TENSILE PROPERTIES OF NEUTRON-IRRADIATED GRAPHITES

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Introduction

The mechanical design of graphite components for high temperature gas-cooled nuclear reactors (HTGRs) requires measurements of the changes in Young's modulus and tensile strength of the structural graphite as functions of neutron fluence and irradiation temperature. This paper summarizes the results from several hundred tensile tests on fuel block graphites irradiated under HTGR conditions.

Materials

Three grades of nuclear graphite were tested. H-327 (Great Lakes Carbon Company) is an extruded needle coke graphite used for the fuel and replaceable reflector blocks of the 330 MW(e) Fort St. Vrain reactor. Grades H-451 (Great Lakes Carbon Company) and TS-1240 (Union Carbide Corporation) are extruded near-isotropic petroleum coke-based graphites which are candidates for future large HTGR's. Specimens from three different extrusion lots of H-451 were included.

Experimental

The specimens were cylinders measuring 6.3 mm diameter × 23 mm long which were cemented between metal end-pieces and tested at ambient temperature, using precision chains to apply the load and a crosshead speed of 2 µm/s. The strain was measured with a 12.7 mm gauge-length extensometer. The specimens were first loaded to 7 MPa, unloaded to 0.7 MPa, and reloaded to failure. Young's modulus was measured from the 0.7 MPa to 7 MPa portion of the reloading curve.

Irradiation took place in a series of three fully instrumented, controlled temperature capsules which were irradiated in the C-3 position of the Oak Ridge Reactor. Each capsule contained ten graphite crucibles operating at temperatures ranging from 870 to 1630 K. Some specimens were transferred from capsule to capsule to increase the neutron fluence. The maximum fluence was 9×10^{25} n/m^2 (E > 29 fJ).

Results

Data for H-451 graphite are shown in Figures 1 and 2. The percent increase in Young's modulus or tensile strength is plotted against the fast neutron fluence, with the data grouped into three temperature regions. Each point shows the mean of about ten specimens, and the error bars indicate plus or minus one standard deviation. Young's modulus undergoes an almost immediate increase, followed by a plateau, and then a second rise which increases the modulus to about three times its original value after a fluence of 9×10^{25} n/m^2 (E > 29 fJ) at 1110-1250 K. The tensile strength follows a similar trend, but the percent increase is lower than for Young's modulus, amounting to about 100% at the highest fluence.

Figures 1 and 2 include data for both axial and radial orientations, midlength-center and midlength-edge locations in the parent log, and three different extrusion lots. The percent increases in modulus and strength for all specimens fall into the same bands, despite considerable variations in the preirradiation properties. Average preirradiation strengths ranged from 10.8 to 18.6 MPa in the axial direction and from 8.5 to 16.6 MPa in the radial direction, depending on the lot and the location of the specimens in the parent log.

TS-1240 graphite showed similar property changes to H-451 graphite. However, needle coke-based H-327 graphite did not show the secondary increase in modulus and strength at a temperature of 1110-1250 K evident in Figures 1 and 2.

The statistical spread in strength values is an important factor in the mechanical design of graphite structures. Irradiation increased the standard deviation of the strengths, but the coefficient of variation (standard deviation divided by the mean) showed no clear trend with irradiation, with the possible exception of the most highly irradiated axial H-327 specimens whose coefficient of variation apparently increased.

The irradiation-induced increase in strength (S) can be related to the irradiation-induced increase in Young's modulus (E) thus:

$$S/S_o = (E/E_o)^k$$

The exponent, k, was evaluated for each graphite grade and orientation, with the following results:

H-451, axial and radial:	$k = 0.64$
TS-1240, axial and radial:	$k = 0.48$
H-327, axial:	$k = 0.67$
H-327, radial:	$k = 0.40$

Discussion

The trend in Young's modulus as a function of neutron fluence is similar to the reported increase in sonic modulus,(1) except that the initial increase in Young's modulus found in the present work was higher. This probably results from the fact that the sonic modulus of unirradiated graphite is typically 20% higher than the static Young's modulus, whereas the two determinations would be expected to agree after irradiation because of the removal of anelastic effects. The initial rise to a plateau may be attributed to pinning of basal dislocations by point defect clusters, which increases the effective C_{44} shear modulus of individual crystallites. The second rise may be explained by the progressive tightening of the structure as microcracks close and intercrystalline restraints increase.

