FINAL REPORT ON GRAPHITE IRRADIATION TEST OG-1

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SUMMARY

This report details the results of dimensional measurements and physical property tests on graphite samples irradiated in capsule OG-1. Samples of H-327 (needle-coke graphite), H-429 and H-451 (near-isotropic petroleum-coke graphites), P₃JHAN (pitch-coke graphite), and other miscellaneous graphites were irradiated at temperatures from 600° to 1400°C to fluences from 1.6 to 3.7×10^{21} n/cm² ($E > 0.18$ MeV).

Irradiation-induced shrinkages were smaller and more isotropic in the H-429 and H-451 graphites than in either the needle-coke or pitch-coke graphites irradiated under similar conditions.

Irradiation-induced changes in the thermal expansivity of H-327 graphite were insignificant. Irradiation caused a small increase in the thermal expansivity of H-429 and H-451 graphites at irradiation temperatures below about 900°C and a slight decrease at higher temperatures.

Irradiation reduced both the thermal conductivity of H-327 and H-451 graphites and its temperature dependence. After irradiation at 600° and 900°C, the radial conductivity of H-451 graphite was about 50% higher than the radial conductivity of H-327 graphite and about equal to the axial conductivity of H-327 graphite.

Irradiation increased both the strength and Young's modulus of H-327 and H-451 graphites, with a greater increase at lower irradiation temperatures than at higher irradiation temperatures. Percentage increases in strength fell in the range 30% to 60%, while increases in Young's modulus ranged from 60% to 130%.

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1. INTRODUCTION

This report describes the results of dimensional measurements and physical property tests on graphite samples irradiated in capsule OG-1. Details of the fabrication and assembly of the capsule are given in Ref. 1, and the operating history of the capsule is described in Ref. 2. A complete list of the samples included in the capsule and their locations is given in Ref. 3.

2. TEST DESCRIPTION AND OBJECTIVES

Capsule OG-1 was the first in a series of graphite irradiation capsules to be irradiated in the C-3 position of the Oak Ridge Reactor (ORR). The two-cell capsule was designed with instrumented temperature-controlled crucibles whose operating temperatures spanned the range of temperatures where significant neutron fluence is experienced in a large HTGR (600° to 1200°C), with one cell additionally operating at a higher temperature (~1400°C) to provide test data under conditions which exceed current designs. The fluences (1.6 to 3.7×10^{21} n/cm², $E > 0.18$ MeV) were chosen so that samples irradiated consecutively in three similar capsules would accumulate data extending beyond end-of-life exposure for current HTGR designs.

The capsule contained 1440 graphite and 70 miscellaneous specimens. A major objective of the experiment was to obtain comparative irradiation data on a needle-coke graphite of the type used in the Fort St. Vrain HTGR (Great Lakes Carbon Company grade H-327) and near-isotropic nuclear graphites of the kind which will be used in future HTGRs. The bulk of the sample space was therefore assigned to H-327 graphite and a production-sized, near-isotropic nuclear graphite made from petroleum coke and its sub-sized prototype (Great Lakes Carbon Company grades H-451 and H-429, respectively). Many of the H-327 and H-429 samples had been previously irradiated in the joint Pacific Northwest Laboratory - General Atomic graphite irradiation capsule GEH-13-422, and a large number of the samples from capsule OG-1 were reloaded into the succeeding capsule, OG-2, to provide higher-fluence data. Other sample space was assigned to graphite types of general interest and to highly irradiated material from previous capsules.

The capsule contained three types of graphite samples: 0.2-in.-diameter by 0.45-in.-long cylinders for dimensional and thermal expansivity measurements, 0.25-in.-diameter by 0.9-in.-long cylinders for dimensional and tensile property measurements, and 0.4-in.-diameter by 0.05-in.-thick discs for thermal diffusivity measurements. A portion of the tensile samples were extended to failure after irradiation, and the remainder were reencapsulated in OG-2. Capsule OG-1 also contained 0.2-in.-diameter by 0.9-in.-long cylinders of H-451 graphite, which are being held for fatigue testing at a later date.

3. MATERIALS INVESTIGATED

The materials investigated are listed in Table 1.

TABLE 1
GRAPHITES AND MISCELLANEOUS MATERIALS IN OG-1

Designation	Type	Log Book Number	Form & Dimensions of Parent Sample	Source ^(a)	Raw Materials		
					Filler	Binder	Impregnant
Graphite							
H-451	Extruded near-isotropic	5651-28	18-in.-diameter x 34-in.-long log	GLCC	Near-isotropic petroleum coke	Coal tar pitch	Petroleum pitch
H-327	Extruded anisotropic	4974-3	18-in.-diameter x 34-in.-long log	GLCC	Needle coke	Coal tar pitch	Coal tar pitch
H-429	Extruded near-isotropic	4974-104-A	6.9-in.-diameter x 8-in.-long log	GLCC	Near-isotropic petroleum coke	Coal tar pitch	Coal tar pitch
2020	Isostatic molded fine-grained	5651-56	18-in.-diameter x 6-in.-long slab	SCCP	Petroleum coke	(b)	(b)
P ₃ JHAN	Extruded near-isotropic	5651-53	8-in. x 8-in. x 8-in. cube	Pechiney	Near-isotropic coal tar pitch coke	Coal tar pitch	Coal tar pitch
H-453	Extruded near-isotropic	5651-34	18-in.-diameter x 34-in.-long half-log	GLCC	Near-isotropic petroleum coke	Coal tar pitch	Petroleum pitch
H-419	(b) near-isotropic		1.25-in.-diameter x 5-in.-long rod	GLCC	(b)	(b)	(b)
H-315A	BKR near-isotropic		4.6-in. OD x 3.5-in. ID tube	GLCC	Gilsocoke	Coal tar pitch	Coal tar pitch
H-328	Molded near-isotropic		17-in.-diameter x 34-in.-long log	GLCC	Gilsocoke	Coal tar pitch	Coal tar pitch
CHN	Extruded anisotropic		4.6-in.-diameter x 12-in.-long log	UCC	Needle coke	Coal tar pitch	Non-graphitizing carbon
H-319	BKR near-isotropic		2.9-in.-diameter x 6-in.-long log	GLCC	Uncalcined petroleum coke	Coal tar pitch	Coal tar pitch

TABLE 1 (Contd)

Designation	Type	Log Book Number	Form & Dimensions of Parent Sample	Source (a)	Raw Materials		
					Filler	Binder	Impregnant
H-430	Molded near-isotropic		8.6-in.-diameter x 7.5-in.-long log	GLCC	Near-isotropic petroleum coke	Coal tar pitch	(b)
H-451C	Extruded near-isotropic	5948-14	18-in.-diameter x 34-in.-long log	GLCC/GA	Near-isotropic petroleum coke	Coal tar pitch	Samples taken from cure-in-place crucibles
IH-451	Extruded near-isotropic	5948-101	18-in.-diameter x 34-in.-long log	GLCC/GA	Near-isotropic petroleum coke	Coal tar pitch	Additional impregnation done at GA
Other Materials							
					Description		
B ₄ C-G	Extruded boronated graphite	5646-13	0.30-in.-OD x 10-in.-long rods	GLCC	Fort St. Vrain lumped burnable poison		
GLSYCN	Glassy carbon	(c)	(b)	Beckwith Lockheed	Commercial glassy carbons		
PYC	Pyrolytic carbon	(c)	(b)	GA	Restrained and unrestrained LTI PyC		
FUSTCK	Inert fuel stick	6042-6	(b)	GA	BISO + TRISO inert particles + shim fuel compacts		
SiC	SiC coatings	6041-7	(b)	GA	GA-produced SiC coatings		
565161	Experimental	5651-61	(b)	ORNL	ORNL experimental graphite		
FSVMTX	Fuel stick matrix	5478-47	(b)	GA	Reconstituted Fort St. Vrain matrix		
KAAE	Pyrolytic carbon	(c)	(b)	GA	Specialty pyrolytic carbons		

(a) GLCC = Great Lakes Carbon Company; UCC = Union Carbide Company; SCCP = Stackpole Carbon Company; GA = General Atomic Company; ORNL = Oak Ridge National Laboratory.

(b) Unknown to author.

(c) GA experiments on pyrolytic carbon.

4. CAPSULE OPERATING CONDITIONS

4.1. DESCRIPTION OF CAPSULE

Capsule OG-1 was a fully instrumented, controlled-temperature graphite irradiation capsule irradiated in the C-3 position of the ORR. Irradiation started on July 7, 1973, and terminated on December 2, 1973 (reactor cycles 113 through 115), for an accumulated irradiation time of 3200 full-power hours.

The capsule contained two cells, each with its own sweep-gas system. Adjustment of the helium-argon ratio in the sweep gas allowed independent temperature control in the upper and lower cells. The cells contained a total of 10 graphite crucibles approximately 2.25 in. in diameter by 2 in. high (except for crucible No. 3, which was 3 in. high), which were drilled with holes to act as sample holders. The center-line temperatures of crucible 3 in cell 1 and crucible 7 in cell 2 were maintained at 1000°C during reactor operation by adjustment of the gas mixtures. The crucibles contained 16 Chromel-Alumel thermocouples and 10 tungsten-rhenium thermocouples. All crucibles had one or more thermocouples located on the center line, and all except two had one or more thermocouples at the periphery. Three sets of in-situ decalibration data on the tungsten-rhenium couples were obtained by locating pairs of Chromel-Alumel and tungsten-rhenium thermocouples in the same holes. The locations of the thermocouples are given in Table 2. Reliable readings were obtained from all thermocouples except K1 and W2.

4.2. OPERATING TEMPERATURES

Details of the methods used to analyze the thermocouple operating records are given in Ref. 2. The neutron-induced decalibration factor for

TABLE 2
AVERAGE TEMPERATURE ESTIMATES FOR OG-1 EXPERIMENT

Crucible Number	Thermocouple Identification and Location				Thermal Fluence $\times 10^{-21}$ (n/cm ² EOL)	Temperature (°C)			
	Center Line	Periphery				Design	Measured Center-Line and Peripheral	Decalibration- Adjusted	
		N	S	W				Avg.	95% Conf.
10	K19				0.8	600	650	NA	NA
9	W10			K18	1.1	800	753 848	860	878
8	K16	K17			1.4	900	836 928	NA	NA
(a) 7(b)	W9 K14	K15			1.6	1000	884 992	NA	NA
6	W7		W8		1.8	1100	918 1054	938 1078	974 1118
5	W5		W6		1.9	1400	1295 1362	1327 1395	1381 1449
4	W4				2.0	1200	1143	1172	1220
(a) 3(b)	K1(c) W1 K4	K8		K10	1.9	1000	887 993	NA	NA
2	K2 W2(d) K5	K9		K6	1.7	800	610 754	NA	NA
(a) 1	W3 K3			K7	1.4	700	558 657	NA	NA

(a) Decalibration estimates obtained from these crucibles.

(b) Control thermocouple.

(c) Data not considered reliable and therefore not used.

(d) Thermocouple did not operate.

the tungsten-rhenium thermocouples was estimated from the thermocouple pairs located in crucibles 1, 3, and 7. The following expression for the true operating temperature, T_t , in terms of the indicated temperature, T_i , of the tungsten-rhenium thermocouples was obtained:

$$T_t = \frac{T_i}{1 - 2.45 \times 10^{-23} f},$$

where f is the thermal fluence (n/cm^2 , $E < 0.17 \text{ eV}$).

The mean operating temperatures of the thermocouples are shown in Table 2. Tungsten-rhenium thermocouple temperatures corrected according to the above formula are listed in the column headed "Decalibration-Adjusted, Avg. " Experimental scatter caused some uncertainty in the decalibration factor; the 95% upper confidence limits on the decalibration-adjusted temperatures are listed in the last column of the table.

The center-line to periphery temperature differential (ΔT) for eight of the crucibles was obtained directly from the thermocouple readings. The ΔT values for crucibles 4 and 10 were obtained by interpolation from the data for neighboring crucibles, allowing for differences in gamma heating rate. In all crucibles, ΔT increased with irradiation owing to the neutron-induced decrease in the thermal conductivity of the graphite. There was a slight long-term drift in the temperatures; over the life of the capsule, the drift in center-line temperatures ranged from $+50^\circ\text{C}$ in crucible 4 to -40°C in crucible 9.

In addition to the long-term drift, normal variations in capsule operating conditions caused fluctuations in the recorded temperatures. The upper limit of the temperature fluctuations (defined as the temperature below which the thermocouple operated for 95% of the time) and the lower limit (the temperature below which the thermocouple operated for 5% of the time) were computed from the operating records.

A summary of the best estimates for the average center-line and peripheral temperatures of each crucible, and the top and bottom of their operating range, appears in Table 3. The mean operating temperatures of individual samples were estimated from the center-line and peripheral temperatures of the crucible, assuming a parabolic temperature distribution along the radius of the crucible.

4.3. NEUTRON FLUENCES

Fast neutron fluences ($E > 0.18$ MeV) were derived from the activation of iron and titanium dosimeter wires, using activation cross sections of 46.5 mb for the $^{54}\text{Fe}(n,p)^{54}\text{Mn}$ reaction and 6.85 mb for the $^{46}\text{Ti}(n,p)^{46}\text{Sc}$ reaction. Thermal fluences were measured from vanadium-cobalt dosimeters, assuming a value of 36.8 b for the cross section for the $^{59}\text{Co}(n,\alpha)^{60}\text{Co}$ reaction. The measured fluences are shown as a function of position in the capsule in Fig. 1, and numerical values are listed in Table 3.

