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FINAL REPORT ON GRAPHITE IRRADIATION TEST OG-2

by
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ABSTRACT

This report describes the results of dimensional, thermal expansivity, thermal conductivity, Young's modulus, and tensile strength measurements on specimens of nuclear graphites irradiated in capsule OG-2. About half the irradiation space was allocated to H-451 near-isotropic petroleum-coke-based graphite or its subsized prototype grade H-429. Most of these specimens had been previously irradiated. Virgin specimens of another near-isotropic graphite, grade TS-1240, were irradiated. Some previously irradiated specimens of needle-coke-based H-327 graphite and pitch-coke-based P₃JHAN were also included.

Data were obtained in the irradiation temperature range 600° to 1400°C. Accumulated neutron fluences now exceed $8 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$) on H-429 graphite and $6 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$) on H-451, P₃JHAN, and H-327 graphites.

The near-isotropic graphites continued to show the good dimensional stability indicated in previous irradiation experiments. Maximum observed shrinkages in H-451/H-429 were 2% in the radial direction and 3.5% in the axial direction, and no net expansion was observed at the irradiation conditions investigated. The low fluence data on TS-1240 graphite indicated dimensional stability as good as, or better than, that of H-451 graphite.

Irradiation-induced changes in the thermal properties followed previously established patterns. The thermal expansivity of the near-isotropic graphites increased marginally at low irradiation temperatures and decreased by up to 30% at high irradiation temperatures. Irradiation reduced the thermal conductivity, with the largest reductions taking place at the lowest temperatures.

Both Young's modulus and tensile strength increased significantly after irradiation for all the tested graphites. The relation between irradiation-induced changes in Young's modulus, E , and strength, S , predicted by the constant strain energy failure criterion,

$$\frac{S_i}{S_o} = \sqrt{\frac{E_i}{E_o}},$$

was approximately obeyed, but the tensile strength of irradiated H-451 specimens and many of the H-327 specimens was somewhat higher than predicted.

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1. INTRODUCTION

1.1. SCOPE OF REPORT

This report describes the results of dimensional, thermal expansivity, thermal conductivity, Young's modulus, and tensile strength measurements on specimens of nuclear graphites irradiated in capsule OG-2. Details of the fabrication and assembly of the capsule are given in Ref. 1, and the capsule operating history is detailed in Ref. 2. A complete list of the specimens, based on their location in the capsule, is contained in Ref. 3.

1.2. FAST FLUENCE UNITS

A change has been made in the units used for reporting fast neutron fluences. Earlier reports on this program, including the topical report on the preceding capsule OG-1 (Ref. 4), presented integrated fluences of neutrons with energies greater than 0.18 MeV in the water-moderated test reactors where the capsules were irradiated $[n/cm^2 (E > 0.18 \text{ MeV})_{\text{ORR}}]$. In the present report, the fluences are converted to the following units:

1. Fluence of neutrons with energies greater than 0.18 MeV in a typical High-Temperature, Gas-Cooled Reactor (HTGR) spectrum $[n/cm^2 (E > 0.18 \text{ MeV})_{\text{HTGR}}]$. This is the unit that will be used in future HTGR design work.
2. Equivalent fission fluence for graphite damage $(n/cm^2, \text{EFFGD})$. This is the unit recommended by an international working group sponsored by the International Atomic Energy Authority (Ref. 5) and forms the basis of the ASTM recommended practice for reporting dosimetry results on graphite.

Conversions are based on the number of carbon atoms displaced, calculated based on the Thompson and Wright model, according to which 1 n/cm^2 (EFFGD) results in 720×10^{-24} displaced carbon atoms per atom. The appropriate conversion factors for the C-3 position of the Oak Ridge Reactor (ORR) are:

$$\begin{aligned}\text{Fluence (E > 0.18 MeV)}_{\text{HTGR}} &= 0.894 \times \text{Fluence (E > 0.18 MeV)}_{\text{ORR}} \\ \text{Fluence (EFFGD)} &= 1.118 \times \text{Fluence (E > 0.18 MeV)}_{\text{ORR}} \\ \text{Fluence (EFFGD)} &= 1.25 \times \text{Fluence (E > 0.18 MeV)}_{\text{HTGR}}\end{aligned}$$

At points in the text where no fluence units are specified, n/cm^2 (E > 0.18 MeV)_{HTGR} should be understood.

Further details of the dosimetry are given in Section 4.3.

2. TEST DESCRIPTION AND OBJECTIVES

Capsule OG-2 was the second in a series of graphite irradiation capsules which are being operated to obtain design basis data on the effects of neutron irradiation on the physical properties of candidate graphites for HTGR replaceable fuel and reflector elements. The Fort St. Vrain (FSV) HTGR used a needle coke graphite (grade H-327), while current designs for large HTGRs favor the use of a near-isotropic graphite. Near-isotropic petroleum-coke-based graphites, extruded in 17- to 18-in.-diameter logs, are now receiving highest priority.

In the OG capsule series, the operating temperatures in nine out of the 10 crucibles in the capsule span the range where significant neutron exposure occurs in HTGRs (600° to 1200°C), and the tenth crucible operates at 1400°C to provide test data at a higher temperature. Capsule OG-2 had a thermal design identical to those of the preceding (OG-1) and succeeding (OG-3) capsules, and many specimens were transferred from capsule to capsule after nondestructive measurements in order to provide data at several increments of fluence.

3. MATERIALS INVESTIGATED

The materials investigated and the numbers of specimens are summarized in Table 3-1.

A major objective of the experiment was to establish the data base for the irradiation-induced property changes in H-451 near-isotropic petroleum-coke-based graphite made by Great Lakes Carbon Company. About half the irradiation space was allocated to specimens of H-451 or its subsized prototype grade H-429. Most of the H-451 specimens had been irradiated in capsule OG-1, and all the H-429 specimens had been irradiated in capsules GEH-13-422 and OG-1. The accumulated fluence on the H-429 specimens in the higher-temperature crucibles now exceeds the end-of-life fluence for current HTGR designs.

Another objective was to complete the collection of data on H-327 needle coke graphite, which was used in the construction of the FSV HTGR. Two hundred specimens of H-327, most of which had been previously irradiated in capsule GEH-13-422 or OG-1, were included in the experiment.

Also included in capsule OG-2 were 134 virgin specimens of TS-1240 graphite, a near-isotropic petroleum-coke-based graphite made by Union Carbide Corporation. Other materials included a pitch-coke-based graphite (Pechiney grade P₃JHAN) and miscellaneous graphites and carbons of general interest to the program.

Three specimen configurations were used: 0.2-in.-diameter by 0.45-in.-long cylinders for nondestructive dimensional and thermal expansivity determinations, 0.4-in.-diameter by 0.05-in.-thick disks for nondestructive thermal diffusivity measurements, and 0.25-in.-diameter by 0.9-in.-long cylinders for dimensional measurements and destructive tensile testing.

TABLE 3-1
GRAPHITES AND OTHER MATERIALS IRRADIATED IN CAPSULE OG-2

Designation	No. of Specimens	Type	GA Log Book Number	Form & Dimensions of Parent Sample	Source (a)	Raw Materials		
						Filler	Binder	Impregnant
Graphite H-451	428	Extruded, near isotropic	5651-28 5651-86	18-in.-diam. x 34-in.-long log	GLCC	Near-isotropic petroleum coke	Coal tar pitch	Petroleum pitch
H-429	69	Extruded, near isotropic	4974-104-A	9-in.-diam. x 8-in.-long log	GLCC	Near-isotropic petroleum coke	Coal tar pitch	Coal tar pitch
TS-1240	134	Extruded, near isotropic	5651-73	18-in.-diam. x 34-in.-long log	UCC	Near-isotropic petroleum coke		
H-327	204	Extruded, anisotropic	4974-3	18-in.-diam. x 34-in.-long log	GLCC	Needle coke	Coal tar pitch	Coal tar pitch
P ₃ JHAN	66	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
2020	120	Isostatic molded, fine grained	5651-56	18-in.-diam. x 6-in.-long slab	SCC	Petroleum coke	(b)	(b)
H-328	1	Molded, near isotropic	--	17-in.-diam. x 34-in.-long log	GLCC	Gilso coke	Coal tar pitch	Coal tar pitch
H-430	1	Molded, near isotropic	--	8.6-in.-diam. x 7.5-in.-long log	GLCC	Near-isotropic petroleum coke	Coal tar pitch	(b)
IH-451	14	Extruded, near isotropic	5948-101	18-in.-diam. x 34-in.-long log	GLCC/GA	Near-isotropic petroleum coke	Coal tar pitch	Additional impregnation done at GA
H-451C	12	Extruded, near isotropic	5948-14	18-in.-diam. x 34-in.-long log	GLCC/GA	Near-isotropic petroleum coke	Coal tar pitch	Samples taken from cure-in-place experiments
565161	16	Experimental	5651-61	(b)	ORNL	(b)	(b)	(b)

TABLE 3-1 (Continued)

Designation	No. of Specimens	Type	GA Log Book Number	Form & Dimensions of Parent Sample	Source ^(a)	Description
Other Materials						
B ₄ C-G	18	Extruded boronated graphite	5646-13 5646-91	0.30-in. o.d. x 10-in.-long rods 0.25-in. o.d. x 0.9-in.-long rods	GLCC (c)	FSV lumped burnable poison Oxidation-resistant shield compacts
MATRIX	4	Binder residue	--	(b)	GA	Coke residue from pitch binder in large HTGR fuel rod matrix
IMPCBN	1	Impregnant carbon	--	(b)	GA	Carbon residue from impregnant
GLSYCN	18	Glassy carbons	--	(b)	GA	Model carbons
PyC	13	Pyrolytic carbon	--	(b)	GA	Fuel particle coating material
SiC	4	SiC coatings	6041-7	(b)	GA	Fuel particle coating material
PALAR	1	Insulation	--	(b)	(b)	Palarite insulation
FPA	1	Insulation	--	(b)	(b)	Carbon foam insulation

(a) . Great Lakes Carbon Company (GLCC); Union Carbide Corporation (UCC); Stackpole Carbon Company (SCC); Pechiney (France); General Atomic Company (GA); Oak Ridge National Laboratory (ORNL).

(b) Unknown.

(c) Rods fabricated by GLCC, GA, Norton Company, Carborundum Company.

Only two batches of H-451 tensile specimens were tested to failure; the majority were reencapsulated in capsule OG-3 for additional exposure. All the H-327 tensile specimens were tested, with the exception of two batches from a low-fluence crucible which were held for reirradiation in capsule OG-3. Half of the TS-1240 tensile specimens were tested, and the remainder were held for reirradiation in capsule OG-3.

4. CAPSULE OPERATING CONDITIONS

4.1. DESCRIPTION OF CAPSULE

Capsule OG-2 was a fully instrumented, controlled-temperature graphite irradiation capsule irradiated in the C-3 position of the ORR. Irradiation started on July 17, 1974 and terminated on January 5, 1975 for a capsule cumulative power of 3886 MWd and an accumulated irradiation time at power of 1.12×10^7 sec.

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 specimen holders. The graphite crucibles were contained in Inconel 600 containment cans, which were housed in an annular aluminum thermal bond inside two 304 stainless steel containment tubes. 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 capsule contained 24 Chromel-Alumel thermocouples and six tungsten-rhenium thermocouples. All crucibles had one or more thermocouples located near the center line, and all except two had one or more thermocouples at the periphery. A schematic diagram of the capsule layout and thermocouple locations is shown in Fig. 4-1. Three sets of in situ decalibration data on the tungsten-rhenium thermocouples were obtained by locating pairs of Chromel-Alumel (K) and tungsten-rhenium (W) thermocouples in the same holes in the crucibles of cell 1, which operated at or below 1000°C. Reliable readings were obtained from all thermocouples until 58% of life, when thermocouples W18 and W19 failed at the start of a cycle. Thermocouple W-8 became intermittent at 68% of life. The remaining 27 thermocouples operated for the full capsule life.

THERMOCOUPLE ID					
1 - K4	6 - W8	11 - K5	16 - K16	21 - K28	26 - K26
2 - W7	7 - K11	12 - K10	17 - W18	22 - K17	27 - K22
3 - K12	8 - K9	13 - K13	18 - W19	23 - K30	28 - K23
4 - K2	9 - K1	14 - K14	19 - W27	24 - K21	29 - K29
5 - K6	10 - W3	15 - K15	20 - K20	25 - K25	30 - K24

K = CHROMEL/ALUMEL THERMOCOUPLE
W = W/3% Re - W/25% Re THERMOCOUPLE

ALL DIMENSIONS IN INCHES

Fig. 4-1. Schematic layout of capsule OG-2 with thermocouple locations

4.2. OPERATING TEMPERATURES

Recorded temperature histories and details of the procedures used to analyze the thermocouple operating records are given in Ref. 2. The neutron-induced decalibration factor for the tungsten-rhenium thermocouples used to monitor the temperatures in high-temperature crucibles 4 and 5 was taken from the W3/K1 thermocouple pair in the closest crucible (No. 3). The factor relating true operating temperature, T_t , and the indicated temperature, T_i , of the tungsten-rhenium thermocouples in crucibles 4 and 5 was taken to be

$$T_t = \frac{T_i}{1 - 4.9 \times 10^{-23} f},$$

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

Two crucibles (4 and 10) had a thermocouple near the center line but not at the periphery. Estimates of the radial temperature gradients in these crucibles were made from the observed temperature gradients in adjacent crucibles, taking into account the gamma heating rates. After the failure of thermocouples W18 and W19, the temperatures at these locations were estimated from thermocouple W27, using the ratios established up to the point of failure.

The average on-test temperatures at the center line and outer thermocouple locations are listed in Table 4-1. Long-term drift in the center-line temperatures was negligible, but the irradiation-induced decrease in graphite thermal conductivity caused a progressive increase in the radial temperature gradients in the crucibles. This resulted in a downward drift in the outside temperatures over the life of the capsule averaging 30°C . In addition to long-term drift in the outer temperatures, changing gamma heating rates resulting from control rod bank travel superimposed a sawtooth pattern on the operating temperatures (with the exception of controlled crucibles 3 and 7). The upper limit of the fluctuations (defined as the

TABLE 4-1
MEAN TEMPERATURES AND FLUENCES IN CAPSULE OG-2

Crucible Number	Fast Fluence ($\times 10^{-21}$)		Thermal Fluence ($\times 10^{-21}$) (n/cm^2)	Nominal Center Line Design Temperature ($^{\circ}\text{C}$)	Operating Temperature at Thermocouple Location ($^{\circ}\text{C}$)						Mean Operating Temperature in OG-1 Capsule	
	n/cm^2 ($E>0.18\text{ MeV}$) HTGR	n/cm^2 (EFFGD)			Center			Outer			Center	Outer
					Mean	Max. (a)	Min. (a)	Mean	Max. (a)	Min. (a)		
1	1.7	2.1	1.2	700	687	713	667	602	626	580	657	558
2	2.2	2.8	1.4	800	778	802	758	664	688	641	754	610
3	2.7	3.4	1.6	1000	998	1014	983	907	930	884	993	887
4	2.9	3.7	1.8	1200	1251	1333	1158	1090	--	--	1172	1024
5	2.9	3.6	1.8	1400	1387	1449	1319	1316	1380	1255	1395	1327
6	2.7	3.4	1.7	1100	1080	1110	1047	937	973	897	1078	938
7	2.5	3.1	1.5	1000	997	1016	983	907	932	881	992	884
8	2.1	2.7	1.2	900	934	970	905	835	866	808	928	836
9	1.7	2.1	0.9	800	830	883	793	752	794	713	860	753
10	1.2	1.5	0.6	600	640	706	602	580	--	--	650	597

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

temperature below which the thermocouple operated for 95% of the on-test time) and the lower limit (the temperature above which the thermocouple operated for 95% of the on-test time) are listed in Table 4-1.

For comparison, Table 4-1 also shows the nominal center-line design temperatures and the mean temperatures recorded during the operation of the preceding capsule, OG-1, which had an identical thermal design. Agreement between the two capsules, and with the design temperatures, is very good.

The mean operating temperatures of individual specimens were calculated from the center-line and outer temperatures of the crucible, assuming a parabolic temperature distribution along the radius.

4.3. NEUTRON FLUENCE

Dosimetry for the capsule was obtained from vanadium - 0.216% cobalt, vanadium - 0.52% iron (88.25% enriched in Fe^{54}), and titanium wires contained in quartz vials placed in grooves in the aluminum thermal bond. Wires were placed at seven axial locations and four circumferential positions 90° apart. After irradiation wires from all positions except one were recovered and analyzed by gamma-ray spectroscopy. Fast $[(E > 0.18 \text{ MeV})_{\text{ORR}}]$ and thermal fluences were calculated assuming activation cross sections of 46.56 mb for the $\text{Fe}^{54}(\text{n,p})\text{Mn}^{54}$ reaction, 6.61 mb for the $\text{Ti}^{46}(\text{n,p})\text{Sc}^{46}$ reaction, and 36.8 b for the $\text{Co}^{59}(\text{n},\gamma)\text{Co}^{60}$ reaction. The fast fluences obtained from the four circumferential positions at a given axial location were averaged. Allowance was made for a 1.3% decrease in flux between the monitor location and specimen locations. The means of the iron and titanium data for fluence in $(E > 0.18 \text{ MeV})_{\text{ORR}}$ were converted to fluence in $(E > 0.18 \text{ MeV})_{\text{HTGR}}$ and equivalent fission fluence for graphite damage through conversion factors based on the number of displaced carbon atoms, using the Thompson and Wright model with 1 n/cm^2 (EFFDG) causing 720×10^{-24} displacements per atom. The following factors were used:

$$\text{Fluence } (E > 0.18 \text{ MeV})_{\text{HTGR}} = 0.894 \times \text{Fluence } (E > 0.18 \text{ MeV})_{\text{ORR}}.$$

$$\text{Fluence (EFFGD)} = 1.118 \times \text{Fluence } (E > 0.18 \text{ MeV})_{\text{ORR}}.$$

Fast and thermal fluences at each of the seven axial locations are plotted in Fig. 4-2 as a function of height above the bottom of the core. The corresponding fluences at the midpoint of each crucible are listed in Table 4-1.

Fig. 4-2. Measured fast ($E > 0.18$ MeV)_{ORR} and thermal fluence values for the OG-2 experiment

5. EXPERIMENTAL RESULTS - DIMENSIONAL CHANGES

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

The OG-2 experiment included specimens from four grades of near-isotropic nuclear graphite. Dimensional changes were measured on 69 H-429 and 394 H-451 graphite specimens taken from GLCC prototype logs. In addition, the dimensions of 98 TS-1240 and 66 P₃JHAN graphite specimens were measured. All specimens were cylinders, either 0.20 in. in diameter by 0.45 in. long or 0.25 in. in diameter by 0.9 in. long.

The total dimensional change of each specimen was calculated from the length of the specimen taken before any irradiation (ℓ_0) and the length of the cylinder following the OG-2 irradiation (ℓ). The dimensional change was calculated as $(\ell - \ell_0)/\ell_0$ and the irradiation strain was calculated as $\ln(\ell/\ell_0)$. For total strains of less than 0.01 in./in., $(\ell - \ell_0)/\ell_0 = \ln(\ell/\ell_0)$. Where $(\ell - \ell_0)/\ell_0 > 0.01$, both values are given in the data tables presented herein. Each graphite specimen was assigned an average irradiation temperature and a mean fast neutron fluence based upon the specimen location in the OG-2 capsule crucibles as detailed earlier. For previously irradiated specimens, the total fast fluence was found by adding the OG-2 fluence to the previous fast fluence value. Average irradiation temperature was calculated using fluence-weighted temperatures for specimens subjected to multiple irradiations (i.e., for specimen 6500, $T_{\text{avg}} = [(2.0 \times 660) + (1.7 \times 690)]/3.7 = 675$). All fast neutron fluences are in HTGR units ($E > 0.18 \text{ MeV}$)_{HTGR}.

Data previously reported in ORR fluences have been restated in HTGR fluences and are presented, along with minor temperature corrections for the OG-1 capsule data and earlier H-429 data, in Tables 5-1 through 5-10. The H-451/H-429 data are plotted in Figs. 5-1 and 5-2. The data plotted in Figs. 5-1 and 5-2 are grouped in 100°C intervals about the midpoint temperature (i.e., 950°C data include all data from 900° to 999°C).

