shows an example of the comparison of different methane holes in the brick. It was noted that for all 2 fpy intervals until 24 fpy the most critical (i.e. with higher stress to strength ratio) methane hole is RMNB (Figure 3). The two humped shape of the curves in Figure 6 is due to the change from plane stress to plane strain towards the brick ends.

PRELIMINARY SENSITIVITY STUDY

In order to find the critical parameters i.e. parameters which have high impact on the stress prediction, a global sensitivity analysis using the method of Oakley and O'Hagan, (2004) was conducted. Briefly, this method involves identifying potentially influential parameters and their ranges, conducting a computer experiment – the process of efficiently varying the model parameters and studying their effect on model outputs - and calculating measures of parameter sensitivity. This is a highly efficient technique which is made computationally feasible with the use of a surrogate model or emulator.

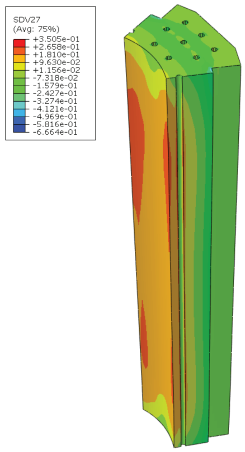


Figure 5: Example of FE results of hoop stress to strength after ratio after 16 fpy at power

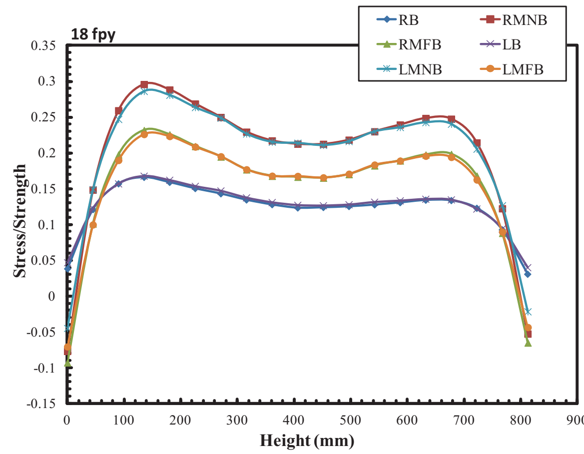


Figure 6: Comparison of SSR at different points along methane holes and bore at power

Finite element simulations with 100 design points were run, varying parameters associated with primary and secondary creep. The range of the parameters (from Properties- British Energy Generation Ltd., 2003), was used to create a table of parameter variations, selected using a maxi-max Latin Hypercube Design, that would give adequate coverage of the design space. A layer 7 brick of HPB was selected, and parameter variations or design points were then implemented into a set of finite element analyses. The maximum SSR along RMNB (refer to Figure 3) for each design point from the FE models were used for statistical analyses. The results from this preliminary study suggested that the maximum hoop stress to strength ratio was always greater at shutdown along the methane hole, regardless of the input conditions. The highest maximum hoop stress to strength was 0.92, as shown in Figure 7.

The sensitivity analysis identified six parameters that dominated the variability seen in the 100 simulations (Figure 7): secondary creep unirradiated static to dynamic Young's modulus ratio (1), secondary creep coefficient (2), secondary creep Poisson's ratio (3), secondary creep Young's modulus weight loss fitting constant F (4), secondary creep Young's modulus weight loss fitting constant k (5) and secondary creep unirradiated dynamic Young's modulus, with grain (WG) (6). Figure 8 shows the average effect on the SSR resulting from varying these six parameters over their range of uncertainty. Whilst these specific results are at 10 fpy for the shutdown condition, the same six parameters had a similar effect on the SSR throughout the time range when pre-stress reversal cracking is postulated to have occurred (10–14fpy) in both under power and at shutdown conditions.