TABLE 3
MEAN TEMPERATURES AND FLUENCES IN CAPSULE OG-1

Crucible Number	Fast Fluence x 10 ⁻²¹ (n/cm ²) (E > 0.18 MeV)	Thermal Fluence x 10 ⁻²¹ (n/cm ²)	Operating Temperature (°C)					
			Center Line			Periphery		
			Mean	Max. (a)	Min. (a)	Mean	Max. (a)	Min. (a)
1	2.2	1.4	657	--	--	558	578	547
2	2.9	1.7	754	789	724	610	624	597
3	3.4	1.9	993	1017	972	887	912	869
4	3.7	2.0	1172	--	--	1024	1117	962
5	3.6	2.0	1395	1465	1347	1327	1399	1271
6	3.4	1.8	1078	1165	1052	938	1043	890
7	3.1	1.6	992	1015	974	884	923	854
8	2.6	1.4	928	968	898	836	875	809
9	2.1	1.1	860	928	821	753	805	722
10	1.6	0.8	650	716	616	597	666	563

(a) Maximum and minimum temperatures denote the range within which temperatures remained for 90% of the time the reactor was at power.

Fig. 1. Fluence as a function of axial position in capsule OG-1

5. EXPERIMENTAL RESULTS - DIMENSIONAL CHANGES

5.1. IRRADIATION-INDUCED DIMENSIONAL CHANGE IN NEAR-ISOTROPIC GRAPHITES

Dimensional changes were calculated from the preirradiation and post-irradiation lengths measured on 607 H-451 graphite cylinders and 70 H-429 graphite cylinders. The H-429 specimens were selected from samples previously irradiated in capsule GEH-13-422. Incorporation of the 70 previously irradiated H-429 specimens brought the peak total fluence to $6.7 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$) for the near-isotropic graphites irradiated in OG-1. The OG-1 dimensional change data are presented in Figs. 2 and 3, which include hand-drawn dimensional change curves through the data presented in Table 4.

The H-451 and H-429 dimensional change data obtained from OG-1 were combined with previously measured data on H-429 and Gilsocoke graphites and used to generate updated design curves. The dimensional change curves presented in Figs. 4 and 5 are isotherms through a three-dimensional surface obtained by a least-squares fit to the data space defined by dimensional change, fast neutron fluence, and irradiation temperature. The data included 820 data points, 677 from the OG-1 experiment.

The OG-1 samples of H-451 and H-429 exhibited about 20% less contraction in the parallel direction between 750° and 1150°C than had been predicted from the earlier H-429 and Gilsocoke data. The dimensional changes observed in the perpendicular direction were as predicted. Samples taken from the edge of the graphite log underwent slightly less (1% to 6%) dimensional change than companion samples taken from the center of the log. No systematic variation of dimensional change with sample size was evident in comparisons between 0.45-in. by 0.20-in.-diameter and 0.90-in. by 0.25-in.-diameter samples.

Fig. 2a. Dimensional changes of near-isotropic graphites H-451/H-429 in the parallel direction for irradiation temperatures of 550° and 750°C

Fig. 2b. Dimensional changes of near-isotropic graphites H-451/H-429 in the parallel direction for irradiation temperatures of 650° and 850°C

Fig. 2c. Dimensional changes of near-isotropic graphites H-451/H-429 in the parallel direction for irradiation temperatures of 950° and 1150°C

Fig. 2d. Dimensional changes of near-isotropic graphites H-451/H-429 in the parallel direction for irradiation temperatures of 1050°, 1250°, and 1350°C

Fig. 3a. Dimensional changes of near-isotropic graphites H-451/H-429 in the perpendicular direction for irradiation temperatures of 550° and 750°C

Fig. 3b. Dimensional changes of near-isotropic graphites H-451/H-429 in the perpendicular direction for irradiation temperatures of 650° and 850°C

Fig. 3c. Dimensional changes of near-isotropic graphites H-451/H-429 in the perpendicular direction for irradiation temperatures of 950° and 1150°C

Fig. 3d. Dimensional changes of near-isotropic graphites H-451/H-429 in the perpendicular direction for irradiation temperatures of 1050°, 1250°, and 1350°C

TABLE 4A
DIMENSIONAL CHANGE IN H-451 AND H-429 GRAPHITES
(PARALLEL ORIENTATION)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_o}\right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Previous Record No.
5000	-0.05	655	2.2	
5001	-0.10	655		
5004	-0.12	640		
5008	-0.11			
5012	-0.10			
5016	-0.10			
5020	-0.14			
5024	-0.09			
5028	-0.05			
5032	-0.12			
5036	-0.24	610		
5040	-0.19			
5044	-0.11			
5045	-0.13			
5048	-0.12			
5049	-0.15			
5050	-0.12			
5051	-0.11			
5054	-0.10			
5055	-0.14			
5058	-0.14			
5059	-0.26			
5060	-0.16			
5061	-0.19			
5064	-0.12			
5065	-0.14			
5068	-0.17			
5069	-0.14			
5090	-0.18	560		
5091	-0.15			
5092	-0.16			
5093	-0.36			
5096	-0.18			
5097	-0.19			
5100	-0.21			
5101	-0.26			
5102	-0.07			
5103	-0.12			
5104	-0.16			
5105	-0.19			

TABLE 4A (Continued)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_0}\right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Previous Record No.
5108	-0.16	560	2.2	
5109	-0.15	↓	↓	
5112	-0.16			
5113	-0.22			
5122	-0.18			
5123	-0.14			
5132	-0.15	↓	↓	
5133	-0.35	755	2.9	
5142	-0.14	755		
5143	-0.23	740		
5146	-0.12			
5150	-0.15	↓		
5154	-0.16			
5158	-0.22			
5162	-0.28			
5166	-0.17			
5170	-0.13	↓		
5174	-0.12			
5178	-0.17	690		
6472	-0.24	↓		
5187	-0.16			
5188	-0.23			
5191	-0.10			
5192	-0.12			
5197	-0.19			
5198	-0.27			
5201	-0.21			
5202	-0.02			
5207	-0.22			
5208	-0.24			
5211	-0.26	↓		
5212	-0.30			
5243	-0.15	610		
5244	-0.17	↓		
5247	-0.24			
5248	-0.23			
5253	-0.25	↓		
5254	-0.28			
5301	-0.72	990	3.4	
5303	-0.78	990	↓	
5305	-1.06	980		
5307	-0.64	↓		
5309	-0.90			
5311	-0.77			

TABLE 4A (Continued)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_o}\right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Previous Record No.
5313	-0.61	980	3.4	
5315	-0.79	↓	↓	
5317	-0.99			
5352	-0.68	945		
5353	-0.86	↓		
5364	-0.61			
5365	-0.86			
5371	-0.56			
5372	-0.74			
5373	-0.78			
5374	-0.59			
5375	-0.77			
5377	-0.59			
5378	-0.82			
5379	-0.51			
5380	-0.60			
5381	-0.80			
5382	-0.83			
5383	-0.67			
5384	-0.85	↓		
5422	-0.50	890		
5423	-0.63	↓		
5425	-0.50			
5426	-0.57			
5427	-0.57			
5428	-0.48			
5429	-0.60			
5430	-0.62			
5431	-0.51			
5432	-0.65			
5434	-0.48			
5435	-0.54			
5436	-0.54			
5437	-0.47			
5438	-0.58			
5439	-0.58			
5440	-0.43			
5441	-0.58			
5443	-0.41			
5444	-0.50			
5445	-0.42			
5446	-0.37			
5447	-0.52			
5448	-0.43			
5449	-0.41			
5450	-0.55	↓	↓	

TABLE 4A (Continued)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_0}\right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Previous Record No.
5452	-0.42	890	3.4	
5453	-0.45			
5454	-0.50			
5455	-0.39			
5456	-0.51			
5457	-0.54			
5458	-0.42			
5459	-0.54			
5461	-0.41			
5462	-0.49			
5463	-0.56			
5464	-0.47			
5465	-0.51			
5468	-0.46			
5469	-0.57			
5471	-0.47			
5472	-0.55			
5475	-0.68			
5476	-0.41			
5479	-1.09	1175	3.7	
5480	-1.20	1175		
5483	-1.07	1155		
5484	-1.14			
5487	-1.02			
5488	-1.13			
5491	-1.07			
5492	-1.11			
5495	-1.04			
5496	-0.99			
5498	-1.01			
5499	-1.17			
5502	-0.97			
5503	-1.08			
5516	-1.27	1110		
5574	-1.22	1040		
5576	-1.19	1040		
5577	-3.00	1395	3.6	
5578	-2.74	1395		
5581	-2.85	1385		
5582	-2.99			
5585	-3.06			
5586	-3.05			
5589	-2.92			

TABLE 4A (Continued)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_o}\right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence x 10 ⁻²¹ (n/cm ²) (E > 0.18 MeV)	Previous Record No.
5590	-3.07	1385	3.6	
5593	-3.01	↓	↓	
5594	-3.05	↓	↓	
5597	-2.88	↓	↓	
5598	-3.02	↓	↓	
5601	-3.07	↓	↓	
5602	-3.00	↓	↓	
5605	-2.76	↓	↓	
5607	-2.81	↓	↓	
5609	-2.77	↓	↓	
5611	-3.09	↓	↓	
5625	-2.88	1365	↓	
5626	-2.63	↓	↓	
5639	-2.90	↓	↓	
5640	-2.71	↓	↓	
5649	-2.61	1325	↓	
5650	-2.43	↓	↓	
5659	-2.43	↓	↓	
5660	-2.45	↓	↓	
5661	-2.58	↓	↓	
5662	-2.49	↓	↓	
5671	-2.50	↓	↓	
5672	-2.21	↓	↓	
5673	-2.35	↓	↓	
5675	-1.80	↓	↓	
5680	-2.59	↓	↓	
5681	-2.25	↓	↓	
5682	-2.61	↓	↓	
5683	-2.30	↓	↓	
5688	-2.48	↓	↓	
5690	-2.39	↓	↓	
5692	-1.26	1080	3.4	
5693	-1.23	1080	↓	
5696	-1.16	1065	↓	
5697	-1.11	↓	↓	
5700	-1.15	↓	↓	
5701	-1.08	↓	↓	
5704	-1.17	↓	↓	
5705	-1.05	↓	↓	
5710	-1.14	↓	↓	
5711	-1.09	↓	↓	
5714	-1.13	↓	↓	
5715	-1.10	↓	↓	

TABLE 4A (Continued)

Record No.	Dimensional Change $\ln \left(1 + \frac{\Delta L}{L_0} \right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Previous Record No.
5718	-1.13	1065	3.4	
5719	-1.08	↓	↓	
5722	-1.17			
5723	-1.06			
5726	-1.12			
5727	-1.03			
5730	-1.10	1020		
5731	-0.97	↓		
5764	-0.63	940		
5773	-0.57	↓		
5777	-0.54			
5781	-0.50			
5782	-0.68			
5786	-0.61			
5788	-0.50			
5789	-0.67			
5793	-0.62			
5795	-0.70			
5799	-0.72			
5801	-0.66	↓		
5803	-0.81	990	3.1	
5810	-0.69	980	↓	
5814	-0.73	↓		
5818	-0.74			
5822	-0.73			
5826	-0.73			
5827	-0.71			
5830	-0.65			
5831	-0.69			
5834	-0.74			
5835	-0.68			
5838	-0.83			
5839	-0.71	↓		
5842	-0.60	945		
5843	-0.60	↓		
5846	-0.65			
5847	-0.64			
5850	-0.72			
5852	-0.56			
5854	-0.78			
5868	-0.47	↓		
5879	-0.50	885		
5889	-0.53	↓		
5891	-0.53			

TABLE 4A (Continued)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_o}\right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Previous Record No.
5897	-0.52	885	3.1	
5900	-0.42	↓	↓	
5902	-0.52			
5904	-0.49			
5906	-0.54	930	2.6	
5910	-0.46	920		
5914	-0.50	↓	↓	
5918	-0.52			
5922	-0.49			
5926	-0.51			
5930	-0.46			
5931	-0.42			
5934	-0.51			
5935	-0.41			
5938	-0.45			
5939	-0.42			
6020	-0.32			
6021	-0.30			
6040	-0.48			
6042	-0.28			
6044	-0.32			
6046	-0.25			
6048	-0.21	860	2.1	
6052	-0.18	850		
6056	-0.18	↓	↓	
6060	-0.18			
6064	-0.17			
6068	-0.21			
6072	-0.18			
6076	-0.16			
6080	-0.22			
6084	-0.34	810		
6088	-0.10	↓	↓	
6094	-0.22			
6098	-0.13			
6104	-0.16			
6108	-0.15			
6114	-0.14			
6118	-0.16			
6150	-0.15	750		
6154	-0.13	↓	↓	
6160	-0.14			
6194	-0.13			