TABLE 5-1
 DIMENSIONAL CHANGE DATA, H-429, AXIAL DIRECTION,
 AFTER IRRADIATION IN CAPSULES GEH-422, 452, 482

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
3624	2.75	525	-0.72	
3600	2.75	↓	-0.66	
3601	2.80		-0.69	
3602	2.90		-0.73	
3603	3.00		-0.74	
3604	3.07	↓	-0.81	
3605	3.10	525	-0.82	
2444	0.27	625	+0.05	
2448	↓	↓	+0.02	
2452			+0.07	
2473			+0.03	
2489			+0.04	
2492			+0.04	
2500		↓	+0.02	
2522	0.27	625	+0.05	
3700	2.75	775	-0.45	
3724	2.75	↓	-0.54	
3701	2.80		-0.53	
3702	2.90		-0.52	
3703	3.00		-0.55	
3704	3.07	↓	-0.51	
3705	3.10	775	-0.63	
2537	0.73	900	-0.03	
2594	↓	↓	-0.06	
2605			-0.01	
2606	↓	↓	-0.03	
2612	0.73	900	-0.02	
2653	1.10	1000	-0.14	
2659	↓	↓	-0.11	
2667			-0.15	
2671			-0.23	
2673			-0.20	
2680			-0.12	
2648			-0.15	
2649	↓	↓	-0.21	
2642	1.10	1000	-0.19	

TABLE 5-1 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
2440	1.55	1100	-0.26	
2689	↓	↓	-0.28	
2692			-0.21	
2694	↓	↓	-0.23	
2706	1.55	1100	-0.28	
2402	2.20	1275	-1.08	
2403	↓	↓	-0.80	
2419			-0.97	
2426	↓	↓	-1.18	-1.17
2754		1275	-1.06	-1.05
2761	↓	1325	-1.22	-1.21
2764	2.20	1325	-1.36	-1.35
2850	2.65	1475	-1.86	-1.84
2853	2.65	1475	-1.91	-1.89
2791	↓	1500	-1.83	-1.81
2815		↓	-2.08	-2.05
2816			-1.85	-1.83
2821			-1.84	-1.82
2866			-1.98	-1.96
2870			-2.36	-2.33
2871	↓	↓	-2.19	-2.16
2872			-2.00	-1.98
2882			-2.22	-2.19

TABLE 5-2
DIMENSIONAL CHANGE DATA, H-429, AXIAL DIRECTION, AFTER IRRADIATION IN CAPSULE OG-1

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
5540	2402	2.20	1275	3.3	1045	5.50	1135	-1.86	-1.84
5542	2403	↓	1275	↓	↓	↓	1135	-1.50	-1.50
5563	2764	↓	1325	↓	↓	↓	1155	-2.14	-2.12
5565	2761	↓	1325	↓	↓	↓	1155	-1.45	-1.44
5571	2426	↓	1275	↓	↓	↓	1135	-2.10	-2.08
5573	2419	2.20	1275	3.3	1045	5.50	1135	-1.71	-1.69
5614	2791	2.65	1500	3.2	1370	5.85	1430	-3.12	-3.07
5616	2816	↓	↓	↓	↓	↓	↓	-2.83	-2.79
5618	2815	↓	↓	↓	↓	↓	↓	-3.74	-3.67
5620	2821	↓	↓	↓	1370	↓	1430	-3.52	-3.46
5653	2882	↓	↓	↓	1335	↓	1410	-3.43	-3.37
5654	2866	↓	↓	↓	↓	↓	↓	-2.84	-2.80
5655	2871	↓	↓	↓	↓	↓	↓	-3.29	-3.23
5665	2872	↓	↓	↓	↓	↓	↓	-3.09	-3.04
5666	2870	↓	1500	↓	↓	↓	1410	-3.40	-3.34
5669	2853	↓	1475	↓	↓	↓	1400	-3.15	-3.10
5670	2850	2.65	1475	3.2	1335	5.85	1400	-2.95	-2.95
5947	2605	0.73	900	2.3	890	3.00	890	-0.54	
5948	2612	↓	↓	↓	↓	↓	↓	-0.48	
5949	2594	↓	↓	↓	↓	↓	↓	-0.36	
5950	2606	↓	↓	↓	↓	↓	↓	-0.61	
5951	2537	0.73	900	↓	↓	3.00	890	-0.53	
5952	2649	1.10	1000	↓	↓	3.40	925	-0.62	
5953	2642	↓	↓	↓	890	3.40	925	-0.56	
6003	2671	↓	↓	↓	850	3.40	900	-0.72	
6004	2653	↓	↓	↓	↓	↓	↓	-0.62	
6005	2673	↓	↓	↓	↓	↓	↓	-0.52	
6010	2659	↓	↓	↓	↓	↓	↓	-0.52	
6011	2680	↓	↓	↓	↓	↓	↓	-0.58	
6012	2648	↓	↓	↓	↓	↓	↓	-0.56	
6013	2667	1.10	1000	2.3	850	3.40	900	-0.46	
6269	2522	0.27	625	1.4	630	1.67	630	-0.24	
6271	2448	↓	↓	↓	↓	↓	↓	-0.20	
6273	2500	↓	↓	↓	↓	↓	↓	-0.24	
6275	2452	0.27	625	1.4	630	1.67	630	-0.16	

TABLE 5-3

DIMENSIONAL CHANGE DATA, H-429, AXIAL DIRECTION, AFTER IRRADIATION IN CAPSULE OG-2

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm 2) (E>0.18 MeV) _{HTGR}	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm 2) (E>0.18 MeV) _{HTGR}	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm 2) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
6924	5540	5.50	1135	2.95	1235	8.45	1170	-2.48	-2.45
6926	5542	↓	1135	↓	↓	8.45	1170	-2.26	-2.19
6928	5563	↓	1155	↓	↓	8.45	1185	-2.75	-2.72
6930	5565	↓	1155	↓	↓	↓	1185	-2.80	-2.76
6932	5571	↓	1135	↓	↓	↓	1170	-2.72	-2.69
6934	5573	5.50	1135	2.95	1235	8.45	1170	-2.74	-2.71
6990	5614	5.85	1430	2.90	1380	8.75	1415	-3.69	-3.62
6992	5616	↓	↓	↓	↓	↓	1415	-3.78	-3.63
6994	5618	↓	↓	↓	↓	↓	1415	-3.73	-3.67
6996	5620	↓	1430	↓	↓	↓	1415	-3.71	-3.64
6997	5653	↓	1410	↓	↓	↓	1400	-3.88	-3.81
6998	5654	↓	↓	↓	↓	↓	1400	-3.74	-3.67
6999	5655	↓	↓	↓	↓	↓	1400	-3.77	-3.70
7005	5665	↓	↓	↓	↓	↓	1400	-3.61	-3.55
7006	5666	↓	1410	↓	↓	↓	1400	-3.95	-3.88
7009	5669	↓	1400	↓	↓	↓	1395	-3.22	-3.17
7010	5670	5.85	1400	2.90	1380	8.75	1395	-3.60	-3.53
7354	5947	3.00	890	2.15	925	5.15	905	-1.40	-1.39
7355	5948	↓	↓	↓	↓	↓	905	-1.32	-1.31
7356	5949	↓	↓	↓	↓	↓	905	-1.25	-1.24
7357	5950	↓	↓	↓	↓	↓	905	-1.60	-1.59
7358	5951	3.00	890	↓	↓	5.15	905	-1.34	-1.33
7359	5952	3.40	925	↓	↓	5.55	925	-1.34	-1.33
7360	5953	↓	925	↓	925	↓	925	-1.24	-1.23
7391	6003	↓	900	↓	850	↓	880	-1.51	-1.50
7392	6004	↓	↓	↓	↓	↓	880	-1.30	-1.29
7393	6005	↓	↓	↓	↓	↓	880	-1.42	-1.41
7394	6010	↓	↓	↓	↓	↓	880	-1.36	-1.35
7395	6011	↓	↓	↓	↓	↓	880	-1.39	-1.38
7396	6012	↓	↓	↓	↓	↓	880	-1.29	-1.28
7397	6013	3.40	900	2.15	850	5.55	880	-1.28	-1.27
7557	6269	1.67	630	1.15	635	2.82	630	-0.48	
7559	6271	↓	↓	↓	↓	↓	630	-0.34	
7561	6273	↓	↓	↓	↓	↓	630	-0.51	
7563	6275	1.67	630	1.15	635	2.82	630	-0.30	

TABLE 5-4
 DIMENSIONAL CHANGE DATA, H-451, AXIAL DIRECTION,
 AFTER IRRADIATION IN CAPSULE OG-1

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain ln(ℓ/ℓ_0) (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
5000	2.0	660	-0.05	
5001	2.0	660	-0.10	
5004	2.0	645	-0.12	
5008			-0.11	
5012			-0.10	
5016			-0.10	
5020			-0.14	
5024			-0.09	
5028		645	-0.05	
5032		620	-0.12	
5036			-0.24	
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		620	-0.14	
5090		570	-0.18	
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	2.0	570	-0.12	

TABLE 5-4 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) ($E > 0.18$ MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
5104	2.0	570	-0.16	
5105			-0.19	
5108			-0.16	
5109			-0.15	
5112			-0.16	
5122			-0.22	
5123			-0.18	
5132			-0.14	
5133	2.0	570	-0.15	
5142	2.6	760	-0.35	
5143	2.6	760	-0.14	
5146	2.6	740	-0.23	
5150			-0.12	
5154			-0.15	
5158			-0.16	
5162			-0.22	
5166			-0.28	
5170			-0.17	
5174		740	-0.13	
5178		700	-0.12	
6472			-0.17	
5187			-0.24	
5188			-0.16	
5191			-0.23	
5192			-0.10	
5197			-0.12	
5198			-0.19	
5201			-0.27	
5202			-0.21	
5207			-0.02	
5208			-0.22	
5211			-0.24	
5212		700	-0.26	
5243		630	-0.30	
5244			-0.15	
5247			-0.17	
5248			-0.24	
5253			-0.23	
5254	2.6	630	-0.25	
			-0.28	

TABLE 5-4 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
5301	3.0 ↓	995	-0.72	-1.05
5303		995	-0.78	
5305		995	-1.06	
5307		980	-0.64	
5309		↓	-0.90	
5311		↓	-0.77	
5313		↓	-0.61	
5315		980	-0.79	
5317		950	-0.99	
5352		↓	-0.68	
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		950	-0.67	
5384		900	-0.85	
5422		↓	-0.50	
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		900	-0.47	
5438	3.0	↓	-0.58	

TABLE 5-4 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
5439	3.0	900	-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	
5452			-0.42	
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	3.0	900	-0.41	
5479	3.3	1180	-1.09	-1.08
5480	3.3	1180	-1.20	-1.20
5483	3.3	1160	-1.07	-1.06
5484	3.3	1160	-1.14	-1.13
5487			-1.02	-1.01
5488			-1.13	-1.13
5491			-1.07	-1.06
5492	3.3	1160	-1.11	-1.10
5495			-1.04	-1.03
5496			-0.99	-0.98

TABLE 5-4 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
5498	3.3	1160	-1.01	-1.00
5499	↓	↓	-1.17	-1.17
5502	↓	↓	-0.97	-0.97
5503	↓	1160	-1.08	-1.07
5516	↓	1115	-1.27	-1.26
5574	↓	1045	-1.22	-1.21
5576	3.3	1045	-1.19	-1.19
5577	3.2	1395	-3.00	-2.96
5578	3.2	1395	-2.74	-2.70
5581	3.2	1385	-2.85	-2.81
5582	↓	↓	-2.99	-2.94
5585	↓	↓	-3.06	-3.01
5586	↓	↓	-3.05	-3.00
5589	↓	↓	-2.92	-2.87
5590	↓	↓	-3.07	-3.03
5593	↓	↓	-3.01	-2.97
5594	↓	↓	-3.05	-3.01
5597	↓	↓	-2.88	-2.84
5598	↓	↓	-3.02	-2.98
5601	↓	↓	-3.07	-3.03
5602	↓	↓	-3.00	-2.96
5605	↓	↓	-2.76	-2.73
5607	↓	↓	-2.81	-2.77
5609	↓	↓	-2.77	-2.74
5611	↓	1385	-3.09	-3.05
5625	↓	1370	-2.88	-2.84
5626	↓	↓	-2.63	-2.60
5639	↓	↓	-2.90	-2.86
5640	↓	1370	-2.71	-2.68
5649	↓	1335	-2.61	-2.58
5650	↓	↓	-2.43	-2.40
5659	↓	↓	-2.43	-2.40
5660	↓	↓	-2.45	-2.42
5661	↓	↓	-2.58	-2.54
5662	↓	↓	-2.49	-2.46
5671	↓	↓	-2.50	-2.47
5672	↓	↓	-2.21	-2.19
5673	↓	↓	-2.35	-2.32
5675	↓	↓	-1.80	-1.78
5680	3.2	1335	-2.59	-2.55

TABLE 5-4 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
5681	3.2	1335	-2.25	-2.23
5682	↓	↓	-2.61	-2.58
5683	↓	↓	-2.30	-2.28
5688	↓	↓	-2.48	-2.45
5690	3.2	1335	-2.39	-2.36
5692	3.0	1085	-1.26	-1.25
5693	↓	1085	-1.23	-1.22
5696	↓	1065	-1.16	-1.15
5697	↓	↓	-1.11	-1.11
5700	↓	↓	-1.15	-1.15
5701	↓	↓	-1.08	-1.07
5704	↓	↓	-1.17	-1.16
5705	↓	↓	-1.05	-1.04
5710	↓	↓	-1.14	-1.14
5711	↓	↓	-1.09	-1.09
5714	↓	↓	-1.13	-1.12
5715	↓	↓	-1.10	-1.09
5718	↓	↓	-1.13	-1.12
5719	↓	↓	-1.08	-1.07
5722	↓	↓	-1.17	-1.16
5723	↓	↓	-1.06	-1.05
5726	↓	↓	-1.12	-1.12
5727	↓	1065	-1.03	-1.02
5730	↓	1025	-1.10	-1.09
5731	↓	1025	-0.97	-0.96
5764	↓	1025	-0.63	-0.62
5773	↓	960	-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	3.0	960	-0.66	
5803	2.8	995	-0.81	
5810	↓	980	-0.69	
5814	2.8	980	-0.73	

TABLE 5-4 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) HTGR	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
5818	2.8 ↓	980	-0.74	
5822		980 ↓	-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		950	-0.60	
5843		950 ↓	-0.60	
5846			-0.65	
5847			-0.64	
5850			-0.72	
5852			-0.56	
5854			-0.78	
5868		950	-0.47	
5879		900	-0.50	
5889		900 ↓	-0.53	
5891			-0.53	
5897			-0.52	
5900			-0.42	
5902			-0.52	
5904	2.8	900	-0.49	
5906	2.3	930	-0.54	
5910	2.3 ↓	915	-0.46	
5914		915 ↓	-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		915	-0.42	
6020		850	-0.32	
6021		850 ↓	-0.30	
6040			-0.48	
6042	2.3		-0.28	

TABLE 5-4 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
6044	2.3	850	-0.32	
6046	2.3	850	-0.25	
6048	1.9	865	-0.21	
6052		850	-0.18	
6056			-0.18	
6060			-0.18	
6064			-0.17	
6068			-0.21	
6072			-0.18	
6076			-0.16	
6080		850	-0.22	
6084		820	-0.34	
6088			-0.10	
6094			-0.22	
6098			-0.13	
6104			-0.16	
6108			-0.15	
6114			-0.14	
6118		820	-0.16	
6150		770	-0.15	
6154			-0.13	
6160			-0.14	
6194			-0.13	
6195			-0.14	
6200			-0.12	
6201			-0.23	
6204			-0.14	
6205	1.9	770	-0.16	
6208	1.4	650	-0.06	
6212		645	-0.04	
6216			0.00	
6220			-0.07	
6224			-0.10	
6228			-0.07	
6232			-0.10	
6236			-0.22	
6240		645	-0.08	
6256		630	-0.16	
6257			-0.13	
6266	1.4	630	-0.12	

TABLE 5-4 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
6267	1.4 ↓	630	-0.09	
6276		630	-0.11	
6277		630	-0.02	
6298		605	-0.15	
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			-0.12	
6341	1.4	605	-0.23	

TABLE 5-5
DIMENSIONAL CHANGE DATA, H-451, AXIAL DIRECTION, AFTER IRRADIATION IN CAPSULE OG-2

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) HTGR	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm ²) (E>0.18 MeV) HTGR	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) HTGR	Irrad Temp (°C)	Irrad Strain ln(ℓ/ℓ_0) (10 ⁻²)	Dimensional Change, $\Delta\ell/\ell_0$ (%)
6500	5000	2.0	660	1.7	690	3.7	675	-0.26	
6501	5001		660		690	3.7	675	-0.33	
6504	5004		645		680	3.7	660	-0.28	
6508	5008		645		680		660	-0.30	
6512	5012				680		660	-0.28	
6513	5016				680			-0.32	
6516	5020							-0.28	
6517	5024	2.0	645			3.7	660	-0.30	
6520(a)	5696	3.0	1065			4.7	(a)	-1.68	-1.67
6521(a)	5697						(a)	-1.67	-1.66
6524(a)	5700						(a)	-1.68	-1.66
6525(a)	5701						(a)	-1.64	-1.63
6528(a)	5704						(a)	-1.64	-1.63
6529(a)	5705						(a)	-1.60	-1.58
6532(a)	5710						(a)	-1.61	-1.60
6533(a)	5711	3.0	1065		680	4.7	945	-1.65	-1.63
6536	--	--	--		660	1.7	660	-0.11	
6537	--	--	--					-0.13	
6538	--	--	--					-0.09	
6539	--	--	--					-0.14	
6540	--	--	--					-0.12	
6541	--	--	--					-0.15	
6542	--	--	--					-0.08	
6543	--	--	--					-0.16	
6544	--	--	--					-0.08	
6545	--	--	--					-0.03	
6546	--	--	--					-0.11	
6547	--	--	--		660	1.7	660	-0.14	
6605	5102	2.0	570		615	3.7	590	-0.42	
6606	5103							-0.55	
6607	5112							-0.41	
6608	5113							-0.58	
6609	5122							-0.43	
6610	5123							-0.55	
6611	5132							-0.42	
6612	5133	2.0	570			3.7	590	-0.65	
6613	--	--	--			1.7	615	-0.12	
6614	--	--	--					-0.15	
6615	--	--	--					-0.16	
6616	--	--	--					-0.23	
6617	--	--	--					-0.11	
6618	--	--	--					-0.16	
6619	--	--	--					-0.21	
6620	--	--	--					-0.23	
6621	--	--	--					-0.13	
6622	--	--	--					-0.16	
6623	--	--	--					-0.13	
6624	--	--	--	1.7	615	1.7	615	-0.15	
6625	5142	2.6	760	2.2	780	4.8	770	-0.49	
6626	5143		760	2.2	780		770	-0.62	
6629	5146		740	2.2	765		750	-0.47	
6633	5150						750	-0.53	
6637	5154						750	-0.53	
6641	5158							-0.52	
6645	5162							-0.62	
6649	5166							-0.54	
6653	5170							-0.50	
6657	5174		740		765		750	-0.49	
6691	5243		630		680		655	-0.59	
6692	5244							-0.65	
6695	5247							-0.64	
6696	5248							-0.62	
6699	5253							-0.63	
6700	5254	2.6	630	2.2	680	4.8	655	-0.67	
6731	5301	3.0	995	2.7	1000	5.7	995	-2.10	-2.08
6733	5303	3.0	995		1000	5.7	995	-2.09	-2.06
6735	5305	3.0	995		1000	5.7	995	-2.54	-2.51
6776	--	--	--		970	2.7	970	-0.41	
6777	--	--	--					-0.52	
6778	--	--	--					-0.56	
6779	--	--	--					-0.42	
6780	--	--	--					-0.58	
6781	--	--	--					-0.67	
6782	--	--	--	2.7	970	2.7	970	-0.47	

TABLE 5-5 (continued)

