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THE IRRADIATION CREEP CHARACTERISTICS OF GRAPHITE TO HIGH FLUENCES

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High-temperature gas-cooled reactors (HTGR) have massive blocks of graphite with thermal and neutron-flux gradients causing high internal stresses. Thermal stresses are transient; however, stresses generated by differential growth due to neutron damage *continue to increase with time.* Fortunately, graphite also experiences creep under irradiation allowing relaxation of stresses to nominally safe levels. Because of complexity of irradiation creep experiments, data demonstrating this phenomenon are generally limited to fairly low fluences compared to the overall fluences expected in most reactors. Notable exceptions have been experiments at 300°C and 500°C run at Petten[1] under tension and compression creep stresses to fluences greater than 4 x 10^{26} (E>50 keV) neutrons/m^2. This study complements the previous results by extending the irradiation temperature to 900°C.

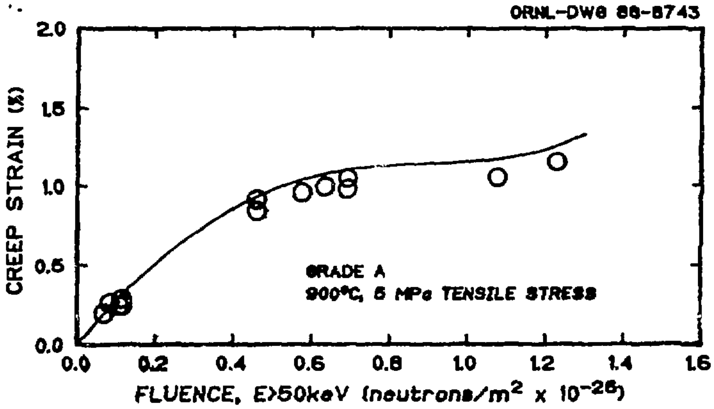

Fig. 1. Irradiation creep of grade A at 900°C.

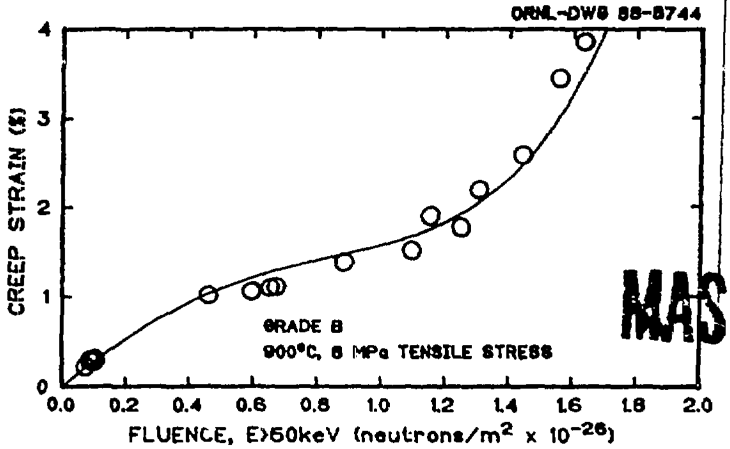

Fig. 2. Irradiation creep of grade B at 900°C.

Specimens of two pitch-coke graphites, candidate materials for HTGR's, were creep tested under tensile stress of 5 and 8 MPa in a HFR creep capsule at Petten. The isothermal capsule temperature of 900°C was maintained by gas mixture and by shifting the capsule vertically as fuel was burned and control rods raised. Creep data were obtained by comparing length changes of the stressed specimens to controls after a period of irradiation. Specimens were then recycled in new experiments and re-irradiated *under creep stresses to obtain final fluences approaching* 2 x 10^{26} (E>50 keV) *neutrons*/m^2. The resulting creep data, given in Figs. 1 and 2, show the characteristic decreasing creep rate followed by an increasing creep rate observed by testing at lower temperatures. The creep rate, however, as will be seen later, is accelerated at the higher temperature.

The deformation process that allows graphite to deform plastically under irradiation is not well defined or understood. Therefore, it is particularly difficult to rationalize structural changes causing the large changes in resistance to creep that were observed. It was suggested in the past studies[1,2] that the strengthening mechanism of graphite reducing the creep rate could be described by changes in Young's modulus, and qualitative descriptions were demonstrated. This model is based on the possible relationship between the elastic constant C_{44} and basal slip that is assumed to be the deformation mode for creep. The qualitative descriptions are not persuasive and question the model's reliability in interpolating or extrapolating available creep data. We have found a simplified concept describing the strengthening affecting the creep behavior under irradiation by density changes in the graphite. That is to say that internal strengthening that alters the creep rate can be best described by volume changes that occur in that particular grade of graphite. This model does not imply that the deformation process in the graphite crystal is altered, but the structural change by densification under irradiation increases the resistance to deformation. We have found that creep can be described as follows:

$$\text{"SECONDARY CREEP RATE"} = K \times \left(\frac{\text{STRESS}}{\text{MODULUS}}\right), \qquad (1)$$

$$K = K' \left[1 - \mu \left(\frac{(\Delta V/V_o)}{(\Delta V/V_o)_m}\right)\right], \qquad (2)$$

where K' and μ are constants and MODULUS is the pre-irradiated Young's Modulus. $(\Delta V/V_o)$ is the volume change with fluence and $(\Delta V/V_o)_m$ is the maximum volume change. The value of K' is essentially the second stage creep constant determined in short term irradiation experiments and will vary with temperature. The value of μ, however, was found to be independent of temperature with a value of 0.75. The volume changes obtained for these two materials are given in Fig. 3 from the 900°C experiment.

The curves in Figs. 1 and 2 were determined using equation (2). Results from the past experiments are given in Fig. 4 where calculated creep curves using equation (2) are compared with creep curves presented previously.[1] The excellent agreement with this creep data adds significance to the consideration that resistance to deformation can be measured by simple density changes under irradiation.

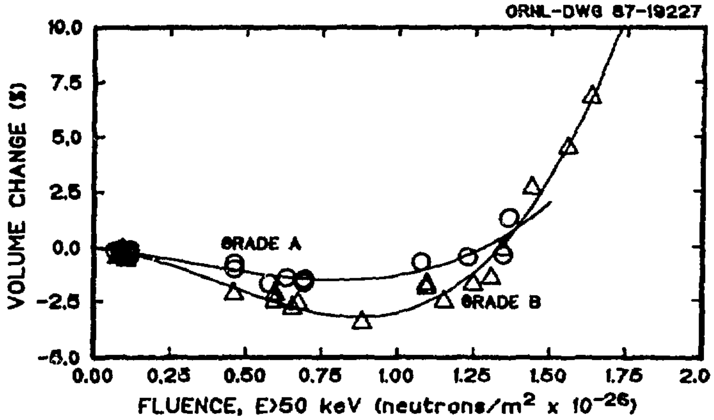

Fig. 3. Volume changes of grades A and B at 900°C.

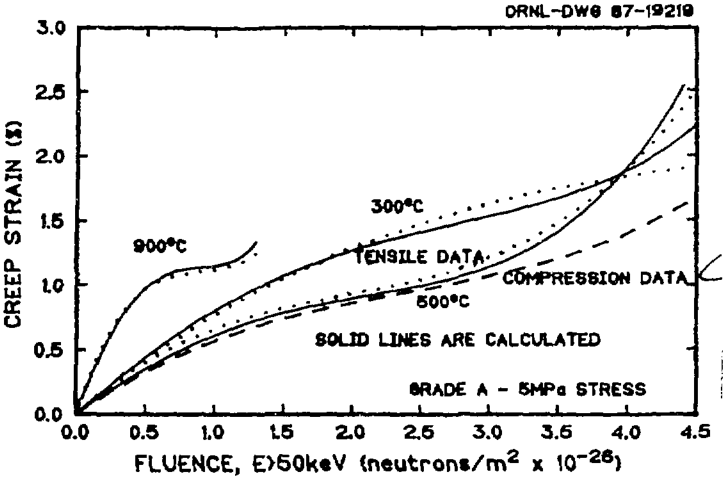

Fig. 4. A comparison of calculated creep curves to data.

The effect of irradiation temperature on the creep of graphite is pronounced as shown in Fig. 4. The results at 900°C demonstrate increased creep rates and also increases in the densification rate and subsequent volume expansion compared to the lower temperature results. Therefore, past short term creep irradiation experimental results include the effect of density change that is also a function of temperature. While these results imply that the creep characteristics are compounded, the model permits a rational formulation of expected behavior from changing stress and/or irradiation temperature. Creep behavior from a change in the irradiation temperature can be predicted by a consideration of the fractional density changes from the initial temperature to the final temperature. The effect of the more common event of changing stress at the same temperature is an even easier prediction. Thus, this model permits a reasonable basis for predicting the creep characteristics of graphites under variable conditions if the unstressed irradiation dimensional or density changes are known. This procedure is to be tested in future experiments where the stress will be reversed and in experiments with alternating irradiation temperatures.

Summarizing the results:

1. The effect of increasing the irradiation temperature to 900°C is to accelerate the behavior observed at the lower temperatures (300 and 500°C).
2. The creep behavior at all temperatures can be characterized by a decreasing creep rate with creep strain followed later by an increase in creep rate.
3. A model to describe the change in resistance to creep considering the densification of the graphite has been presented. The agreement of the results with the model is shown to be excellent.
4. The use of this model to define future experiments is recommended.

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2. B. T. Kelly and J. E. Brocklehurst, "UKAEA Reactor Group Studies of Irradiation-Induced Creep in Graphite," J. Nuclear Materials, 65, 79 (1977).