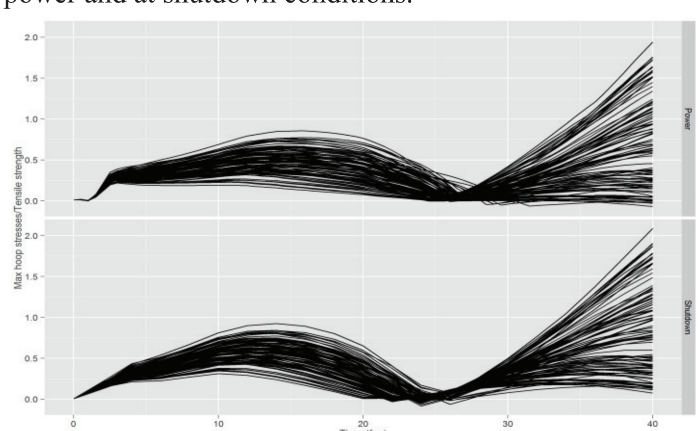


Figure 7: Maximum hoop stress to strength ratio at power and shutdown along the methane hole for the 100 FE model runs

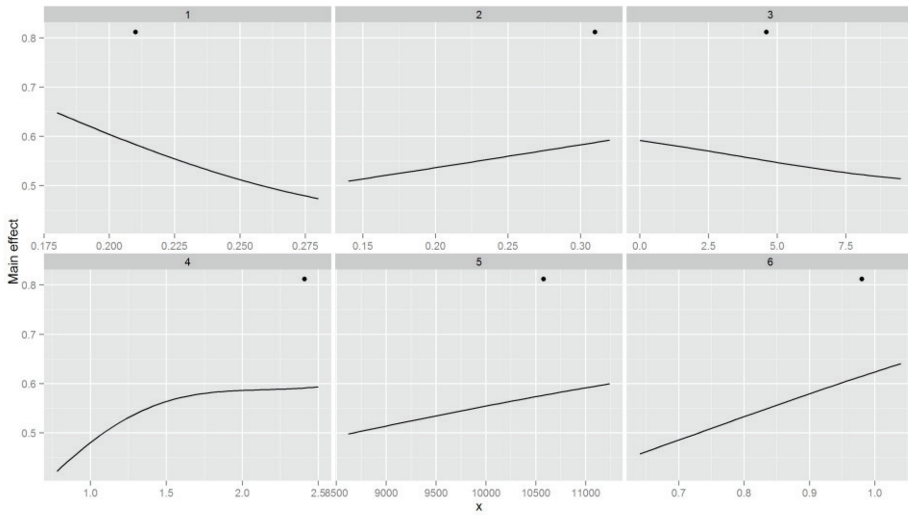


Figure 8: Main sensitivity plots for the six most important parameters for the stress to strength ratio at 10fpy shutdown condition. The maximum stress to strength ratio in the design and the corresponding input values are shown in each panel

SENSITIVITY STUDY I

The 'preliminary sensitivity study' demonstrated that the parameter limits were sufficiently wide to raise the maximum hoop stress to strength ratios (SSRs) close to a critical value of 1.0 (pre-stress reversal, i.e. between 0-24 fpy), but not sufficiently to raise it to or exceed 1.0. This sensitivity analysis was conducted to study the effect of oxidation parameters on creep, as these parameters have the largest influence on the variability of the SSR. This was conducted by varying the secondary creep Young's modulus weight loss fitting constant *Fi* and secondary creep Young's modulus weight loss fitting constant *ki,* in equation 1 (Tsang and Marsden, 2013), while using the baseline values for other parameters. Both the parameters were varied simultaneously and separately, as shown in the scheme of sensitivity study I in Table 1.

$$\frac{E_{creep}}{E^0_{creep}} = \left\{1 + A\left(\frac{\vartheta}{B}\right)^{C-1} \exp\left[-\left(\frac{\vartheta}{B}\right)^{C}\right]\right\} \exp\left[-F\omega^k\right] f_0 \tag{1}$$

where ϑ is dose ratio, ω is weight loss (%), f_0 is the ratio of static to dynamic Young's modulus and A , B and C are amplitude function, location function and shape function of irradiation temperature, respectively.