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm 2) (E>0.18 MeV) HTGR	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm 2) (E>0.18 MeV) HTGR	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm 2) (E>0.18 MeV) HTGR	Irrad Temp (°C)	Irrad Strain ln(ℓ/ℓ_0) (10 $^{-2}$)	Dimensional Change, $\Delta\ell/\ell_0$ (%)
6783	--	--	--	2.7	970	2.7	970	-0.60	
6784	--	--	--					-0.71	
6785	--	--	--					-0.45	
6786	--	--	--			2.7	970	-0.74	
6787	--	--	--			5.7	960	-0.51	-1.93
6800	5371	3.0	950					-1.95	-2.26
6801	5372							-2.29	-2.30
6802	5373							-2.33	-1.94
6803	5377							-1.95	-2.32
6804	5378							-2.34	-2.36
6805	5379							-2.39	-1.91
6806	5380							-1.93	-2.31
6807	5381		950		970		960	-2.34	-2.35
6808	5382		900		920		910	-2.38	-1.58
6815	5440							-1.60	-1.84
6816	5441							-1.85	-1.56
6818	5449							-1.58	-1.83
6819	5450							-1.85	-1.53
6821	5458							-1.55	-1.86
6822	5459							-1.88	-1.63
6824	5468							-1.64	-1.88
6825	5469							-1.89	-1.79
6839	5425							-1.81	-2.00
6840	5426							-2.02	-2.07
6841	5427							-2.09	-1.68
6842	5428							-1.69	-2.02
6843	5429							-2.04	-2.07
6844	5430							-2.10	-1.58
6845	5434							-1.59	-1.80
6846	5435							-1.82	-1.83
6847	5436							-1.85	-1.51
6848	5437							-1.52	-1.80
6849	5438							-1.82	-1.95
6850	5439	3.0	900	2.7	920	5.7	910	-1.97	-2.26
6899	5479	3.3	1180	2.95	1255	6.25	1215	-2.29	-2.31
6900	5480		1180		1255		1215	-2.34	-2.31
6903	5483		1160		1235		1195	-2.29	-2.26
6904	5484	3.3	1160	2.95	1235	6.25	1195	-2.37	-2.34
6911	5491			2.95	1235	6.25	1195	-2.35	-2.32
6912	5492	3.3	1160	2.95	1235	6.25	1195	-2.36	-2.33
6985	5577	3.2	1395	2.9	1390	6.10	1395	-3.89	-3.82
6986	5578	3.2	1395		1390	6.10	1395	-3.80	-3.73
7011	5581	3.2	1385		1380	6.10	1385	-3.60	-3.53
7021	--	--	--		1365	2.9	1365	-1.94	-1.93
7022	--	--	--					-1.88	-1.87
7023	--	--	--					-1.88	-2.04
7024	--	--	--					-2.06	-1.96
7025	--	--	--					-1.98	-2.19
7026	--	--	--					-2.22	-2.09
7027	--	--	--					-2.11	-2.24
7028	--	--	--					-2.27	-1.09
7029	--	--	--					-1.09	-2.05
7030	--	--	--					-2.07	-1.85
7072	5673	3.2	1335		1365	2.9	1365	-1.86	-3.47
7074	5675				1325	6.10	1330	-3.53	-3.13
7075	5661							-3.18	-3.65
7076	5662							-3.71	-3.57
7077	5671							-3.64	-3.65
7078	5672							-3.72	-3.46
7079	5680							-3.52	-3.77
7080	5681							-3.84	-3.54
7081	5682							-3.61	-3.66
7082	5683	3.2	1335			6.10	1330	-3.73	-3.43
7083	--	--	--			2.9	1325	-3.49	-2.02
7084	--	--	--					-2.04	-2.01
7085	--	--	--					-2.03	-1.98
7086	--	--	--					-2.00	-1.92
7087	--	--	--					-1.94	-1.86
7088	--	--	--					-1.88	-1.82
7089	--	--	--					-1.83	-1.80
7090	--	--	--					-1.82	-1.79
7091	--	--	--					-1.81	-1.72
7092	--	--	--					-1.73	-1.64
7097	5764	3.0	1025	2.9	1325	2.9	1325	-1.66	-2.61
				2.7	1085	5.7	1055	-2.64	

TABLE 5-5 (continued)

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm 2) (E>0.18 MeV) HTGR	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm 2) (E>0.18 MeV) HTGR	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm 2) (E>0.18 MeV) HTGR	Irrad Temp (°C)	Irrad Strain ln(ℓ/ℓ_0) (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
7099	5773	3.0	960	2.7	1065	5.7	1010	-2.36	-2.33
7101	5777							-2.23	-2.20
7103	5781							-2.29	-2.27
7104	5782							-2.55	-2.51
7106	5789							-1.16	-1.15
7108	5793							-2.44	-2.41
7110	5795	3.0	960		1065	5.7	1010	-2.42	-2.39
7127(a)	5092	2.0	570		1035	4.7	(a)	-0.19	
7128(a)	5093						(a)	-1.47	-1.46
7131(a)	5096						(a)	-1.34	-1.33
7132(a)	5097						(a)	-1.28	-1.28
7135(a)	5104						(a)	-1.36	-1.35
7136(a)	5105						(a)	-1.37	-1.36
7139(a)	5108						(a)	-1.44	-1.43
7140	5109	2.0	570			4.7	835	-1.33	-1.32
7144	5799	3.0	960			5.7	995	-2.45	-2.42
7146	5801	3.0	960	2.7	1035	5.7	995	-2.34	-2.31
7215	5803	2.8	995	2.5	1000	5.3	1000	-2.18	-2.16
7219	5810		980		990		985	-2.06	-2.04
7223	5814							-2.12	-2.10
7227	5818							-2.17	-2.15
7231	5822							-2.16	-2.14
7235	5826							-1.93	-1.92
7236	5827							-2.07	-2.05
7239	5830							-1.91	-1.89
7240	5831							-2.13	-2.11
7243	5834							-2.12	-2.10
7244	5835		980		990		985	-2.05	-2.03
7249	5868		950		970		960	-2.13	-2.10
7307	5879		900		920		910	-1.84	-1.82
7308	5889							-1.76	-1.74
7309	5891							-1.85	-1.83
7310	5897							-1.70	-1.68
7311	5902							-1.78	-1.76
7312	5904	2.8	900	2.5	920	5.3	910	-1.70	-1.68
7325	5930	2.3	915	2.15	940	4.45	930	-1.57	-1.55
7326	5931				940		930	-1.41	-1.40
7329	5934				925		920	-1.44	-1.43
7330	5935							-1.27	-1.26
7333	5938							-1.42	-1.41
7334	5939	2.3	915		925	4.45	920	-1.36	-1.35
7361	--	--	--		905	2.15	905	-0.30	
7362	--	--	--					-0.26	
7363	--	--	--					-0.30	
7364	--	--	--					-0.22	
7365	--	--	--					-0.30	
7366	--	--	--					-0.22	
7367	--	--	--					-0.32	
7368	--	--	--					-0.28	
7369	--	--	--					-0.34	
7370	--	--	--					-0.23	
7371	--	--	--					-0.29	
7372	--	--	--		905		905	-0.23	
7410	--	--	--		850		850	-0.24	
7412	--	--	--					-0.26	
7413	--	--	--					-0.18	
7414	--	--	--					-0.26	
7415	--	--	--					-0.19	
7416	--	--	--					-0.23	
7417	--	--	--	2.15	850	2.15		-0.23	
7422	6048	1.9	865	1.7	835	3.6	850	-0.67	
7424	6052		850		835		845	-0.54	
7426	6056				820		835	-0.57	
7428	6060							-0.52	
7430	6064							-0.60	
7432	6068							-0.51	
7434	6072							-0.60	
7436	6076							-0.49	
7438	6080		850				835	-0.62	
7440	6084		820				820	-0.49	
7442	6088							-0.52	
7444	6094							-0.40	
7446	6098							-0.52	
7448	6104	1.9	820	1.7	820	3.6	820	-0.35	
7528	6208	1.4	650	1.15	645	2.55	650	-0.24	

TABLE 5-5 (continued)

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10 ⁻²)	Dimensional Change, $\Delta l/l_0$ (%)
7532	6212	1.4	645	1.15	635	2.55	640	-0.27	
7536	6216		↓		↓		↓	-0.27	
7540	6220							-0.23	
7544	6224		645		635		640	-0.22	
7589	6304		605		590		600	0.01	
7590	6305							-0.24	
7593	6312							-0.32	
7594	6313							-0.28	
7605	6310							-0.35	
7606	6311							-0.24	
7607	6320							-0.25	
7608	6321							-0.18	
7609	6330							-0.33	
7610	6331							-0.24	
7611	6340							-0.42	
7612	6341	1.4	605	1.15	590	2.55	600	-0.25	

(a) Temperature change samples.

TABLE 5-6
 DIMENSIONAL CHANGE DATA, H-429, RADIAL DIRECTION,
 AFTER IRRADIATION IN CAPSULES GEH-422, 452, 482

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) HTGR	Irrad Temp (°C)	Irrad Strain ln(ℓ/ℓ_0) (10^{-2})
3609	3.35	475	-0.60
3610	3.40	475	-0.59
3611	3.45	475	-0.60
3625	2.80	525	-0.59
3606	3.20	525	-0.62
3607	3.25	525	-0.65
3608	3.30	525	-0.61
2461	0.27	625	0.00
2467	↓	↓	-0.01
2488	↓	↓	+0.02
2497	↓	↓	+0.01
2518	↓	↓	+0.02
2521	↓	↓	+0.00
2524	↓	↓	+0.02
2532	0.27	625	+0.00
3725	2.80	775	-0.34
3706	3.20	775	-0.43
3707	3.25	775	-0.47
3708	3.30	775	-0.52
3709	3.35	800	-0.50
3710	3.40	800	-0.45
3711	3.45	800	-0.53
2564	0.73	900	+0.12
2580	↓	↓	+0.01
2598	↓	↓	+0.03
2601	↓	↓	+0.01
2608	0.73	900	+0.03
2645	1.10	1000	-0.20
2652	↓	↓	-0.10
2655	↓	↓	-0.10
2662	↓	↓	-0.10
2663	↓	↓	-0.06
2665	↓	↓	-0.05
2672	↓	↓	-0.14
2681	↓	↓	-0.08
2687	1.10	1000	-0.03
2688	1.50	1100	-0.06
2690	↓	↓	-0.08
2691	↓	↓	-0.14
2702	↓	↓	-0.14
2712	1.50	1100	-0.12

TABLE 5-6 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) HTGR	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})
2428	2.20	1275	-0.64
2430	↓	↓	-0.86
2436	↓	↓	-0.81
2442	↓	1275	-0.98
2748	2.20	1325	-1.11
2855	2.65	1475	-1.61
2861	↓	1475	-1.60
2800	↓	1500	-1.55
2804	↓	↓	-1.46
2807	↓	↓	-1.59
2823	↓	↓	-1.48
2849	↓	↓	-1.54
2858	↓	↓	-1.62
2864	↓	↓	-1.68
2875	↓	↓	-1.66
2877	2.65	1500	-1.64

TABLE 5-7
 DIMENSIONAL CHANGE DATA, H-429, RADIAL DIRECTION, AFTER IRRADIATION IN CAPSULE OG-1

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10 ⁻²)	Dimensional Change, $\Delta l/l_0$ (%)
5539	2436	2.2	1275	3.3	1045	5.5	1135	-1.16	-1.15
5541	2428	↓	1275	↓	↓	↓	1135	-1.01	-1.00
5562	2748	↓	1325	↓	↓	↓	1155	-1.47	-1.46
5570	2442	↓	1275	↓	↓	↓	1135	-1.40	-1.39
5572	2430	2.2	1275	3.3	1045	5.5	1135	-1.25	-1.24
5613	2823	2.65	1500	3.2	1370	5.85	1430	-2.19	-2.17
5615	2804	↓	↓	↓	↓	↓	↓	-2.12	-2.10
5617	2807	↓	↓	↓	↓	↓	↓	-2.33	-2.30
5619	2800	↓	↓	↓	1370	↓	1430	-2.14	-2.12
5656	2858	↓	↓	↓	1335	↓	1410	-2.38	-2.35
5657	2849	↓	↓	↓	↓	↓	↓	-2.23	-2.21
5658	2875	↓	↓	↓	↓	↓	↓	-2.23	-2.21
5663	2864	↓	↓	↓	↓	↓	↓	-2.25	-2.23
5664	2877	↓	1500	↓	↓	↓	1410	-2.28	-2.26
5667	2861	↓	1475	↓	↓	↓	1400	-2.15	-2.13
5668	2855	2.65	1475	3.2	1335	5.85	1400	-2.37	-2.34
5942	2598	0.73	900	2.3	890	3.0	890	-0.31	
5943	2580	↓	↓	↓	↓	↓	↓	-0.30	
5944	2601	↓	↓	↓	↓	↓	↓	-0.22	
5945	2564	↓	↓	↓	↓	↓	↓	-0.28	
5946	2608	0.73	900	↓	890	3.0	890	-0.33	
5998	2665	1.1	1000	↓	850	3.4	900	-0.37	
5999	2663	↓	↓	↓	↓	↓	↓	-0.38	
6000	2672	↓	↓	↓	↓	↓	↓	-0.48	
6001	2655	↓	↓	↓	↓	↓	↓	-0.33	
6002	2681	↓	↓	↓	↓	↓	↓	-0.37	
6014	2662	↓	↓	↓	↓	↓	↓	-0.37	
6015	2652	↓	↓	↓	↓	↓	↓	-0.40	
6016	2645	↓	↓	↓	↓	↓	↓	-0.41	
6017	2687	1.1	1000	2.3	850	3.4	900	-0.26	
6268	2497	0.27	625	1.4	630	1.67	630	-0.24	
6270	2524	0.27	625	1.4	630	1.67	630	-0.15	
6272	2488	0.27	625	1.4	630	1.67	630	-0.23	

TABLE 5-8

DIMENSIONAL CHANGE DATA, H-429, RADIAL DIRECTION, AFTER IRRADIATION IN CAPSULE OG-2

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm 2) (E>0.18 MeV) _{HTGR}	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm 2) (E>0.18 MeV) _{HTGR}	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm 2) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
6923	5539	5.5	1135	2.95	1235	8.45	1170	-1.27	-1.26
6925	5541	↓	1135	↓	↓	↓	1170	-1.20	-1.19
6927	5562	↓	1155	↓	↓	↓	1185	-1.62	-1.61
6931	5570	↓	1135	↓	↓	↓	1170	-1.43	-1.42
6333	5572	5.5	1135	2.95	1235	8.45	1170	-1.35	-1.34
6989	5613	5.85	1430	2.9	1380	8.75	1415	-2.17	-2.14
6991	5615	↓	↓	↓	↓	↓	↓	-1.87	-1.85
6993	5617	↓	↓	↓	↓	↓	↓	-1.79	-1.78
6995	5619	↓	1430	↓	↓	↓	1415	-1.06	-1.06
7000	5656	↓	1410	↓	↓	↓	1400	-2.30	-2.28
7001	5657	↓	↓	↓	↓	↓	↓	-2.18	-2.16
7002	5658	↓	↓	↓	↓	↓	↓	-2.36	-2.34
7003	5663	↓	↓	↓	↓	↓	↓	-2.04	-2.02
7004	5664	↓	1410	↓	↓	↓	1400	-2.07	-2.05
7007	5667	↓	1400	↓	↓	↓	1395	-1.42	-1.41
7008	5668	5.85	1400	2.9	1380	8.75	1395	-1.68	-1.67
7349	5942	3.0	890	2.15	925	5.15	905	-0.78	
7350	5943	↓	↓	↓	↓	↓	↓	-0.73	
7351	5944	↓	↓	↓	↓	↓	↓	-0.61	
7352	5945	↓	↓	↓	↓	↓	↓	-0.74	
7353	5946	3.0	890	↓	925	5.15	905	-0.76	
7386	5998	3.4	900	↓	850	5.55	880	-0.91	
7387	5999	↓	↓	↓	↓	↓	↓	-0.86	
7388	6000	↓	↓	↓	↓	↓	↓	-0.95	
7389	6001	↓	↓	↓	↓	↓	↓	-0.91	
7390	6002	↓	↓	↓	↓	↓	↓	-0.80	
7398	6014	↓	↓	↓	↓	↓	↓	-0.97	
7399	6015	↓	↓	↓	↓	↓	↓	-0.92	
7400	6016	↓	↓	↓	↓	↓	↓	-0.88	
7401	6017	3.4	900	2.15	850	5.55	880	-0.48	
7556	6268	1.67	630	1.15	635	2.82	630	-0.46	
7558	6270	1.67	630	1.15	635	2.82	630	-0.33	
7560	6272	1.67	630	1.15	635	2.82	630	-0.45	

TABLE 5-9
DIMENSIONAL CHANGE DATA, H-451, RADIAL DIRECTION,
AFTER IRRADIATION IN CAPSULE OG-1

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
5002	2.0 ↓	660	-0.04	
5014		645	-0.10	
5010		645	-0.11	
5006		645	-0.07	
5003		660	-0.06	
5111		570	-0.19	
5110		↓	-0.14	
5107		↓	-0.19	
5106		↓	-0.15	
5099		↓	-0.22	
5098		↓	-0.15	
5095		↓	-0.02	
5094		570	-0.18	
5067		620	-0.12	
5066		↓	-0.15	
5063		↓	-0.08	
5062		↓	-0.15	
5057		↓	-0.03	
5056		↓	-0.14	
5053		↓	-0.11	
5052		↓	-0.12	
5047		↓	-0.18	
5046		↓	-0.13	
5042		↓	-0.16	
5038		620	-0.19	
5034		645	-0.09	
5030		↓	-0.09	
5026		↓	-0.10	
5022		↓	-0.05	
5018	2.0	645	-0.04	
5144	2.6	760	-0.19	
5148	↓	740	-0.08	
5145		760	-0.13	
5164		740	-0.16	
5160		↓	-0.13	
5156		↓	-0.10	
5152		740	-0.10	
5256		630	-0.23	
5255		630	-0.14	
5250	2.6	630	-0.15	

TABLE 5-9 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
5249	2.6	630	-0.15	
5246		630	-0.16	
5245		630	-0.06	
5214		700	-0.16	
5213			-0.19	
5210			-0.16	
5209			-0.20	
5204			-0.18	
5203			-0.16	
5200			-0.16	
5199			-0.10	
5194			-0.13	
5193			-0.12	
5190			-0.19	
5189			-0.15	
5183			-0.11	
5180		700	-0.05	
5176		740	-0.06	
5172		740	-0.13	
5168	2.6	740	-0.14	
5302	3.0	995	-0.43	
5318		980	-0.59	
5316			-0.54	
5314			-0.39	
5312			-0.31	
5310			-0.46	
5308		980	-0.43	
5306		995	-0.48	
5304		995	-0.55	
5433		900	-0.30	
5424		900	-0.37	
5385		950	-0.44	
5376			-0.38	
5368			-0.41	
5367			-0.29	
5366			-0.33	
5361			-0.36	
5360			-0.33	
5356			-0.52	
5355			-0.31	
5354			-0.40	
5351			-0.42	
5350	3.0	950	-0.38	

TABLE 5-9 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
5349	3.0	950	-0.34	
5348		950	-0.55	
5347		950	-0.41	
5346		950	-0.31	
5345		980	-0.44	
5344			-0.54	
5343			-0.45	
5342			-0.67	
5341			-0.55	
5340			-0.46	
5339			-0.55	
5338			-0.50	
5337		980	-0.32	
5442		900	-0.30	
5470			-0.30	
5460			-0.31	
5451	3.0	900	-0.33	
5481	3.3	1180	-0.81	
5489		1160	-0.82	
5486		1160	-0.68	
5485		1160	-0.94	
5482		1180	-0.63	
5575		1045	-0.65	
5518		1115	-0.59	
5512		1115	-0.65	
5505		1160	-0.83	
5504			-0.81	
5501			-0.58	
5500			-0.87	
5497			-0.54	
5494			-0.60	
5493			-0.71	
5490			-0.67	
6471	3.3	1160	-0.91	
5579	3.2	1395	-2.08	-2.06
5587		1385	-2.06	-2.04
5584		1385	-1.77	-1.75
5583		1385	-2.09	-2.07
5580		1395	-1.89	-1.87
5588		1385	-1.90	-1.88
5592			-1.60	-1.58
5591			-2.10	-2.08
5600	3.2	1385	-1.78	-1.76

TABLE 5-9 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
5599	3.2	1385	-2.00	-1.98
5596	↓	↓	-1.94	-1.92
5595	↓	↓	-2.04	-2.02
5603	↓	↓	-2.10	-2.08
5606	↓	↓	-1.97	-1.95
5604	↓	1385	-2.03	-2.01
5674	↓	1335	-1.60	-1.58
5612	↓	1385	-1.87	-1.85
5610	↓	1385	-2.02	-2.00
5608	↓	1385	-1.64	-1.62
5691	↓	1335	-1.47	-1.46
5689	3.2	1335	-1.74	-1.74
5695	3.0	1085	-0.53	
5694	↓	1085	-0.60	
5703	↓	1065	-0.50	
5702	↓	↓	-0.61	
5699	↓	↓	-0.49	
5698	↓	↓	-0.64	
5721	↓	↓	-0.49	
5720	↓	↓	-0.55	
5717	↓	↓	-0.50	
5716	↓	↓	-0.56	
5713	↓	↓	-0.51	
5712	↓	↓	-0.57	
5709	↓	↓	-0.52	
5708	↓	↓	-0.60	
5724	↓	1065	-0.63	
5778	↓	960	-0.28	
5774	↓	960	-0.31	
5765	↓	1025	-0.50	
5733	↓	1025	-0.49	
5732	↓	1025	-0.47	
5729	↓	1065	-0.71	
5728	↓	1065	-0.58	
5725	↓	1065	-0.52	
5802	↓	960	-0.34	
5800	↓	↓	-0.41	
5796	↓	↓	-0.33	
5794	↓	↓	-0.27	
5790	↓	↓	-0.33	
5787	↓	↓	-0.30	
5783	3.0	960	-0.33	
5820	2.8	980	-0.33	

