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INDUCED CONTRACTION OF GRAPHITE

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THE EFFECT OF TENSILE STRESS ON THE RADIATION-
INDUCED CONTRACTION OF GRAPHITE*

J. L. Jackson

ABSTRACT

The effect of tensile stresses of 600 and 800 psi on the contraction of EGCR graphite during neutron irradiation at 485° C has been studied at exposures up to 1.5×10^{21} neutrons/cm², $E > 0.18$ Mev. Stress-dependent restrained contraction has been found, and "irradiation creep" rates comparable to those determined by other investigators for a different graphite have been calculated. Results suggest that only a limited amount of the normal contraction can be restrained without fracture of the sample. The relationship between irradiation creep and this restraint limit must be determined before any valid predictions on graphite-core integrity can be stated.

INTRODUCTION

Individual graphite blocks in graphite-moderated reactor cores may in some cases operate with large temperature and flux gradients. These gradients result in different rates of dimensional change and subsequently result in stresses being generated within the moderator blocks. A detailed discussion of the problem as related to the Experimental Gas-Cooled reactor (EGCR) was given by Neely⁽¹⁾. Calculation of the stresses generated and the maximums expected was given by Hulbert and Redmond⁽²⁾. These studies indicate that localized tensile stresses in excess of the tensile strength of EGCR graphite could be generated during the design life of the reactor.

Since nuclear graphite contracts when exposed to neutron irradiation at high temperatures, several questions are raised.

1. Will a tensile stress restrain all or part of this contraction?

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2. If the contraction is restrained, will the amount of restraint vary with the imposed stress?
3. Would the combined stress generated by the opposing tensile load and the contraction be relieved by "irradiation creep" or will there be a restraint limit at which fracture occurs?

Early investigations⁽³⁾ of the response of graphite to stress while being irradiated at low flux and temperature, indicated that some stress relief could be expected from radiation-induced creep. Several other investigators have studied the response of graphite to the simultaneous application of an external load and neutron irradiation⁽⁴⁻⁶⁾. The only data on constant tensile loading, however, was obtained by Perks & Simmons⁽⁵⁾ who irradiated Pile Grade A graphite with a maximum stress of 500 psi at 300° C, and a maximum exposure of 4.6×10^{20} neutron/cm². They concluded that radiation-induced creep occurred under these conditions. Since the available data were for a condition quite different from the EGCR, it appeared necessary to use EGCR graphite at EGCR temperatures and to irradiate to much higher exposures. In order to reduce the time required for experimentation, a higher neutron flux than that in the EGCR was selected.

This paper will present the results of tensile loading graphite specimens at both 600 and 800 psi in the core of the Engineering Test Reactor at the National Reactor Testing Station.

EXPERIMENTAL

The EGCR moderator graphite used for these tests was manufactured by conventional methods⁽⁷⁾ from Continental Lake Charles No. 1. coke and coal-tar pitch and graphitized at about 2800° C. From the large finished bars, 16" x 16", specimens were machined with their longitudinal axes parallel to the axis of extrusion of the bar. The mean tensile strength was 1088 ± 71 psi.

The specimens were fabricated as shown in Figure I. The overall length was approximately 4 in. with a gauge length of 3 in. and a gauge diameter of 0.5 in. A control specimen, 1/8 in. diameter and 1/8 in. shorter than the stressed specimen was included to obtain the amount of contraction in an unstressed specimen under similar irradiation conditions.

All specimens were radiographed to detect any large flaws, annealed at 1000° C to remove any machining stress produced during specimen fabrication, and then pretested to at least 200 psi above the operating load. The dimensions of both stressed and control specimens were measured with a Bausch and Lomb DR-25 optical gauge (type 33-15-23) with a precision of $\pm 1 \times 10^{-4}$ inches. Gauge section diameters were measured to the closest 0.001 in. and each sample was weighed to the closest 10^{-4} g.