Table 1: Scheme of sensitivity study I

S/No	Scheme 1		Scheme 2		Scheme 3	
	F	*k*	*F*	*k*	*F*	*k*
1	12.05	2.396	30.125	7.908	6.025	2.396
2	18.075	3.954	24.1	7.908	6.025	3.594
3	24.1	5.272	18.075	7.908	6.025	4.792
4	30.125	6.59	12.05	7.908	6.025	5.99
5	36.15	7.908	6.025	7.908	6.025	7.188

Maximum SSR along the methane hole (RMNB) was extracted from the FE analyses between 0 and 40 fpy. It can be seen in Figure 9 that in scheme 1 and 3 the oxidation fitting constants are dominant in later life i.e. after 24 fpy while there is no significant effect between 0 and 24 fpy. Scheme 2 has a trivial effect on the ratios before and after 24 fpy, which implies that *Fi* and *ki* have a negligible effect. This analysis suggested that these two parameters are important post-stress reversal (in scheme 1 and 3) but do not have a significant effect pre-stress reversal when varied in isolation.

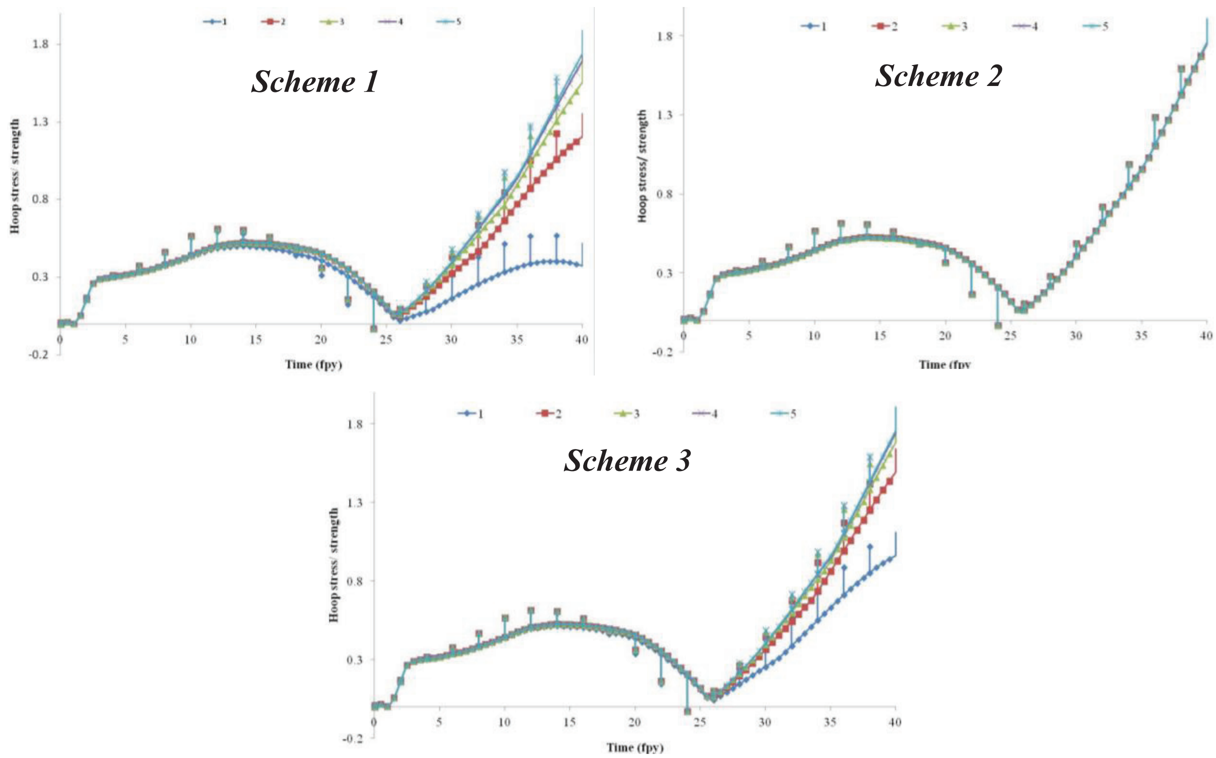


Figure 9: Maximum hoop stress to strength ratio for the scheme 1, 2 and 3

SENSITIVITY STUDY II

In this section another important parameter was studied: the secondary creep coefficient (SCC), which showed (in the preliminary sensitivity study) significant influence on the variability in the maximum hoop stress to strength ratios (SSRs). Initially SCC was reduced to a half and then to a quarter of a baseline value (i.e. 0.23), whilst keeping the other parameters at baseline values. This was conducted to obtain a pre-stress reversal envelope; and then the SCC was refined within this envelope to get the SSRs to reach the critical value of 1.0. Figure 10 (a) shows the envelope for the initial SCC values considered.