TABLE 5-9 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) ($E > 0.18$ MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
5816	2.8	980	-0.41	
5812		980	-0.38	
5808		995	-0.41	
5855		950	-0.35	
5853			-0.20	
5851			-0.50	
5849			-0.23	
5848			-0.36	
5845			-0.14	
5844		950	-0.30	
5841		980	-0.26	
5840			-0.34	
5837			-0.32	
5836			-0.40	
5833			-0.42	
5832			-0.37	
5829			-0.16	
5828			-0.51	
5824		980	-0.40	
5869		950	-0.31	
5905		900	-0.23	
5903			-0.24	
5901			-0.25	
5899			-0.32	
5898			-0.27	
5880			-0.22	
5892	2.8	900	-0.24	
5890		850	-0.18	
6045	2.3		-0.13	
6047			-0.10	
6043			-0.11	
6041			-0.15	
6023		850	-0.09	
6022		915	-0.04	
5941		930	-0.18	
5908		915	-0.22	
5916			-0.21	
5912			-0.18	
5940	2.3		-0.20	
5937			-0.25	
5936			-0.17	
5933		915	-0.19	
5932				

TABLE 5-9 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
5928	2.3	915	-0.28	
5924	2.3	915	-0.22	
5920	2.3	915	-0.23	
6050	1.9	865	-0.12	
6066		850	-0.08	
6062			-0.10	
6058			-0.04	
6054			-0.09	
6070			-0.07	
6078			-0.05	
6074		850	-0.06	
6096		820	-0.09	
6090		820	-0.03	
6086		820	-0.12	
6082		850	-0.08	
6207		770	-0.08	
6206			-0.14	
6203			-0.06	
6202			-0.09	
6197			-0.12	
6196			-0.08	
6162			-0.12	
6156			-0.03	
6152		770	-0.07	
6120		820	-0.12	
6116			-0.07	
6110			-0.03	
6106			-0.04	
6100	1.9	820	-0.10	
6214	1.4	645	-0.03	
6210		650	-0.03	
6218		645	-0.07	
6306		605	-0.15	
6302		605	-0.13	
6242		645	-0.02	
6238			-0.11	
6234			-0.12	
6230			-0.04	
6226			-0.06	
6222		645	-0.05	
6329		605	-0.06	
6328		605	-0.15	
6315	1.4	605	-0.03	

TABLE 5-9 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
6314	1.4	605	-0.11	
6307	↓	↓	-0.10	
6325			-0.04	
6324			-0.06	
6319	↓	↓	-0.14	
6318	1.4	605	-0.05	

TABLE 5-10
DIMENSIONAL CHANGE DATA, H-451, RADIAL DIRECTION,
AFTER IRRADIATION IN CAPSULE OG-2

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm 2) (E>0.18 MeV) HTGR	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm 2) (E>0.18 MeV) HTGR	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm 2) (E>0.18 MeV) HTGR	Irrad Temp (°C)	Irrad Strain ln(ℓ/ℓ_0) (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
6502	5002	2.0	660	1.7	690	3.7	675	-0.27	
6503	5003		660		690		675	-0.28	
6506	5006		645		680		660	-0.29	
6510	5010		570				620	-0.29	
6514	5014		645				660	-0.31	
6515	5018							-0.30	
6518	5022							-0.29	
6519	5026	2.0	645			3.7	660	-0.28	
6522(a)	5698	3.0	1065			4.7	(a)	-1.07	-1.06
6523(a)	5699						(a)	-0.98	
6526(a)	5702						(a)	-1.00	-0.99
6527(a)	5703						(a)	-0.96	
6530(a)	5708						(a)	-0.97	
6531(a)	5709						(a)	-0.88	
6534(a)	5712						(a)	-0.91	
6535	5713	3.0	1065	1.7	680	4.7	925	-0.93	
6627	5144	2.6	760	2.2	780	4.8	770	-0.39	
6628	5145		760		765		770	-0.46	
6631	5148		740				750	-0.38	
6635	5152							-0.36	
6639	5156							-0.41	
6643	5160							-0.44	
6647	5164							-0.41	
6651	5168		740		765		750	-0.40	
6655	5172		630		680		655	-0.39	
6693	5245							-0.49	
6694	5246							-0.50	
6697	5249							-0.52	
6698	5250							-0.46	
6701	5255							-0.48	
6702	5256	2.6	630	2.2	680	4.8	655	-0.49	
6732	5302	3.0	995	2.7	1000	5.7	1000	-0.89	
6734	5304		995		1000		1000	-0.87	
6736	5306		995		1000		1000	-0.87	
6755	5337		980		990		985	-0.98	-1.08
6756	5338							-1.08	-1.10
6757	5339							-1.11	-1.10
6758	5340							-1.15	-1.14
6759	5341							-1.18	-1.17
6760	5342							-1.08	-1.07
6761	5343							-1.18	-1.17
6762	5344							-1.05	-1.05
6763	5345							-1.07	-1.06
6788	5346		980		990		985	-0.98	
6789	5347		950		970		960	-0.98	
6790	5348							-1.03	-1.02
6791	5349							-1.19	-1.18
6792	5350							-1.01	-1.00
6793	5351							-1.01	-1.00
6794	5355							-1.01	-1.01
6795	5356							-1.17	-1.16
6796	5360							-1.01	-1.01
6797	5361							-0.92	
6798	5367				970		960	-1.01	-1.00
6799	5368				920		935	-1.04	-1.03
6809	5354							-1.05	-1.04
6810	5366							-1.02	-1.01
6811	5376		950				935	-1.02	-1.01
6812	5385		900				910	-1.03	-1.02
6813	5424							-1.05	-1.02
6814	5433							-1.00	-1.00
6817	5442							-0.94	
6820	5451							-0.97	
6823	5460							-0.93	
6826	5470	3.0	900			5.7	910	-0.92	
6827	---	---	---			2.7	920	-0.26	
6828	---	---	---			2.7	920	-0.30	
6829	---	---	---					-0.37	
6830	---	---	---					-0.23	
6831	---	---	---					-0.32	
6832	---	---	---					-0.37	
6833	---	---	---					-0.29	
6834	---	---	---	2.7	920	2.7	920	-0.33	
6835	---	---	---					-0.38	

TABLE 5-10 (continued)

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) HTGR	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm ²) (E>0.18 MeV) HTGR	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) HTGR	Irrad Temp (°C)	Irrad Strain ln(ϵ/ϵ_0) (10-2)	Dimensional Change, $\Delta\epsilon/\epsilon_0$ (%)
6836	--	--	--	2.7	920	2.7	920	-0.27	
6837	--	--	--					-0.35	
6838	--	--	--					-0.33	
6901	5481	3.3	1180	2.95	1255	6.25	1215	-1.08	-1.08
6902	5482		1180		1255		1215	-1.20	-1.19
6905	5485		1160		1235		1195	-1.15	-1.14
6913	5493	3.3	1160	2.95	1235	6.25	1195	-1.05	-1.04
6987	5579	3.2	1395	2.9	1390	6.1	1395	-1.65	-1.63
6988	5580		1395		1390		1395	-1.76	-1.74
7012	5583		1385		1380		1385	-1.58	-1.57
7073	5674	3.2	1385		1325	6.1	1360	-1.72	-1.71
7093	--	--	--			2.9	1325	-1.55	-1.54
7094	--	--	--					-1.31	-1.31
7095	--	--	--					-1.51	-1.50
7096	--	--	--					-1.45	-1.44
7098	5765	3.0	1025	2.9	1325	2.9	1325	-1.24	-1.23
7100	5774		960	2.7	1085	5.7	1055	-1.19	-1.18
7102	5778				1065		1010	-1.06	-1.05
7105	5783							-1.18	-1.17
7107	5790							-2.41	-2.38
7109	5794	3.0	960		1065	5.7	1010	-1.09	-1.09
7129(a)	5094	2.0	570		1035	4.7	(a)	-0.84	
7130(a)	5095						(a)	-0.81	
7133(a)	5098						(a)	-0.83	
7134(a)	5099						(a)	-0.82	
7137(a)	5106						(a)	-0.85	
7138(a)	5107						(a)	-0.85	
7141(a)	5110						(a)	-0.89	
7142(a)	5111	2.0	570			4.7	840	-0.86	
7143	5796	3.0	960			5.7	995	-1.15	-1.15
7145	5800	3.0	960			5.7	995	-1.19	-1.18
7147	5802	3.0	960			5.7	995	-1.13	-1.13
7217	5808	2.8	995	2.7	1035	5.3	1000	-0.97	
7221	5812		980	2.5	1000		985	-0.98	
7225	5816				990			-1.01	-1.00
7229	5820							-0.89	-0.89
7233	5824							-1.01	-1.00
7237	5828							-0.94	
7238	5829							-0.78	
7241	5832							-0.99	
7242	5833							-1.03	-1.03
7245	5836							-0.93	
7246	5837	2.8	980	2.5	990	5.3	985	-0.82	
7327	5932	2.3	915	2.15	940	4.45	930	-0.59	
7328	5933				940		930	-0.56	
7331	5936				925		920	-0.65	
7332	5937				925		920	-0.59	
7335	5940	2.3	915		925	4.45	920	-0.51	
7411	--	--	--		850	2.15	850	-0.17	
7418	--	--	--					-0.16	
7419	--	--	--					-0.12	
7420	--	--	--					-0.11	
7421	--	--	--					-0.11	
7423	6050	1.9	865	2.15	850	2.15	850	-0.28	
7425	6054		850	1.7	835	3.6	850	-0.21	
7427	6058				835		845	-0.21	
7429	6062				820		835	-0.22	
7431	6066							-0.22	
7433	6070							-0.18	
7435	6074							-0.24	
7437	6078							-0.18	
7439	6082		850				835	-0.23	
7441	6086		820				820	-0.12	
7443	6090							-0.22	
7445	6096							-0.20	
7447	6100							-0.20	
7449	6106	1.9	820	1.7	820	3.6	820	-0.17	
7530	6210	1.4	650	1.15	645	2.55	650	-0.12	
7534	6214		645		635		640	-0.15	
7538	6218							-0.14	
7542	6222							-0.10	
7546	6226		645		635		640	-0.10	
7591	6306		605		590		600	-0.03	
7592	6307							-0.13	
7595	6314							-0.14	
7596	6315	1.4	605	1.15	590	2.55	600	-0.15	

(a) Temperature change samples.

Fig. 5-1(a). Dimensional change of H-451/H-429 graphite, axial orientation, as a function of fast neutron fluence at irradiation temperatures of 550° and 750°C

Fig. 5-1(b). Dimensional change of H-451/H-429 graphite, axial orientation, as a function of fast neutron fluence at irradiation temperatures of 650° and 850°C

Fig. 5-1(c). Dimensional change of H-451/H-429 graphite, axial orientation, as a function of fast neutron fluence at irradiation temperatures of 950° and 1150°C

Fig. 5-1(d). Dimensional change of H-451/H-429 graphite, axial orientation, as a function of fast neutron fluence at irradiation temperatures of 1050°, 1250°, and 1350°C

Fig. 5-2(a). Dimensional change of H-451/H-429 graphite, radial orientation, as a function of fast neutron fluence at irradiation temperatures of 550° and 750°C

Fig. 5-2(b). Dimensional change of H-451/H-429 graphite, radial orientation, as a function of fast neutron fluence at irradiation temperatures of 650° and 850°C

Fig. 5-2(c). Dimensional change of H-451/H-429 graphite, radial orientation, as a function of fast neutron fluence at irradiation temperatures of 950° and 1150°C

Fig. 5-2(d). Dimensional change of H-451/H-429 graphite, radial orientation, as a function of fast neutron fluence at irradiation temperatures of 1050°, 1250°, and 1350°C

Design curves of the dimensional change in near-isotropic graphite (H-451/H-429) were derived from the data in the following manner:

1. The data of Tables 5-1 through 5-10 (shown in Figs. 5-1 and 5-2) were tabulated, reviewed, and input to a computer-fitting code.
2. Supplementary low-temperature (300°-600°C), high-fluence data from Gilsocoke graphites from Ref. 6 were added to the data base for the 300° to 600°C range.
3. The computer code fit a surface through the three-dimensional data space (fluence, temperature, dimensional change) by a least-squares, Gram-Schmitt orthogonalization process. One surface was generated for each orientation of graphite specimens.
4. Isotherms were taken from the computer-fit surface, compared with the actual data, and then plotted in Figs. 5-3 and 5-4 to represent the design curves. A polynomial generated by the computer fit describing the surface is actually used for design work.

The resulting surface and its isotherms plotted in Figs. 5-3 and 5-4 differ somewhat from earlier design curves because of the change in fast fluence units. The shift of approximately 11% along the fluence axis was observed to be larger than the shift in the curve resulting from the addition of OG-2 data. The design curves plotted in ORR fluence units (Ref. 4) shifted approximately 5% with the addition of OG-2 data in the same ORR units.

The data in Figs. 5-1 through 5-4 illustrate the dimensional stability of H-451 under neutron irradiation. These data have been obtained at sufficiently high fluences to demonstrate that the contraction of H-451 will be <2.0% radially and <3.0% axially during the graphite residence time in a large HTGR core.

Fig. 5-3. Design curves for irradiation-induced axial dimensional change in H-451/H-429 graphite

Fig. 5-4. Design curves for irradiation-induced radial dimensional change in H-451/H-429 graphite

Specimens of H-451 were irradiated in OG-1 at T_1 and subsequently irradiated in OG-2 at T_2 . The following data sets are plotted in Fig. 5-5 along with isothermal curves:

1. $T_1 = 570^\circ\text{C}$, $T_2 = 1035^\circ\text{C}$, isotherm at 650°C .
2. $T_1 = 1065^\circ\text{C}$, $T_2 = 680^\circ\text{C}$, isotherm at 1050°C .

When the specimens were irradiated first at 570°C and then at 1035°C , the contraction rate increased during the 1035°C increment and equaled the isothermal rate at 1050°C . When the specimens were irradiated first at 1065°C and then at 680°C , the contraction rate decreased for the axial specimens but remained unchanged for the radial specimens. There is not a sufficient quantity of data to permit further conclusions at this time. These specimens will be irradiated to higher fluences at T_2 .

Axial H-451 specimens irradiated side by side in OG-2 showed midlength edge (MLE) specimens to contract by 10% to 20% less than midlength center (MLC) specimens. These data are shown in Table 5-11 for H-451 graphite. No size effect has been discerned for the two sizes of specimens irradiated.

The TS-1240 graphite specimens irradiated for the first time in OG-2 exhibited excellent dimensional stability. None of the specimens contracted more than 1% up to fast fluences of $2.95 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} and temperatures of 1105°C . These data are given in Tables 5-12 and 5-13.

P_3 JHAN graphite specimens carried over from the OG-1 experiment continued to show high contraction in the axial orientation. In the radial direction, specimens at several sets of irradiation conditions went through turnaround to net expansion. Tables 5-14 through 5-17 give data for P_3 JHAN irradiated in capsules OG-1 and OG-2.

5.2. DIMENSIONAL CHANGE IN NEEDLE COKE GRAPHITES

Samples of H-327 graphite were carried over from the OG-1 experiment for further neutron exposure. As reported earlier (Ref. 4), the H-327

Fig. 5-5. Dimensional change in H-451 graphite for non-isothermal irradiation

TABLE 5-11
COMPARISON OF DIMENSIONAL CHANGES IN MIDLENGTH CENTER (MLC)
AND MIDLENGTH EDGE (MLE) H-451 SPECIMENS

Record Numbers	Irradiation Conditions		No. Samples	Location	Orientation	Dimensional Change, $\ln(\ell_n/\ell_o)$		Difference in Dimensional Change between MLC and MLE Samples (%)
	Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Temp. (°C)				Mean (10^{-2} in./in.)	Std. Dev. (10^{-2} in./in.)	
7215-7246	5.2	990	11	MLE	Axial	-2.08	0.09	-4.3
7099-7110	5.2 ^(a)	1010	6	MLC	Axial	-2.17 ^(a)	0.11	
7217-7246	5.2	990	11	MLE	Radial	-0.94	0.08	-11.3
7143-7147	5.2 ^(a)	995	3	MLC	Radial	-1.06 ^(a)	0.03	
7361-7372	2.15	905	6	MLE	Axial	-0.24	0.02	-22.6
7361-7372	2.15	905	6	MLC	Axial	-0.31	0.02	
7410-7421	2.15	850	3	MLE	Axial	-0.20	0.03	-20.0
7410-7421	2.15	850	4	MLC	Axial	-0.25	0.02	

^(a) Actual measurements made at a fluence of 5.7×10^{21} n/cm². Dimensional change values at 5.2×10^{21} n/cm² were calculated by linear interpolation between 0 and 5.7×10^{21} n/cm².

TABLE 5-12
DIMENSIONAL CHANGE DATA, TS-1240, AXIAL DIRECTION,
AFTER IRRADIATION IN CAPSULE OG-2

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})
6967	2.95	1105	-0.78
6968			-0.82
6969			-0.67
6970			-0.74
6971			-0.65
6972			-0.72
6973			-0.66
6974			-0.72
6975			-0.69
6976			-0.75
6977			-0.72
6978			-0.76
6979			-0.64
6980			-0.74
6981			-0.68
6982			-0.73
6983			-0.76
6984	2.95	1105	-0.83
7251	2.5	970	-0.31
7252			-0.24
7253			-0.26
7254			-0.21
7255			-0.27
7256			-0.24
7257			-0.26
7258		970	-0.20
7313		920	-0.23
7314			-0.25
7315			-0.25
7316			-0.20
7317			-0.23
7318			-0.19
7319			-0.22
7320	2.5	920	-0.20
7510	1.70	765	-0.13
7511			-0.02
7512			-0.02
7513			-0.06
7514	1.70	765	-0.01

TABLE 5-12 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain ln(l/l ₀) (10 ⁻²)
7515	1.7	765	-0.02
7516	↓	↓	-0.03
7517	↓	↓	-0.03
7518	↓	↓	-0.05
7519	↓	↓	-0.02
7520	↓	↓	-0.03
7521	↓	↓	-0.01
7522	↓	↓	+0.01
7523	↓	↓	-0.04
7524	↓	↓	-0.04
7525	↓	↓	-0.04
7526	↓	↓	-0.06
7527	1.7	765	-0.03
7564	1.15	620	-0.07
7565	↓	↓	-0.06
7566	↓	↓	-0.06
7567	↓	↓	-0.02
7568	↓	↓	-0.04
7569	↓	↓	-0.02
7570	↓	↓	-0.05
7571	↓	↓	-0.02
7572	↓	↓	-0.06
7573	↓	↓	-0.07
7574	↓	↓	-0.11
7575	↓	620	-0.08
7613	↓	590	-0.07
7614	↓	↓	-0.09
7615	↓	↓	-0.10
7616	↓	↓	-0.08
7617	↓	↓	-0.09
7618	↓	↓	-0.07
7619	↓	↓	-0.08
7620	1.15	590	-0.08

TABLE 5-13
 DIMENSIONAL CHANGE DATA, TS-1240, RADIAL DIRECTION,
 AFTER IRRADIATION IN CAPSULE OG-2

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})
6935	2.95	1200	-0.48
6936	↓	↓	-0.45
6937	↓	↓	-0.45
6938	↓	↓	-0.45
6939	↓	↓	-0.47
6940	↓	↓	-0.49
6941	↓	↓	-0.53
6942	2.95	1200	-0.46
7321	2.5	920	-0.05
7322	↓	↓	-0.04
7323	↓	↓	-0.05
7324	2.5	920	-0.04
7462	1.7	805	+0.02
7463	↓	↓	+0.02
7464	↓	↓	-0.05
7465	↓	↓	0.00
7466	↓	↓	-0.02
7467	↓	↓	-0.02
7468	↓	↓	+0.01
7469	↓	↓	-0.02
7470	↓	↓	0.00
7471	1.7	805	-0.01
7621	1.15	590	-0.13
7622	↓	↓	-0.07
7623	↓	↓	-0.11
7624	1.15	590	-0.07

TABLE 5-14
 DIMENSIONAL CHANGE DATA, P₃JHAN, AXIAL DIRECTION,
 AFTER IRRADIATION IN CAPSULE OG-1

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain ln(ℓ/ℓ_0) (10^{-2})
5319	3.0	980	-1.53
5321	↓	↓	-2.04
5323	↓	↓	-2.02
5325	↓	↓	-1.48
5327	↓	↓	-1.99
5329	↓	↓	-2.00
5331	↓	↓	-1.44
5333	↓	↓	-1.82
5335	3.0	980	-2.11
5676	3.2	1335	-3.96
5678	↓	↓	-4.00
5684	↓	↓	-4.19
5686	3.2	1335	-4.06
5734	3.0	1025	-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	3.0	1025	-1.82
6164	1.9	770	-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	1.9	770	-0.28