The in-reactor tensile capsule shown in Figure II was designed to provide a constant tensile load on the graphite specimen in a helium atmosphere. The 4-in. long graphite specimen was positioned between the stainless-steel specimen grips. The grip method and specimen shape were chosen for convenience in handling and ease of removal. The lower grip was held in a fixed position by the 1/4 in. aluminum capsule wall. The upper grip was attached to the bellows by means of a 3-ft. long stainless-steel draw-bar assembly.

Tensile load was applied by the bellows. The effective bellows pressure was the difference between the capsule and bellows pressure. Since the experimental system allows selection and control of the load during irradiation, loads could be varied if desired.

The system utilizes the gamma and neutron heat generated in the sample and the associated tensile assembly to maintain the desired operating temperature. The aluminum heat-transfer block that surrounds the specimen was designed with appropriate clearances to minimize the temperature gradient along the specimen.

A heat-transfer computer program^(8,9) was used to select gas gaps, mass of materials, etc. The temperatures actually obtained were within 25° C of goal conditions.

Each specimen was monitored by two Geminol-N - Geminol-P thermocouples, one in each end of the sample. By measuring the electrical continuity between a contact and the bellows assembly (not shown in Figure 2) it was possible to determine whether a specimen had broken.

The centerline of the specimen was positioned just below the vertical centerline of the reactor so that the entire specimen was in a region of fairly uniform neutron flux during the reactor cycle. Neutron exposures were calculated from the activation of metallic foils, using effective cross sections developed for the specific reactor positions^(10,11).

All data were obtained at 600 psi and 800 psi in a helium atmosphere with temperatures in the range of 485° C. Variations due to fuel burnup, and position, etc. were $\pm 10^\circ$ C in any one cycle and $\pm 25^\circ$ C for different cycles. The highest exposure to data has been 1.5×10^{21} neutrons/cm², $E > 0.18$ Mev.

DISCUSSION

Ex-reactor creep tests were conducted at 540° C, in helium at varying loads to determine if any thermal creep existed. No long-term creep was detected in tests of over 2000 hrs., with an optical strain system sensitive to changes of 10^{-6} in. Permanent sets of 0.01 to 0.02 per cent were found for the unirradiated specimens.

Since any stress relief due to irradiation should manifest itself as an increase in permanent set, the specimens were measured both before and after irradiation while unloaded. The dimensional changes of both the loaded specimens and the unloaded control specimens are shown in Figure 3.

The limited amount of data makes statistical analysis difficult, but analysis indicates that there is a significant effect of loading at the 90 per cent confidence level. The dimensional changes of the loaded specimens clearly indicates that some of the normal contraction can be restrained and, at the lowest exposure, tensile loading actually enhanced the expansion.

In Figure 3, the corrected lengths for the two broken specimens were determined by fitting the broken specimens back together and taking measurements of the length changes. These length changes were then corrected for the mean length change that could be attributed to the refitting method. This fitting correction was determined from measurements made before and after breaking on a group of unirradiated tensile specimens. The errors in such a procedure were quite large and amounted to subtracting from 0.05 to 0.10 per cent from the refitted measurements.

Inspection of Figure 3 shows that the per cent restraint, the difference between the per cent length change of the loaded specimen and the control, is apparently greater for 800 psi loads than for 600 psi loads.

The difference in contraction between the stressed and unstressed specimens logically leads one to the consideration of the effects of the smaller size and higher temperature for the control specimen. The contraction of the unstressed control appears slightly low when compared to data published by Davidson and Helm⁽¹²⁾. This may be due to the fact that the temperature of the control specimen was slightly higher than the stressed sample. Heat-transfer calculations indicate that the control specimen temperature was about 50° C higher than the stressed specimen. This would then cause it to contract less, making the differences between the control and stressed specimen even larger on a comparable temperature bases.

The smaller size of the unstressed control specimen may also cause a difference in contraction rate. Since it has been found^(13,14) that small specimens contract less than larger ones, this effect may cause the unstressed control to contract less than the stressed specimen. Hence, the real difference between the two should again be greater. The combination of temperature and size factors could increase the differences in contraction between the stressed and unstressed specimens by about a factor of 2. It is reasonable to conclude, therefore, that an applied stress does restrain contraction to at least the extent shown in Figure 3, and possibly even more would have been observed had both specimens been identical in size and temperature.