TABLE 4A (Continued)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_o}\right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Previous Record No.
6195	-0.14	750	2.1	
6200	-0.12	↓	↓	
6201	-0.23			
6204	-0.14			
6205	-0.16			
6208	-0.06	650	1.6	
6212	-0.04	645		
6216	+0.0	↓		
6220	-0.07			
6224	-0.10			
6228	-0.07			
6232	-0.10			
6236	-0.22			
6240	-0.08			
6256	-0.16	625		
6257	-0.13	↓		
6266	-0.12			
6267	-0.09			
6276	-0.11			
6277	-0.02			
6298	-0.15	595		
6299	-0.06	↓		
6300	-0.11			
6304	+0.05			
6305	-0.05			
6308	-0.13			
6309	-0.13			
6310	-0.14			
6311	-0.03			
6312	-0.12			
6313	-0.11			
6316	-0.14			
6317	-0.13			
6320	-0.13			
6321	-0.10			
6322	-0.13			
6323	-0.16			
6326	-0.15			
6327	-0.12			
6330	-0.15			
6331	-0.12			
6340	-0.23			
6341	-0.12	↓	↓	

TABLE 4A (Continued)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_o}\right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Previous Record No.
5540	-1.86	1140	6.26	2402
5571	-2.10	1140	↓	2426
5565	-1.45	1160	↓	2761
5563	-2.14	1160	↓	2764
5542	-1.50	1140	↓	2403
5573	-1.71	1140	↓	2419
5614	-3.12	1425	6.64	2791
5618	-3.74	↓	↓	2815
5616	-2.83	↓	↓	2816
5655	-3.29	1390	6.66	2871
5654	-2.84	↓	↓	2866
5653	-3.43	↓	↓	2882
5620	-3.52	1425	6.64	2821
5670	-2.95	1385	6.66	2850
5669	-3.15	1385	↓	2853
5666	-3.40	1390	↓	2870
5665	-3.09	1390	↓	2872
5950	-0.61	890	3.44	2606
5949	-0.36	↓	↓	2594
5947	-0.54	↓	↓	2605
6013	-0.46	↓	3.88	2667
6012	-0.56	↓	↓	2648
6011	-0.58	↓	↓	2680
6010	-0.52	↓	↓	2659
6005	-0.52	↓	↓	2673
6004	-0.62	↓	↓	2653
6003	-0.72	↓	↓	2671
5953	-0.56	925	↓	2642
5952	-0.62	925	↓	2649
5951	-0.53	890	↓	2537
6271	-0.20	625	1.91	2448
6269	-0.24	↓	↓	2522
6275	-0.16	↓	↓	2452
6273	-0.24	↓	↓	2500

TABLE 4B
DIMENSIONAL CHANGE IN H-451 AND H-429 GRAPHITES
(PERPENDICULAR ORIENTATION)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_o}\right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Previous Record No.
5002	-0.04	655	2.2	
5003	-0.06	655		
5006	-0.07	640		
5010	-0.11			
5014	-0.10			
5018	-0.04			
5022	-0.05			
5026	-0.10			
5030	-0.09			
5034	-0.09			
5038	-0.19	610		
5042	-0.16			
5046	-0.13			
5047	-0.18			
5052	-0.12			
5053	-0.11			
5056	-0.14			
5057	-0.03			
5062	-0.15			
5063	-0.08			
5066	-0.15			
5067	-0.12			
5094	-0.18	560		
5095	-0.02			
5098	-0.15			
5099	-0.22			
5106	-0.15			
5107	-0.19			
5110	-0.14			
5111	-0.19			
5144	-0.19	755	2.9	
5145	-0.13	755		
5148	-0.08	740		
5152	-0.10			
5156	-0.10			
5160	-0.13			
5164	-0.16			
5168	-0.14			
5172	-0.13			
5176	-0.06			

TABLE 4B (Continued)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_o}\right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Previous Record No.
5180	-0.05	690	2.9	
5183	-0.11	↓	↓	
5189	-0.15			
5190	-0.19			
5193	-0.12			
5194	-0.13			
5199	-0.10			
5200	-0.16			
5203	-0.16			
5204	-0.18			
5209	-0.20			
5210	-0.16			
5213	-0.19			
5214	-0.16	↓		
5245	-0.06	610		
5246	-0.16	↓		
5249	-0.15			
5250	-0.15			
5255	-0.14			
5256	-0.23	↓		
5302	-0.43	990	3.4	
5304	-0.55	↓		
5306	-0.48	980		
5308	-0.43			
5310	-0.46			
5312	-0.31			
5314	-0.39			
5316	-0.54			
5318	-0.59			
5337	-0.32			
5338	-0.50			
5339	-0.55			
5340	-0.46			
5341	-0.55			
5342	-0.67			
5343	-0.45			
5344	-0.54	↓		
5345	-0.44	945		
5346	-0.31	↓		
5347	-0.41			
5348	-0.55			
5349	-0.34			
5350	-0.38	↓		

TABLE 4B (Continued)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_0}\right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Previous Record No.
5351	-0.42	945	3.4	
5354	-0.40	↓	↓	
5355	-0.31			
5356	-0.52			
5360	-0.33			
5361	-0.36			
5366	-0.33			
5367	-0.29			
5368	-0.41			
5376	-0.38	↓		
5385	-0.44	890		
5424	-0.37	↓		
5433	-0.30			
5451	-0.33			
5460	-0.31			
5470	-0.30	↓		
5442	-0.30			
5481	-0.81	1175	3.7	
5482	-0.63	1175	↓	
5485	-0.94	1155		
5486	-0.68	↓		
5489	-0.82			
5490	-0.67			
5493	-0.71			
5494	-0.60			
5497	-0.54			
5500	-0.87			
5501	-0.58			
6471	-0.91			
5504	-0.81	↓		
5505	-0.83			
5512	-0.65	1110		
5518	-0.59	1110		
5575	-0.65	1040		
5579	-2.08	1395	3.6	
5580	-1.89	1395	↓	
5583	-2.09	1385		
5584	-1.77	↓		
5587	-2.06			
5588	-1.90			
5591	-2.10			
5592	-1.60	↓	↓	
5595	-2.04			

TABLE 4B (Continued)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_0}\right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Previous Record No.
5596	-1.94	1385	3.6	
5599	-2.00	↓	↓	
5600	-1.78			
5604	-2.03			
5603	-2.10			
5606	-1.97			
5608	-1.64			
5610	-2.02			
5612	-1.87			
5674	-1.60	1325		
5689	-1.74	↓		
5691	-1.47			
5694	-0.60	1080	3.4	
5695	-0.53	1080		
5698	-0.64	1065		
5699	-0.49	↓		
5702	-0.61			
5703	-0.50			
5708	-0.60			
5709	-0.52			
5712	-0.57			
5713	-0.51			
5716	-0.56			
5717	-0.50			
5720	-0.55			
5721	-0.49			
5724	-0.63			
5725	-0.52			
5728	-0.58			
5729	-0.71			
5732	-0.47	1020		
5733	-0.49	↓		
5765	-0.50			
5774	-0.31	940		
5778	-0.28	↓		
5783	-0.33			
5787	-0.30			
5790	-0.33			
5794	-0.27			
5796	-0.33			
5800	-0.41			
5802	-0.34			
5808	-0.41	990	3.1	

TABLE 4B (Continued)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_0}\right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Previous Record No.
5812	-0.38	980	3.1	
5816	-0.41	↓	↓	
5820	-0.33			
5824	-0.40			
5828	-0.51			
5829	-0.16			
5832	-0.37			
5833	-0.42			
5836	-0.40			
5837	-0.32			
5840	-0.34	↓		
5841	-0.26			
5844	-0.30	945		
5845	-0.14	↓		
5848	-0.36			
5849	-0.23			
5851	-0.50			
5853	-0.20			
5855	-0.35	↓		
5869	-0.31			
5880	-0.22	885		
5890	-0.27	↓		
5892	-0.24			
5898	-0.27			
5899	-0.32			
5901	-0.25			
5903	-0.24			
5905	-0.23	↓		
5908	-0.18	930	2.6	
5912	-0.21	920	↓	
5916	-0.22	↓		
5920	-0.23			
5924	-0.22			
5928	-0.27			
5932	-0.19			
5933	-0.17			
5936	-0.25			
5937	-0.20			
5940	-0.18	↓		
5941	-0.04			
6022	-0.09	835		
6023	-0.15	↓		
6041	-0.11			
6043	-0.10	↓		

TABLE 4B (Continued)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_0}\right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Previous Record No.
6047	-0.13	835	2.6	
6045	-0.18	835	2.6	
6050	-0.12	860	2.1	
6054	-0.09	850		
6058	-0.04			
6062	-0.10			
6066	-0.08			
6070	-0.07			
6074	-0.06			
6078	-0.05			
6082	-0.08			
6086	-0.12	810		
6090	-0.03			
6096	-0.09			
6100	-0.10			
6106	-0.04			
6110	-0.03			
6116	-0.07			
6120	-0.12			
6152	-0.07	750		
6156	-0.03			
6162	-0.12			
6196	-0.08			
6197	-0.12			
6202	-0.09			
6203	-0.06			
6206	-0.14			
6207	-0.08			
6210	-0.03	650	1.6	
6214	-0.03	645		
6218	-0.07			
6222	-0.05			
6226	-0.06			
6230	-0.04			
6234	-0.12			
6238	-0.11			
6242	-0.02			
6302	-0.13	595		
6306	-0.15			
6307	-0.10			
6314	-0.11			
6315	-0.03			
6318	-0.05			

TABLE 4B (Continued)

Record No.	Dimensional Change $\ln 1\left(+\frac{\Delta L}{L_o}\right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Previous Record No.
6319	-0.14	595	1.6	
6324	-0.06	↓	↓	
6325	-0.04	↓	↓	
6328	-0.15	↓	↓	
6329	-0.06	↓	↓	
5539	-1.16	1136	6.26	2436
5541	-1.01	1136	↓	2428
5562	-1.47	1156	↓	2748
5570	-1.40	1136	↓	2442
5572	-1.25	1136	↓	2430
5613	-2.19	1427	6.64	2823
5615	-2.12	↓	↓	2804
5617	-2.33	↓	↓	2807
5619	-2.14	↓	↓	2800
5656	-2.38	1405	6.66	2858
5657	-2.23	↓	↓	2849
5658	-2.23	↓	↓	2875
5663	-2.25	↓	↓	2864
5664	-2.28	↓	↓	2877
5667	-2.15	1394	↓	2861
5668	-2.37	1394	↓	2855
5942	-0.31	888	3.44	2598
5943	-0.30	↓	↓	2580
5944	-0.22	↓	↓	2601
5945	-0.28	↓	↓	2564
5946	-0.33	↓	↓	2608
5998	-0.37	890	3.88	2665
5999	-0.38	↓	↓	2663
6000	-0.48	↓	↓	2672
6001	-0.33	↓	↓	2655
6002	-0.37	↓	↓	2681
6014	-0.37	↓	↓	2662
6015	-0.40	↓	↓	2652
6016	-0.41	↓	↓	2645
6017	-0.26	↓	↓	2687
6268	-0.24	625	1.91	2497
6270	-0.15	↓	↓	2524
6272	-0.23	↓	↓	2488

Fig. 4. Irradiation-induced dimensional changes in near-isotropic graphite; parallel (axial) orientation

Fig. 5. Irradiation-induced dimensional changes in near-isotropic graphite; perpendicular (radial) orientation

Ninety samples of P₃JHAN, a near-isotropic, pitch-coke graphite manufactured by Pechiney, were irradiated in OG-1 for comparison with the petroleum-coke near-isotropic graphites. As indicated by the data in Table 5, the P₃JHAN exhibited considerably more dimensional change under irradiation than the H-451 graphite. P₃JHAN was also more anisotropic in its behavior.

5.2. DIMENSIONAL CHANGE IN NEEDLE-COKE GRAPHITES

The OG-1 experiment contained 195 parallel and 123 perpendicular specimens of H-327 graphite, 66 of which had been previously irradiated. The dimensional change data are given in Table 6. For the most part, the H-327 was more dimensionally stable than had been observed in previous irradiations. As in the H-451 data, no systematic variation of dimensional change with sample size was evident.

5.3. MISCELLANEOUS GRAPHITES

The dimensional changes observed in other graphites irradiated in OG-1 are described in Table 7. The H-453 underwent dimensional changes similar to other Great Lakes Carbon Company near-isotropic graphites. The 2020 graphite exhibited moderate dimensional changes whose orientation dependence was typical of molded materials.

The H-451C material, which was subjected to infiltration of fuel-rod binder pitch during cure-in-place treatment, exhibited the same dimensional change as the standard material (-0.67% mean versus -0.62%) after irradiation at 960°C to 3.4×10^{21} n/cm². Several H-451 samples (IH-451, record numbers 6461-6465) were char-loaded by impregnation with oligofurane and heat-treated to 1100°C, then irradiated together with standard H-451 companion samples (record numbers 6466-6470). The char-loaded specimens contracted an average of 0.58%, compared with 0.69% for the companion samples of standard H-451. Other specimens of standard H-451 contracted an average of 0.62% under the same conditions.