TABLE 5-14 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})
6332	1.4	605	-0.23
6334	↓	↓	-0.16
6336			-0.20
6338			-0.19
6342			-0.20
6344			-0.22
6347			-0.17
6349	1.4	605	-0.21

TABLE 5-15
DIMENSIONAL CHANGE DATA, P₃JHAN, AXIAL DIRECTION,
AFTER IRRADIATION IN CAPSULE OG-2

Record No.	Previous Record No.	Previous Fluence (10 ²¹ n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp (°C)	Fluence This Irrad (10 ²¹ n/cm ²) (E>0.18 MeV) _{HTGR}	Temp This Irrad (°C)	Total Fluence (10 ²¹ n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain ln(l/l ₀) (10 ⁻²)
6737	5319	3.0	980	2.7	990	5.7	985	-3.36
6739	5321	↓	↓	↓	↓	↓	↓	-3.59
6741	5323	↓	↓	↓	↓	↓	↓	-3.54
6743	5325	↓	↓	↓	↓	↓	↓	-3.52
6745	5327	↓	↓	↓	↓	↓	↓	-3.74
6747	5329	3.0	980	2.7	990	5.7	985	-3.44
7013	5676	3.2	1335	2.9	1380	6.1	1355	-3.67
7015	5678	↓	↓	↓	↓	↓	↓	-3.60
7017	5684	↓	↓	↓	↓	↓	↓	-4.12
7019	5686	3.2	1335	2.9	1380	6.1	1355	-3.68
7170	5734	3.0	1025	2.7	960	5.7	995	-3.88
7172	5736	↓	↓	↓	↓	↓	↓	-3.68
7174	5740	↓	↓	↓	↓	↓	↓	-3.69
7176	5742	↓	↓	↓	↓	↓	↓	-3.39
7178	5744	↓	↓	↓	↓	↓	↓	-3.46
7180	5746	↓	↓	↓	↓	↓	↓	-3.64
7182	5750	↓	↓	↓	↓	↓	↓	-3.46
7184	5752	3.0	1025	2.7	960	5.7	995	-3.72
7450	6164	1.9	770	1.7	820	3.6	795	-0.98
7451	6165	↓	↓	↓	↓	↓	↓	-0.88
7454	6170	↓	↓	↓	↓	↓	↓	-1.07
7455	6171	↓	↓	↓	820	↓	795	-0.90
7488	6184	↓	↓	↓	765	3.6	770	-0.88
7489	6185	↓	↓	↓	↓	↓	↓	-0.80
7492	6190	↓	↓	↓	↓	↓	↓	-0.97
7493	6191	↓	↓	↓	↓	↓	↓	-0.89
7496	6174	↓	↓	↓	↓	↓	↓	-0.95
7497	6175	↓	↓	↓	↓	↓	↓	-0.77
7500	6180	↓	↓	↓	↓	↓	↓	-0.90
7501	6181	1.9	770	1.7	765	3.6	770	-0.78
7597	6332	1.4	605	1.15	590	2.55	600	-0.50
7599	6334	↓	↓	↓	↓	↓	↓	-0.40
7601	6336	↓	↓	↓	↓	↓	↓	-0.49
7603	6338	1.4	605	1.15	590	2.55	600	-0.38

TABLE 5-16
 DIMENSIONAL CHANGE DATA, P₃JHAN, RADIAL DIRECTION,
 AFTER IRRADIATION IN CAPSULE OG-1

Record No.	Total Fluence (10 ²¹ n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10 ⁻²)
5320	3.0	980	-0.69
5322	↓	↓	-0.76
5324	↓	↓	-0.58
5326	↓	↓	-0.73
5328	↓	↓	-0.87
5330	↓	↓	-0.83
5332	↓	↓	-0.66
5334	↓	↓	-0.78
5336	3.0	980	-0.73
5677	3.2	1335	-1.66
5679	↓	↓	-1.44
5685	↓	↓	-1.65
5687	3.2	1335	-1.68
5735	3.0	1025	-0.81
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	3.0	1025	-0.83
6166	1.9	770	-0.11
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	1.9	770	-0.11
6333	1.4	605	-0.15
6335	↓	↓	-0.10
6337	↓	↓	-0.17
6339	1.4	605	-0.06

TABLE 5-16 (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})
6343	1.4	605	-0.18
6345	↓	↓	-0.06
6348	↓	↓	-0.15
6350	1.4	605	-0.13

TABLE 5-17
DIMENSIONAL CHANGE DATA, P₃JHAN, RADIAL DIRECTION,
AFTER IRRADIATION IN CAPSULE OG-2

Record No.	Previous Record No.	Previous Fluence (10 ²¹ n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp (°C)	Fluence This Irrad (10 ²¹ n/cm ²) (E>0.18 MeV) _{HTGR}	Temp This Irrad (°C)	Total Fluence (10 ²¹ n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain ln(l/l ₀) (10 ⁻²)
6738	5320	3.0	980	2.7	990	5.7	985	+0.19
6740	5322	↓	↓	↓	↓	↓	↓	+0.82
6742	5324	↓	↓	↓	↓	↓	↓	+1.64
6744	5326	↓	↓	↓	↓	↓	↓	+0.06
6746	5328	3.0	980	2.7	990	5.7	985	+0.71
7014	5677	3.2	1335	2.9	1380	6.1	1355	+3.43
7016	5679	↓	↓	↓	↓	↓	↓	2.66
7018	5685	↓	↓	↓	↓	↓	↓	3.46
7020	5687	3.2	1335	2.9	1380	6.1	1355	2.02
7171	5735	3.0	1025	2.7	960	5.7	995	+0.32
7173	5737	↓	↓	↓	↓	↓	↓	-0.91
7175	5741	↓	↓	↓	↓	↓	↓	+0.10
7177	5743	↓	↓	↓	↓	↓	↓	-0.60
7179	5745	↓	↓	↓	↓	↓	↓	+0.72
7181	5747	↓	↓	↓	↓	↓	↓	-0.67
7183	5751	3.0	1025	2.7	960	5.7	995	+0.55
7452	6166	1.9	770	1.7	820	3.6	795	-0.43
7453	6167	↓	↓	↓	↓	↓	↓	-0.36
7456	6172	↓	↓	↓	↓	↓	↓	-0.43
7457	6173	↓	↓	↓	820	↓	795	-0.35
7490	6186	↓	↓	↓	765	↓	770	-0.41
7491	6187	↓	↓	↓	↓	↓	↓	-0.35
7494	6192	↓	↓	↓	↓	↓	↓	-0.46
7495	6193	↓	↓	↓	↓	↓	↓	-0.36
7498	6176	↓	↓	↓	↓	↓	↓	-0.37
7499	6177	↓	↓	↓	↓	↓	↓	-0.32
7502	6182	↓	↓	↓	↓	↓	↓	-0.41
7503	6183	1.9	770	1.7	765	3.6	770	-0.32
7598	6333	1.4	605	1.15	590	2.55	600	-0.37
7600	6335	↓	↓	↓	↓	↓	↓	-0.33
7602	6337	↓	↓	↓	↓	↓	↓	-0.08
7604	6339	1.4	605	1.15	590	2.55	600	-0.27

demonstrated more moderate dimensional changes than observed in earlier irradiations. Tables 5-18 and 5-19 list the OG-1 and OG-2 data in terms of HTGR fluence ($E > 0.18 \text{ MeV}$)_{HTGR} for 434 H-327 specimens.

5.3. MISCELLANEOUS GRAPHITES

Impregnated H-451 graphites were irradiated in capsule OG-2. The data obtained are presented in Table 5-20. The H-451C material, which was used as web material during cure-in-place studies, exhibited the same dimensional change as standard H-451 irradiated under the same conditions.

Other miscellaneous graphites were also irradiated in capsule OG-2. These data are presented in Tables 5-21, 5-22, and 5-23.

TABLE 5-18
DIMENSIONAL CHANGE DATA, H-327, AXIAL DIRECTION, AFTER IRRADIATION IN CAPSULES OG-1 AND OG-2

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV)HTGR	Previous Temp. (°C)	Fluence This Irrad. (10^{21} n/cm ²) (E>0.18 MeV)HTGR	Temp. This Irrad. (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV)HTGR	Irrad. Temp. (°C)	Irrad. Strain, $\ln (\ell/\ell_0)$ (10^{-2})	Dimen. Change, $\Delta \ell/\ell$ (%)
5005						2.0	645	-0.15	
5009								-0.16	
5013								-0.17	
5017								-0.14	
5021								-0.11	
5025								-0.13	
5029								-0.11	
5033								-0.15	
5037						2.0	620	-0.20	
5041						2.0	620	-0.18	
5114						2.0	570	-0.14	
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						2.6	740	-0.25	
5151								-0.24	
5155								-0.17	
5159								-0.24	
5163								-0.26	
5167								-0.20	
5171								-0.23	
5175								-0.17	
5179						2.6	700	-0.24	
5182								-0.28	
5185								-0.24	
5186								-0.17	
5195								-0.21	
5196								-0.10	
5205								-0.25	
5206								-0.21	
5215								-0.22	
5216								-0.23	
5241						2.6	630	-0.28	
5242								-0.33	
5251								-0.28	
5252								-0.31	
5257								-0.24	
5258								-0.34	
5261								-0.32	
5262								-0.27	
5263								-0.34	
5264								-0.33	
5267								-0.25	
5268								-0.21	

TABLE 5-18 (Continued)

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp. (°C)	Fluence This Irrad. (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Temp. This Irrad. (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad. Temp. (°C)	Irrad. Strain, ln (ℓ/ℓ_0) (10^{-2})	Dimen. Change, $\Delta\ell/\ell$ (%)
5271						2.6	630	-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						3.0	900	-0.62	
5467								-0.50	
5473								-0.65	
5474								-0.54	
5477								-0.69	
5478								-0.58	
5513						3.3	1115	-1.70	-1.69
5514								-1.83	-1.82
5523								-1.79	-1.78
5524								-1.96	-1.94
5533						3.3	1045	-1.19	-1.18
5534								-1.48	-1.47
5543								-1.75	-1.74
5544								-1.03	-1.02
5546								-1.40	-1.39
5547								-1.57	-1.56
5556								-1.19	-1.18
5557								-1.37	-1.36
5566								-1.22	-1.21
5567								-1.32	-1.31
5568								-1.29	-1.28
5569								-1.47	-1.46
5738						3.0	1025	-1.31	-1.30
5748								-1.18	-1.17
5758								-1.11	-1.11
5766								-1.30	-1.29
5771						3.0	960	-0.83	
5775								-0.88	
5779								-0.83	
5784								-0.77	
5791								-0.71	
5797								-0.71	
5804						2.8	995	-1.09	
5811						2.8	980	-0.91	
5815								-1.07	
5819								-1.00	
5823								-1.00	
5856						2.8	950	-0.79	
5857								-0.78	
5860								-0.72	
5861								-0.72	
5864								-0.75	
5865								-0.70	

TABLE 5-18 (continued)

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp. (°C)	Fluence This Irrad. (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Temp. This Irrad. (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad. Temp. (°C)	Irrad. Strain, ln (ℓ/ℓ_0) (10^{-2})	Dimen. Change, $\Delta\ell/\ell$ (%)
5907						2.3	930	-0.60	
5911						2.3	915	-0.49	
5915						↓	↓	-0.52	
5919						↓	↓	-0.56	
5923						↓	↓	-0.52	
5927						↓	↓	-0.51	
5954						2.3	890	-0.42	
5955						↓	↓	-0.34	
5964						↓	↓	-0.39	
5965						↓	↓	-0.30	
5974						↓	↓	-0.43	
5975						↓	↓	-0.31	
5996						2.3	850	-0.33	
5997						↓	↓	-0.25	
6006						↓	↓	-0.29	
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						1.9	820	-0.17	
6093						↓	↓	-0.11	
6102						↓	↓	-0.15	
6103						↓	↓	-0.11	
6112						↓	↓	-0.15	
6113						↓	↓	-0.12	
6122						↓	↓	-0.05	
6123						↓	↓	-0.11	
6148						1.9	770	-0.15	
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	

TABLE 5-18 (continued)

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm 2) (E>0.18 MeV) _{HTGR}	Previous Temp. (°C)	Fluence This Irrad. (10^{21} n/cm 2) (E>0.18 MeV) _{HTGR}	Temp. This Irrad. (°C)	Total Fluence (10^{21} n/cm 2) (E>0.18 MeV) _{HTGR}	Irrad. Temp. (°C)	Irrad. Strain, $\ln (\ell/\ell_0)$ (10^{-2})	Dimen. Change, $\Delta \ell/\ell$ (%)
6209						1.4	650	-0.06	
6213						1.4	645	-0.09	
6217								-0.12	
6221								-0.11	
6225								-0.24	
6229								-0.10	
6233								-0.16	
6237								-0.15	
6241								-0.10	
6301						1.4	605	-0.15	
6505	5005	2.0	645	1.7	680	3.7	660	-0.42	
6509	5009	2.0	645	1.7	680	3.7	660	-0.43	
6589	5114	2.0	570	1.7	615	3.7	590	-0.42	
6590	5115							-0.50	
6593	5118							-0.40	
6594	5119							-0.48	
6597	5124							-0.40	
6598	5125							-0.50	
6601	5128							-0.39	
6602	5129							-0.54	
6630	5147	2.6	740	2.2	765	4.8	750	-0.61	
6634	5151							-0.68	
6638	5155							-0.65	
6642	5159							-0.64	
6646	5163							-0.65	
6650	5167							-0.65	
6654	5171							-0.59	
6658	5175							-0.62	
6661						2.2	740	-0.17	
6662								-0.18	
6663								-0.16	
6664								-0.18	
6665								-0.16	
6666								-0.18	
6667								-0.17	
6668								+0.10	
6669								-0.18	
6670								-0.21	
6671								-0.16	
6672								-0.18	
6673								-0.17	
6674								-0.20	
6703	5257	2.6	630	2.2	680	4.8	655	-0.67	
6704	5258	2.6	630	2.2	680	4.8	655	-0.73	
6707	5185	2.6	700	2.2	680	4.8	690	-0.74	
6708	5195							-0.75	
6709	5205							-0.76	
6710	5215							-0.72	
6711	5241	2.6	630	2.2	680	4.8	655	-0.71	
6712	5251							-0.75	
6713	5261							-0.73	
6714	5271							-0.76	
6715	5281							-0.67	
6716	5291							-0.73	

TABLE 5-18 (continued)

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp. (°C)	Fluence This Irrad. (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Temp. This Irrad. (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad. Temp. (°C)	Irrad. Strain, $\ln (\ell/\ell_0)$ (10^{-2})	Dimen. Change, $\Delta\ell/\ell$ (%)
6717						2.2	680	-0.20	
6718						↓	↓	-0.22	
6719								-0.22	
6720								-0.23	
6767	5466	3.0	900	2.7	990	5.7	940	-2.18	-2.15
6768	5467							-2.39	-2.36
6769	5473							-2.51	-2.48
6773	5474							-2.37	-2.34
6774	5477							-2.48	-2.45
6775	5478							-2.33	-2.30
6943	5513	3.3	1115	2.95	1200	6.25	1155	-3.98	-3.90
6944	5523	3.3	1115	2.95	1200	6.25	1155	-4.33	-4.24
6961	5533	3.3	1045	2.95	1105	6.25	1075	-3.18	-3.13
6962	5543							-4.33	-4.24
6963	5546							-3.25	-3.19
6964	5556							-3.38	-3.32
6965	5566							-2.61	-2.57
6966	5568							-3.49	-3.43
7119	5738	3.0	1025	2.7	1035	5.7	1030	-3.87	-3.80
7120	5748							-3.43	-3.37
7121	5758							-3.78	-3.71
7122	5766							-3.85	-3.78
7123						2.7	1035	-1.48	-1.47
7124						↓	↓	-1.13	-1.13
7125								-1.28	-1.27
7126								-0.99	
7150	5771	3.0	960	2.7	960	5.7	960	-2.67	-2.63
7151	5775							-2.42	-2.39
7152	5779							-2.71	-2.67
7153	5784							-2.16	-2.14
7154	5791							-2.39	-2.36
7155	5797							-2.04	-2.01
7156						2.7	960	-1.02	
7157						↓	↓	-0.71	
7158								-0.98	
7159								-0.81	
7160								-1.06	
7161								-0.78	
7216	5804	2.8	995	2.5	1000	5.3	995	-3.20	-3.15
7220	5811	2.8	995	2.5	980	5.3	985	-2.79	-2.75
7224	5815							-3.06	-3.01
7228	5819							-2.93	-2.89
7232	5823							-3.10	-3.05
7304	5857	2.8	950	2.5	920	5.3	935	-2.18	-2.15
7402	6008	2.3	850	2.15	850	4.45	850	-0.98	
7403	6009							-0.75	
7404	6018							-0.93	
7405	6019							-0.71	
7406	6028							-0.97	
7407	6029							-0.71	
7408	6038							-1.37	-1.36
7409	6039							-0.75	

TABLE 5-18 (continued)

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp. (°C)	Fluence This Irrad. (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Temp. This Irrad. (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad. Temp. (°C)	Irrad. Strain, $\ln(l/l_0)$ (10^{-2})	Dimen. Change, $\Delta l/l$ (%)
7458	6092	1.9	820	1.7	805	3.6	815	-0.49	
7459	6102							-0.44	
7460	6112							-0.54	
7461	6122							-0.49	
7504	6148	1.9	770	1.7	765	3.6	770	-0.43	
7505	6158							-0.35	
7506	6168							-0.41	
7507	6178							-0.42	
7508	6188							-0.41	
7509	6198							-0.38	
7529	6209	1.4	650	1.15	645	2.55	650	-0.24	
7533	6213	1.4	645	1.15	635	2.55	640	-0.28	
7537	6217							-0.27	
7541	6221							-0.23	
7545	6225							-0.28	

TABLE 5-19
DIMENSIONAL CHANGE DATA, H-327, RADIAL DIRECTION, AFTER IRRADIATION IN CAPSULES OG-1 AND OG-2

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp. (°C)	Fluence This Irrad. (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Temp. This Irrad. (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad. Temp. (°C)	Irrad. Strain, $\ln(l/l_0)$ (10^{-2})	Dimen. Change, $\Delta l/l$ (%)
5007						2.0	645	-0.12	
5011						↓	↓	-0.12	
5015						↓	↓	-0.11	
5019						↓	↓	-0.10	
5023						↓	↓	-0.06	
5027						↓	↓	-0.08	
5031						↓	↓	-0.08	
5035						↓	↓	-0.16	
5039						2.0	620	-0.14	
5043						2.0	620	-0.16	
5116						2.0	570	-0.16	
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						2.6	740	-0.13	
5153						↓	↓	-0.16	
5157						↓	↓	-0.17	
5161						↓	↓	-0.14	
5165						↓	↓	-0.10	
5169						↓	↓	-0.11	
5173						↓	↓	-0.16	
5177						↓	↓	-0.04	
5181						2.6	700	-0.24	
5184						2.6	700	-0.19	
5259						2.6	630	-0.26	
5260						↓	↓	-0.28	
5265						↓	↓	-0.16	
5266						↓	↓	-0.19	
5269						↓	↓	-0.22	
5270						↓	↓	-0.23	
5275						↓	↓	-0.20	
5276						↓	↓	-0.21	
5279						↓	↓	-0.26	
5280						↓	↓	-0.26	
5353						3.0	950	-0.43	
5358						↓	↓	-0.36	
5362						↓	↓	-0.48	
5363						↓	↓	-0.42	
5369						↓	↓	-0.65	
5370						↓	↓	-0.40	
5739						3.0	1025	-0.32	
5749						↓	↓	-0.51	
5759						↓	↓	-0.50	
5767						↓	↓	-0.52	

TABLE 5-19 (continued)