The amount of contraction restrained at 600 psi at the highest exposure is 0.08 per cent. If this were indeed low by a factor of 2 due to temperature and size effects, and if this were added to the strain due to elasticity and permanent set found in the absence of irradiation (0.1 to 0.2 per cent), differential strains on the order of 0.26 to 0.36 per cent would be possible. Strains of this magnitude would reduce considerably the possibility of cracking in graphite pieces subjected to high differential stress.

In Figure 4, the per cent restraint is shown. This is the difference between the contraction of the control and the stressed specimen uncorrected for temperature or size effects. Again the effect of load can be clearly seen. The broken specimens are shown in this plot by a line at the maximum exposure for the test. The lower exposure specimen was at 800 psi and the higher at 600 psi. The refitting error discussed for Figure 3 negates any significance for these restraint values.

Probably the best evidence for the effect of load on the amount of restraint is shown by the mixed-load point in Figure 4. The specimen was first loaded at 600 psi for approximately 3×10^{20} n/cm² and then, while still in reactor, to 800 psi for the rest of the test. Assuming the response follows the 600

psi curve for the first exposure to obtain the restraint at the changeover and then drawing a line from this point through the final restraint value, the slope of the last line is approximately the same as the slope of the 800 psi curve. This along with the obvious difference in the slopes of the 800 psi and 600 psi lines indicates that the restraint per unit time is dependent on stress.

In order to compare these results with other investigators, the 600 psi data were analyzed according to the method suggested by Perks & Simmons⁽⁵⁾. Modulus changes due to irradiation were taken from a curve for EGCR graphite by Davidson and Helm⁽¹²⁾. The results of the analysis are compared in Table I. Considering the differences in the conditions of these tests, the agreement is good.

TABLE I
COMPARISON OF CREEP RATES

Exposure	<u>Creep rate, psi⁻¹ per 10²⁰ n. cm⁻²</u>		
	<u>4.6 x 10²⁰ n. cm⁻²</u>	<u>6.8 x 10²⁰ n. cm⁻²</u>	<u>9 x 10²⁰ n. cm⁻²</u>
This work (485°C, 600 psi)	---	0.68 x 10 ⁻⁷	0.62 x 10 ⁻⁷
This work corrected for temperature and size	---	1.3 x 10 ⁻⁷	1.2 x 10 ⁻⁷
Perks & Simmons ⁽⁵⁾ (300° C, 500 psi)	1 to 2 x 10 ⁻⁷	---	---

The possibility of a restraint limit as evidence by the failure of two specimens should not be dismissed lightly. Careful study of the operation and handling of each test suggests that the failure of the specimen exposed to 9×10^{20} neutrons/cm² might possibly be attributed to a possible overload of the specimen during operation. As far as can be determined, the failure of the specimen exposed to 1.0×10^{21} neutrons/cm² was not due to operational

error but rather to some natural restraint limit in the material. However, one specimen survived to an exposure of 1.5×10^{21} neutrons/cm² without fracture, which casts some doubt on the existence of a restraint limit. Further studies in search of a limit are now in progress.

CONCLUSIONS

Graphite subjected to a tensile stress and neutron irradiation contracts less than an unstressed control. The amount of restrained contraction is stress dependent. "Radiation creep" as described by Perks & Simmons exists at these exposures and temperatures, although apparently to a lesser degree in EGCR graphite than Pile Grade A. The possibility of a restraint limit exists and the creep rate at higher exposures may not be sufficient to relieve the differential stress generated within the graphite. Additional data at higher exposures is necessary before any reliable predictions can be made as to the effect of this "radiation creep" on reactor graphite integrity.

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FIGURE I

In-Reactor Tensile Specimen

- 11 -

FIGURE II

In-Reactor Tensile Capsule

FIGURE III

Length Change of Loaded vs. Unloaded Specimens

FIGURE IV

Restrained Contraction vs. Exposure