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**BORONATED GRAPHITE IRRADIATION STUDIES
SUMMARY REPORT
OF THERMAL-NEUTRON-SHIELDED EXPERIMENTS
CONDUCTED IN THE ETR**

L. O. GATES and R. NEIDNER

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CONDUCTED IN THE ETR

By

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INTRODUCTION

Experimental programs to evaluate the effects of neutron irradiation on boronated graphite, a fast-reactor shielding material, have been conducted by the Pacific Northwest Laboratory (formerly Hanford Laboratories) since July, 1963. The initial study was made for the Enrico Fermi Reactor and experiments were conducted in the predominately thermal-neutron spectrum of a Hanford reactor test facility.⁽¹⁾ Irradiation conditions, as a result, were vastly different from those of a fast reactor, and the data obtained could not be equated directly to a specific neutron exposure attained in a fast-flux environment. As a basis for correlating the Hanford test results to fast-reactor conditions, a program of boronated graphite testing was initiated in the Engineering Test Reactor (ETR) to provide irradiation-damage data from a nuclear environment having a neutron energy distribution intermediate to the intense high-energy spectrum of a fast reactor and the thermally rich spectrum of the Hanford reactor test facility. This program, designated GEH-23, was performed as part of the Nuclear Graphite Studies sponsored by the Division of Reactor Development and Technology of the US Atomic Energy Commission.

Neutron-induced dimensional distortion results are presented

in this report for two grades of boronated graphite, each containing either 5 or 7 wt% boron in the form of boron carbide (B_4C). These data were determined from samples contained in three long-term GEH-23 capsules irradiated consecutively in the M-6 position of the ETR at temperatures ranging from 260 to 540 °C. Generally, each capsule contained previously unirradiated samples. However several samples from the first capsule were measured and placed in the third and final capsule to increase the exposure range.

To achieve the desired spectral results for the experiment, it was necessary to modify the neutron flux in the M-6 position from normal ETR conditions. This was accomplished by surrounding the test capsule with a shroud tube of boron stainless steel which effectively reduced the thermal-neutron flux reaching the experimental apparatus and provided thermal-to-fast neutron ratios of approximately 0.07 to 1, whereas in the Hanford test facility the ratio was 8.3 to 1.

SUMMARY

A program of irradiation testing was conducted in the Engineering Test Reactor to determine the dimensional stability characteristics of four types of boronated graphite after neutron exposure. The graphites tested were identical to those used in the nuclear shield of the

Enrico Fermi Reactor and were composed of a nuclear-graphite matrix containing boron carbide in sufficient quantity to give nominal boron concentrations of either 5 or 7 wt%. Two dissimilar grades of material were produced at both boron concentrations as a result of manufacturing techniques and were classified as either "black" or "grey" according to the appearance and nature of the boron distribution in the materials. Samples of the four materials were exposed in a neutron environment having an energy distribution intermediate to that of a fast-reactor and a facility with a predominately thermal flux. Operating temperatures ranged from 540 °C (1000 °F) for samples located near the mid-plane of the reactor to 260 °C (500 °F) for samples positioned near the upper or lower edges of the reactor core.

Length-change results were accumulated at neutron exposures intermediate to and including the maximum condition of 1.6×10^{20} n/cm², thermal, and 2.2×10^{21} n/cm², fast ($E > 0.18$ MeV), from samples irradiated in three thermal-neutron, shielded capsules. Distinct behavioral differences were observed for the 5 and 7 wt% grey types as compared to the black materials. Transverse and parallel grey boronated graphite samples of both boron concentrations showed initial contractions of about 0.5% followed by expansion of the materials. The black transverse-orientation samples behaved similarly but with smaller absolute length changes. Black

parallel-orientation samples contracted at all exposures and showed significant length changes greater than 1.0% at the maximum exposure attained in this irradiation series. A systematic error in the length changes of samples irradiated in the first shielded capsule, GEH-23-8, has limited the usefulness of these data and the results from several GEH-23-8 samples which were reirradiated in capsule GEH-23-16 to indicating length change trends only.