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp. (°C)	Fluence This Irrad. (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Temp. This Irrad. (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad. Temp. (°C)	Irrad. Strain, $\ln(l/l_0)$ (10^{-2})	Dimen. Change, $\Delta l/l$ (%)
5772						3.0	960	-0.36	
5776						↓	↓	-0.40	
5780						↓	↓	-0.42	
5785						↓	↓	-0.41	
5792						↓	↓	-0.32	
5798						↓	↓	-0.40	
5809						2.8	995	-0.30	
5813						2.8	980	-0.16	
5817						↓	↓	-0.26	
5821						↓	↓	-0.35	
5825						↓	↓	-0.37	
5858						2.8	950	-0.43	
5859						↓	↓	-0.12	
5862						↓	↓	-0.39	
5863						↓	↓	-0.37	
5866						2.8	950	-0.37	
5867						2.8	950	-0.35	
5909						2.3	930	-0.25	
5913						2.3	915	-0.12	
5917						↓	↓	-0.08	
5921						↓	↓	-0.02	
5925						↓	↓	-0.24	
5929						↓	↓	-0.22	
6026						2.3	850	-0.19	
6027						↓	↓	-0.12	
6032						↓	↓	-0.23	
6033						↓	↓	-0.02	
6036						↓	↓	-0.14	
6037						↓	↓	-0.08	
6211						1.4	650	-0.06	
6215						1.4	645	-0.12	
6219						↓	↓	-0.07	
6223						↓	↓	-0.04	
6227						↓	↓	-0.06	
6231						↓	↓	-0.04	
6235						↓	↓	-0.09	
6239						↓	↓	-0.05	
6243						↓	↓	-0.06	
6303						1.4	605	-0.06	
6507	5007	2.0	645	1.7	680	3.7	660	-0.38	
6511	5011	2.0	645	1.7	680	3.7	660	-0.39	
6591	5116	2.0	570	1.7	615	3.7	590	-0.41	
6592	5117							-0.41	
6595	5120							-0.38	
6596	5121							-0.60	
6599	5126							-0.44	
6600	5127							-0.46	
6603	5130							-0.46	

TABLE 5-19 (continued)

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp. (°C)	Fluence This Irrad. (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Temp. This Irrad. (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad. Temp. (°C)	Irrad. Strain, ln (ℓ/ℓ_0) (10 ⁻²)	Dimen. Change, $\Delta\ell/\ell$ (%)
6632	5149	2.6	740	2.2	765	4.8	750	-0.44	
6636	5153							-0.44	
6640	5157							-0.44	
6644	5161							-0.44	
6648	5165							-0.40	
6652	5169							-0.44	
6656	5173							-0.46	
6705	5259	2.6	630	2.2	680	4.8	655	-0.58	
6706	5260	2.6	630	2.2	680	4.8	655	-0.58	
6721						2.2	680	-0.15	
6722								-0.17	
6723								-0.15	
6724								-0.15	
6725								-0.16	
6726								-0.18	
6727								-0.17	
6728								-0.17	
6729								-0.15	
6730								-0.17	
6764	5357	3.0	950	2.7	990	5.7	970	-0.68	
6765	5358							-0.62	
6766	5362							-0.68	
6770	5363							-0.81	
6771	5369							-0.93	
6772	5370							-0.67	
7162						2.7	960	-0.58	
7163								-0.48	
7164								-0.59	
7165								-0.51	
7166								-0.60	
7167								-0.47	
7168								-0.58	
7169								-0.43	
7218	5809	2.8	995	2.5	1000	5.3	995	-0.52	
7222	5813	2.8	980	2.5	980	5.3	985	-0.64	
7226	5817							-0.72	
7230	5821							-0.69	
7234	5825							-0.57	
7305	5858	2.8	950	2.5	920	5.3	935	-0.72	
7306	5859	2.8	950	2.5	920	5.3	935	-0.71	
7531	6211	1.4	650	1.15	645	2.55	650	-0.09	
7535	6215	1.4	645	1.15	635	2.55	640	-1.38	
7539	6219							-0.15	
7543	6223							-0.08	

TABLE 5-20
DIMENSIONAL CHANGE DATA, TREATED H-451 GRAPHITES, AXIAL DIRECTION, AFTER IRRADIATION IN CAPSULE OG-2

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp. (°C)	Fluence This Irrad. (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Temp. This Irrad. (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad. Temp. (°C)	Irrad. Strain, $\ln (\ell/\ell_0)$ (10^{-2})	Dimen. Change, $\Delta \ell/\ell$ (%)
IH-451									
6749						2.7	990	-0.58	
6750								-0.74	
6751								-0.90	
6752								-0.71	
6753								-0.74	
6754								-0.95	
7111	6462	3.0	960	2.7	1065	5.7	1010	-1.77	
7112	6467							-2.42	
7113	6468							-1.76	
7114	6463							-2.25	
7115	6469							-2.28	
7116	6464							-1.76	
7117	6465							-1.98	
7118	6470							-2.35	
H-451C									
7195	5768	3.0	995	2.7	960	5.7	980	-2.31	
7196	5769							-2.20	
7197	5770							-2.01	
7198	6480							-1.72	
7199	6481							-2.40	
7200	6482							-1.50	
7201	6483							-2.59	
7202	6484							-1.76	
7203	6485							-2.33	
7204	6486							-1.53	
7205	6487							-2.44	
7206	6488							-1.69	

TABLE 5-21
DIMENSIONAL CHANGE DATA FOR B₄C-GRAPHITE, 2020, AND 565161 GRAPHITES,
AXIAL DIRECTION, AFTER IRRADIATION IN CAPSULE OG-2

Record No.	Previous Record No.	Previous Fluence (10 ²¹ n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp. (°C)	Fluence This Irrad. (10 ²¹ n/cm ²) (E>0.18 MeV) _{HTGR}	Temp. This Irrad. (°C)	Total Fluence (10 ²¹ n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad. Temp. (°C)	Irrad. Strain, ln (ℓ/ℓ ₀) (10 ⁻²)	Dimen. Change, Δℓ/ℓ (%)
Grade 2020									
6548	5070	2.0	595	1.7	640	3.7	615	-0.59	
6549	5072							-0.63	
6552	5074							-0.58	
6553	5076							-0.67	
6556	5078							-0.57	
6557	5080							-0.62	
6675	5217	2.6	670	2.2	720	4.8	695	-0.56	
6677	5219							-0.47	
6679	5221							-0.48	
6681	5223							-0.50	
6683	5225							-0.66	
6685	5227							-0.38	
6687	5229							-0.50	
6689	5231							-0.52	
6851	5386	3.0	930	2.7	920	5.7	925	+0.53	
6853	5388							+0.80	
6857	5392							+0.50	
6859	5394							+0.66	
6863	5398							+0.43	
6865	5400							+0.52	
6869	5404							+0.55	
6871	5406							+0.63	
6875	5410							+0.46	
6877	5412							+0.56	
6881	5416							+0.41	
6883	5418							+0.47	
6887								-0.18	
6889								-0.17	
6891								-0.10	
6893								-0.16	
6895								-0.12	
6897								-0.14	
6951	5525	3.3	1085	2.95	1175	6.25	1125	+0.41	
6953	5527							+0.50	
6955	5529							+0.57	
6957	5531							+0.71	
7207								-0.22	
7209								-0.25	
7211								-0.18	
7213								-0.22	
7373	5976	2.3	870	2.15	885	4.45	875	+0.29	
7375	5978							+0.23	
7377	5980							+0.31	
7379	5982							+0.23	
7381	5984							+0.28	
7383	5986							+0.18	

TABLE 5-21 (continued)

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp. (°C)	Fluence This Irrad. (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Temp. This Irrad. (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad. Temp. (°C)	Irrad. Strain, $\ln(l/l_0)$ (10^{-2})	Dimen. Change, $\Delta l/l$ (%)
7472	6124	1.9	795	1.7	795	3.6	795	-0.03	
7474	6126							-0.13	
7476	6128							-0.05	
7478	6130							-0.14	
7480	6132							-0.07	
7482	6134							-0.19	
7484	6136							-0.10	
7486	6138							-0.19	
7576	6278	1.4	620	1.15	610	2.55	615	-0.56	
7578	6280							-0.48	
7580	6282							-0.52	
7582	6284							-0.34	
7584	6286							-0.54	
7586	6288							-0.49	
Grade 565161									
6855	5390	3.0	930	2.7	920	5.7	925	+1.86	
6861	5396							+2.00	
6867	5402							+1.64	
6873	5408							+1.56	
6879	5414							+2.11	
6885	5420							+1.95	
7037	5645	3.2	1355	2.9	1355	6.1	1355	+0.51	
7039	5647	3.2	1355	2.9	1355	6.1	1355	+0.65	
B ₄ C-Graphite									
6915	6438	3.3	1160	2.95	1235	6.25	1195	-3.16	
6916	6439							-3.34	
6917	6440							-3.34	
6918	6441							-3.31	
6919	6442							-3.06	
6920	6443							-3.33	
6921	6444							-3.42	
6922	6445							-3.39	
7295	6446	2.8	900	2.5	920	5.3	910	-2.81	
7296	6447							-2.85	
7297	6448							-2.76	
7298	6449							-2.70	
7299	6450							-2.90	
7300	6451							-2.87	
7301	6452							-2.77	
7302	6453							-2.16	

TABLE 5-22
DIMENSIONAL CHANGE DATA FOR 2020 AND 565161 GRAPHITES,
RADIAL DIRECTION, AFTER IRRADIATION IN CAPSULE OG-2

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp. (°C)	Fluence This Irrad. (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Temp. This Irrad. (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad. Temp. (°C)	Irrad. Strain, ln (ℓ/ℓ_0) (10 ⁻²)	Dimen. Change, $\Delta\ell/\ell$ (%)
Grade 2020									
6550	5071	2.0	595	1.7	640	3.7	615	-0.77	
6551	5073							-0.99	
6554	5075							-0.77	
6555	5077							-0.88	
6558	5079							-0.72	
6559	5081							-0.89	
6676	5218	2.6	670	2.2	720	4.8	695	-0.82	
6678	5220							-0.82	
6680	5222							-0.81	
6682	5224							-0.78	
6684	5226							-1.20	-1.18
6686	5228							-0.42	
6688	5230							-1.22	-1.20
6690	5232							-0.62	
6852	5387	3.0	930	2.7	920	5.7	925	-0.84	
6854	5389							-0.92	
6858	5393							-0.94	
6860	5395							-0.91	
6864	5399							-0.78	
6866	5401							-0.93	
6870	5405							-1.34	-1.32
6872	5407							-0.68	
6876	5411							-1.01	-1.00
6878	5413							-0.82	
6882	5417							-1.22	-1.20
6884	5419							-0.89	
6888						2.7	920	-0.46	
6890								-0.47	
6892								-0.52	
6894								-0.48	
6896								-0.67	
6952	5526	3.3	1085	2.95	1175	6.25	1125	-1.18	-1.17
6954	5528							-1.16	-1.15
6956	5530							-1.14	-1.12
6958	5532							-1.20	-1.18
7208						2.7	960	-0.65	
7210								-0.57	
7212								-0.62	
7214								-0.60	
7374	5977	2.3	870	2.15	885	4.45	875	-0.68	
7376	5979							-0.58	
7378	5981							-0.54	
7380	5983							-0.64	
7382	5985							-0.67	
7384	5987							-0.64	

TABLE 5-22 (continued)

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp. (°C)	Fluence This Irrad. (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Temp. This Irrad. (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad. Temp. (°C)	Irrad. Strain, $\ln (\ell/\ell_0)$ (10^{-2})	Dimen. Change, $\Delta\ell/\ell$ (%)
7473	6125	1.9	795	1.7	795	3.6	795	-0.52	
7475	6127							-0.49	
7477	6129							-0.50	
7479	6131							-0.43	
7481	6133							-0.58	
7483	6135							-0.46	
7485	6137							-0.50	
7487	6139							-0.39	
7577	6279	1.4	620	1.15	610	2.55	615	-0.87	
7579	6281							-0.47	
7581	6283							-0.62	
7583	6285							-0.47	
7585	6287							-0.65	
7587	6289							-0.82	
Grade 565161									
6856	5391	3.0	930	2.7	920	5.7	925	+1.01	
6862	5397							+0.79	
6868	5403							+1.28	
6874	5409							+1.23	
6880	5415							+0.92	
6886	5421							+0.86	
7038	5646	3.2	1355	2.9	1355	6.1	1355	-0.42	
7040	5648	3.2	1355	2.9	1355	6.1	1355	-0.26	

TABLE 5-23
DIMENSIONAL CHANGES IN CARBON INSULATING MATERIALS IRRADIATED IN CAPSULES OG-1 AND OG-2

Material	Specimen No.	Crucible	Irradiation Temperature (°C)	Fast Neutron Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Direction of Measurement	Dimensional Change (%)
FPA-20 carbon foam	I	7	900	2.8	Axial	-6
					Radial	-8
	II		900	2.8	Axial	-9
					Radial	-11
	I	↓	900-990	5.3	Axial	-7
					Radial	-11
Grafoil	(10 specimens)	5	1350	3.2	In-plane	0 to -5
		5	1350	6.1	In-plane	+3 to -6
Palarite C	I	7	900	2.8	Parallel to layers	-11
	II		900	2.8	Parallel to layers	-11
			900	2.8	Perpendicular to layers	+15
			900-990	5.3	Parallel to layers	-14
			900-990	5.3	Perpendicular to layers	+20
		↓				

6. EXPERIMENTAL RESULTS - THERMAL PROPERTIES

6.1. THERMAL EXPANSIVITY

Thermal expansivity measurements were made on 98 specimens of irradiated graphite measuring either 0.2 in. in diameter by 0.45 in. long or 0.25 in. in diameter by 0.9 in. long. Measurements were made in a silica dilatometer between room temperature and 100°C less than the irradiation temperature (maximum 1000°C). The graphites tested were near-isotropic grades H-451, H-429 (subsize prototype of H-451), and TS-1240 and needle coke grade H-327. The H-451, H-429, and H-327 graphite specimens had been irradiated in previous capsules, and lower-fluence thermal expansivity data are given in Ref. 4.

The thermal expansivities between room temperature and 500°C are listed in Tables 6-1 through 6-3, together with mean values for unirradiated material. The fractional changes in thermal expansivity are plotted as functions of fluence for the near-isotropic graphites in Fig. 6-1 and for H-327 (needle coke) graphite in Fig. 6-2. Figures 6-1 and 6-2 also include data obtained during postirradiation tests on specimens from capsule OG-1 (Ref. 4). The near-isotropic graphites (Fig. 6-1) show a small increase in thermal expansivity (generally less than 10%) in both the axial and radial directions when irradiated at 590° to 680°C and no significant changes when irradiated at 765° to 925°C. At higher irradiation temperatures, there is a pronounced decrease in thermal expansivity, with the values falling 30% after irradiation to about 7×10^{21} n/cm² above 1100°C. These irradiation-induced changes are similar in nature to, but smaller in magnitude than, those reported for Gilsocarbon-based isotropic nuclear graphites. H-327 graphite showed a small decrease in thermal expansivity on irradiation, with some indication of recovery at high fluences for the highest irradiation temperatures (Fig. 6-2).

TABLE 6-1
THERMAL EXPANSIVITY OF H-429 AND H-451 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-2

Graphite Grade	Specimen No.	Log Location	Orien- tation	Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) HTGR (E>0.18 MeV)	Coefficient of Thermal Expansivity x 10 ⁶ °C ⁻¹ (22° - 500°C)
H-451	.305.	MLC	Axial	1	4	640-680	3.7	3.84
	.306.	MLC	Axial	↓	4	↓	↓	3.87
	.307.	MLC	Axial	↓	5	↓	↓	4.00
	.430.	MLC	Radial	↓	4	↓	↓	4.87
	.431.	MLC	Radial	↓	4	↓	↓	5.21
	.432.	MLC	Radial	↓	5	↓	↓	4.94
H-451	.616.	MLE	Axial	9	3	820-850	3.6	3.83
	.617.	MLE	Axial	↓	3	↓	↓	4.06
	.618.	MLE	Axial	↓	4	↓	↓	3.95
	.716.	MLE	Radial	↓	3	↓	↓	4.85
	.717.	MLE	Radial	↓	3	↓	↓	4.93
	.718.	MLE	Radial	↓	4	↓	↓	4.92
H-451	.371.	MLC	Axial	8	1	920-940	4.5	3.08
	.372.	MLC	Axial	↓	1	↓	↓	3.24
	.373.	MLC	Axial	↓	2	↓	↓	3.35
	.496.	MLC	Radial	↓	1	↓	↓	4.43
	.497.	MLC	Radial	↓	1	↓	↓	3.55
	.498.	MLC	Radial	↓	2	↓	↓	4.78
H-429	389	--	Axial	8	8	890-925	5.2	4.01
	390	--	Axial	↓	8	↓	↓	4.10
	391	--	Axial	↓	8	↓	↓	4.20
H-429	424	--	Radial	8	20	850-890	5.6	5.22
	425	--	Radial	↓	20	↓	↓	5.21
	426	--	Radial	↓	20	↓	↓	4.75
H-451	.602.	MLE	Axial	7	7	980-990	5.3	3.33
	.603.	MLE	Axial	↓	7	↓	↓	2.96
	.604.	MLE	Axial	↓	8	↓	↓	2.99
	.702.	MLE	Radial	↓	7	↓	↓	3.99
	.703.	MLE	Radial	↓	7	↓	↓	3.88
	.704.	MLE	Radial	↓	8	↓	↓	4.04
H-451	.582.	MLE	Axial	4	1	1155-1255	6.3	2.75
	.583.	MLE	Axial	↓	2	↓	↓	2.93
	.584.	MLE	Axial	↓	2	↓	↓	2.46
	.682.	MLE	Radial	↓	1	↓	↓	3.30
	.683.	MLE	Radial	↓	2	↓	↓	3.64
	.684.	MLE	Radial	↓	2	↓	↓	3.62
H-429	408	--	Axial	4	9	1140-1235	8.6	2.94
	409	--	Axial	↓	9	↓	↓	3.18
	438	--	Radial	↓	9	↓	↓	3.68
	439	--	Radial	↓	9	↓	↓	3.45
H-451	.331.	MLC	Axial	5	1	1380-1395	6.1	2.17
	.332.	MLC	Axial	↓	1	↓	↓	2.64
	.333.	MLC	Axial	↓	7	↓	↓	2.64
	.456.	MLC	Radial	↓	1	↓	↓	2.80
	.457.	MLC	Radial	↓	1	↓	↓	3.32
	.458.	MLC	Radial	↓	7	↓	↓	3.22
H-429	.141	--	Axial	5	2	1380-1425	8.8	3.33
	.142	--	Axial	↓	2	↓	↓	2.90
	.143	--	Axial	↓	3	↓	↓	2.67
	.161	--	Radial	↓	2	↓	↓	4.38
	.162	--	Radial	↓	2	↓	↓	3.43
	.163	--	Radial	↓	3	↓	↓	2.70
H-451	(Mean)	MLC	Axial	↓	--	↓	0	3.78
	(Mean)	MLE	Axial	↓	--	↓	↓	3.86
	(Mean)	MLC	Radial	↓	--	↓	↓	4.68
	(Mean)	MLE	Radial	↓	--	↓	↓	4.81
H-429	(Mean)	--	Axial	--	--	--	0	4.25
	(Mean)	--	Radial	--	--	--	0	5.00

TABLE 6-2
THERMAL EXPANSIVITY OF TS-1240 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-2

Specimen No.	Log Location	Orientation	Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) _{HTGR}	Coefficient of Thermal Expansivity x 10 ⁶ °C ⁻¹ (22° - 500°C)
T40105	MLC	Axial	10	10	620	1.2	4.18
T40107	MLC	Axial	↓	10	↓	↓	4.26
T40109	MLC	Axial	↓	11	↓	↓	5.25
T40149	MLC	Radial	↓	32	590	↓	4.89
T40151	MLC	Radial	↓	32	↓	↓	4.86
T40153	MLC	Radial	↓	33	↓	↓	4.66
T40069	MLC	Axial	9	28	765	1.7	4.14
T40071	MLC	Axial	↓	28	↓	↓	4.53
T40073	MLC	Axial	↓	29	↓	↓	4.30
T40129	MLC	Radial	↓	12	805	↓	4.66
T40131	MLC	Radial	↓	12	↓	↓	4.47
T40133	MLC	Radial	↓	13	↓	↓	4.86
T40053	MLC	Axial	7	25	920	2.5	4.69
T40055	MLC	Axial	↓	25	↓	↓	4.06
T40057	MLC	Axial	↓	26	↓	↓	3.90
T40121	MLC	Radial	↓	29	↓	↓	4.67
T40123	MLC	Radial	↓	29	↓	↓	4.73
T40125	MLC	Radial	↓	30	↓	↓	4.55
T40017	MLC	Axial	4	28	1105	2.9	3.98
T40019	MLC	Axial	↓	28	↓	↓	4.40
T40021	MLC	Axial	↓	29	↓	↓	4.49
T40157	MLC	Radial	↓	10	1200	↓	4.15
T40159	MLC	Radial	↓	10	↓	↓	4.67
T40161	MLC	Radial	↓	11	↓	↓	4.12
(Mean)	MLC	Axial	--	--	--	0	4.26
(Mean)	MLC	Radial	--	--	--	0	4.84

TABLE 6-3
THERMAL EXPANSIVITY OF H-327 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-2

Specimen No.	Log Location	Orien- tation	Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E 0.18 MeV) _{HTGR}	Coefficient of Thermal Expansivity x 10 ⁶ °C ⁻¹ (22° - 500°C)
.203.	MLE	Axial	1	21	560-615	3.7	1.58
.204.	MLE	Axial	↓	21	↓	↓	1.34
.205.	MLE	Axial	↓	22	↓	↓	4.58
.253.	MLE	Radial	↓	21	↓	↓	3.94
.254.	MLE	Radial	↓	21	↓	↓	3.49
.255.	MLE	Radial	↓	22	↓	↓	3.63
140	MLC	Axial	8	6	890-1225	8.5	2.28
141	MLE	Axial	↓	6	↓	↓	1.60
138	MLC	Radial	↓	6	↓	↓	3.36
139	MLE	Radial	↓	6	↓	↓	3.87
.225.	MLE	Axial	7	5	980-990	5.3	1.70
.28.	MLC	Axial	↓	21	920-945	↓	1.55
.275.	MLE	Radial	↓	5	980-990	↓	2.98
.127.	MLC	Radial	↓	21	920-945	↓	3.53
.128.	MLC	Radial	↓	21	920-945	↓	3.50
T-263	MLC	Axial	4	21	1040-1105	6.3	1.21
T-264	MLC	Axial	↓	21	↓	↓	1.27
T-265	MLC	Axial	↓	22	↓	↓	1.20
216	MLC	Axial	↓	3	1115-1500	12.0	2.29
217	MLE	Axial	↓	3	↓	↓	2.06
214	MLC	Radial	↓	3	↓	↓	3.62
215	MLE	Radial	↓	3	↓	↓	4.33
(Mean)	--	Axial	--	--	--	0	1.96
(Mean)	--	Radial	--	--	--	0	3.70

Fig. 6-1(a). Percent change in thermal expansivity (22°-500°C) for H-451 and TS-1240 near-isotropic graphites as a function of fast neutron fluence at irradiation temperatures of 590° to 1060°C

Fig. 6-1(b). Percent change in thermal expansivity (22°-500°C) for H-451 and TS-1240 near-isotropic graphites as a function of fast neutron fluence at irradiation temperatures of 1105° to 1500°C

Fig. 6-2. Percent change in thermal expansivity (22°-500°C) for H-327 needle-coke graphite as a function of fast neutron fluence

6.2. THERMAL CONDUCTIVITY

Thermal diffusivity measurements were made on 87 disks (0.45 in. in diameter by 0.05 in. thick) of graphite irradiated in three crucibles in the OG-2 capsule. The graphite grades were near-isotropic H-451 and TS-1240 and needle coke H-327; both axial and radial specimens were tested. The H-451 and H-327 specimens had been irradiated previously in the OG-1 capsule, and lower-fluence data are reported in Ref. 4. Thermal diffusivity measurements were made by the heat-pulse method (ASTM Method of Test C-741), and thermal conductivity values were calculated by multiplying the thermal diffusivity by the density of the irradiated specimen and values for the heat capacity taken from the literature. Readings were taken at 100°C intervals between room temperature and 100°C below the irradiation temperature (maximum 800°C).