TABLE 5
DIMENSIONAL CHANGE OF P₃JHAN

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_o}\right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence x 10 ⁻²¹ (n/cm) (E > 0.18 MeV)
Parallel Orientation			
5319	-1.53	980	3.4
5321	-2.04	↓	↓
5323	-2.02		
5325	-1.48		
5327	-1.99		
5329	-2.00		
5331	-1.44		
5333	-1.82	↓	↓
5335	-2.11	1325	3.6
5676	-3.96	↓	↓
5678	-4.00		
5684	-4.19	1020	3.4
5686	-4.09	↓	↓
5734	-2.42		
5736	-1.97		
5740	-2.31		
5742	-1.83		
5744	-2.17		
5746	-1.87		
5750	-2.13		
5752	-1.83		
5754	-2.03		
5756	-1.77		
5760	-2.21	↓	↓
5762	-1.82	750	2.1
6164	-0.26	↓	↓
6165	-0.23		
6170	-0.37		
6171	-0.24		
6174	-0.35		
6175	-0.23		
6180	-0.28		
6181	-0.28		
6184	-0.28		
6185	-0.28		
6190	-0.30	↓	↓
6191	-0.28	595	1.6
6332	-0.23	↓	↓
6334	-0.16		
6336	-0.20		
6338	-0.19		

TABLE 5 (Continued)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_o}\right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence $\times 10^{-21}$ (n/cm) (E > 0.18 MeV)
Parallel Orientation			
6342	-0.20	595	1.6
6344	-0.22	↓	↓
6347	-0.17		
6349	-0.21		
Perpendicular			
5320	-0.69	980	3.4
5322	-0.76	↓	↓
5324	-0.58		
5326	-0.73		
5328	-0.87		
5330	-0.83		
5332	-0.66		
5334	-0.78		
5336	-0.73		
5677	-1.66	1325	3.6
5679	-1.44	↓	↓
5685	-1.65		
5687	-1.68		
5735	-0.81	1020	3.4
5737	-0.90	↓	↓
5741	-0.87		
5743	-0.84		
5745	-0.81		
5747	-0.86		
5751	-0.71		
5753	-0.67		
5757	-0.70		
5761	-0.81		
5763	-0.83		
6166	-0.11	750	2.1
6167	-0.08	↓	↓
6172	-0.17		
6173	-0.13		
6176	-0.18		
6177	-0.01		
6182	-0.22		
6183	-0.11		
6186	-0.10		
6187	-0.09		
6192	-0.16		
6193	-0.11		

TABLE 5 (Continued)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_o}\right)$ (%)	Average Irradiation Temperature (°C)	Total Fluence $\times 10^{-21}$ (n/cm) (E > 0.18 MeV)
Perpendicular			
6333	-0.15	595	1.6
6335	-0.10	↓	↓
6337	-0.17		
6339	-0.06		
6343	-0.18		
6345	-0.06		
6348	-0.15		
6350	-0.13		

TABLE 6A
 DIMENSIONAL CHANGES OF NEEDLE-COKE H-327 GRAPHITE
 FROM CAPSULE OG-1
 PARALLEL ORIENTATION

Record No.	Dimensional Change $\ln \left(1 + \frac{\Delta L}{L_0} \right)$ (%)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Average Irradiation Temperature (°C)	Previous Record No.
5005	-0.15	2.2	645	
5009	-0.16			
5013	-0.17			
5017	-0.14			
5021	-0.11			
5025	-0.13			
5029	-0.11			
5033	-0.15			
5037	-0.20		615	
5041	-0.18		615	
5114	-0.14		560	
5115	-0.16			
5118	-0.16			
5119	-0.20			
5124	-0.15			
5125	-0.21			
5128	-0.14			
5129	-0.18			
5134	-0.14			
5135	-0.20			
5147	-0.25	2.9	740	
5151	-0.24			
5155	-0.17			
5159	-0.24			
5163	-0.26			
5167	-0.20			
5171	-0.23			
5175	-0.17			
5179	-0.24		690	
5182	-0.28			
5185	-0.24			
5186	-0.17			
5195	-0.25			
5196	-0.10			
5205	-0.25			
5215	-0.22			
5216	-0.23			
5241	-0.28		610	
5242	-0.33			
5251	-0.28			

TABLE 6A (Continued)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_0}\right)$ (%)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Average Irradiation Temperature (°C)	Previous Record No.
5252	-0.31	2.9	610	
5257	-0.24	↓	↓	
5258	-0.34			
5261	-0.32			
5262	-0.27			
5263	-0.34			
5264	-0.33			
5267	-0.25			
5268	-0.21			
5271	-0.29			
5272	-0.27			
5273	-0.21			
5274	-0.33			
5277	-0.31			
5278	-0.28			
5281	-0.20			
5282	-0.28			
5291	-0.33	↓	↓	
5292	-0.28			
5466	-0.62	3.4	890	
5467	-0.50	↓	↓	
5473	-0.65			
5474	-0.54			
5477	-0.69	↓	↓	
5478	-0.53			
5509	-8.96	14.9	1255	2914
5510	-9.74	↓	↓	2920
5511	-9.61			2906
5513	-1.70	3.7	1110	
5514	-1.83	↓	↓	
5523	-1.79			
5524	-1.96			
5533	-1.19		1040	
5534	-1.48		↓	
5543	-1.75			
5544	-1.03			
5546	-1.40	↓	↓	
5547	-1.57			
5550	-5.28	9.9	1220	2433
5551	-5.37	↓	1220	2447
5555	-3.98		1185	2774
5556	-1.19	3.7	1040	
5557	-1.37	3.7	1040	

TABLE 6A (Continued)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_0}\right)$ (%)	Total Fluence $\times 10^{-21}$ (n/cm ²)(E > 0.18 MeV)	Average Irradiation Temperature (°C)	Previous Record No.
5560	-4.60	9.9	1185	2450
5561	-4.01	9.9	1185	2407
5566	-1.22	3.7	1040	
5567	-1.32	↓	↓	
5568	-1.29			
5569	-1.47			
5629	-7.73	11.3	1510	2842
5738	-1.31	3.4	1020	
5748	-1.18	↓	↓	
5758	-1.11			
5766	-1.30		940	
5771	-0.83		↓	
5775	-0.88			
5779	-0.83			
5784	-0.77			
5791	-0.71			
5797	-0.71			
5804	-1.09	3.1	990	
5811	-0.91	↓	980	
5815	-1.07		↓	
5819	-1.00			
5823	-1.00			
5856	-0.79		945	
5857	-0.78		↓	
5860	-0.72			
5861	-0.72			
5864	-0.75			
5865	-0.70			
5907	-0.60	2.6	930	
5911	-0.49	↓	920	
5915	-0.52		↓	
5919	-0.56			
5923	-0.52			
5927	-0.51			
5954	-0.42		885	
5955	-0.34		885	
5958	-1.31	4.6	890	2585
5959	-1.30	4.6	890	2616
5965	-0.30	2.6	885	
5974	-0.43	↓	885	
5975	-0.43		885	
5996	-0.33		835	
5997	-0.25		835	

TABLE 6A (Continued)

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_0}\right)$ (%)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Average Irradiation Temperature (°C)	Previous Record No.
6006	-0.29	2.6	835	
6007	-0.20	↓	↓	
6008	-0.31			
6009	-0.20			
6018	-0.27			
6019	-0.16			
6024	-0.32			
6025	-0.27			
6028	-0.29			
6029	-0.20			
6030	-0.26			
6031	-0.28			
6034	-0.27			
6035	-0.30			
6038	-0.64			
6039	-0.20			
6092	-0.17	2.1	810	
6093	-0.11	↓	↓	
6102	-0.15			
6103	-0.11			
6112	-0.15			
6113	-0.12			
6122	-0.05			
6123	-0.11			
6148	-0.15		750	
6149	-0.18		↓	
6158	-0.11			
6159	-0.07			
6168	-0.18			
6169	-0.09			
6178	-0.12			
6179	-0.15			
6188	-0.13			
6189	-0.13			
6198	-0.15			
6199	-0.08			
6209	-0.06	1.6	650	
6213	-0.09	↓	645	
6217	-0.12		↓	
6221	-0.11			
6225	-0.24			
6229	-0.10			
6233	-0.16	↓	↓	

TABLE 6A (Continued)

Record No.	Dimensional Change $\ln \left(1 + \frac{\Delta L}{L_0} \right)$ (%)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Average Irradiation Temperature (°C)	Previous Record No.
6237	-0.15	1.6	645	
6241	-0.10	1.6	645	
6246	-0.41	2.4	625	2465
6250	-0.34			2458
6251	-0.20			2410
6254	-0.37			2472
6255	-0.25			2457
6260	-0.40			2493
6261	-0.19			2435
6264	-0.43			2474
6265	-0.34			2698
6301	-0.15	1.6	595	

TABLE 6B
 DIMENSIONAL CHANGES OF NEEDLE-COKE H-327 GRAPHITE
 FROM CAPSULE OG-1
 PERPENDICULAR ORIENTATION

Record No.	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_0}\right)$ (%)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Average Irradiation Temperature (°C)	Previous Record No.
5007	-0.12	2.2	645	
5011	-0.12	↓	↓	
5015	-0.11			
5019	-0.10			
5023	-0.06			
5027	-0.08			
5031	-0.08			
5035	-0.16			
5039	-0.14		615	
5043	-0.16		615	
5116	-0.16		560	
5117	-0.08		↓	
5120	-0.14			
5121	-0.35			
5126	-0.19			
5127	-0.19			
5130	-0.19			
5131	-0.14			
5136	-0.26			
5137	-0.17			
5149	-0.13	2.9	740	
5153	-0.16	↓	↓	
5157	-0.17			
5161	-0.14			
5165	-0.10			
5169	-0.11			
5173	-0.16			
5177	-0.04			
5181	-0.24		690	
5184	-0.19		↓	
5206	-0.21			
5259	-0.26		610	
5260	-0.28		↓	
5265	-0.16			
5266	-0.19			
5269	-0.22			
5270	-0.23			
5275	-0.20			
5276	-0.21			
5279	-0.26			

TABLE 6B (Continued)

Record No.	Dimensional Change $\ln \left(1 + \frac{\Delta L}{L_0} \right) (\%)$	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Irradiation Temperature (°C)	Previous Record No.
5280	-0.26	2.9	610	
5357	-0.43	3.4	945	
5358	-0.36	↓	↓	
5362	-0.48			
5363	-0.42			
5369	-0.65	↓	↓	
5370	-0.40			
5506	9.43	14.9	1255	2910
5507	8.70	14.9	1255	2909
5548	-0.06	9.9	1220	2443
5549	0.91	↓	1220	2455
5552	-0.25	↓	1190	2772
5553	0.90	↓	↓	2760
5558	-0.04	↓	↓	2451
5559	0.35	↓	↓	2429
5630	2.39	11.3	1510	2839
5739	-0.32	3.4	1020	
5749	-0.51	↓		
5759	-0.50	↓		
5767	-0.52	↓	940	
5772	-0.36	↓	↓	
5776	-0.40	↓	↓	
5780	-0.42	↓	↓	
5785	-0.41	↓	↓	
5792	-0.32	↓	↓	
5798	-0.40	↓	↓	
5809	-0.30	3.1	990	
5813	-0.16	↓	980	
5817	-0.26	↓	↓	
5821	-0.35	↓	↓	
5825	-0.37	↓	945	
5858	-0.43	↓	↓	
5859	-0.12	↓	↓	
5862	-0.39	↓	↓	
5863	-0.37	↓	↓	
5866	-0.37	↓	↓	
5867	-0.35	↓	↓	
5909	-0.25	2.6	930	
5913	-0.12	↓	920	
5917	-0.08	↓	↓	
5921	-0.02	↓	↓	
5925	-0.24	↓	↓	
5929	-0.22	↓	↓	

TABLE 6B (Continued)

Record No.	Dimensional Change $\ln \left(1 + \frac{\Delta L}{L_0} \right)$ (%)	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Average Irradiation Temperature (°C)	Previous Record No.
5956	-0.79	4.6	890	2638
5957	-0.59	4.6	890	2552
6026	-0.19	2.6	835	
6027	-0.12	↓	↓	
6032	-0.23			
6033	-0.02			
6036	-0.14			
6037	-0.08			
6211	-0.06	1.6	650	
6215	-0.12	↓	645	
6219	-0.07		↓	
6223	-0.04			
6227	-0.06			
6231	-0.04			
6235	-0.09			
6239	-0.05			
6243	-0.06			
6244	-0.54	2.4	625	
6245	-0.31	↓	↓	
6248	-0.39			
6249	-0.33			
6252	-0.46			
6253	-0.33			
6258	-0.46			
6259	-0.25			
6262	-0.43			
6263	-0.29		↓	
6303	-0.06	↓	595	

TABLE 7
DIMENSIONAL CHANGES IN OG-1 GRAPHITES

Grade	Orientation	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Average Irradiation Temperature (°C)	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_0}\right)$ (%)	Record No.	Previous Record No.
H-453	Parallel	2.2	560	-0.18	5138	
		2.2	560	-0.22	5139	
		2.9	610	-0.34	5283	
		↓	↓	-0.34	5284	
		↓	↓	-0.32	5287	
		↓	↓	-0.35	5288	
		↓	↓	-0.21	5293	
		↓	↓	-0.28	5294	
		↓	↓	-0.22	5297	
		↓	↓	-0.26	5298	
		3.1	885	-0.50	5881	
		↓	↓	-0.45	5882	
		↓	↓	-0.49	5885	
		↓	↓	-0.45	5886	
		↓	↓	-0.55	5893	
		↓	↓	-0.51	5894	
		2.1	850	-0.18	6049	
		↓	↓	-0.20	6053	
		↓	↓	-0.20	6057	
		↓	↓	-0.17	6061	
		↓	↓	-0.17	6065	
		↓	↓	-0.17	6069	
		↓	↓	-0.15	6073	
		↓	↓	-0.20	6077	
		↓	↓	-0.19	6081	
		↓	810	-0.15	6085	
		↓	↓	-0.14	6089	
		↓	↓	-0.15	6095	
		↓	↓	-0.17	6099	
		↓	↓	-0.16	6105	
		↓	↓	-0.14	6109	
		↓	↓	-0.15	6115	
		↓	↓	-0.17	6119	
		↓	750	-0.14	6151	
		↓	↓	-0.09	6155	
		↓	↓	-0.23	6161	
H-453	Perpendicular	2.2	560	-0.18	5140	
		2.2	560	-0.19	5141	
		2.9	610	-0.27	5285	
		↓	↓	-0.17	5286	
		↓	↓	-0.34	5289	
		↓	↓	-0.20	5290	
		↓	↓	-0.18	5295	

