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PROPERTY CHANGES IN NEAR-ISOTROPIC GRAPHITES IRRADIATED AT 300° TO 600°C: A LITERATURE SURVEY

by
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ABSTRACT

Irradiation data on graphite at 300°-600°C are needed to evaluate the useful lifetime of large high-temperature gas-cooled reactor (HTGR) replaceable top reflector elements. A literature survey disclosed sufficient data on near-isotropic graphites, mostly from the United Kingdom Atomic Energy Authority (UKAEA) and the Dragon Project, enabling reasonable predictions to be made on the effects of irradiation on graphite dimensions, thermal expansivity, thermal conductivity, Young's modulus, strength, and creep. Recommended design values for these properties are given.

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1. INTRODUCTION

To assess the useful lifetime of replaceable top reflector elements in a large high-temperature gas-cooled reactor (HTGR), irradiation data on graphite are required for temperatures down to 300°C and fluences up to $1.2 \times 10^{22} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$). The OG series of graphite capsules currently being irradiated at General Atomic Company (GA) are generating data at temperatures down to 550°C (Ref. 1). In some future capsules, the minimum specimen temperature will be reduced to 300° to 350°C, although it will take several years to accumulate sufficient data.

This report summarizes the results of a literature survey of published measurements on near-isotropic graphites irradiated between 300° and 600°C and recommends interim design values which may be used for stress and distortion calculations.

2. SCOPE OF PUBLISHED RESULTS

2.1. UNITED KINGDOM ATOMIC ENERGY AUTHORITY (UKAEA) DATA (REFS. 2 TO 7)

A large amount of data on irradiation-induced property changes in pile grade A (PGA) graphite irradiated between 150° and 650°C was produced by the Magnox reactor program (Ref. 2-5). Dimensional changes and changes in thermal conductivity and expansivity and Young's modulus were measured on samples irradiated to 4×10^{21} n/cm² nickel DIDO equivalent fluence (NDE) in the DIDO and PLUTO (Harwell) reactors. The capsules were well controlled and instrumented, and samples were examined at short increments of fluence. Unfortunately, PGA is a needle-coke-type graphite, and the data cannot be directly applied to near-isotropic graphite. However, the data are useful for establishing trends.

The UKAEA advanced gas-cooled reactors (AGRs) use near-isotropic graphites with properties which are generally similar to those selected for large HTGRs. A considerable amount of irradiation data in the temperature range of 360° to 700°C to fluences of up to 2.7×10^{22} n/cm² (NDE) were obtained from irradiations in the Dounreay Fast Reactor (DFR), with some supplemental irradiations in PLUTO at temperatures of 475°C and above (Refs. 5-7). The DFR capsules did not contain thermocouples, and temperatures were obtained from silicon carbide temperature monitors. Because of the very high flux in the DFR, no points are obtained at fluences less than 2 to 5×10^{21} n/cm² (NDE). Normally, data from uninstrumented fast reactor capsules must be given little weight because of the indirect temperature determination and the very high flux. However, in this case, the data can be accepted because at such low temperatures silicon carbide temperature monitors have a proven reliability ($\pm 25^\circ\text{C}$) and DFR results on PGA graphite are in excellent agreement with data from instrumented capsules in PLUTO (Refs. 3,5). In addition, data obtained on needle-coke graphites

in instrumented capsules at Battelle Northwest Laboratories (BNWL) (see Section 2.2) agree well with DFR results on PGA graphite when the appropriate fluence conversion is made.

2.2. BNWL DATA (REFS. 8-10)

A large number of measurements on graphites irradiated at temperatures above 425°C in the General Electric Test Reactor (GETR) and the Engineering Test Reactor (ETR) were made at BNWL. The majority of the samples were made from early needle-coke grades; additional measurements were made on a variety of experimental and prototype materials. However, no systematic data were obtained on commercial near-isotropic graphites. The BNWL work is principally useful for confirming European results and verifying fluence conversions from the units used in Europe to those used in the U.S.

2.3. DRAGON DATA (REF. 11)

Dragon has irradiated many graphite specimens in fully controlled and instrumented capsules in the High-Flux Reactor (HFR, Petten). Recent irradiations have included samples operating at temperatures down to 400°C and fluences up to $3 \text{ to } 4 \times 10^{21} \text{ n/cm}^2$ (NDE). The most complete results are given in Ref. 11. The graphite types studied include a near-isotropic extruded petroleum-coke graphite (Dragon code No. 120) and an extruded pitch-coke graphite (Dragon code No. 100) which had properties similar to those of the material planned for large HTGR graphite. Dimensional, Young's modulus, and thermal expansivity data on these graphites at irradiation temperatures of 400° and 600°C are given in Ref. 11.