The SCC value was modified within the envelope until the SSRs reached the critical value. It can be inferred from Figure 10 (b) that a 61% (approx) reduction in SCC value from baseline raised the maximum SSRs to a critical value of 1.0. This suggests that SCC can significantly influence the stress behaviour in the nuclear graphite brick both pre- and post stress reversal. Although the SCC value of 0.09 raised the SRR along the methane hole to a critical value of 1.0, it was necessary to examine the effect of this on the underlying creep curve. Figure 11 shows a comparison of irradiation creep curves for inert and oxidising conditions using the UKAEA creep law (Kelly and Brocklehurst, 1971; and Xiang et al., 2012), with the baseline value of SCC (0.23) and with the reduced SCC value (0.09). The lower creep with SCC 0.09 confers a reasonable cause of the higher predicted stresses, and hence, higher SSRs.

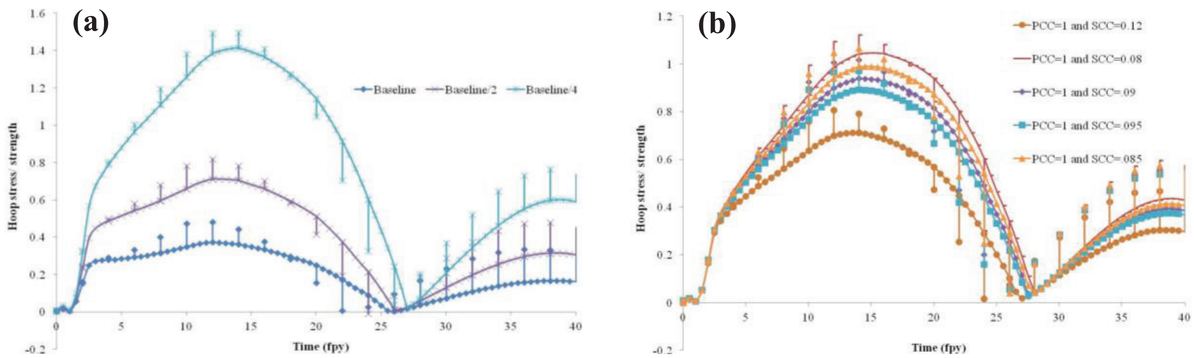


Figure 10: Maximum SSR (a) after reducing the baseline value by half and quarter (b) Variation of maximum SSR with secondary creep coefficient (SCC)

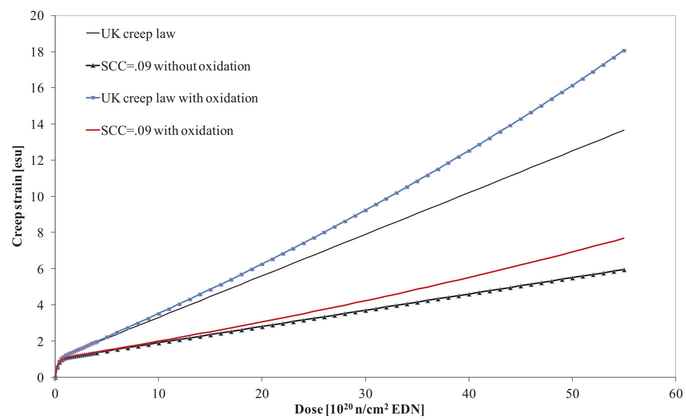


Figure 11: Variation in creep with secondary creep coefficient

SENSITIVITY STUDY III

As stated above, 100 design point FE simulations were run and the "preliminary sensitivity study" showed that the highest SSR was 0.92 at design point 42. In this section a comparative study between FE simulations using baseline parameters and design point 42 parameters is discussed. An example of parameters corresponding to the baseline and design point 42 analyses is shown in Table 2 (only the parameters which have high influence are shown).