TABLE 7 (Continued)

Grade	Orientation	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Average Irradiation Temperature (°C)	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_0}\right)$ (%)	Record No.	Previous Record No.
H-453	Perpendicular	2.9 ↓	610 ↓	-0.15	5296	
		3.1 ↓	885 ↓	-0.16 -0.19 -0.24 -0.10 -0.23 -0.20 -0.26 -0.07 -0.09 -0.10 -0.02 -0.04 -0.09 -0.06 -0.05 -0.07 -0.04 -0.06 -0.06 -0.02 -0.14 -0.07 -0.08 -0.08 -0.04 -0.07 -0.02 -0.10 -0.37 -0.45 -0.35 -0.45 -0.30 -0.44 -0.23 -0.38 -0.40 -0.56 -0.30 -0.50 -0.32 -0.50 -0.67 -0.36 -0.28	5299 5300 5883 5884 5887 5888 5895 5896 6051 6055 6059 6063 6067 6071 6075 6079 6083 6087 6091 6097 6101 6107 6111 6117 6121 6153 6157 6163 5070 5072 5074 5076 5078 5080 5082 5084 5086 5088 5217 5219 5221 5223 5225 5227 5229	
2020	Parallel	2.1 ↓	850 ↓			
		2.2 ↓	810 ↓			
		2.9 ↓	750 ↓			
			585 ↓			
			630 ↓			

TABLE 7 (Continued)

Grade	Orientation	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Average Irradiation Temperature (°C)	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_0}\right)$ (%)	Record No.	Previous Record No.
2020	Parallel	2.9	630	-0.51	5231	
		↓	↓	-0.42	5233	
				-0.40	5235	
				-0.57	5237	
				-0.49	5239	
		3.4	915	-0.02	5386	
		↓	↓	+0.03	5388	
				+0.00	5392	
				+0.04	5394	
				-0.08	5398	
				-0.07	5400	
				+0.05	5404	
				-0.04	5406	
				-0.08	5410	
				-0.02	5412	
				-0.05	5416	
				-0.05	5418	
		3.7	1070	-0.24	5425	
		↓	↓	-0.23	5427	
				-0.08	5429	
				+0.09	5431	
		3.1	900	-0.09	5870	
		↓	↓	-0.15	5872	
				-0.12	5874	
				-0.12	5876	
		2.6	850	-0.16	5976	
		↓	↓	-0.18	5978	
				-0.19	5980	
				-0.19	5982	
				-0.21	5984	
				-0.25	5986	
				-0.20	5988	
				-0.22	5990	
				-0.15	5992	
				-0.18	5994	
		2.1	770	-0.25	6124	
		↓	↓	-0.23	6126	
				-0.23	6128	
				-0.27	6130	
				-0.27	6132	
				-0.24	6134	
				-0.28	6136	
				-0.28	6138	
				-0.25	6140	
				-0.36	6142	

TABLE 7 (Continued)

Grade	Orientation	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Average Irradiation Temperature (°C)	Dimensional Change $\ln 1\left(+\frac{\Delta L}{L_o}\right)$ (%)	Record No.	Previous Record No.
2020	Parallel	2.1	770	-0.33	6144	
		2.1	770	-0.18	6146	
		1.6	605	-0.34	6278	
				-0.28	6280	
				-0.31	6282	
				-0.25	6284	
				-0.30	6286	
				-0.20	6288	
				-0.34	6290	
				-0.31	6292	
				-0.33	6294	
				-0.25	6296	
				-0.49	5071	
				-0.57	5073	
2020	Perpendicular	2.2	585	-0.44	5075	
				-0.52	5077	
				-0.45	5079	
				-0.48	5081	
				-0.49	5083	
				-0.33	5085	
				-0.56	5087	
				-0.61	5089	
		2.9	630	-0.47	5218	
				-0.59	5220	
				-0.56	5222	
				-0.56	5224	
				-0.87	5226	
				-0.07	5228	
				-0.85	5230	
				-0.32	5232	
				-0.55	5234	
				-0.55	5236	
				-0.53	5238	
				-0.22	5240	
		3.4	915	-0.55	5387	
				-0.55	5389	
				-0.50	5393	
				-0.52	5395	
				-0.46	5399	
				-0.35	5401	
				-0.71	5405	
				-0.39	5407	
				-0.63	5411	
				-0.48	5413	

TABLE 7 (Continued)

Grade	Orientation	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Average Irradiation Temperature (°C)	Dimensional Change $\ln \left(1 + \frac{\Delta L}{L_0} \right)$ (%)	Record No.	Previous Record No.
2020	Perpendicular	3.4	915	-0.48	5417	
		3.4	915	-0.58	5419	
		3.7	1070	-0.93	5526	
		↓	↓	-0.57	5528	
		↓	↓	-0.81	5530	
		3.1	900	-0.76	5532	
		↓	↓	-0.66	5871	
		↓	↓	-0.44	5873	
		↓	↓	-0.50	5875	
		2.6	850	-0.36	5877	
		↓	↓	-0.51	5977	
		↓	↓	-0.38	5979	
		↓	↓	-0.50	5981	
		↓	↓	-0.29	5983	
		↓	↓	-0.43	5985	
		↓	↓	-0.31	5987	
		↓	↓	-0.46	5989	
		↓	↓	-0.36	5991	
		↓	↓	-0.55	5993	
		2.1	770	-0.36	5995	
		↓	↓	-0.40	6125	
		↓	↓	-0.35	6127	
		↓	↓	-0.40	6129	
		↓	↓	-0.23	6131	
		↓	↓	-0.50	6133	
		↓	↓	-0.26	6135	
		↓	↓	-0.33	6137	
		↓	↓	-0.25	6139	
		↓	↓	-0.49	6141	
		↓	↓	-0.44	6143	
		↓	↓	-0.20	6145	
		1.6	605	-0.36	6147	
		↓	↓	-0.62	6279	
		↓	↓	-0.28	6281	
		↓	↓	-0.46	6283	
		↓	↓	-0.24	6285	
		↓	↓	-0.36	6287	
		↓	↓	-0.29	6289	
		↓	↓	-0.39	6291	
		↓	↓	-0.23	6293	
		↓	↓	-0.35	6295	
		↓	↓	-0.23	6297	

TABLE 7 (Continued)

Grade	Orientation	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Average Irradiation Temperature (°C)	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_0}\right)$ (%)	Record No.	Previous Record No.
545161	Parallel	3.6	1340	+0.33	5641	
				+0.49	5643	
				+0.30	5645	
				+0.41	5647	
	Perpendicular			-0.14	5642	
				-0.09	5644	
				-0.24	5646	
				-0.19	5648	
B ₄ C-G	Parallel	3.7	1155	-1.93	6438	
				-2.16	6439	
				-2.06	6440	
				-2.05	6441	
				-1.96	6442	
				-2.15	6443	
				-2.26	6444	
				-2.38	6445	
		3.1	885	-1.64	6446	
				-1.59	6447	
				-1.61	6448	
				-1.41	6449	
				-1.61	6450	
				-1.64	6451	
				-1.62	6452	
				-1.10	6453	
H-419	Perpendicular	11.32	1510	-0.54	5621	2836
	Parallel	11.32	1510	-1.09	5622	2843
H-315A	Perpendicular	11.32	1510	-2.42	5623	2833
	Parallel	11.32	1510	+2.57	5624	2835
H-328	Parallel	11.32	1510	-2.38	5627	2841
	Perpendicular	11.32	1510	-2.98	5628	2832
CHN	Parallel	11.32	1510	-7.32	5631	2845
	Perpendicular	11.32	1510	+4.21	5632	2834
H-319	Parallel	11.32	1510	-2.26	5633	2847
	Perpendicular	11.32	1510	+0.57	5634	2848
H-430	Perpendicular	6.78	1450	-0.71	5635	2846
				-0.53	5636	2837
				-0.93	5637	2838
	Parallel			-2.31	5638	2844
				-2.47	5651	2831
				-0.74	5652	2840
H-451C	Parallel	3.4	960	-0.93	5768	
				-0.41	5769	
				-0.67	5770	

TABLE 7 (Continued)

Grade	Orientation	Total Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Average Irradiation Temperature (°C)	Dimensional Change $\ln\left(1 + \frac{\Delta L}{L_o}\right)$ (%)	Record No.	Previous Record No.
IH-451 (char- loaded)	Parallel	3.4 ↓	940 ↓	-0.59	6461	
				-0.63	6462	
				-0.58	6463	
				-0.56	6464	
				-0.54	6465	
				-0.66	6466	
				-0.66	6467	
				-0.66	6468	
				-0.69	6469	
				-0.70	6470	
IH-451 (control samples)						

5.4. COMPARISON

Table 8 compares the dimensional changes observed in H-451, H-327, and P₃JHAN graphites irradiated under identical conditions. The H-451 was the most stable of the three graphites, while the P₃JHAN clearly exhibited the largest dimensional changes. At moderate temperatures and fluence, H-327 behaved in a manner comparable to H-451, but it exhibited more dimensional change at higher temperatures and fluences.

5.5. CARBON INSULATING MATERIALS

A few samples of carbon insulating materials were irradiated in capsule OG-1. The materials were a rigid carbon foam (FPA-20), a flexible graphite foil (Grafoil), and a resilient layered fibrous carbon (Palarite C). Postirradiation dimensions were measured from photographs, and the results are shown in Table 9. All samples retained their integrity except the small (0.18-in. diameter) cores of Palarite C, which were fragile and one of which became delaminated into pieces. The results may be summarized as follows:

FPA-20 Carbon Foam. Shrank 6% to 11% in both directions after irradiation to 3.1×10^{21} n/cm² at 900°C.

Grafoil. Retained some flexibility. Less than 5% in-plane shrinkage after irradiation to 3.6×10^{21} n/cm² at 1350°C.

Palarite C. Retained some resiliency. Shrank 11% parallel to the layers after irradiation to 3.1×10^{21} n/cm² at 900°C or 3.6×10^{21} n/cm² at 500° to 1200°C. Insignificant dimensional change at 1.1 to 1.3×10^{21} n/cm² at 400° to 700°C. Expanded 15% perpendicular to the layers after irradiation to 3.1×10^{21} n/cm² at 900°C.

TABLE 8
DIMENSIONAL CHANGES IN H-451, H-327, AND P₃JHAN

Average Irradiation Temperature (°C)	Total Fluence x 10 ⁻²¹ (n/cm ²) (E > 0.18 MeV)	Dimensional Change, $\ln\left(1 + \frac{\Delta L}{L_0}\right)$ (%)					
		Perpendicular			Parallel		
		H-451	H-327	P ₃ JHAN	H-451	H-327	P ₃ JHAN
595	1.6	-0.09	-0.06	-0.13	-0.12	-0.15	-0.20
750	2.1	-0.09		-0.12	-0.15	-0.13	-0.28
980	3.4	-0.48	-0.4	-0.74	-0.78	-1.0	-1.83
1020	3.4	-0.49	-0.46	-0.80	-0.90	-1.22	-2.03
1325	3.6	-1.57		-1.61	-2.34		-4.06

TABLE 9
CARBON INSULATING MATERIALS IRRADIATED IN CAPSULE OG-2

Material	Sample Number	Irradiation Conditions			Postirradiation Properties					
		Crucible	Mean Temperature (°C)	Fast Fluence $\times 10^{-21}$ (n/cm ²)	Integrity	Resiliency	Dimensions			
							Direction	Before	After	% Change
FPA-20 carbon foam	I	7	900	3.1	Intact	--	Parallel	0.900	0.850	-6
							Perpendicular	0.190	0.175	-8
	II	7	900	3.1	Intact	--	Parallel	0.900	0.820	-9
							Perpendicular	0.180	0.160	-11
Grafoil	(11 samples)	5	1350	3.6	Intact	Still flexible but stiffer. Broke after one sharp bend.	In-plane	0.170	0.162-0.170	0 to -5
Palarite C (cored samples)	I	7	900	3.1	Delaminated into three pieces	Still resilient	Perpendicular to layers	0.875	--	--
							Parallel to layers	0.180	0.160	-11
	II	7	900	3.1	Cracked but intact	Still resilient	Perpendicular to layers	0.825	0.950	+15
							Parallel to layers	0.180	0.160	-11
Palarite C (spacer discs)	1B	Below 1	430-700 ^(a)	1.3	Intact	Still resilient	Parallel to layers	2.12	2.10	-0.9
	1T	Above 3	500-1100 ^(a)	3.6	Intact	Still resilient	Parallel to layers	2.12	1.87	-11.8
	2B	Below 4	570-1190 ^(a)	3.7	Intact	Still resilient	Parallel to layers	1.98	1.77	-10.6
	2T	Above 10	400-500 ^(a)	1.1	Intact	Still resilient	Parallel to layers	1.98	1.99	+0.5

^(a) Design temperature range, periphery to center line.