3. COMPILATION OF DATA FOR DESIGN

3.1. DIMENSIONAL CHANGES

The main body of data has been taken from UKAEA results on a near-isotropic graphite (code No. PI) irradiated in the DFR at temperatures between 360° and 600°C (Ref. 7). This graphite has a thermal expansivity (20° to 120°C) of $3.5 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ parallel to extrusion and $4.1 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ perpendicular to extrusion (Ref. 6), and its behavior would be expected to be similar to that of large HTGR near-isotropic graphites. After converting the fluence to units with $E > 0.18 \text{ MeV}$ using the conversion factor

$$\text{fluence (NDE)} = 0.6 \times \text{fluence (E > 0.18 MeV)} ,$$

the data points from Ref. 7 were tabulated (see Tables 1 and 2) and plotted in Figs. 1 and 2. Tables 1 and 2 and Figs. 1 and 2 also show the Dragon data on extruded near-isotropic graphites 100 and 120 (Ref. 11). The few available GA data points on H-451 graphite are also included in Figs. 1 and 2, and it can be seen that agreement between the three sets of data is good.

No irradiation data below 360° to 400°C have been reported for near-isotropic graphites. However, Ref. 3 includes results for PGA (needle-coke) graphite irradiated in DIDO and PLUTO at 300°, 350°, and 450°C. The probable behavior of near-isotropic graphite at 300°C can be predicted from the PGA data by calculating the volumetric shrinkage rates at 300° and 450°C and assuming that the ratio between the rates at these two temperatures is the same for near-isotropic graphite and PGA. This procedure was applied to the near-isotropic 450°C experimental data in Fig. 1. The calculated 300°C volumetric shrinkages were then converted to linear shrinkage by assuming that the ratio of axial to radial shrinkage is the same at 300°C as at 450°C. The calculated 300°C behavior is given in Tables 1 and 2.

TABLE 1
SUPPLEMENTARY DIMENSIONAL CHANGE DATA FOR EXTRUDED NEAR-ISOTROPIC GRAPHITE, AXIAL ORIENTATION

Source of Data	Reference	Material (code number)	Irradiation Facility	Irradiation Temperature (°C)	Fast Fluence, NDE (n/cm ² x 10 ⁻²¹)	Fast Fluence, E > 0.18 MeV (n/cm ² x 10 ⁻²¹)	Dimensional Change (%)
UKAEA	7	PI	DFR	380	15.7	26.2	-3.23
					20.6	34.3	-3.29
					24.4	40.7	-3.00
					425	2.5	-0.50
					3.0	4.2	-0.72
					5.0	5.0	-0.99
					5.3	8.3	-1.37
					10.8	8.8	-2.64
					11.2	18.0	-2.59
					13.8	18.7	-3.09
					16.0	23.0	-3.22
					16.2	26.7	-3.22
				475	18.2	27.0	-3.29
					20.8	30.3	-3.43
					21.0	34.7	-3.21
					21.4	35.0	-2.81
					24.6	35.7	-3.10
					25.0	41.0	-3.00
					25.0	41.7	-0.81
					2.9	4.8	-1.50
					5.2	8.7	-2.65
					9.7	16.2	-2.65
					11.2	18.7	-3.41
					12.8	21.3	-3.35
					15.3	25.5	-0.72
				525	2.8	4.7	-1.33
					5.1	8.5	-2.51
					9.7	16.2	

TABLE 1 (continued)

Source of Data	Reference	Material (code number)	Irradiation Facility	Irradiation Temperature (°C)	Fast Fluence, NDE (n/cm ² x 10 ⁻²¹)	Fast Fluence, E > 0.18 MeV (n/cm ² x 10 ⁻²¹)	Dimensional Change (%)
UKAEA	7	PI	DFR	575	2.6	4.3	-0.59
					4.5	7.5	-1.15
					4.7	7.8	-1.15
					5.9	9.8	-1.68
					6.8	11.3	-2.05
					7.1	11.8	-1.69
					7.3	12.2	-2.13
					9.1	15.2	-2.51
					11.8	19.7	-3.08
					13.9	23.2	-3.19
					14.5	24.2	-3.25
					15.0	25.0	-3.07
					16.8	28.0	-2.77
					18.5	30.8	-2.48
					21.4	35.7	-0.80
					21.4	35.7	-1.76
					22.9	38.2	-0.75
Dragon	11	120	HFR	400	0.2	0.3	-0.05
					0.3	0.5	-0.10
					0.7	1.2	-0.19
					1.1	1.8	-0.40
					1.8	3.0	-0.59
					2.9	4.8	-0.98
				600	0.5	0.8	-0.08
					0.6	1.0	-0.10
					1.0	1.7	-0.23
					1.0	1.7	-0.30
					1.5	2.5	-0.46
					1.5	2.5	-0.52