MATERIALS

The four types of boronated graphite studied in this program were obtained from production run stocks manufactured for the Fermi Reactor Shield. Materials, having nominal boron concentrations of either 5 or 7 wt%, were prepared by combining the appropriate weight fractions of B₄C particles with a petroleum-coke, pitch-binder mix and then graphitizing. Graphitization of the mixtures was conducted near the melting temperature of the B₄C (2450 °C) and resulted in the formation of two distinctively different grades of graphite within the same furnace and at both boron concentration levels. The grades were termed "black" and "grey" by the graphite manufacturer, corresponding to the visual characteristics of the material. Black 5 and 7 wt% were similar in appearance and structure to normal nuclear graphites except for the dispersion of boron-carbide particles. A shiny, metallic lustre, resulting from extensive crystallization, was exhibited by the grey boronated graphites. Located centrally in the

graphitizing furnace, the grey materials either reached or exceeded the melting point of boron carbide. Recrystallization of the graphite occurred, producing a highly isotropic material and allowing a more uniform dispersion of boron in the graphite lattice. To distinguish the types of material for experimental purposes the letter codes "D," "E," "H," and "J" were assigned to black, 5 wt% boron; grey, 5 wt% boron; black, 7 wt% boron; and grey, 7 wt% boron graphites, respectively.

Microscopic observations and characterizations have been made for the four material types.⁽¹⁾ Boron carbide was visible in the graphite matrix of the black grades as sharp angular particles with no evidence of melting in 5 wt% type and only slight melting in the 7 wt% material. In the grey boronated graphites, however, generalized melting and conformity of the B_4C particles to the adjacent graphite structure appeared to have occurred. A highly crystalline graphite structure was observed in both grey materials with a greater degree of recrystallization evidenced in the 7 wt% than the 5 wt% stock.

Phase equilibrium studies of the boron graphite system⁽²⁾ have shown that approximately 2.3% boron is soluble in graphite at the melting point of B_4C (2450 °C). Specific boron concentration levels in the crystal lattices of the boronated graphites studied are not known. However, it is believed that the concentration increases according to a sample ordering of D, H, E, and J.

Nominal boron percentage of 5 and 7 wt% were used for convenience in describing the boronated graphite examined in this study and exact concentrations differed slightly from the stated values. Table I presents average boron and lithium concentrations for each of the four material types.

EXPERIMENTAL TECHNIQUES

Preparation of Samples

Samples of the four boronated graphite types installed in GEH-23 experiments were obtained from separate 6-in. cubes. These blocks were supplied by the manufacturer with the furnace number, production designations, and an arrow indicating the direction of the extrusion axis

TABLE I
AVERAGE BORON AND LITHIUM CONCENTRATION
OF UNIRRADIATED BORONATED GRAPHITE

<u>Material Code</u>	<u>Description</u>	<u>Boron Concentration, wt%</u>	<u>Lithium Concentration, wt%</u>
D	5 wt%, Black	6.17	4.5
E	5 wt%, Grey	6.42	<1.5
H	7 wt%, Black	8.25	2.4
J	7 wt%, Grey	8.09	1.1

inscribed on the surface of each one. Individual samples were trepanned from the sample sections previously removed from the larger specimen block according to the sampling scheme shown in Figure 1.

Due to the abrasive nature of the boronated materials, diamond-tipped tools were used to machine the samples into cylinders 0.750 ± 0.005 in. long and 0.450 ± 0.001 in. in diameter. Each sample was marked, after machining was completed, with a code number to locate its former position in the appropriate sample block and to prevent errors in sample identification.

Preirradiation Measurements

Accurate length and weight measurements were made on the samples prior to irradiation so that changes in the graphite resulting from neutron bombardment could be determined. Lengths were determined with a Bausch and Lomb DR-25 Optical Gage accurate to within 0.000024 in. A minimum of six measurements were made on each sample, and from these determinations the average length and standard deviation were calculated. Sample weights

were measured to the nearest tenthousandth of a gram.

Capsule Design and Fabrication

The design of the GEH-23 irradiation capsule was based on the experimental requirements of the test series and the characteristics and conditions of an available test position in the ETR. Specifically, it was desired that the operating temperatures of the boronated samples remain relatively constant during irradiation, that the ratio of fast ($E > 0.18$ MeV) to thermal flux be equal to or greater than 10, and also that the capsules be capable of efficient and safe operation for more than one reactor cycle. Heat transfer, hydraulic, spectral, and hazards analyses^(3,4) were conducted, and based on these studies several unique features were incorporated into the capsule design so that the necessary conditions could be realized.