Figure 12 shows a significant difference in maximum SSR between the baseline and design point 42 analyses. Therefore, it was important to observe how the creep parameters affected the other properties, including bore shape and underlying properties. A difference in the bore shape was observed, which showed divergence towards the mid height of the brick, an example at 16 fpy is shown in Figure 13.

Table 2 Parameters corresponding to the maximum stress to strength ratio (design point 42).

Label	Parameter of secondary creep	Min	Max	Design point 42
1	Creep coefficient	0.184	0.276	0.21
2	Creep Poisson's ratio	0.14	0.32	0.31
3	Young's modulus weight loss fitting constant F_i	0.000	9.500	4.61
4	Young's modulus weight loss fitting constant k_i	0.780	2.500	2.41
5	Un-irradiated dynamic Young's modulus (WG)	8620	11240	10578.38
6	Un-irradiated static to dynamic Young's modulus ratio	0.64	1.04	0.98

It can be seen in Figures 14 and 15 that the irradiation creep curve and secondary creep Young's modulus behaviour with the design point 42 parameters is closer to the baseline (inert) irradiation curves, as compared to the irradiation creep curve in sensitivity study II (Figure 10). On the contrary, it was expected to follow the oxidised baseline curves.

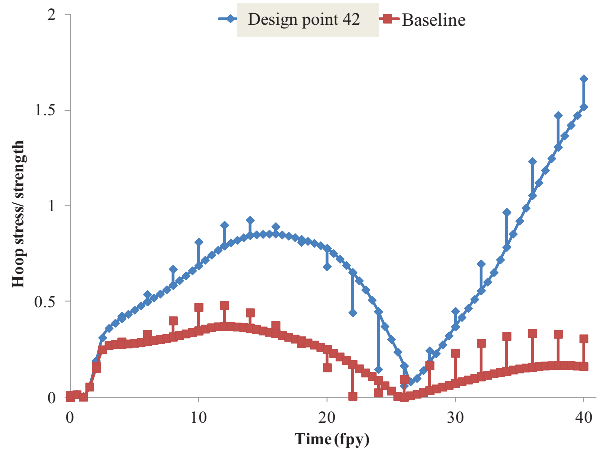


Figure 12: Variation in the SSRs with the baseline and design point 42 parameters