6. EXPERIMENTAL RESULTS - THERMAL PROPERTIES

6.1. THERMAL EXPANSIVITY

Thermal expansivity measurements were made on 102 irradiated graphite samples 0.2 in. in diameter by 0.45 in. long. Measurements were made in a silica dilatometer between room temperature and 100°C less than the irradiation temperature. Graphites included H-327, H-451, and H-429. The H-429 samples and some of the H-327 samples had been irradiated previously in capsule GEH-13-422; the H-429 samples provided high-fluence data on a near-isotropic petroleum-coke-based material.

The mean expansivities between room temperature and 500°C are listed in Tables 10 and 11. The expansivity of H-327 graphite is plotted as a function of fast neutron fluence in Fig. 6, and that of H-429 and H-451 is shown in Fig. 7. Neutron-induced changes in the thermal expansivity of H-327 graphite were very small (Fig. 6). There was some indication of a downward drift in the perpendicular expansivity, but the parallel expansivity was apparently unaffected. The near-isotropic graphites (H-429 and H-451) (Fig. 7) showed a small increase in thermal expansivity at irradiation temperatures below about 900°C and a slight decrease in expansivity for the highest irradiation temperatures (1370° to 1500°C). At intermediate temperatures, there was no systematic trend. These changes are much smaller than those occurring in Gilsocoke-based graphites, whose thermal expansivities first increase and later decrease to about half their preirradiation value at around 5×10^{21} n/cm² ($E > 0.18$ MeV) for temperatures in the vicinity of 1000°C.

TABLE 10
THERMAL EXPANSIVITY OF H-327 GRAPHITE SPECIMENS
IRRADIATED IN CAPSULE OG-1

Specimen No.	Orientation and Location (a)	Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E > 0.18 MeV)	Coefficient of Thermal Expansivity, $\alpha \times 10^6 \text{ } ^\circ\text{C}^{-1}$ (22°-500°C)
1	C para	1	2	640	2.2	1.84
2	C para	↓	3	640	↓	1.87
201	E para	↓	40	580	↓	1.72
202	E para	↓	40	580	↓	1.65
101	C perp	↓	2	640	↓	3.47
102	C perp	↓	3	640	↓	3.25
251	E perp	↓	40	580	↓	3.55
252	E perp	↓	40	580	↓	3.54
.226.	E para	8	41	840	2.6	1.72
.227.	E para	↓	41	↓	↓	1.68
.228.	E para	↓	43	↓	↓	2.05
.276.	E perp	↓	41	↓	↓	3.61
.277.	E perp	↓	41	↓	↓	3.72
.278.	E perp	↓	43	↓	↓	3.70
176	C para	↓	19	875-890	↓	2.03
177	E para	↓	19	↓	↓	2.27
174	C perp	↓	19	↓	↓	3.18
175	E perp	↓	19	↓	↓	3.70
222	E para	7	2	980	3.1	1.97
223	E para	↓	3	↓	↓	1.96
224	E para	↓	4	↓	↓	1.93
272	E perp	↓	2	↓	↓	3.10
273	E perp	↓	3	↓	↓	3.38
274	E perp	↓	4	↓	↓	3.27
146	C perp	4	35	1050-1325	9.9	2.99
150	C perp	↓	36	1050-1275	↓	3.24
147	E perp	↓	35	1050-1325	↓	3.59
151	E perp	↓	36	1050-1275	↓	3.48
148	C para	↓	35	1050-1325	↓	2.05
152	C para	↓	36	1050-1275	↓	1.85
149	E para	↓	35	1050-1325	↓	1.87
153	E para	↓	36	1050-1275	↓	1.58
240	E para	5	20	1370-1575	11.3	2.12
241	E perp	5	20	1370-1575	11.3	3.04

(a) C = center, E = edge; para - parallel, perp = perpendicular.

TABLE 11
THERMAL EXPANSIVITY OF H-429 AND H-451 GRAPHITE SPECIMENS
IRRADIATED IN CAPSULE OG-1

Graphite Grade	Specimen No.	Log Location and Orientation ^(a)	Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Coefficient of Thermal Expansivity $\alpha \times 10^6$ °C ⁻¹ (22°-500°C)
H-451	303	C para	1	2	640	2.2	3.98
	304	C para	↓	3	↓	↓	3.80
	305	C para	↓	4	↓	↓	3.72
	428	C perp	↓	2	↓	↓	4.82
	429	C perp	↓	3	↓	↓	4.89
	430	C perp	↓	4	↓	↓	4.73
H-451	.629.	E para	9	33	770	2.1	4.19
	.630.	E para	↓	34	↓	↓	3.87
	.399.	C para	↓	48	↓	↓	3.92
	.400.	C para	↓	48	↓	↓	4.06
	.729.	E perp	↓	33	↓	↓	5.09
	.730.	E perp	↓	34	↓	↓	4.75
	.524.	C perp	↓	48	↓	↓	5.02
	.525.	C perp	↓	48	↓	↓	5.20
	613	E para	↓	2	850	↓	3.92
	614	E para	↓	3	↓	↓	3.83
	615	E para	↓	4	↓	↓	4.09
	713	E perp	↓	2	↓	↓	5.04
	714	E perp	↓	3	↓	↓	4.85
	715	E perp	↓	4	↓	↓	4.78
H-451	371	C para	8	7	920	2.6	3.52
	372	C para	↓	7	↓	↓	3.75
	373	C para	↓	8	↓	↓	3.61
	496	C perp	↓	7	↓	↓	4.39
	497	C perp	↓	7	↓	↓	4.15
	498	C perp	↓	8	↓	↓	4.16
H-429	389	Para	8	16	890	3.4	3.70
	390	Para	↓	16	↓	↓	3.90
	391	Para	↓	16	↓	↓	4.06
	419	Perp	↓	15	↓	↓	4.93
	420	Perp	↓	15	↓	↓	5.19
	421	Perp	↓	15	↓	↓	5.16
H-451	596	E para	7	2	980	3.1	3.33
	597	E para	↓	3	↓	↓	3.38
	598	E para	↓	4	↓	↓	3.58
	696	E perp	↓	2	↓	↓	4.11
	697	E perp	↓	3	↓	↓	4.25
	698	E perp	↓	4	↓	↓	4.44

TABLE 11 (Continued)

Graphite Grade	Specimen No.	Log Location and Orientation ^(a)	Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Coefficient of Thermal Expansivity, $\alpha \times 10^6$ °C ⁻¹ (22°-500°C)
II-451	.355.	C para	6	6	1060	3.4	3.01
	.356.	C para	6	6			3.76
	.357.	C para	7	7			3.79
	.480.	C perp	6	6			4.52
	.481.	C perp	6	6			4.37
	.482.	C perp	7	7			4.08
II-451	583	E para	4	2	1150	3.7	3.49
	584	E para	2	2			3.55
	585	E para	3	3			3.64
	683	E perp	2	2			3.70
	684	E perp	2	2			4.01
	685	E perp	3	3			3.78
II-429	404	Para	4	30	1050-1275	6.3	3.77
	405	Para	30	30			3.67
	406	Para	30	30			3.66
	434	Perp	30	30			4.70
	435	Perp	30	30			4.52
	436	Perp	40	40			4.37
II-451	341	C para	5	6	1390	3.6	3.49
	342	C para	6	6			3.73
	343	C para	7	7			3.69
	466	C perp	6	6			4.30
	467	C perp	6	6			4.37
	468	C perp	7	7			4.16
II-429	141	Para	5	16	1370-1500	6.6	3.58
	142	Para	16	16			3.38
	143	Para	17	17			3.05
	161	Perp	16	16			4.16
	162	Perp	16	16			4.07
	163	Perp	17	17			4.29

^(a) C = center, E = edge; para = parallel, perp = perpendicular.

Fig. 6. Thermal expansivity of H-327 graphite as a function of fast neutron fluence

Fig. 7a. Thermal expansivity of H-451 and H-429 graphites irradiated at 640° to 1060°C as a function of fast neutron fluence

Fig. 7b. Thermal expansivity of H-451 and H-429 graphites irradiated at 1050° to 1500°C as a function of fast neutron fluence

Fig. 7a. Thermal expansivity of H-451 and H-429 graphites irradiated at 1050° to 1500°C as a function of fast neutron fluence

6.2. THERMAL CONDUCTIVITY

Thermal diffusivity measurements were made on 87 discs (0.45 in. in diameter by 0.05 in. thick) of H-327 and H-451 graphites after irradiation in the OG-1 capsule. The H-327 discs had previously been irradiated in capsule GEH-13-422. Thermal diffusivity measurements were made by the heat-pulse method (ASTM Method of Test C-741), and the thermal diffusivity values were converted to thermal conductivities by multiplying by the density and literature values for the heat capacity of graphite. About half the samples were tested at room temperature only, and half were measured with the temperature increasing in 100°C steps to 100°C less than the irradiation temperature, or to 800°C, whichever was lower.

The results are listed in Tables 12 and 13. The conductivity at the irradiation temperature was estimated by extrapolating the data points, assuming a temperature dependence curve appropriate for irradiated graphite (Ref. 4). The conductivities at room temperature and at the irradiation temperature are plotted as a function of fluence in Figs. 8 through 11; these figures also include data from samples irradiated earlier in capsule GEH-13-422. Because of its high degree of orientation, the H-327 graphite had a higher conductivity parallel to extrusion than perpendicular to extrusion. For H-451 graphite, the difference was much less marked. At 600° and 920°C, the conductivity of irradiated H-451 in the perpendicular direction was considerably greater than that of irradiated H-327; the H-451 conductivity in the perpendicular direction was similar to that of H-327 in the parallel direction.

Typical examples of the thermal conductivity of irradiated H-327 and H-451 graphites as a function of measurement temperature are shown in Fig. 12. Irradiation reduces both the level and the temperature sensitivity of the thermal conductivity, the effect being most pronounced for low irradiation temperatures.

TABLE 12
THERMAL CONDUCTIVITY OF H-327 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-1

Specimen No.	Log Location and Orientation(a)	Crucible No.	Mean Irradiation Temperature (°C)	Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Thermal Conductivity (cal/cm-sec-°C)					Irradiated Temperature (extrapolated)
					22°C	200°C	400°C	600°C	800°C	
1	E perp	1	600-625	2.9	0.038	0.044	0.044			0.044
2	E perp	1	600-625	2.9	0.038	0.044	0.043			0.041
13	E perp	1	600-625	2.9	0.040	--	--			--
14	E perp	1	600-625	2.9	0.052	0.061	0.060			0.055
18	E perp	1	600-625	2.9	0.042	--	--			--
65	E perp	1	600-625	2.5	0.047	0.054	0.054			0.050
66	E perp	1	600-625	2.5	0.055	0.062	0.057			0.053
81	E para	1	600-625	2.9	0.059	0.066	0.070			0.063
82	E para	1	600-625	2.9	0.064	0.081	0.080			0.071
93	E para	1	600-625	2.9	0.082	0.096	0.099			0.095
94	E para	1	600-625	2.9	0.074	--	--			--
95	E para	1	600-625	2.9	0.076	--	--			--
96	E para	1	600-625	2.9	0.086	--	--			--
97	E para	1	600-625	2.9	0.073	--	--			--
116	E para	1	600-625	2.5	0.080	0.094	0.091			0.087
43	E perp	5	1225-1350	9.9	0.133	0.159	0.143	0.127	0.112	0.085
44	E perp	5	1225-1350	9.9	0.131	0.136	0.118	0.105	0.093	0.078
45	E perp	5	1225-1350	9.9	0.149	--	--	--	--	--
46	E perp	5	1225-1350	9.9	0.137	0.130	0.117	0.104	0.094	0.078
47	E perp	5	1225-1350	9.9	0.129	--	--	--	--	--
69	E perp	5	1300-1350	6.2	0.174	0.166	0.153	0.136	0.121	0.090
70	E perp	5	1300-1350	6.2	0.175	0.189	0.173	0.152	0.136	0.105
86	E para	5	1225-1350	9.9	0.212	0.222	0.195	0.176	0.139	0.10
87	E para	5	1225-1350	9.9	0.198	0.219	0.203	0.170	0.144	0.10
88	E para	5	1225-1350	9.9	0.189	0.192	0.179	0.150	0.141	0.11
103	E para	5	1225-1350	9.9	0.179	--	--	--	--	--
104	E para	5	1225-1350	9.9	0.176	--	--	--	--	--
119	E para	5	1300-1350	6.2	0.198	0.201	0.181	0.167	0.144	0.11
120	E para	5	1300-1350	6.2	0.199	0.220	0.188	0.176	0.153	0.12
3	E perp	7	875-920	5.1	0.079	0.097	0.083	0.078	0.072	0.070
4	E perp	7	875-920	5.1	0.072	0.076	0.071	0.066	0.058	0.055
32	E perp	7	875-920	5.1	0.085	--	--	--	--	--
33	E perp	7	875-920	5.1	0.077	0.086	0.077	0.061	0.056	0.053
34	E perp	7	875-920	5.1	0.082	--	--	--	--	--
35	E perp	7	875-920	5.1	0.077	--	--	--	--	--
67	E perp	7	900-920	3.9	0.078	0.087	0.083	0.072	0.061	0.060
83	E para	7	900-920	5.1	0.095	0.094	0.083	0.081	0.077	0.075
84	E para	7	900-920	5.1	0.094	0.110	0.100	0.094	0.085	0.080
99	E para	7	900-920	5.1	0.101	0.116	0.105	0.099	0.091	0.090
100	E para	7	900-920	5.1	0.100	--	--	--	--	--
101	E para	7	900-920	5.1	0.117	--	--	--	--	--
117	E para	7	900-920	3.9	0.108	0.135	0.133	0.123	0.108	0.100

(a) E = edge; para = parallel; perp = perpendicular.