TABLE 1 (continued)

Source of Data	Reference	Material (code number)	Irradiation Facility	Irradiation Temperature (°C)	Fast Fluence, NDE (n/cm ² x 10 ⁻²¹)	Fast Fluence, E > 0.18 MeV (n/cm ² x 10 ⁻²¹)	Dimensional Change (%)
Dragon	11	100	HFR	400	1.6	2.7	-0.29
					1.9	3.2	-0.54
					2.1	3.5	-0.62
					2.7	4.5	-0.97
					3.5	5.8	-1.26
					3.8	6.3	-1.26
					4.9	8.2	-1.66
				600	1.0	1.6	-0.25
					1.1	1.8	-0.20
					1.3	2.1	-0.30
					1.5	2.6	-0.32
					1.8	3.0	-0.56
					2.5	4.2	-0.86
					0.3	0.5	-0.03
					0.4	0.7	-0.03
					0.5	0.8	-0.03
					0.6	1.0	-0.08
					1.4	2.4	-0.33
					1.4	2.4	-0.42
					1.6	2.7	-0.43
					3.0	5.0	-0.96
Calculation		Calculated data points	--	300		5.0	-0.60
						10.0	-1.15
						15.0	-1.70
						20.0	-2.25
						25.0	-2.75
						30.0	-3.10

TABLE 2
SUPPLEMENTARY DIMENSIONAL CHANGE DATA FOR EXTRUDED NEAR-ISOTROPIC GRAPHITE, RADIAL ORIENTATION

Source of Data	Reference	Material (code number)	Irradiation Facility	Irradiation Temperature (°C)	Fast Fluence, NDE (n/cm ² x 10 ⁻²¹)	Fast Fluence, E > 0.18 MeV (n/cm ² x 10 ⁻²¹)	Dimensional Change (%)
UKAEA	7	PI	DFR	380	15.7	26.2	-2.27
					20.6	34.3	-2.07
					24.4	40.7	-1.43
					425	2.5	-0.39
					3.0	5.0	-0.60
					5.0	8.3	-0.80
					5.3	8.8	-1.00
					10.8	18.0	-2.07
					11.2	18.7	-1.87
					13.8	23.0	-1.97
					16.0	26.7	-1.75
					16.2	27.0	-1.97
					18.2	30.3	-1.73
					20.8	34.7	-1.40
					21.0	35.0	-1.57
				475	21.4	35.7	-0.92
					24.6	41.0	-0.76
					25.0	41.7	-0.76
					2.9	4.8	-0.67
					5.2	8.7	-1.09
					11.1	18.5	-1.75
					12.8	21.3	-2.04
					15.3	25.3	-2.07
				525	2.7	4.5	-0.55
					2.8	4.7	-0.60
					4.7	7.8	-0.96
					5.1	8.5	-1.01

TABLE 2 (continued)

Source of Data	Reference	Material (code number)	Irradiation Facility	Irradiation Temperature (°C)	Fast Fluence, NDE (n/cm ² x 10 ⁻²¹)	Fast Fluence, E > 0.18 MeV (n/cm ² x 10 ⁻²¹)	Dimensional Change (%)
UKAEA	7	PI	DFR	575	4.5	7.5	-1.04
					5.9	9.8	-1.35
					6.8	11.3	-1.49
					7.1	11.8	-1.19
					7.3	12.2	-1.56
					9.1	15.2	-1.80
					9.7	16.2	-1.73
					11.8	19.7	-1.55
					13.9	23.2	-1.35
					14.5	24.2	-1.08
					15.0	25.0	-1.28
					16.8	28.0	+0.49
					18.5	30.8	+0.67
Dragon	11	120	HFR	400	0.2	0.3	-0.05
					0.8	1.3	-0.19
					1.0	1.7	-0.25
					2.3	3.8	-0.61
				600	0.4	0.7	-0.07
					1.4	2.3	-0.35
					1.6	2.7	-0.83
					2.9	4.8	-0.81
					3.3	5.5	-0.85
					3.9	6.5	-1.10
					4.7	7.8	-1.11
Dragon	11	100	HFR	400	0.8	1.4	-0.12
					2.1	3.5	-0.26
					2.8	4.7	-0.45