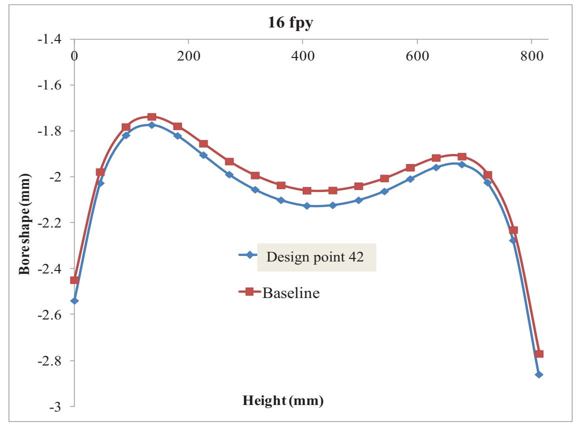


Figure 13: Variation in the bore shape with the two sets of parameters at power

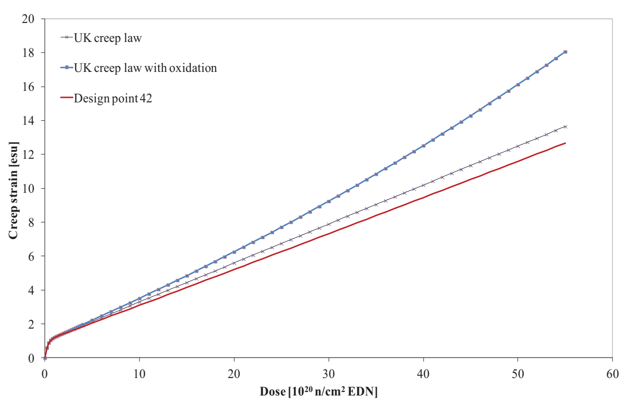


Figure 14: Variation in creep with the baseline and design point 42 parameters

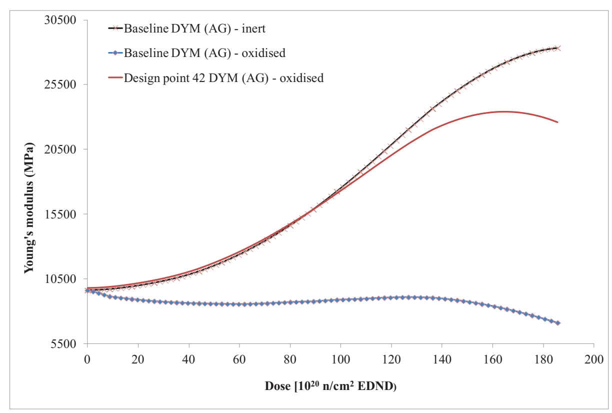


Figure 15: Variation in the dynamic Young's modulus with baseline and design point 42 parameters, where *AG* is against grain.

VARIATION IN STRENGTH

This phase of work considered the metric of SSR. The strength is calculated from an empirical model with irradiated density as the primary explanatory variable. In deriving the metric in this work the mean strength from this model was used; however, there is considerable variation in strength for a given density (strength follows a log-normal distribution). It is more precise to state that the computer experiment studied the stress to mean strength ratio.

A small piece of additional work was undertaken in order to determine what value of the stress to mean strength ratio would be required for a proportion of bricks to have strength at the methane hole that was below the calculated stress. The objective of the simulation study was to assess whether the parameter ranges in this study could result in conditions where cracks could initiate from the methane hole. This was a simplistic preliminary analysis and should not be considered as a formal calibration: many conceptual issues (such as size effects, bi-axiality, variation in irradiated density, variation in start-of-life material properties etc.) would need to be addressed in order to formally attempt a model calibration.

The average value of irradiated density at the methane hole was extracted from the FE model over the 0 to 40 fpy range of simulations (the variation in irradiated density was negligible over the 100 FE runs of the computer experiment). The density corresponding to 14 fpy was used in this work, since the stress to mean strength ratio was close to its peak value at this point. The mean strength corresponding to this density was calculated.

For a stress to mean strength ratio of 0.5 to 1 in increments of 0.01 the following calculation was repeated:

1. Given the mean strength and the stress to mean strength ratio, the stress at the methane hole was calculated.
2. Four strength values per brick were simulated, corresponding to four methane holes where a crack could initiate.
3. The minimum of the four strength values was compared with the stress (step 1). A crack which propagates through to the bore was assumed to occur if the stress exceeded the strength.
4. This was repeated 10,000 times in order to estimate the proportion of bricks where a crack would occur.

Results from this calculation are shown in Figure 16 for a stress to mean strength ratio of 0.5 to 0.85; the proportion of cracked bricks rose very rapidly above this upper bound. For comparison, approximately 1.5% of inspected layer 7 bricks at HPB have an axial crack. This corresponds to a stress to mean strength ratio of approximately 0.75. A ratio of this magnitude was observed in the computer experiment, although it was at the upper range of the simulations.