TABLE 13
THERMAL CONDUCTIVITY OF H-451 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-1

Specimen No.	Orientation (a)	Crucible No.	Mean Irradiation Temperature (°C)	Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Thermal Conductivity (cal/cm-sec-°C)					Irradiated Temperature (extrapolated)
					22°C	200°C	400°C	600°C	800°C	
221	Perp	1	600	2.2	0.085	0.081	0.082			0.080
222	Perp	1	600	2.2	0.078	0.083	0.080			0.077
223	Perp	1	600	2.2	0.078	0.082	0.082			0.081
224	Perp	1	600	2.2	0.077	--	--			--
225	Perp	1	600	2.2	0.068	--	--			--
226	Perp	1	600	2.2	0.074	--	--			--
227	Perp	1	600	2.2	0.076	--	--			--
228	Perp	1	600	2.2	0.073	--	--			--
229	Perp	1	600	2.2	0.080	0.095	0.086			0.080
230	Perp	1	600	2.2	0.077	0.086	0.080			0.073
201	Para	1	600	2.2	0.079	0.083	0.080			0.075
202	Para	1	600	2.2	0.087	0.095	0.097			0.084
203	Para	1	600	2.2	0.083	--	--			--
204	Para	1	600	2.2	0.083	--	--			--
242	Perp	5	1350	3.6	0.195	0.175	0.164	0.143	0.123	0.09
243	Perp	5	1350	3.6	0.202	0.213	0.190	0.161	0.127	0.085
244	Perp	5	1350	3.6	0.216	0.203	0.185	0.162	0.129	0.09
245	Perp	5	1350	3.6	0.205	--	--	--	--	--
246	Perp	5	1350	3.6	0.214	--	--	--	--	--
247	Perp	5	1350	3.6	0.202	--	--	--	--	--
248	Perp	5	1350	3.6	0.205	--	--	--	--	--
249	Perp	5	1350	3.6	0.215	--	--	--	--	--
250	Perp	5	1350	3.6	0.162	0.173	0.158	0.144	0.131	0.105
251	Perp	5	1350	3.6	0.179	0.182	0.173	0.151	0.134	0.10
210	Para	5	1350	3.6	0.193	0.216	0.188	0.158	0.142	0.10
211	Para	5	1350	3.6	0.195	0.209	0.182	0.159	0.143	0.10
212	Para	5	1350	3.6	0.195	--	--	--	--	--
213	Para	5	1350	3.6	0.198	--	--	--	--	--
214	Para	5	1350	3.6	0.173	0.179	0.162	0.150	0.133	0.095
231	Perp	7	920	3.1	0.104	0.131	0.112	0.101	0.092	0.090
232	Perp	7	920	3.1	0.097	0.111	0.105	0.092	0.085	0.082
233	Perp	7	920	3.1	0.109	0.113	0.100	0.092	0.082	0.080
234	Perp	7	920	3.1	0.110	--	--	--	--	--
235	Perp	7	920	3.1	0.114	--	--	--	--	--
236	Perp	7	920	3.1	0.099	--	--	--	--	--
237	Perp	7	920	3.1	0.104	--	--	--	--	--
238	Perp	7	920	3.1	0.085	--	--	--	--	--
239	Perp	7	920	3.1	0.099	0.111	0.097	0.091	0.085	0.082
240	Perp	7	920	3.1	0.106	0.120	0.113	0.104	0.096	0.092
241	Perp	7	920	3.1	0.102	--	--	--	--	--
205	Para	7	920	3.1	0.117	0.132	0.123	0.110	0.100	0.095
206	Para	7	920	3.1	0.118	0.130	0.117	0.107	0.096	0.092
207	Para	7	920	3.1	0.112	--	--	--	--	--
208	Para	7	920	3.1	0.113	--	--	--	--	--
209	Para	7	920	3.1	0.123	0.130	0.121	0.116	0.103	0.100

(a) Perp = perpendicular; Para = parallel.

Fig. 8. Thermal conductivity at room temperature of H-327 graphite as a function of fast neutron fluence

Fig. 9. Thermal conductivity at irradiation temperature of H-327 graphite as a function of fast neutron fluence

Fig. 10. Thermal conductivity at room temperature of H-451 graphite as a function of fast neutron fluence. (Some data points on Gilsocarbon H-328 graphite from capsule GEH-13-422 are included.)

Fig. 11. Thermal conductivity at irradiation temperature of H-451 graphite as a function of fast neutron fluence. (Some data points on Gilsocarbon H-328 graphite from capsule GEH-13-422 are included.)

Fig. 12. Thermal conductivity of unirradiated and irradiated H-327 and H-451 graphites (perpendicular orientation) as a function of measurement temperature. (Unirradiated data show mean and range of 10 samples.)

The thermal conductivity of the irradiated H-451 samples was in good agreement with values predicted earlier from published data on Gilsocarbon-based graphites (Ref. 4). However, the thermal conductivities of the H-327 samples irradiated at 600° and 900°C were 20% to 30% lower than the earlier predictions. There is no obvious explanation of why the conductivity of the needle-coke graphite should have been reduced more than that of the isotropic graphite.

7. EXPERIMENTAL RESULTS - TENSILE PROPERTIES

Tensile tests were conducted in air at room temperature on 0.25-in.-diameter by 0.9-in.-long cylinders of H-327 and H-451 graphite irradiated in capsule OG-1. A crosshead speed of 0.005 in./mm was used, and strains were measured with a 0.5-in. gauge length clip-on extensometer. The samples were cemented to metal end-pieces with high-strength epoxy cement, and the load was applied through roller-link chains to maintain uniaxial alignment during testing. Typical stress-strain curves for unirradiated and irradiated H-451 graphite are shown in Fig. 13. Because of the inelastic component in the deformation of graphite, the unloading curve does not retrace the initial loading curve but reaches zero load with a positive "permanent set." The second loading curve superimposes on the unloading curve, and beyond the first strain reversal point it forms a continuation of the initial loading curve. Irradiation greatly reduces the inelastic strain component and the stress-strain curve loses much of its curvature, particularly for irradiation at lower temperature (see Fig. 13). In the present tests, Young's modulus was measured from the 100- to 1000-psi reloading portion of the curve, because this represents the effective modulus of a graphite component after its first stress excursion and because its slope is more accurately measured than that of a tangent to the curve at the origin.

The results of the tensile tests are listed in Tables 14 and 15. The tensile data for unirradiated material were obtained from companion samples from the same log locations as the irradiated samples. The changes in strength and Young's modulus with neutron exposure are illustrated in Figs. 14 and 15. The strength and Young's modulus of H-327 graphite and H-451 graphite increased, with a greater increase occurring for lower-temperature irradiation than for higher-temperature

Fig. 13. Typical stress-strain curves of unirradiated and irradiated H-451 graphite

TABLE 14
TENSILE TESTS ON H-327 GRAPHITE IRRADIATED IN OG-1 CAPSULE

Crucible No.	Hole No.	Irradiation Temperature (°C)	Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Log Location and Orientation (a)	Specimen No.	Strain at Failure (%)	Ultimate Tensile Strength (psi)	Young's Modulus (b) (10 ⁶ psi)	Secant Modulus (c) (10 ⁶ psi)
--	--	--	0 ↓	E para	1	0.226	1874	1.61	0.83
				E para	2	0.248	2669	1.91	1.08
				E para	3	0.170	1956	2.16	1.15
				E para	4	0.132	1690	1.77	1.28
				E para	5	0.250	2648	1.87	1.06
				E para	6	0.203	2220	1.73	1.09
				E para	7	0.176	2281	2.49	1.30
				E para	8	0.224	2241	1.78	1.00
				E para	9	0.180	2159	1.85	1.20
				E para	10	0.185	2119	2.12	1.15
				Mean		0.199	2186	1.93	1.11
				Std dev		± 0.035	± 293	± 0.25	± 0.13
				C para	11	0.112	1141	1.15	1.02
				C para	12	0.147	1508	1.43	1.03
--	--	--	0 ↓	C para	13	0.124	1182	1.32	0.95
				C para	15	0.160	1324	1.12	0.83
				C para	16	0.176	1569	1.22	0.89
				C para	17	0.105	1222	1.43	1.16
				C para	18	0.134	1406	1.41	1.05
				C para	19	--	1222	1.33	--
				Mean		0.137	1321	1.30	0.99
				Std dev		± 0.026	± 158	± 0.12	± 0.11
				C perp	21	0.144	815	0.73	0.57
				C perp	22	0.216	896	0.67	0.42
				C perp	24	0.256	1161	0.63	0.45
				C perp	25	0.160	896	0.77	0.56
				C perp	26	0.230	957	0.70	0.42
				C perp	28	0.249	713	0.51	0.29
--	--	--	0 ↓	C perp	29	--	244	--	--
				C perp	30	--	488	--	--
				C perp	31	--	468	--	--
				C perp	32	0.262	957	0.58	0.37
				C perp	33	0.240	1120	0.56	0.47
				C perp	34	0.196	754	0.62	0.38
				C perp	35	0.336	1201	0.64	0.36
				Mean		0.229	820	0.64	0.43
				Std dev		± 0.055	± 286	± 0.08	± 0.09
				E perp	36	0.368	1609	0.62	0.44
				E perp	37	0.360	1426	0.68	0.40
				E perp	38	0.373	1548	0.68	0.42
				E perp	39	0.421	1711	0.68	0.41
				E perp	40	0.373	1507	0.66	0.40
--	--	--	0 ↓	E perp	41	0.360	1385	0.62	0.38
				E perp	42	0.332	1385	0.59	0.42
				E perp	43	0.472	1691	0.56	0.36
				E perp	44	0.405	1589	0.60	0.39
				E perp	45	0.368	1528	0.69	0.42
				E perp	46	0.338	1324	0.64	0.39
				E perp	47	0.223	1019	0.66	0.46
				E perp	48	0.305	1365	0.71	0.45
				E perp	49	0.317	1182	0.59	0.37
				E perp	50	0.392	1487	0.69	0.38
				E perp	51	0.260	1263	0.74	0.49
				E perp	52	0.372	1405	0.66	0.38
				E perp	53	0.386	1691	0.71	0.44
				E perp	54	0.232	1059	0.63	0.46
				Mean		0.350	1430	0.65	0.41
				Std dev		± 0.062	± 200	± 0.05	0.04

TABLE 14 (Continued)

Crucible No.	Hole No.	Irradiation Temperature (°C)	Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Log Location and Orientation ^(a)	Specimen No.	Strain at Failure (%)	Ultimate Tensile Strength (psi)	Young's Modulus ^(b) (10 ⁶ psi)	Secant Modulus ^(c) (10 ⁶ psi)
2	16	700	2.9	E para	351	0.109	2933	3.93	2.69
	19			E para	352	0.115	3504	4.18	3.05
	22			E para	353	0.089	2709	3.77	3.04
	25			E para	354	0.118	3606	3.77	3.06
	32	640		E para	355	0.093	2995	4.38	3.22
	35			E para	356	0.114	3056	3.29	2.68
	39			E para	357	0.112	3422	3.85	3.06
	42			E para	358	0.124	3321	3.62	2.68
	45			E para	359	0.091	3035	4.23	3.34
	49			E para	360	0.104	2934	3.46	2.82
					Mean	0.107	3152	3.85	2.96
					Std dev	± 0.012	± 278	± 0.33	± 0.20
4	18	1100	3.7	E para	361	0.095	2485	3.32	2.62
	22	1100		E para	362	0.130	3198	3.18	2.46
	27	1050		E para	363	0.094	2445	3.22	2.60
	31			E para	364 ^(d)	(0.057)	(1263)	(2.67)	(2.22)
	34			E para	365	0.131	3035	2.93	2.32
	37			E para	366	0.102	2832	3.14	2.78
	41			E para	367	0.118	2893	3.18	2.45
	44			E para	368	0.115	2872	3.61	2.50
					Mean	0.112	2822	3.23	2.53
					Std dev	± 0.014	± 254	± 0.19	± 0.14
6	16	1020	3.4	C perp	401	0.154	1080	1.18	0.86
	19			C perp	402	0.154	1120	0.96	0.73
	22			C perp	403	0.097	856	1.22	0.88
	25			C perp	404	0.126	733	0.94	0.58
	32	960		C perp	405	0.162	1243	1.08	0.77
	35			C perp	406	0.111	978	1.33	0.88
	39			C perp	407	0.058	774	1.66	1.33
	42			C perp	408	0.110	1283	1.44	1.17
	45			C perp	409	0.062	754	1.30	1.22
	49			C perp	410	0.096	795	1.20	0.83
					Mean	0.110	962	1.23	0.93
					Std dev	± 0.032	± 198	± 0.20	± 0.23
8	18	900	2.6	C para	279	0.075	1996	3.12	2.66
	18			C para	280	0.099	2098	2.85	2.12
	21			C para	281	0.113	2648	3.38	2.34
	21			C para	282	0.084	2058	2.83	2.45
	24			C para	283	0.092	2017	2.67	2.19
	24			C para	284	0.108	2282	2.97	2.11
	30	860		C para	285	--	1732	3.12	--
	30			C para	286	0.082	1752	3.12	2.14
	33			C para	287	0.142	2159	2.59	1.52
	33			C para	288	0.106	2526	3.16	2.38
					Mean	0.100	2127	3.02	2.21
					Std dev	± 0.019	± 281	± 0.27	± 0.30
9	16	810	2.1	E para	369	0.143	3259	2.91	2.28
	19			E para	370	0.110	2730	3.10	2.48
	22			E para	371	0.099	2628	3.57	2.65
	25			E para	372	0.151	2995	2.55	1.98
	32	770		E para	373	0.107	2546	3.18	2.38
	35			E para	374	0.112	2832	3.26	2.53
	39			E para	375	0.118	3015	3.10	2.56
	42			E para	376	0.110	2445	3.04	2.22
	45			E para	377	0.129	2913	2.99	2.26
	49			E para	378	0.100	2506	3.34	2.51
					Mean	0.118	2787	3.10	2.39
					Std dev	± 0.017	± 249	± 0.26	± 0.19

(a) E = edge, C = center; para = parallel, perp = perpendicular.