The irradiation-induced strength increase was roughly proportional to the square root of the increase in Young's modulus, as would be expected from the Griffiths fracture model if neither the surface energy nor the critical flaw size is influenced by irradiation. The same relationship has been observed after low temperature irradiations,(2) whereas work at higher temperatures(3) has suggested a linear relationship between strength and sonic modulus. The apparent discrepancy is again largely attributable to the difference between sonic and static determinations of Young's modulus in unirradiated graphites.

Acknowledgements

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References

(1) M.R. Everett, et al., Dragon Project Report DP 877 (1974).

(2) P.T. Nettley, et al., Proc. Symp. on Advanced and High Temperature Gas Cooled Reactors, p. 603, (IAEA, Vienna, 1969).

(3) M.R. Everett and F. Ridealgh, High Temperatures - High Pressures, 4, 329 (1972).

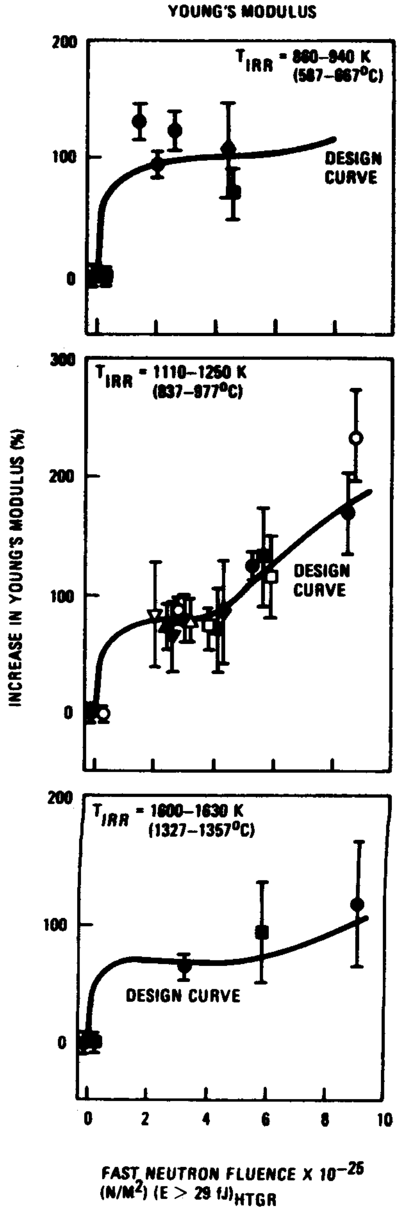

Figure 1. Change in Young's Modulus of H-451 Graphite as a Function of Fast Neutron Fluence

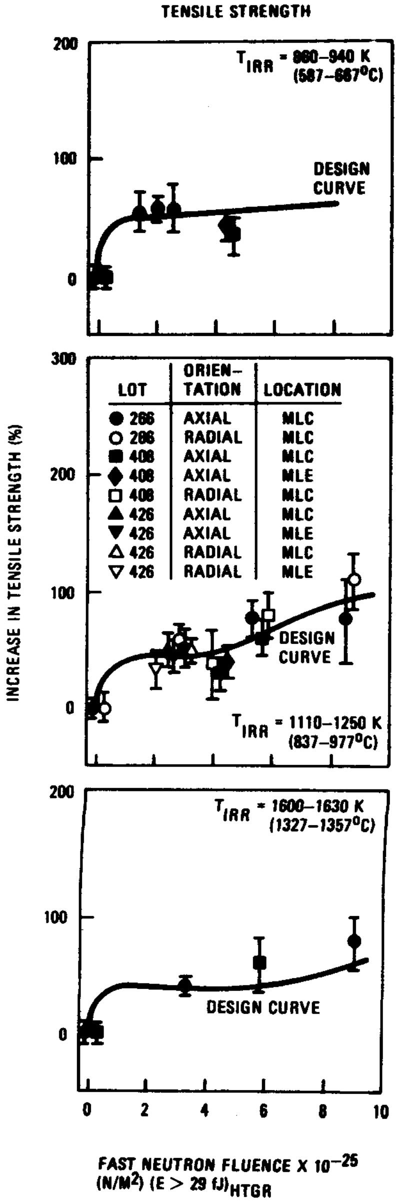

Figure 2. Change in Tensile Strength of H-451 Graphite as a Function of Fast Neutron Fluence