The measured values are given in Tables 6-4 through 6-6, together with extrapolated values at the irradiation temperature. The thermal conductivity at the irradiation temperature is plotted as a function of fast fluence in Fig. 6-3 for H-327 (needle coke) graphite. Figures 6-3 and 6-4 also include data from previous capsules GEH-13-422 and OG-1 (Ref. 4). Irradiation reduces the thermal conductivity to a saturation level which increases with increasing irradiation temperature. For fluences above about 7×10^{21} n/cm² at 1225° to 1350°C, H-327 graphite undergoes a second decline in thermal conductivity as the density of the material is reduced. The effect of grain orientation on the conductivity of the oriented needle coke H-327 is evident in Fig. 6-4. There is no significant difference between the thermal conductivities of irradiated H-451 graphite and irradiated TS-1240 graphite.

For design purposes, it is convenient to express the thermal conductivity of irradiated graphite, K_i , as an approach to saturation (Ref. 7):

$$K_i = K_{sat}(T) + [K_o - K_{sat}(T)] \exp\left[-\frac{\phi t}{\tau(T)}\right], \quad (6-1)$$

TABLE 6-4
THERMAL CONDUCTIVITY OF H-451 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-2
(All Specimens at Midlength-Center Location)

Specimen No.	Orientation	Crucible No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) _{HTGR}	Thermal Conductivity (cal/cm-sec-°C)					
					22°C	200°C	400°C	600°C	800°C	Irradiation Temperature (Extrapolation)
201	Axial	1	600-635	3.7	0.069	0.077	0.064	--	--	0.064
202	Axial	↓	↓	↓	0.072	0.080	0.079	--	--	0.077
203	Axial	↓	↓	↓	0.073	0.095	0.095	--	--	0.088
204	Axial	↓	↓	↓	0.074	0.089	0.086	--	--	0.082
221	Radial	↓	↓	↓	0.067	--	--	--	--	--
222	Radial	↓	↓	↓	0.055	--	--	--	--	--
223	Radial	↓	↓	↓	0.068	--	--	--	--	--
224	Radial	↓	↓	↓	0.068	--	--	--	--	--
225	Radial	↓	↓	↓	0.060	0.101	0.083	--	--	0.080
226	Radial	↓	↓	↓	0.067	0.074	0.076	--	--	0.067
227	Radial	↓	↓	↓	0.065	0.081	0.082	--	--	0.073
228	Radial	↓	↓	↓	0.081	0.071	0.067	--	--	0.062
205	Axial	7	920-945	5.3	0.069	0.085	0.083	0.097	0.095	0.085
206	Axial	↓	↓	↓	0.104	0.132	0.127	0.127	0.113	0.100
207	Axial	↓	↓	↓	0.109	0.132	0.129	0.118	0.113	0.100
208	Axial	↓	↓	↓	0.113	0.137	0.122	0.114	0.103	0.095
231	Radial	↓	↓	↓	0.076	--	--	--	--	--
232	Radial	↓	↓	↓	0.077	--	--	--	--	--
233	Radial	↓	↓	↓	0.069	--	--	--	--	--
234	Radial	↓	↓	↓	0.100	--	--	--	--	--
235	Radial	↓	↓	↓	0.087	0.090	0.085	0.087	0.082	0.076
236	Radial	↓	↓	↓	0.091	0.100	0.086	0.080	0.075	0.071
237	Radial	↓	↓	↓	0.080	0.098	0.085	0.077	0.085	0.071
238	Radial	↓	↓	↓	0.073	0.081	0.078	0.071	0.068	0.064

TABLE 6-4 (Continued)

Specimen No.	Orientation	Crucible No.	Mean Irradiation Temperature (°C)	Fluence $\times 10^{-21}$ (n/cm ²) (E>0.18 MeV) _{HTGR}	Thermal Conductivity (cal/cm-sec-°C)					
					22°C	200°C	400°C	600°C	800°C	Irradiation Temperature (Extrapolated)
210	Axial	5	1350	6.1	0.198	0.213	0.183	0.161	0.137	0.095
211	Axial	↓	↓	↓	0.204	0.183	0.176	0.169	0.149	0.098
212	Axial	↓	↓	↓	0.188	0.208	0.183	0.158	0.154	0.098
213	Axial	↓	↓	↓	0.183	0.196	0.184	0.165	0.152	0.098
242	Radial	↓	↓	↓	0.140	--	--	--	--	--
243	Radial	↓	↓	↓	0.136	--	--	--	--	--
244	Radial	↓	↓	↓	0.150	--	--	--	--	--
245	Radial	↓	↓	↓	0.135	--	--	--	--	--
246	Radial	↓	↓	↓	0.187	0.177	0.161	0.142	0.133	0.090
247	Radial	↓	↓	↓	0.170	0.169	0.145	0.130	0.128	0.084
248	Radial	↓	↓	↓	0.173	0.185	0.170	0.145	0.143	0.092
249	Radial	↓	↓	↓	0.166	0.183	0.147	0.136	0.121	0.082
(Mean of 12)	Axial	--	--	0	0.347	0.302	0.247	0.206	0.174	--
(Mean of 12)	Radial	--	--	0	0.294	0.262	0.222	0.185	0.158	--

TABLE 6-5
THERMAL CONDUCTIVITY OF TS-1240 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-2
(All Specimens at Midlength-Center Location)

Specimen No.	Orientation	Crucible No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) _{HTGR}	Thermal Conductivity (cal/cm-sec-°C)					
					22°C	200°C	400°C	600°C	800°C	Irradiation Temperature (Extrapolated)
74D-63	Axial	1	635	1.7	0.077	0.092	0.087	--	--	0.077
74D-64	Axial				0.071	0.097	0.087	--	--	0.079
74D-65	Axial				0.071	0.100	0.094	--	--	0.085
74D-66	Axial				0.073	0.093	0.091	--	--	0.085
74D-93	Radial				0.065	--	--	--	--	--
74D-94	Radial				0.068	--	--	--	--	--
74D-95	Radial				0.067	--	--	--	--	--
74D-96	Radial				0.067	--	--	--	--	--
74D-97	Radial				0.056	0.084	0.084	--	--	0.078
74D-98	Radial				0.075	0.084	0.083	--	--	0.079
74D-99	Radial	7	945	2.5	0.069	0.092	0.082	--	--	0.077
74D-100	Radial				0.078	0.088	0.084	--	--	0.078
74D-71	Axial	7	945	2.5	0.097	0.108	0.104	0.100	0.091	0.085
74D-72	Axial				0.116	0.125	0.120	0.109	0.103	0.094
74D-73	Axial				0.115	0.123	0.114	0.104	0.096	0.098
74D-74	Axial				0.107	0.117	0.110	0.102	0.094	0.088
74D-109	Radial				0.091	--	--	--	--	--
74D-110	Radial				0.088	--	--	--	--	--
74D-111	Radial				0.088	--	--	--	--	--
74D-112	Radial				0.086	--	--	--	--	--
74D-113	Radial				0.085	0.094	0.085	0.071	0.080	0.068
74D-114	Radial				0.082	0.088	0.079	0.068	0.083	0.068
74D-115	Radial				0.087	0.102	0.100	0.080	0.084	0.076
74D-116	Radial				0.100	0.101	0.090	0.077	0.088	0.074

TABLE 6-5 (Continued)

Specimen No.	Orientation	Crucible No.	Mean Irradiation Temperature (°C)	Fluence $\times 10^{-21}$ (n/cm ²) (E>0.18 MeV) _{HTGR}	Thermal Conductivity (cal/cm-sec-°C)					
					22°C	200°C	400°C	600°C	800°C	Irradiation Temperature (Extrapolated)
74D-67	Axial	5	1345	2.9	0.178	0.162	0.162	0.144	0.126	0.092
74D-68	Axial				0.162	0.191	0.154	0.138	0.127	0.092
74D-69	Axial				0.170	0.176	0.158	0.138	0.127	0.092
74D-70	Axial				0.154	0.167	0.153	0.138	0.118	0.085
74D-101	Radial				0.139	--	--	--	--	--
74D-102	Radial				0.139	--	--	--	--	--
74D-103	Radial				0.146	--	--	--	--	--
74D-104	Radial				0.156	--	--	--	--	--
74D-105	Radial				0.167	0.170	0.133	0.111	0.112	0.082
74D-106	Radial				0.148	0.162	0.112	0.110	0.107	0.078
74D-107	Radial				0.167	0.173	0.142	0.120	0.112	0.083
74D-108	Radial				0.172	0.147	0.129	0.108	0.105	0.077
(Mean of 8)	Axial	--	--	0	0.234	0.223	0.192	0.165	0.145	--
(Mean of 8)	Radial	--	--	0	0.247	0.231	0.195	0.167	0.148	--

TABLE 6-6
THERMAL CONDUCTIVITY OF H-327 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-2
(All Specimens at Midlength-Edge Location)

Specimen No.	Orientation	Crucible No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) _{HTGR}	Thermal Conductivity (cal/cm-sec-°C)					
					22°C	200°C	400°C	600°C	800°C	Irradiation Temperature (Extrapolated)
81	Axial	1	600-635	4.3	0.069	0.118	0.120	--	--	0.105
82	Axial	↓	↓	↓	0.086	0.108	0.109	--	--	0.095
1	Radial	↓	↓	↓	0.046	0.055	0.053	--	--	0.049
2	Radial	↓	↓	↓	0.047	0.057	0.056	--	--	0.051
13	Radial	↓	↓	↓	0.052	0.060	0.064	--	--	0.056
83	Axial	7	900-945	7.1	0.074	0.087	0.076	0.077	0.077	0.072
84	Axial	↓	900-945	↓	0.072	0.076	0.074	0.073	0.069	0.064
3	Radial	↓	875-945	↓	0.048	0.064	0.057	0.054	0.051	0.048
4	Radial	↓	↓	↓	0.053	0.060	0.058	0.061	0.068	0.056
32	Radial	↓	↓	↓	0.056	0.064	0.062	0.065	0.069	0.062
86	Axial	5	1225-1345	11.7	0.120	0.127	0.105	0.100	0.092	0.064
87	Axial	↓	↓	↓	0.131	0.123	0.108	0.103	0.105	0.069
43	Radial	↓	↓	↓	0.114	0.115	0.097	0.086	0.085	0.060
44	Radial	↓	↓	↓	0.102	0.104	0.092	0.113	0.095	0.062
45	Radial	↓	↓	↓	0.088	0.084	0.073	0.066	0.071	0.053
(Mean of 6)	Axial	--	--	0	0.450	0.367	0.293	0.240	0.194	--
(Mean of 6)	Radial	--	--	0	0.331	0.261	0.201	0.170	0.140	--

○ H-451, PERPENDICULAR TO EXTRUSION
 △ TS-1240, PERPENDICULAR TO EXTRUSION

● H-451, PARALLEL TO EXTRUSION
 ▲ TS-1240, PARALLEL TO EXTRUSION
 ■ H-328, PERPENDICULAR TO MOLDING

Fig. 6-3. Observed thermal conductivity of H-451 and TS-1240 near-isotropic graphites at irradiation temperature as a function of fast neutron fluence

Fig. 6-4. Observed thermal conductivity of H-327 needle coke graphite at irradiation temperature as a function of fast neutron fluence

where $K_{\text{sat}}(T)$ is the saturation thermal conductivity for irradiation temperature T , K_0 is the unirradiated thermal conductivity, ϕt is the fast neutron fluence, and $\tau(T)$ is the time constant for irradiation temperature T . Equation 6-1 may be assumed to hold until volume expansion starts and the second decline in conductivity begins. $\tau(T)$ and $K_{\text{sat}}(T)$ can be stated empirically in terms of the irradiation temperature, T :

$$\tau(T) = A + BT \quad , \quad (6-2)$$

$$K_{\text{sat}}(T) = \exp(C + DT) \quad . \quad (6-3)$$

The experimental data for the room-temperature thermal conductivity of irradiated H-451, TS-1240, and H-327 graphites contained in Tables 6-4 through 6-6 and in Ref. 4 were fitted to Eqs. 6-1 through 6-3 by graphical and least-squares methods to obtain best-fit values for the parameters A, B, C, and D. The new values are listed in Table 6-7. These values can be used to calculate the room-temperature thermal conductivity (cal/cm-sec-°C) in terms of fluence (10^{21} n/cm²) ($E > 0.18$ MeV)_{HTGR} and irradiation temperature (°C). A model for calculating the conductivity at other temperatures is described in Ref. 7. The calculated values for conductivity at the irradiation temperature are plotted as functions of fast neutron fluence and irradiation temperature in Figs. 6-5 and 6-6 for grades H-451 and TS-1240 and grade H-327, respectively.

TABLE 6-7
THERMAL CONDUCTIVITY PARAMETERS FOR IRRADIATED GRAPHITES
(Eqs. 6-1, 6-2, 6-3)(a)

Grade	Orientation	Value Of Parameter			
		$(10^{21} \text{ }^A \text{ n/cm}^2)$ ($E > 0.18 \text{ MeV}$) _{HTGR}	$(10^{21} \text{ }^B \text{ n/cm}^2 / ^\circ\text{C})$	C (Unitless)	D ($^\circ\text{C}^{-1}$)
H-451 } TS-1240 }	Axial	-0.3059	9.58×10^{-4}	-3.317	1.207×10^{-3}
H-451 } TS-1240 }	Radial	-0.3059	9.58×10^{-4}	-3.430	1.222×10^{-3}
H-327	Axial	-0.3059	9.58×10^{-4}	-3.429	1.305×10^{-3}
H-327	Radial	-0.3059	9.58×10^{-4}	-4.215	1.821×10^{-3}

(a) K in cal/cm-sec- $^\circ\text{C}$.

Fig. 6-5. Calculated thermal conductivity of H-451 and TS-1240 near-isotropic graphites at irradiation temperature as a function of irradiation temperature

Fig. 6-6. Calculated thermal conductivity of H-327 needle coke graphite at irradiation temperature as a function of irradiation temperature

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-451, TS-1240, and H-327 graphite from capsule OG-2. All specimens were from the midlength-center region of the parent log. The specimens of H-451 and some of the H-327 specimens had been irradiated previously in capsule OG-1. An Instron tensile testing machine with a crosshead speed of 0.005 in./min was used, and strains were measured with a 0.5-in. gauge length extensometer. The specimens were cemented to metal end-pieces with high-strength epoxy cement, and the load was applied through roller-link chains to maintain uniaxial alignment. The specimens were loaded to 1000 psi, unloaded to 100 psi, and reloaded to failure. Young's modulus was measured from the 100 to 1000 psi reloading part of the curve.

The tensile strengths, strains at failure, Young's moduli, and secant moduli (tensile strength divided by failure strain) are given in Tables 7-1 through 7-3, together with test data for unirradiated companion specimens. The changes in strength and Young's modulus are plotted as functions of fast neutron fluence in Figs. 7-1, 7-2, and 7-3 for H-451, TS-1240, and H-327 graphites, respectively. Figures 7-1 through 7-3 also include data from specimens irradiated in capsule OG-1 (Ref. 4). A summary of tensile data from both capsules appears in Table 7-4.