The basic GEH-23 capsule consisted of one or more aluminum sample holders enclosed in a continuous aluminum tube. Two sample-loading schemes were used in this series and each method required the fabrication of a different type of sample holder. The initial capsule design was similar to that shown in Figure 2A. This design used a single tubular holder having a 0.500 in. diam hole the full length of the tube. Small alumina insulator pins were used to maintain the 0.025 in. annulus between the tube surface and the 0.450 in. diam samples. During irradiation of the first test capsule, GEH-23-8, the samples rested end to end in a vertical column

FIGURE 1

Sampling Scheme
Boronated Graphite

1. Boronated Graphite Irradiation Capsule (Design #1)
2. Boron Stainless Steel Shield Tube
3. E T R 3 x 3 Aluminum Filler Piece

FIGURE 2A

GEH-23 Shielded Capsules
and ETR Irradiation Facility

causing length changes attributable to axial self-loading and vibration-induced abrasion of the measuring surfaces. This configuration was abandoned; and in the succeeding two capsules, 23-13 and 23-16, the loading arrangement illustrated in Figure 2B was used. In this second design samples were positioned horizontally within individual sample holders which prevented any mechanically induced length changes, yet securely held each specimen laterally and axially within the 0.500 in. diam by 1.375 in. long cavity. An all-welded construction was used to insure the integrity and continuity of the active portion of the capsule with the instrumentation lead tube. At the lead tube termination an in-tank connector was used to extend the monitoring and control leads to an access

FIGURE 2B

Boronated Graphite Irradiation Capsule
(Design 2)

junction on the surface of the reactor vessel.

Both capsule designs used gamma heating and the heat resulting from

the $B^{10}(n,\alpha)Li^7$ reaction to achieve the desired sample temperatures. Variations in nuclear heating resulted from changes in reactor power and fuel loading in the vicinity of the capsules and from boron burnout in the samples themselves. However, temperature variations resulting from these changes were minimized by adjusting the thermal conductivity of the heat transfer path from the test samples to the reactor coolant. Heat was conducted from the samples, across a gas gap, to the sample holders and from the sample holders, across a second gas gap, to the water-cooled wall. Conductivity changes were achieved by supplying metered amounts of helium and argon gas to occupy the gas annuli within the capsule. These gases were introduced into the apparatus, after deoxygenation, drying, and mixing, through a small tube which entered the capsule lead tube and extended to the bottom of the active test section. The flowing gases were exhausted from the capsule through a similar tube extending from the top of the sample column and out the reactor stack. Several samples, located at selected positions within each irradiation capsule, were temperature monitored by thermocouples which penetrated through a high-pressure, molded-glass hermetic seal. A continuous recording system was used to collect the temperature information, and to prevent over-temperature excursions automatic safety controls were installed in a gas metering and temperature recording console assembled for the GEH-23 experiments.

The neutron spectrum desired for the GEH-20 tests was achieved in the

ETR by modifying the normal M-6 position flux to suit the experimental conditions. A reduction in thermal flux was accomplished by surrounding the 1.500 in. OD aluminum capsule with a 2.250 in. OD by 1.750 in. ID stainless steel cylinder in which 1.70 wt% natural boron had been alloyed. This cylinder, shown in Figure 2A, enclosed the active portion of the irradiation capsule, shielding the test samples from a portion of the incident thermal neutrons by the $B^{10}(n,\alpha)Li^7$ reaction. Because of the B^{10} isotope burnout in the shield during irradiation, each cylinder was removed after completing a reactor cycle and replaced with a new one to stabilize the neutron spectrum over the complete test period of a capsule. Nickel and cobalt flux monitors were positioned adjacent to the boronated graphite samples to determine accurately the fast and thermal neutron exposures for each specimen.

Irradiation Facility

Experiments in the GEH-23 shielded series were conducted in the M-6 position of the ETR. This location provided sufficiently high fast neutron fluxes (~ 1 to 3×10^{14} n/cm²-sec) to attain the desired exposures in a reasonable length of time as well as space for the experimental apparatus. The location was fitted with an aluminum filler piece (Figure 2A) built according to the external dimensions of a standard 3 by 3 in. ETR core unit and bored, internally, to a 2.500 in. diam. Within this filler unit the shield tube and irradiation capsule were nested, supported at the bottom

of the capsule (36 11/16 in. below the top of the reactor core) by two 5/16 in. metal pins.

Reactor water at inlet conditions of 225 psig and 120 °F was used to cool the capsules. A water flow of approximately 90 gal/min was supplied to remove heat from the boron stainless steel shield tube as well as the irradiation capsule.