TABLE 2 (continued)

Source of Data	Reference	Material (code number)	Irradiation Facility	Irradiation Temperature (°C)	Fast Fluence, NDE (n/cm ² x 10 ⁻²¹)	Fast Fluence, E > 0.18 MeV (n/cm ² x 10 ⁻²¹)	Dimensional Change (%)
Calculation		Calculated data points	--	600	1.4	2.3	-0.27
					1.5	2.5	-0.23
					1.7	2.8	-0.28
					2.7	4.5	-0.56
					2.9	4.9	-0.70
					3.1	5.1	-0.66
					3.7	6.2	-0.75
				300		5.0	-0.40
						10.0	-0.85
						15.0	-1.25
						20.0	-1.55
						25.0	-1.80
						30.0	-1.95

Fig. 1. Dimensional changes in near-isotropic graphite irradiated at 360° to 500°C (data from Refs. 7 and 11)

Fig. 2. Dimensional changes in near-isotropic graphite irradiated at 500° to 600°C (data from Refs. 7 and 11)

The data in Tables 1 and 2 and experimental data on near-isotropic graphites irradiated at higher temperatures in capsules OG-1 and OG-2 were fitted by a least-squares procedure to a polynomial of the form

$$\begin{aligned}\epsilon = & (C_1 + C_2T + C_3T^2 + C_4T^3 + C_5T^4) \Phi \\ & + (C_6 + C_7T + C_8T^2 + C_9T^3 + C_{10}T^4) \Phi^2 \\ & + (C_{11} + C_{12}T + C_{13}T^2 + C_{14}T^3 + C_{15}T^5) \Phi^3 ,\end{aligned}$$

where ϵ is the radiation-induced strain (%), T is the irradiation temperature ($^{\circ}\text{C}$), and Φ is the fast neutron fluence (10^{21} n/cm^2 , $E > 0.18 \text{ MeV}$). The values of the constants are tabulated below

	<u>Axial Orientation</u>	<u>Radial Orientation</u>
C_1	$+0.72518 \times 10^{-1}$	$+0.87109$
C_2	-0.21463×10^{-2}	-0.62595×10^{-2}
C_3	$+0.56343 \times 10^{-5}$	$+0.13246 \times 10^{-4}$
C_4	-0.47151×10^{-8}	-0.10604×10^{-7}
C_5	$+0.10360 \times 10^{-11}$	$+0.26822 \times 10^{-11}$
C_6	$+0.28385 \times 10^{-1}$	-0.96873×10^{-1}
C_7	-0.17129×10^{-3}	$+0.62636 \times 10^{-3}$
C_8	$+0.54867 \times 10^{-6}$	-0.12780×10^{-5}
C_9	-0.87999×10^{-9}	$+0.87792 \times 10^{-9}$
C_{10}	$+0.41594 \times 10^{-12}$	-0.15809×10^{-12}
C_{11}	-0.54523×10^{-2}	$+0.11730 \times 10^{-2}$
C_{12}	$+0.42719 \times 10^{-4}$	-0.48514×10^{-5}
C_{13}	-0.12171×10^{-6}	-0.84116×10^{-9}
C_{14}	$+0.14475 \times 10^{-9}$	-0.19531×10^{-10}
C_{15}	-0.55405×10^{-13}	-0.12701×10^{-13}

3.2. THERMAL EXPANSIVITY

The thermal expansivity of near-isotropic graphite samples irradiated in the DFR is reported in Ref. 7, and the data are reproduced in Fig. 3.

Fig. 3. Change in thermal expansivity of near-isotropic graphite irradiated at 350° to 550°C (data from Ref. 7)

No irradiation temperature effect is apparent for the temperature range 350° to 550°C.

The ratio of postirradiation thermal expansivity to preirradiation expansivity taken from Fig. 3 is tabulated as a function of fast fluence in Table 3. It is recommended that this factor be used to calculate the thermal expansivity of near-isotropic graphite irradiated at temperatures between 300° and 600°C.