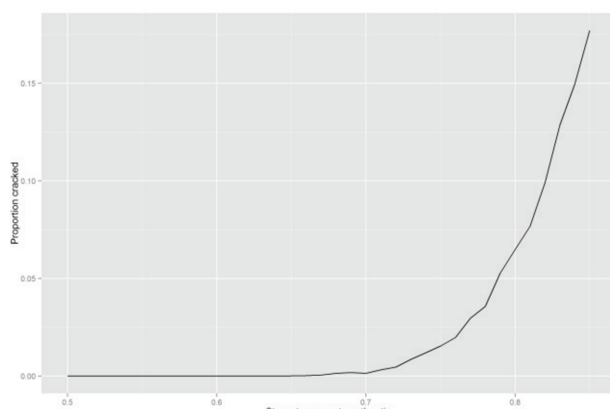


Figure 16: Proportion of cracked bricks resulting from a stress to mean strength ratio of 0.5 to 0.85

CONCLUSIONS

- Four sensitivity analyses were conducted to show the effect of irradiation creep parameters on predicted stresses.
- Oxidation parameters corresponding to irradiation creep have a trivial effect on the stresses before stress reversal when varied exclusively.
- The secondary creep coefficient has a significant effect on the stresses, both when varied in combination with other creep parameters and in isolation.

- A formal calibration can only be attempted once the conceptual issues described above (preliminary sensitivity study) have been resolved, and additionally the assumption that a crack initiates and propagates from the methane hole if stress exceeds strength over a small region may be erroneous. This additional work has, however, demonstrated that the parameter limits considered in this study are sufficiently wide. Further studies are in progress and will be presented in future publications.

ACKNOWLEDGEMENT

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DISCLAIMER

Any views or opinions presented are those of the authors and do not necessarily represent those of the sponsor.

REFERENCES

Chang, S.J. (1974). "Viscoelastic analysis of irradiated graphite with variable creep coefficient," *Journal of Nuclear Engineering and Design*, 30, 286-292.

Eason E, Hall G, Marsden B, Heys G. (2005), " Development of a Model of Dimensional Change in AGR Graphites irradiated in Inert Environments," *Conference on Ageing Management of Graphite Reactor Cores*, Wales, 43-45.

Eason E, Hall G, Marsden B, Heys G. (2008),"Development of a Young's modulus model for Gilsocarbon graphites irradiated in inert environments," *Journal of Nuclear Materials,* 381(1-2): 145-151.

Fahad, M., Hall, G., McNally, K., Marsden, B.J., Mummery, P. and Warren, N. (2013)" A statistical and finite element modelling approach used in the derivation of moderator graphite behaviour", *Transactions, SMiRT-22,* San Francisco, California, USA - August 18-23.

Kelly, B.T. and Brocklehurst, J.E. (1971), "Analysis of irradiation creep in reactor graphite", *Proceeding of Third Conference on Industrial Carbons and Graphite. Society of Chemical Industry*, London, p. 363.

McNally, K., Hall, G., Tan, E., Marsden, B.J. and Warren, N. (2014), "Calibration of dimensional change in finite element models using AGR moderator brick measurements ", *Journal of Nuclear Materials,* 451,179–188.

Neighbour, G.B. (2000), "Modelling of dimensional changes in irradiated nuclear graphites", *Journal of Physics D, Applied Physics*, 33, 2966–2972

Oakley, J. E., and O'Hagan, A. (2004). "Probabilistic sensitivity analysis of complex models: a Bayesian approach." *Journal of the Royal Statistical Society. Series B (Statistical Methodology)*, 66(3), 751-769.

Properties- British Energy Generation Ltd. (2003), "Compendium of CAGR core and sleeve data and methods," *British Energy Generation Limited*, CSDMC, Paper 28.

Tsang, D.K and Marsden, B.J. (2008), "Constitutive material model for the prediction of stresses in irradiated anisotropic graphite components," *Journal of Nuclear Materials,* 381, 129-136.

Tsang D.K.L. and Marsden B.J. (2013), *MAN UMAT V.2 Theory Manual*, The University of Manchester, NGRG R236, 2013.

Xiang, F., Haitao, W., Suyuan, Y. and Chenfeng, L., (2012) "The various creep models for irradiation behavior of nuclear graphite ", *Nuclear Engineering and Design*, 242, 19– 25.