Capsule Discharge and Disassembly

After completion of the irradiation periods, the GEH-23 capsules were removed from the reactor and transferred to the ETR holding basin. The capsules were stored for several days to allow time for the decay of short half-life elements produced by irradiation and then were placed into a shipping cask and returned for disassembly.

Capsules were remotely disassembled in a shielded hot cell. Samples and flux-monitor wires were removed from the sample holders and freed from all excess radioactive material. The samples were then removed from the hot cell and transferred to the graphite laboratories for examination and measurement. Flux monitors were separated, identified, and then shipped to the counting laboratory.

Postirradiation Measurements and Determinations

Length and weight measurements were obtained from the irradiated samples by techniques identical to those used in the preirradiation determinations. These postirradiation data were compared with the preirradiated results to arrive at neutron induced damage in the boronated graphites tested.

Average operating temperatures for the thermocouple monitored samples were calculated by graphically integrating the time-temperature curves plotted for each capsule and then dividing by time. These average temperatures were used to plot temperature profile curves for each capsule so that the irradiation temperatures of unmonitored samples could be estimated. Temperatures determined by this method ranged from 540 ± 25 °C to 260 ± 35 °C depending on the location of the sample in the capsule.

Fast ($E > 0.18$ MeV) and thermal neutron exposure values were determined experimentally from nickel and cobalt flux monitors. Disintegration rates and appropriate activation cross-sections were determined for the monitors, and with a computer code⁽⁵⁾ the neutron exposures for each sample were calculated.

EXPERIMENTAL RESULTS

Irradiation induced length change was the principal parameter studied in the GEH-23 program. Data have been obtained from samples contained in three long-term shielded experiments and are presented by capsule number in Tables II through IV. Average operating temperatures, the fast and thermal exposures, and the percentage weight changes have also been compiled for each sample and are presented in the tabulations. The percentage length and weight changes are cumulative and are based on the initial unirradiated value and the final or total change through the capsule being tabulated. For convenience in analysis and presentation, the length change results

TABLE II

LENGTH AND WEIGHT CHANGES FOR SAMPLES IRRADIATED IN CAPSULE GEH-23-8*

Sample	Irradiation Temperature, °C	Neutron Exposure, $n/cm^2 \times 10^{-20}$		Length Change $\Delta L/L, \%$	Weight Change $\Delta W/W, \%$
		Thermal	Fast ($E > 0.18$ MeV)		
<u>Black, 5 wt% Boron</u>					
D30T (I)	371	0.547	7.0	-0.090	-0.357
D31T (I)	393	0.635	9.1	-0.096	+0.047
D32T (I)	427	0.696	9.6	-0.187	-0.333
D33T (I)	516	0.798	11.1	-0.209	-0.060
D42L (II)	377	0.583	7.9	-0.560	-0.012
D43L (II)	385	0.611	8.6	-0.566	-0.024
D44L (II)	438	0.714	9.7	-0.722	-0.039
D45L (II)	524	0.803	11.2	-0.857	-0.031
<u>Grey, 5 wt% Boron</u>					
E25T (I)	449	0.731	9.9	-0.702	-0.049
E26T (I)	519	0.802	11.0	-0.735	-0.037
E37L (II)	463	0.746	10.2	-0.970	-0.123
E38L (II)	510	0.800	11.1	-0.937	-0.096
<u>Black, 7 wt% Boron</u>					
H25T (I)	404	0.657	9.4	-0.138	-0.046
H26T (I)	507	0.792	11.0	-0.200	-0.064
H27T (I)	527	0.804	10.9	-0.236	-0.073
H37L (II)	416	0.677	9.5	-0.661	-0.034
H38L (II)	496	0.784	10.9	-0.815	-0.359
<u>Grey, 7 wt% Boron</u>					
J30T (I)	474	0.760	10.5	-0.759	+0.003
J31T (I)	529	0.806	11.2	-0.757	-0.026
J32T (I)	535	0.808	10.9	-0.783	-0.029
J33T (I)	532	0.807	10.8	-0.802	-0.045
J34T (I)	501	0.796	11.1	-0.716	-0.196
J45L (II)	485	0.773	10.7	-0.840	-0.023
J46L (II)	535	0.808	11.2	-0.797	-0.023
J47L (II)	538	0.808	11.1	-0.753	-0.367
J48L (II)	491	0.790	11.1	-0.730	-0.048

*Samples subjected to mechanical load during irradiation. The absolute values for length change are in error but may be used for studying length change trends.