3.3. THERMAL CONDUCTIVITY

The thermal conductivity (at room temperature) of near-isotropic graphites irradiated in the DFR was measured at UKAEA. Changes in thermal resistivity for the grade code-numbered PI (parallel to extrusion) are given in Ref. 6 and are replotted in Fig. 4 after converting the fluence units to neutrons, with $E > 0.18$ MeV. Higher fluence results are contained in Ref. 7. A few data points at 435°-650°C on near-isotropic pitch-coke graphites were reported by Dragon (Ref. 11); these points are also included in Fig. 4.

The experimental data on near-isotropic graphites do not extend down to 300°C and are not sufficient to show the shape of the curve at low fluences. However, a considerable amount of thermal conductivity data on PGA graphite irradiated between 250° and 650°C is available from the AGR program (Refs. 2,4,12). Curves taken from Ref. 12 showing the fractional change in thermal resistivity of PGA graphite are included in Fig. 4. The solid curves correspond to experimental data, and the dashed curves are extrapolations. The data points for near-isotropic graphite are in good agreement with the PGA curves.

To obtain values useful for design, the fractional changes in thermal resistivity given by the smooth curves in Fig. 4 were applied to the measured room temperature conductivity of H-451 graphite, interpolating between the curves for calculations at intermediate temperatures. The conductivity at the irradiation temperature was calculated by assuming that

TABLE 3
THERMAL EXPANSIVITY OF NEAR-ISOTROPIC GRAPHITE IRRADIATED BETWEEN
350° AND 550°C

Fast Fluence, E > 0.18 MeV (n/cm ² x 10 ⁻²¹)	Ratio of Postirradiation Expansivity to Preirradiation Expansivity, α/α_0
0	1.00
1	1.09
2	1.13
3	1.15
4	1.18
5	1.19
6	1.20
7	1.21
8	1.22
9	1.21
10	1.20
11	1.20
12	1.19
13	1.18
14	1.18
15	1.17

Fig. 4. Irradiation-induced changes in thermal resistivity of near-isotropic graphite (data points from Refs. 6 and 11; curves from Ref. 12)

for given irradiation conditions, irradiation adds the same increment to the thermal resistivity at all measurement temperatures (Ref. 13). The results of the calculations are given in Table 4.

3.4. YOUNG'S MODULUS AND STRENGTH

Measurements of changes in sonic modulus and strength determinations from tensile and "brittle ring" tests were obtained on near-isotropic graphite irradiated in the DFR under the UKAEA program (Refs. 6,7). Figure 5 shows results from Ref. 6 for material irradiated at 350° to 440°C. The fractional increase in strength equals the square root of the fractional increase in Young's modulus, indicating that the strain energy to failure remains constant. Later data (Ref. 7) show that this relationship holds to about 2×10^{22} n/cm² (NDE), but the strength may decrease somewhat at higher fluences.

Dragon has reported changes in the sonic modulus of near-isotropic graphites irradiated at 400° and 600°C to fluences of 3 to 4×10^{21} n/cm² (NDE) (Ref. 11); an example is shown in Fig. 6. The 400°C increases are consistent with the higher fluence data shown in Fig. 5. Fractional increases in sonic modulus should not be directly used for design purposes because the sonic modulus of unirradiated graphite is higher than the static Young's modulus taken from a stress-strain curve, whereas after irradiation the two determinations coincide. Design curves for the static Young's modulus have been derived from the Dragon data using a multiple of 0.8 to convert dynamic modulus to static modulus (unirradiated graphite) and a multiple of 0.6 to convert fluence ($E > 0.18$ MeV) to fluence (NDE). For irradiated graphite, the sonic and static moduli were assumed equal. Curves for temperatures other than 400° and 600°C were obtained by interpolation. The calculated design curves are shown in Fig. 7. The increase in strength may be assumed equal to the square root of the increase in modulus:

$$\frac{S}{S_o} = \left(\frac{E}{E_o} \right)^{1/2} .$$

TABLE 4
CALCULATED THERMAL CONDUCTIVITY AT IRRADIATION TEMPERATURE OF NEAR-ISOTROPIC GRAPHITE
IRRADIATED BETWEEN 300° AND 600°C