The increases in Young's modulus follow the pattern established by Dragon project measurements of the dynamic modulus of irradiated graphites (Ref. 8). During irradiation the modulus rises to a plateau whose level decreases with increasing irradiation temperature. There is an indication of a second increase at higher fluences in the data for H-451 graphite irradiated at 890° to 970°C to 5×10^{21} n/cm² (Fig. 7-1). The fractional increases in Young's modulus are greater than the increases in dynamic

TABLE 7-1
TENSILE PROPERTIES OF H-451 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-2
(All Specimens at Midlength-Center Location)

Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) HTGR	Orien- tation	Specimen No.	Ultimate Tensile Strength (psi)	Strain at Failure (%)	Young's Modulus (10 ⁶ psi)	Secant Modulus (10 ⁶ psi)
10 ↓	24	590 ↓	2.6 ↓	Axial ↓	T-173	2532	0.110	2.61	2.30
	24				T-174	2589	0.138	2.35	1.88
	25				T-175	2326	0.090	2.73	2.58
	25				T-176	1775	0.097	2.21	1.83
	26				T-177	2624	0.121	2.58	2.17
	26				T-178	2861	0.123	2.84	2.33
	27				T-179	2641	0.134	2.51	1.97
	27				T-180	2496	0.117	2.50	2.13
					Mean	2481	0.116	2.54	2.15
					Std Dev	±322	±0.017	±0.20	±0.25
7 ↓	10	950-970 950-970 890-920 ↓	5.3 ↓	Axial ↓	T-155	2240	0.105	2.50	2.13
	10				T-156	2822	0.130	2.70	2.17
	22				T-157	3027	0.136	2.59	2.23
	22				T-158	2877	0.127	2.74	2.27
	23				T-159	2857	0.125	2.61	2.29
	23				T-160	3004	0.150	2.28	2.00
	24				T-161	2550	0.122	2.52	2.09
	24				T-162	2835	0.145	2.43	1.96
					Mean	2777	0.130	2.55	2.14
					Std Dev	±261	±0.014	±0.15	±0.12
-- ↓	--	-- ↓	0 ↓	Axial ↓	T-181	1446	0.130	1.22	1.11
	--				T-182	1630	0.230	1.02	0.71
	--				T-183	1650	0.212	1.15	0.78
	--				T-184	1589	0.169	1.17	0.94
	--				T-185	1548	0.152	1.20	1.02
	--				T-186	1731	0.211	1.23	0.82
	--				T-187	1243	0.182	0.95	0.68
	--				T-188	1609	0.187	1.17	0.86
	--				T-190	1630	0.184	1.17	0.89
	--				Mean	1564	0.184	1.14	0.87
	--				Std Dev	±135	±0.029	±0.09	±0.13
	--								
	--								
-- ↓	--	-- ↓	0 ↓	Radial ↓	T-219	1589	0.210	0.97	0.76
	--				T-220	1751	0.215	0.98	0.81
	--				T-221	1874	0.252	1.02	0.74
	--				T-222	1731	0.223	1.02	0.77
	--				T-223	1650	0.210	0.94	0.79
	--				T-224	2037	0.267	1.02	0.76
	--				T-225	1283	0.172	0.97	0.75
	--				T-226	1609	0.181	1.12	0.89
	--				T-227	1853	0.241	1.06	0.77
	--				T-228	1344	0.147	1.02	0.91
	--				1	1446	0.227	0.92	0.64
	--				2	1508	0.242	0.91	0.62
	--				3	2220	0.342	1.03	0.65
	--				5	1609	0.219	0.99	0.73
	--				6	1562	0.214	1.08	0.73
	--				Mean	1671	0.224	1.00	0.75
	--				Std Dev	±242	±0.043	±0.05	±0.08
	--								
	--								

TABLE 7-2
TENSILE PROPERTIES OF TS-1240 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-2
(All Specimens at Midlength-Center Location)

Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence $\times 10^{-21}$ (n/cm ²) _{HTGR} (E>0.18 MeV)	Orien- tation	Specimen No.	Ultimate Tensile Strength (psi)	Strain At Failure (%)	Young's Modulus (10 ⁶ psi)	Secant Modulus (10 ⁶ psi)
10	10	620	1.2	Axial	T40105	1940	0.104	2.16	1.87
	10				T40107	1426	0.116	1.34	1.23
	11				T40109	1104	0.100	1.22	1.10
	11				T40111	1492	0.096	1.99	1.55
	12				T40113	2221	0.156	1.64	1.42
	12				T40115	2528	0.148	1.93	1.71
	13				T40117	2202	0.133	2.09	1.66
	13				T40118	1653	--	1.54	--
	14				T40119	1629	0.114	1.70	1.43
	14				T40120	2246	0.167	1.57	1.34
					Mean	1844	0.126	1.72	1.48
					Std Dev	±452	±0.026	±0.32	±0.24
9	28	765	1.7	Axial	T40069	1204	0.089	1.56	1.35
	28				T40071	1981	0.140	1.62	1.42
	29				T40073	2270	0.182	1.47	1.25
	29				T40075	1964	0.127	1.78	1.55
	30				T40077	2354	0.150	2.05	1.57
	30				T40079	1822	0.122	1.67	1.49
	31				T40081	1309	0.144	1.84	1.60
	31				T40083	2516	0.163	1.81	1.54
	32				T40085	2385	0.153	1.85	1.56
	32				T40087	1895	0.143	1.58	1.32
					Mean	2070	0.141	1.72	1.47
					Std Dev	±385	±0.025	±0.17	±0.12
9	12	805	1.7	Radial	T40129	2163	0.140	1.74	1.55
	12				T40131	1940	0.113	1.88	1.72
	13				T40133	1816	0.131	1.56	1.39
	13				T40135	1899	0.168	1.33	1.13
	14				T40137	2180	0.166	1.48	1.31
	14				T40139	1181	0.138	0.99	0.86
	15				T40141	2302	0.174	1.54	1.32
	15				T40143	2100	0.144	1.62	1.46
	16				T40145	1979	0.160	1.38	1.24
	16				T40147(a)	1084(a)	0.194(a)	0.66(a)	0.56(a)
					Mean	1951	0.148	1.50	1.33
					Std Dev	±327	±0.020	±0.26	±0.25
7	25	920	2.5	Axial	T40053	2330	0.162	1.72	1.44
	25				T40055	1696	0.136	1.63	1.25
	26				T40057	2385	0.178	1.55	1.34
	26				T40059	2467	0.166	1.83	1.49
	27				T40061	1918	0.138	1.50	1.39
	27				T40063	2042	0.144	1.81	1.42
	28				T40065	2122	0.151	1.74	1.41
	28				T40067	2023	0.172	1.52	1.18
					Mean	2123	0.156	1.66	1.37
					Std Dev	±259	±0.016	±0.13	±0.10
4	28	1105	2.9	Axial	T40017	2485	0.197	1.64	1.26
	28				T40019	1438	0.114	1.56	1.26
	29				T40021	1729	0.125	1.70	1.38
	29				T40023	2798	0.220	1.56	1.27
	30				T40025	2205	0.144	1.92	1.53
	30				T40027	2328	0.153	1.91	1.52
	31				T40029	1235	0.098	1.48	1.26
	31				T40031	1706	0.154	1.40	1.11
	32				T40033	1214	--	1.70	--
	32				T40035	1855	0.106	2.06	1.75
					Mean	1899	0.146	1.69	1.37
					Std Dev	±540	±0.041	±0.21	±0.20

(a) Specimen flawed; excluded from averages.

TABLE 7-2 (Continued)

Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) _{HTGR}	Orientation	Specimen No.	Ultimate Tensile Strength (psi)	Strain At Failure (%)	Young's Modulus (10 ⁶ psi)	Secant Modulus (10 ⁶ psi)
--	--	--	0	Axial	3A-6B	1427	0.210	0.90	0.68
					7B	1711	0.270	0.95	0.63
					12B	2015	0.310	1.00	0.65
					13B	1896	0.320	0.90	0.59
					18B	1469	0.200	0.86	0.73
					19B	1406	0.285	0.69	0.49
					24B	1796	0.275	0.95	0.65
					25B	1691	0.250	1.00	0.68
					27B	1449	0.245	0.86	0.59
					28B	1672	0.265	0.90	0.63
					3B-6B	1976	0.323	1.00	0.61
					7B	1670	0.245	1.00	0.68
					12B	1438	0.185	1.00	0.78
					13B	1141	0.145	0.95	0.79
					18B	1080	0.240	0.60	0.45
					19B	1283	0.190	0.86	0.68
					24B	1487	0.215	0.88	0.69
					25B	1569	0.295	0.90	0.53
					27B	1507	0.275	0.86	0.55
					28B	1731	0.335	0.86	0.52
					Mean	1571	0.254	0.90	0.63
					Std Dev	±252	±0.051	±0.10	±0.09
--	--	--	0	Radial	3A-36B	957	0.140	--	0.68
					37B	1428	0.220	0.95	0.65
					42B	1367	0.205	1.00	0.67
					43B	1266	0.300	0.78	0.42
					48B	1388	0.245	0.72	0.57
					49B	1120	0.130	1.00	0.86
					54B	1450	0.210	0.90	0.69
					55B	1531	0.250	0.95	0.61
					60A	2400	0.350	1.06	0.69
					60B	1170	0.175	0.90	0.67
					3B-36B	1448	0.330	0.75	0.44
					37B	958	0.165	--	0.58
					42B	1428	0.210	0.95	0.68
					43B	1287	0.195	0.88	0.66
					48B	1594	0.252	0.90	0.63
					49B	1491	0.255	0.95	0.58
					54B	1384	0.205	1.00	0.68
					55B	1428	0.233	0.91	0.61
					60A	1428	0.295	0.83	0.48
					60B	1144	0.255	0.68	0.45
					Mean	1383	0.231	0.90	0.62
					Std Dev	±298	±0.058	±0.11	±0.11

TABLE 7-3
TENSILE PROPERTIES OF H-327 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-2
(All Specimens at Midlength-Center Location)

Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence $\times 10^{-21}$ (n/cm ²) (E>0.18 MeV) _{HTGR}	Orien- tation	Specimen No.	Ultimate Tensile Strength (psi)	Strain At Failure (%)	Young's Modulus (10 ⁶ psi)	Secant Modulus (10 ⁶ psi)
2	10	740	2.2	Axial	T-307	1682	0.102	1.90	1.65
	10				T-308	1962	0.136	2.03	1.44
	11				T-309	2267	0.116	2.41	1.95
	11				T-310	1945	0.123	2.15	1.58
	12				T-311	1722	0.133	1.81	1.29
	12				T-312	1500	--	3.14	--
	13				T-313	2551	0.147	1.90	1.74
	13				T-314	2324	0.112	2.59	2.08
	14				T-315	2105	0.114	2.27	1.85
	14				T-316	1378	0.076	2.29	1.81
					Mean	1944	0.118	2.25	1.71
					Std Dev	±377	±0.021	±0.40	±0.25
9	10	750-765	3.6	Axial	T-297	2015	0.098	2.20	2.06
	10				T-298	2606	0.132	2.56	1.97
	11				T-299	2421	0.104	2.96	2.33
	11				T-300	1892	0.093	2.56	2.03
	25				T-301	2319	0.113	2.44	2.05
	25				T-302	2518	0.102	3.05	2.47
	26				T-303	2341	0.124	2.36	1.89
	26				T-304	3133	0.102	3.91	3.07
	27				T-305	2603	0.138	2.64	1.89
	27				T-306	2382	0.096	2.97	2.48
					Mean	2423	0.110	2.77	2.22
					Std Dev	±341	±0.016	±0.49	±0.37
8	24	835-850	4.5	Axial	T-289	2467	0.111	2.71	2.22
	24				T-290	2482	--	2.82	--
	25				T-291	3199	0.144	2.65	2.22
	25				T-292	2297	0.108	2.44	2.13
	26				T-293	2510	0.101	2.98	2.49
	26				T-294	2425	0.105	2.53	2.31
	27				T-295	2020	0.087	2.39	2.32
	27				T-296	2077	0.136	1.91	1.53
					Mean	2435	0.113	2.55	2.17
					Std Dev	±361	±0.020	±0.32	±0.31
6	12	960	2.7	Axial	T-325	2120	0.107	2.33	1.98
	12				T-326	2385	0.149	2.53	1.60
	13				T-327	2085	0.123	2.00	1.70
	13				T-328	1328	0.053	3.02	2.51
	24				T-329	1899	0.106	2.14	1.79
	24				T-330	2336	0.118	2.46	1.98
	25				T-331	1714	0.061	3.24	2.81
	25				T-332	1590	--	2.08	--
	26				T-333	1862	0.087	2.39	2.14
	26				T-334	2078	0.096	2.59	2.16
					Mean	1940	0.100	2.48	2.07
					Std Dev	±331	±0.030	±0.40	±0.39

TABLE 7-3 (Continued)

Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence $\times 10^{-21}$ (n/cm ²) (E>0.18 MeV)HTGR	Orien- tation	Specimen No.	Ultimate Tensile Strength (psi)	Strain At Failure (%)	Young's Modulus (10 ⁶ psi)	Secant Modulus (10 ⁶ psi)
6 ↓	10	1020-1035	5.7 ↓	Axial ↓	T-269	2206	0.116	2.07	1.90
	10	↓			T-270	2829	0.150	2.05	1.89
	11	↓			T-271	2161	0.099	2.58	2.18
	11	↓			T-272	1904	0.135	2.01	1.41
	21	940-960			T-273	1907	0.104	2.30	1.83
	21	↓			T-274	2289	0.140	1.81	1.64
	22	↓			T-275	1412	0.071	2.54	1.99
	22	↓			T-276	2095	0.090	2.71	2.33
	23	↓			T-277	3058	0.134	2.65	2.28
	23	↓			T-278	2360	0.122	2.44	1.93
					Mean	2222	0.116	2.32	1.94
					Std Dev	±468	±0.025	±0.31	±0.28
4 ↓	14	1110-1200	6.3 ↓	Axial ↓	T-261	2185	0.110	2.19	1.99
	14	1110-1200			T-262	1148	0.055	2.48	2.09
	21	1040-1105			T-263	1711	0.082	2.52	2.09
	21	↓			T-264	3046	0.142	2.50	2.15
	22	↓			T-265	2489	0.104	2.69	2.39
	22	↓			T-266	1695	0.110	1.72	1.54
	23	↓			T-267	1658	0.090	2.17	1.84
	23	↓			T-268	2094	0.105	2.32	1.99
					Mean	2003	0.100	2.32	2.01
					Std Dev	±585	±0.025	±0.30	±0.25
--	--	--	0 ↓	Axial ↓	11	1141	0.112	1.15	1.02
					12	1508	0.147	1.43	1.03
					13	1182	0.124	1.32	0.95
					15	1324	0.160	1.12	0.83
					16	1569	0.176	1.22	0.89
					17	1222	0.105	1.43	1.16
					18	1406	0.134	1.41	1.05
					19	1222	--	1.33	--
					Mean	1321	0.137	1.30	0.99
					Std Dev	±158	±0.026	±0.12	±0.11
--	--	--	0 ↓	Radial ↓	21	815	0.144	0.73	0.57
					22	896	0.216	0.67	0.42
					24	1161	0.256	0.63	0.45
					25	896	0.160	0.77	0.56
					26	957	0.230	0.70	0.42
					28	713	0.249	0.51	0.29
					29	244	--	--	--
					30	488	--	--	--
					31	468	--	--	--
					32	957	0.262	0.58	0.37
					33	1120	0.240	0.56	0.47
					34	754	0.196	0.62	0.38
					35	1201	0.336	0.64	0.36
					Mean	820	0.229	0.64	0.43
					Std Dev	±286	±0.055	±0.08	±0.09

Fig. 7-1. Observed tensile strength and Young's modulus of H-451 near-isotropic graphite as functions of fast neutron fluence

Fig. 7-2. Observed tensile strength and Young's modulus of TS-1240 near-isotropic graphite as functions of fast neutron fluence

Fig. 7-3(a). Observed tensile strength and Young's modulus of H-327 needle coke graphite as functions of fast neutron fluence at irradiation temperatures of 640° to 900°C

Fig. 7-3(b). Observed tensile strength and Young's modulus of H-327 needle coke graphite as functions of fast neutron fluence at irradiation temperatures of 940° to 1200°C

TABLE 7-4
SUMMARY OF MECHANICAL PROPERTY DATA FOR GRAPHITES IRRADIATED IN CAPSULES OG-1 AND OG-2

Material	Orientation	Location in Log	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) _{HTGR}	Ultimate Tensile Strength (psi)		Young's Modulus (10 ⁶ psi)	
					Observed (± Std Dev)	Predicted ^(a)	Observed (± Std Dev)	Predicted ^(a)
H-451 ↓	Axial ↓ Radial Radial	Midlength-center ↓	--	0	1564 ± 135	--	1.14 ± 0.09	--
			580-630	1.4	2424 ± 265	2140	2.63 ± 0.20	2.2
			580-630	2.0	2485 ± 177	2160	2.22 ± 0.11	2.2
			580-630	2.6	2481 ± 322	2180	2.54 ± 0.20	2.2
			910-950	3.0	2371 ± 271	2040	2.06 ± 0.24	2.0
			890-970	5.3	2777 ± 261	2200	2.55 ± 0.15	2.4
			1340-1370	3.2	2233 ± 115	2000	1.79 ± 0.08	1.9
			--	0	1671 ± 242	--	1.00 ± 0.05	--
TS-1240 ↓	Axial ↓ Radial Radial	Midlength-center ↓	900-950	2.8	2648 ± 270	2190	1.88 ± 0.13	1.8
			--	0	1571 ± 252	--	0.90 ± 0.10	--
			620	1.2	1844 ± 452	2140	1.72 ± 0.32	1.7
			765	1.7	2070 ± 385	2100	1.72 ± 0.17	1.6
			920	2.5	2123 ± 259	2070	1.66 ± 0.13	1.6
			1105	2.9	1899 ± 540	2050	1.69 ± 0.21	1.6
			--	0	1383 ± 298	--	0.90 ± 0.11	--
			805	1.7	1951 ± 327	1850	1.50 ± 0.26	1.6
H-327 ↓	Axial ↓ Radial Radial	Midlength-center ↓	--	0	1321 ± 158	--	1.30 ± 0.12	--
			740	2.2	1944 ± 377	1790	2.25 ± 0.40	2.4
			750-810	3.6	2423 ± 341	1800	2.77 ± 0.49	2.4
			835-850	4.5	2435 ± 361	1810	2.55 ± 0.32	2.5
			860-900	2.3	2127 ± 281	1740	3.02 ± 0.27	2.3
			960-1035	2.7	1940 ± 331	1730	2.48 ± 0.40	2.3
			940-1035	5.7	2222 ± 468	1890	2.32 ± 0.31	2.6
			1040-1200	6.3	2003 ± 585	1850	2.32 ± 0.30	2.5
			--	0	2186 ± 293	--	1.93 ± 0.25	--
			640-700	2.6	3152 ± 278	3000	3.85 ± 0.33	3.7
			770-810	1.9	2787 ± 249	2930	3.10 ± 0.26	3.5
			1050-1100	3.3	2822 ± 254	2860	3.23 ± 0.19	3.4
			--	0	820 ± 286	--	0.64 ± 0.08	--
			960-1020	3.0	962 ± 198	1070	1.23 ± 0.20	1.1

(a) Predicted from Figs. 6-5 and 6-6.

Young's modulus found during the Dragon project work (Ref. 8). The difference probably occurs because a static determination of Young's modulus on unirradiated graphite is usually lower than a dynamic determination, but the two methods give similar results on irradiated graphite. The present results become consistent with Dragon project data on similar graphites if it is assumed that the static Young's modulus of unirradiated graphite is 80% of the dynamic modulus, while the two values are the same for irradiated graphite (see Section 8.4).

Increases in tensile strength followed a pattern similar to the increases in Young's modulus; but for given irradiation conditions, the fractional increase in strength was always less than the fractional increase in Young's modulus. The condition of constant strain energy to failure would require that the irradiated and unirradiated strengths, S_i and S_o , be related to the irradiated and unirradiated Young's moduli, E_i and E_o , as follows:

$$\frac{S_i}{S_o} = \sqrt{\frac{E_i}{E_o}} \quad .$$

The strengths of all groups of irradiated H-451 specimens and most groups of H-327 specimens were higher than expected from this relationship, but the strengths of the TS-1240 specimen groups and some H-327 specimen groups were about as predicted.

Irradiation-induced changes in the coefficient of variation of the strength (standard deviation divided by the mean) were not statistically significant, with the exception of the specimens of TS-1240 irradiated at 1105°C to 2.9×10^{21} n/cm² and the H-327 specimens irradiated at 940° to 1035°C to 5.7×10^{21} n/cm² and at 1040° to 1200°C to 6.3×10^{21} n/cm². For these specimens there was a significant increase in the coefficient of variation at the 95% confidence level.

8. IMPACT OF TEST DATA ON CURRENT DESIGN PROCEDURES

8.1. DIMENSIONAL CHANGES

The additional data generated by the OG-2 experiment agree very well with design curves fit and extrapolated from earlier data. The only significant change in H-451 design curves is caused by the shift to HTGR fluence. This will result in slightly larger (10% to 20%) dimensional changes at $8 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR}.

8.2. THERMAL EXPANSIVITY

Figures 6-1(a) and 6-1(b) show the irradiation-induced fractional changes in thermal expansivity at various irradiation temperatures. Compared with the design curves currently in use, the new data show a somewhat smaller increase at low irradiation temperatures and a greater decrease at high irradiation temperatures. Compared with the current curves, the new data indicate thermal expansivities for near-isotropic graphite that are lower by about $0.5 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ at fluences of 5 to $7 \times 10^{21} \text{ n/cm}^2$ at or above 900°C .

8.3. THERMAL CONDUCTIVITY

New parameters to be used in the thermal conductivity model currently employed (Ref. 7) are listed in Table 6-7. For near-isotropic graphites, the new values correspond to thermal conductivities of irradiated graphite about 5% lower than the current values. For H-327 graphite, the new values are 15% to 25% lower than current design values.

8.4. MECHANICAL PROPERTIES

Current design basis curves for the fractional increase in Young's modulus and strength as a function of fluence and temperature were derived from Dragon project sonic modulus data on comparable near-isotropic graphites (Ref. 8), based on the following assumptions:

1. Neutron fluence in units of n/cm^2 (NDE) = $0.6 \times$ fluence in units of n/cm^2 ($E > 0.18$ MeV)_{ORR} [$0.67 \times$ fluence in units of n/cm^2 ($E > 0.18$ MeV)_{HTGR}].
2. Static Young's modulus of unirradiated graphite = $0.8 \times$ dynamic Young's modulus.
3. Static Young's modulus of irradiated graphite = dynamic Young's modulus.
4. Strength (S) and Young's modulus (E) of unirradiated and irradiated specimens are related as follows:

$$\frac{S_i}{S_o} = \sqrt{\frac{E_i}{E_o}} .$$

The current curves are reproduced in Figs. 8-1 and 8-2. Modulus and strength values predicted from Figs. 8-1 and 8-2 are included in Table 7-4 for comparison with the measurements. The modulus values are in fairly good agreement with the design curve predictions. Observed strengths for H-451 graphite and most of the H-327 specimen groups are higher than predicted. However, there are not yet sufficient experimental measurements to justify the use of a less conservative prediction. No changes are proposed in the strength and Young's modulus design curves (Figs. 8-1 and 8-2).

Fig. 8-1. Calculated curves for the percent increase in Young's modulus of near-isotropic graphites as a function of fast neutron fluence and irradiation temperature

Fig. 8-2. Calculated curves for the percent increase in tensile strength of near-isotropic graphites as a function of fast neutron fluence and irradiation temperature

9. REFERENCES

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