TABLE III

LENGTH AND WEIGHT CHANGES FOR SAMPLES IRRADIATED IN CAPSULE GEH-23-13

Sample	Irradiation Temperature, °C	Neutron Exposure, $n/cm^2 \times 10^{-20}$		Length Change $\Delta L/L, \%$	Weight Change $\Delta W/W, \%$
		Thermal	Fast ($E > 0.18$ MeV)		
<u>Black, 5 wt% Boron</u>					
D10T (I)	364	0.167	2.33	-0.018	+0.000
D11T (I)	404	0.230	3.35	-0.037	-0.003
D12T (I)	360	0.248	3.48	-0.064	-0.012
D13T (I)	320	0.214	2.96	-0.037	-0.025
D10L (II)	396	0.177	2.50	-0.188	-0.006
D11L (II)	448	0.235	3.40	-0.212	-0.012
D12L (II)	407	0.247	3.44	-0.197	-0.015
D13L (II)	317	0.209	2.86	-0.175	-0.033
<u>Grey, 5 wt% Boron</u>					
E3T (I)	426	0.186	2.65	-0.195	-0.051
E4T (I)	416	0.243	3.51	-0.198	-0.026
E5T (I)	345	0.243	3.40	-0.200	-0.058
E6T (I)	314	0.204	2.76	-0.181	-0.046
E3L (II)	445	0.195	2.81	-0.255	-0.069
E4L (II)	431	0.240	3.46	-0.262	-0.101
E5L (II)	341	0.239	3.35	-0.238	-0.051
E6L (II)	311	0.198	2.64	-0.245	-0.076
<u>Black, 7 wt% Boron</u>					
H4T (I)	319	0.158	2.17	+0.019	+0.009
H5T (I)	473	0.225	3.25	-0.028	-0.016
H6T (I)	368	0.250	3.50	-0.026	-0.015
H7T (I)	323	0.219	3.04	-0.021	-----
H8T (I)	301	0.173	2.15	-0.002	-----
H3L (II)	269	0.147	1.95	-0.139	-----
H4L (II)	477	0.218	3.17	-0.182	-----
H5L (II)	377	0.250	3.52	-0.165	-----
H6L (II)	327	0.224	3.14	-0.168	-0.045
H7L (II)	304	0.180	2.27	-0.157	-0.041
<u>Grey, 7 wt% Boron</u>					
J11T (I)	462	0.202	2.95	-0.181	-0.111
J12T (I)	403	0.246	3.53	-0.168	-0.072
J13T (I)	332	0.229	3.22	-0.186	-0.052
J14T (I)	308	0.187	2.40	-0.173	-0.066
J13L (II)	471	0.210	3.06	-0.173	-0.099
J14L (II)	392	0.248	3.54	-0.182	-0.046
J15L (II)	337	0.234	3.28	-0.203	-0.053
J16L (II)	308	0.192	2.53	-0.181	-0.068