Temperature (°C)	Fast Fluence, E > 0.18 MeV (n/cm ² x 10 ⁻²¹)	Thermal Conductivity (cal/cm-sec-°C)		Temperature (°C)	Fast Fluence, E > 0.18 MeV (n/cm ² x 10 ⁻²¹)	Thermal Conductivity (cal/cm-sec-°C)	
		Radial	Axial			Radial	Axial
300	1	0.028	0.032	500	1	0.069	0.080
	2	0.022	0.025		2	0.050	0.058
	3	0.019	0.022		3	0.044	0.052
	4	0.017	0.020		4	0.040	0.046
	5	0.016	0.019		5	0.036	0.042
	10	0.014	0.017		10	0.031	0.036
	15	0.014	0.016		15	0.028	0.033
400	1	0.047	0.055	600	1	0.077	0.089
	2	0.035	0.041		2	0.058	0.067
	3	0.031	0.036		3	0.049	0.057
	4	0.028	0.033		4	0.043	0.050
	5	0.026	0.030		5	0.040	0.047
	10	0.023	0.027		10	0.037	0.043
	15	0.021	0.025		15	0.033	0.039

Fig. 5. Change in sonic Young's modulus (E) and strength (S) of near-isotropic graphite irradiated at 350° to 700°C (from Ref. 6)

Fig. 6. Fractional changes in sonic Young's modulus of extruded near-isotropic pitch coke graphite (Dragon code No. 100) (from Ref. 11)

Fig. 7. Calculated percent increases in static Young's modulus of near-isotropic graphites (solid parts of curves correspond to data in Refs. 6 and 11; broken parts are extrapolated)

3.5. IRRADIATION CREEP

The only controlled-stress creep experiments on near-isotropic graphites irradiated in the range 300° to 650°C were conducted at UKAEA (Ref. 14), and a summary plot of these results for creep strain versus fluence is shown in Fig. 8. The data show no systematic dependence on temperature, and the steady-state creep coefficient calculated from the data in Fig. 8 is $1.2 \pm 0.1 \times 10^{-27} \text{ (psi)}^{-1} \text{ (n/cm}^2, E > 0.18 \text{ MeV)}^{-1}$, and the total transient creep strain found in these experiments was $0.9 \pm 0.1 \times 10^{-6} \text{ (psi)}^{-1}$ (equal to the initial elastic strain computed using the unirradiated Young's modulus).

It should be noted that the steady-state creep constant given above is somewhat higher than values calculated from a least-squares analysis of all available data at all temperatures (Ref. 15). The latter analysis gives a value rising from $0.58 \times 10^{-27} \text{ (psi)}^{-1} \text{ (n/cm}^2, E > 0.18 \text{ MeV)}^{-1}$ at 300°C to $1.02 \times 10^{-27} \text{ (psi)}^{-1} \text{ (n/cm}^2, E > 0.18 \text{ MeV)}^{-1}$ at 600°C.

Fig. 8. Irradiation creep strain versus neutron fluence (NDE) for near-isotropic graphites irradiated under constant stress of 900 psi (from Ref. 14)

4. SUMMARY AND CONCLUSIONS

Published data on the effects of neutron irradiation of near-isotropic graphites at 300° to 600°C have been analyzed, and the following design basis property values are recommended.

1. Dimensional change: axial and radial dimensional changes are given as a polynomial function of fluence and temperature in Section 3.1.
2. Thermal expansivity: the ratio of postirradiation to preirradiation thermal expansivity is given as a function of neutron fluence in Table 3. This ratio may be used at any irradiation temperature between 300° and 600°C.
3. Thermal conductivity: the thermal conductivity of near-isotropic graphite at various irradiation temperatures (based on H-451 preirradiation values) is listed as a function of neutron fluence and irradiation temperature in Table 4.
4. Young's modulus: the percent increase in Young's modulus is plotted as a function of neutron fluence and irradiation temperature in Fig. 7.
5. Strength: the irradiation-induced change in strength, S , may be calculated from the irradiation-induced change in Young's modulus, E (Fig. 7), from the expression:

$$\frac{S}{S_o} = \left(\frac{E}{E_o} \right)^{1/2} .$$

6. Irradiation creep: the total transient creep strain for an applied stress, σ , may be taken as σ/E_0 , where E_0 is the unirradiated value of Young's modulus. The steady-state creep coefficient may be taken as $1.2 \times 10^{-27} (\text{psi})^{-1} (\text{n/cm}^2, E > 0.18 \text{ MeV})^{-1}$. Both parameters can be assumed to be independent of irradiation temperature in the range 300° to 600°C.

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