(b) 100-1000 psi (parallel samples) or 100-600 psi (perpendicular samples) after preloading to 1000 psi (parallel samples) or 600 psi (perpendicular samples), unloading sample, and reloading.

(c) Ultimate tensile strength divided by fracture strain.

(d) Sample contained flaw; excluded from averages.

TABLE 15
TENSILE TESTS ON H-451 GRAPHITE IRRADIATED IN OG-1 CAPSULE

Crucible No.	Hole No.	Irradiation Temperature (°C)	Fluence $\times 10^{-21}$ (n/cm ²) (E > 0.18 MeV)	Log Location and Orientation (a)	Specimen No.	Strain at Failure (%)	Ultimate Tensile Strength (psi)	Young's Modulus (b) (10 ⁶ psi)	Secant Modulus (c) (10 ⁶ psi)
-	-	-	0	C para	T-181	0.130	1446	1.22	1.11
				C para	182	0.230	1630	1.02	0.71
				C para	183	0.212	1650	1.15	0.78
				C para	184	0.169	1589	1.17	0.94
				C para	185	0.152	1548	1.20	1.02
				C para	186	0.211	1731	1.23	0.82
				C para	187	0.182	1243	0.95	0.68
				C para	188	0.187	1609	1.17	0.86
				C para	190	0.184	1630	1.17	0.89
					Mean	0.184	1564	1.14	0.87
					Std dev	± 0.029	± 135	± 0.09	± 0.13
-	-	-		C perp	T-219	0.210	1589	0.97	0.76
				C perp	220	0.215	1751	0.98	0.81
				C perp	221	0.252	1874	1.02	0.74
				C perp	222	0.223	1731	1.02	0.77
				C perp	223	0.210	1650	0.94	0.79
				C perp	224	0.267	2037	1.02	0.76
				C perp	225	0.172	1283	0.97	0.75
				C perp	226	0.181	1609	1.12	0.89
				C perp	227	0.241	1853	1.06	0.77
				C perp	228	0.147	1344	1.02	0.91
				C perp	1	0.227	1446	0.92	0.64
				C perp	2	0.242	1508	0.91	0.62
				C perp	3	0.342	2220	1.03	0.65
				C perp	5	0.219	1609	0.99	0.73
				C perp	6	0.214	1562	1.08	0.73
					Mean	0.224	1671	1.00	0.75
					Std dev	± 0.043	± 242	± 0.05	± 0.08
1	18	620	2.2	C para	T-101	0.142	2587	2.08	1.82
	18			C para	102	0.104	2384	2.31	2.29
	21			C para	103	0.122	2240	1.99	1.84
	21			C para	104	0.110	2343	2.29	2.13
	24			C para	105	0.138	2628	2.18	1.90
	24			C para	106	0.117	2383	2.32	2.04
	30	580		C para	107	0.126	2445	2.19	1.94
	30			C para	108	0.145	2852	2.30	1.97
	33			C para	109	0.130	2343	2.15	1.80
	33			C para	110	0.128	2648	2.30	2.07
					Mean	0.126	2485	2.22	1.98
					Std dev	± 0.013	± 177	± 0.11	± 0.15
3	16	950	3.4	C para	T-119	-	2200	2.12	-
	16			C para	120	0.144	2608	2.23	1.81
	19			C para	121	0.161	2608	1.93	1.62
	19			C para	122	0.142	1976	1.63	1.39
	22			C para	123	0.153	2485	2.04	1.62
	22			C para	124	0.154	2078	1.81	1.35
	25			C para	125	0.130	2811	2.39	2.16
	25			C para	126	0.149	2505	1.73	1.68
	32	910		C para	127	0.162	2587	2.04	1.60
	32			C para	128	0.126	2058	2.21	1.63
	35			C para	129	0.104	2037	2.44	1.96
	35			C para	130	0.152	2506	2.12	1.65
					Mean	0.143	2371	2.06	1.68
					Std dev	± 0.017	± 271	± 0.24	± 0.22

TABLE 15 (Continued)

Crucible No.	Hole No.	Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E > 0.18 MeV)	Log Location and Orientation ^(a)	Specimen No.	Strain at Failure (%)	Ultimate Tensile Strength (psi)	Young's Modulus ^(b) (10 ⁶ psi)	Secant Modulus ^(c) (10 ⁶ psi)
5	19	1370	3.6	C para	T-139	-	2384	-	-
	19	↓	↓	C para	140	0.166	2241	1.74	1.35
	23	↓	↓	C para	141	0.164	2058	1.83	1.25
	23	↓	↓	C para	142	0.172	2302	1.86	1.34
	28	1340	↓	C para	143	0.170	2118	1.79	1.25
	28	↓	↓	C para	144	0.188	2139	1.72	1.14
	32	↓	↓	C para	145	0.198	2383	1.69	1.20
	32	↓	↓	C para	146	0.163	2241	1.93	1.37
					Mean	0.174	2233	1.79	1.27
					Std dev	±0.012	±115	±0.08	±0.08
7	19	950	3.1	C perp	T-211	0.140	2058	1.88	1.47
	23	950	↓	C perp	212	0.172	2628	1.85	1.53
	28	900	↓	C perp	213	0.200	2770	1.60	1.39
	32	↓	↓	C perp	214	0.168	2505	1.76	1.49
	35	↓	↓	C perp	215	0.185	2974	1.95	1.61
	39	↓	↓	C perp	216	0.162	2669	1.99	1.65
	43	↓	↓	C perp	217	0.176	2954	2.01	1.68
	46	↓	↓	C perp	218	0.179	2628	1.83	1.47
					Mean	0.172	2648	1.88	1.54
					Std dev	±0.016	±270	±0.13	±0.09
10	18	630	1.6	C para	T-163	0.126	2608	2.57	2.07
	18	↓	↓	C para	164	0.110	2648	2.55	2.41
	21	↓	↓	C para	165	0.103	2098	2.67	2.04
	21	↓	↓	C para	166	0.144	2872	2.51	1.99
	24	↓	↓	C para	167	0.132	1956	2.24	1.48
	24	↓	↓	C para	168	0.107	2384	2.81	2.23
	30	610	↓	C para	169	0.098	2322	3.00	2.37
	30	↓	↓	C para	170	0.128	2587	2.45	2.02
	33	↓	↓	C para	171	0.096	2221	2.74	2.31
	33	↓	↓	C para	172	0.114	2546	2.71	2.23
					Mean	0.116	2424	2.63	2.12
					Std dev	±0.015	±265	±0.20	±0.26

(a) C = center, E = edge; para = parallel, perp = perpendicular.

(b) 100-1000 psi, after preloading to 1000 psi, unloading sample, and reloading.

(c) Ultimate tensile strength divided by fracture strain.

Fig. 14a. Ultimate tensile strength and Young's modulus of H-327 graphite irradiated at 640° to 900°C as a function of fast neutron fluence. Error bands indicate $\pm$ one standard deviation.

Fig. 14b. Ultimate tensile strength and Young's modulus of H-327 graphite irradiated at 960° to 1100°C as a function of fast neutron fluence. Error bands indicate $\pm$ one standard deviation.

Fig. 15. Ultimate tensile strength and Young's modulus of H-451 graphite as a function of fast neutron fluence. Error bands indicate $\pm$ one standard deviation.

irradiation. The percentage increases in strength were in the range 30% to 60%, while increases in elastic modulus ranged from 60% to 130%. There was no significant change in the scatter of the strength data following irradiation, with the coefficient of variation remaining at about 10%. Average strength values (plus or minus one standard deviation) for material from the center of the log (the weakest portion) irradiated to 2.6 to 3.4×10^{21} n/cm² at 860° to 1080°C were as follows:

H-327 parallel	2127 ± 281 psi
H-327 perpendicular	962 ± 198 psi
H-451 parallel	2371 ± 271 psi
H-451 perpendicular	2648 ± 270 psi

8. IMPACT OF TEST DATA ON CURRENT DESIGN-BASIS CURVES

8.1. DIMENSIONAL CHANGES

The dimensional changes observed in capsule OG-1 for H-451 and H-429 graphites are the first measurements on a full-size near-isotropic graphite produced for use in the HTGR. The data agreed very well in the perpendicular direction with the predicted curves used in design. The parallel-direction data exhibited ~20% less contraction than predicted. The OG-1 data have been fit, and new dimensional change curves have been generated (Figs. 4 and 5).

The OG-1 data on H-327 implied that H-327 was more dimensionally stable than earlier data had indicated. These data will be combined with earlier data to obtain a new dimensional change curve representative of H-327.

8.2. THERMAL EXPANSIVITY

The measured thermal expansivities of irradiated H-451 and H-429 graphites showed little change from unirradiated values. The present design curves overestimate the change in thermal expansivity by 10% to 30%. The curves will be changed in light of the OG-1 data.

The design-basis curves for the thermal expansivity of H-327 predict no change under irradiation to 8×10^{21} n/cm². The OG-1 data indicate a small increase in the coefficient of thermal expansion in the parallel direction for H-327. This small increase is not significant in light of the decreasing importance of H-327 to large HTGR design.

8.3. THERMAL CONDUCTIVITY

The measured thermal conductivities of irradiated H-451 graphite were within a few percent of the predicted curves in Ref. 4. However, the conductivities of the H-327 samples irradiated at 600° and 900°C averaged 25% lower than the predicted curves for both the parallel and perpendicular directions (Ref. 4). The samples irradiated at 1350°C agreed with the predicted curves. Because of the decline in importance of needle-coke graphites to the HTGR program, there are no present plans to revise the design-basis thermal conductivity curves for H-327 graphite.

8.4. MECHANICAL PROPERTIES

The design-basis curves for change in modulus during irradiation are being revised to represent the fluence and temperature dependence observed in OG-1. The present design-basis curves, based on changes in the dynamic modulus of Gilsocarbon-based graphites, underestimate the change in modulus up to 65% at 600°C, with the error decreasing to 5% at 1350°C. The change in ultimate tensile strength with irradiation is also being tabulated for incorporation in a revised design basis. No increase in ultimate tensile strength with irradiation was previously assumed, so OG-1 data will justify the use of increased allowable stress limits. However, the higher absolute limits will probably result in nearly the same safety margins owing to the increased effects on the modulus.

9. CONCLUSIONS

The petroleum-coke near-isotropic graphites (H-451, H-429, H-453) exhibit significantly improved dimensional stability over other production-scale nuclear graphites (H-327, CHN, P₃JHAN). The petroleum-coke near-isotropic graphites approach the dimensional stability of the Gilsocoke graphites. The production-grade needle-coke graphite H-327 displayed better dimensional stability than in earlier tests, possibly because of improvements during production and/or improvements in capsule instrumentation and analysis. The pitch-coke-based P₃JHAN graphite showed poorer dimensional stability than either H-451 or H-327 graphites under the irradiation conditions of capsule OG-1.

Irradiation-induced changes in the thermal expansivity of H-327 graphite are insignificant. Irradiation causes a small increase in the thermal expansivity of H-429 and H-451 graphites below about 900°C and a slight decrease at higher temperatures.

Irradiation reduces both the thermal conductivity and the temperature dependence of the thermal conductivity of H-327 and H-451 graphites. After irradiation at 600° and 900°C, the radial conductivity of H-451 graphite is about 50% higher than the radial conductivity of irradiated H-327 graphite and about equal to the axial conductivity of H-327 graphite.

Irradiation increases both the strength and Young's modulus of H-327 and H-451 graphites, with a greater increase occurring at lower irradiation temperatures. Percentage increases in strength fall in the range 30% to 60%, while increases in Young's modulus range from 60% to 130% for irradiation temperatures of 600° to 1350°C.

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