TABLE IV

LENGTH AND WEIGHT CHANGE FOR SAMPLES IRRADIATED IN CAPSULE GEH-23-16

Sample	Irradiation Temperature, °C	Neutron Exposure, n/cm ² x 10 ⁻²⁰		Length Change ΔL/L, %	Weight Change ΔW/W, %
		Thermal	Fast (E > 0.18 MeV)		
<u>Black, 5 wt% Boron</u>					
D14T (I)	432	0.610	8.35	-0.101	-0.054
D15T (I)	499	0.757	10.45	-0.175	-0.035
D16T (I)	480	0.738	10.07	-0.173	-0.022
D17T (I)	290	0.470	6.31	-0.125	-0.262
D14L (II)	393	0.753	10.45	-0.535	-0.193
D15L (II)	393	0.753	10.45	-0.553	-0.305
D16L (II)	410	0.587	8.13	-0.399	-0.116
D17L (II)	454	0.548	7.43	-0.401	-0.007
*D42L (II)	415	1.097	14.80	-1.136	-0.022
*D44L (II)	454	1.412	19.64	-1.507	+0.009
*D45L (II)	516	1.562	21.72	-1.642	+0.012
<u>Grey, 5 wt% Boron</u>					
E8T (I)	388	0.566	7.81	-0.371	-0.058
E9T (I)	458	0.580	7.91	-0.395	-0.057
E7L (II)	493	0.738	10.44	-0.579	-0.037
E8L (II)	366	0.548	7.46	-0.488	-0.090
E9L (II)	263	0.444	5.95	-0.434	-----
<u>Black, 7 wt% Boron</u>					
H9T (I)	449	0.628	8.70	-0.135	-0.141
H10T (I)	457	0.677	9.37	-0.239	-0.122
H11T (I)	454	0.489	6.21	-0.133	-0.010
*H25T (I)	432	1.257	17.81	-0.057	+0.033
H8L (II)	466	0.647	8.96	-0.407	-0.132
H9L (II)	488	0.741	10.30	-0.452	-0.063
H10L (II)	460	0.437	5.58	-0.332	-0.103
<u>Grey, 7 wt% Boron</u>					
J15T (I)	482	0.664	9.21	-0.389	-0.093
J16T (I)	316	0.497	6.76	-0.435	-0.304
J17T (I)	464	0.633	8.73	-0.366	-0.628
J18T (I)	527	0.734	10.20	-0.204	-0.142
*J30T (I)	478	1.480	20.65	-0.129	+0.143
*J31T (I)	518	1.502	20.85	-0.376	-0.406
*J32T (I)	528	1.531	20.94	-0.392	-0.097
J17L (II)	496	0.775	9.35	-0.426	-0.104
J18L (II)	341	0.520	7.10	-0.438	-0.178
J19L (II)	469	0.643	8.96	-0.435	-0.066
*J46L (II)	520	1.566	21.65	-0.164	+0.051
*J47L (II)	527	1.552	21.47	-0.193	-0.325

* Samples irradiated in 23-8 and reirradiated in 23-16. Length changes data for these samples are not valid except for studying distortion trends.

for the transverse and parallel orientations of each type of boronated graphite are shown in Figures 3 through 10.

The reader is cautioned to remember that an error exists in the length-change results from samples irradiated in capsule GEH-23-8 and for several 23-8 samples reirradiated to higher exposures in capsule GEH-23-16. It has been demonstrated by other investigators^(6,7) that the application of an external load to nuclear graphite during irradiation results in a modification of the dimensional-change characteristics. Absolute values,

therefore, cannot be relied upon for these compressively loaded specimens, and results are to be used only for studying length-change trends for the materials tested.

It is seen from the several length-change curves presented in this section that up to a thermal-neutron exposure of about $6 \times 10^{17} n/cm^2$ all the boronated graphite irradiated in the GEH-23 shielded experiments exhibit similar dimensional distortion behavior, regardless of orientation. Parallel and transverse samples of the four boronated materials all show varying rates of contraction in this

FIGURE 3

Effect of Exposure on 5 wt% (Black) Boronated Graphite—Transverse

FIGURE 4

Effect of Exposure on 5 wt% (Black) Boronated Graphite—Parallel

FIGURE 5

Effect of Exposure on 5 wt% (Grey) Boronated Graphite—Transverse

FIGURE 6

Effect of Exposure on 5 wt% (Grey) Boronated Graphite—Parallel

FIGURE 7

Effect of Exposure on 7 wt% (Black) Boronated Graphite—Transverse

FIGURE 8

Effect of Exposure on 7 wt% (Black) Boronate Graphite—Parallel

FIGURE 9

Effect of Exposure on 7 wt% (Grey) Boronated Graphite—Transverse

FIGURE 10

Effect of Exposure on 7 wt% (Grey) Boronated Graphite—Parallel

interval, but with increased exposure definite differences in length-change behavior begin to appear. Both parallel and transverse samples of the 5 and 7 wt% recrystallized grey types show maximum contractions of approximately 0.4% at $6 \times 10^{19} \text{ n/cm}^2$, and after additional irradiation the 7 wt% samples expand. Since 5 wt% grey samples were not irradiated to higher exposures experimental results are not available beyond $7 \times 10^{19} \text{ n/cm}^2$; however, similarities in graphite structure and the isotropic nature of the grey materials suggest that the 5 and 7 wt% grey types might behave alike. The black 5 and 7 wt% transverse specimens exhibit a maximum contraction of 0.2% and with increased exposure, expansion of the 7 wt% material is seen. As in the case of the 5 wt% grey samples, insufficient data are available for the 5 wt%, black, transverse type; but behavior paralleling that of the 7 wt% black, transverse material would be expected. Parallel black samples continue to contract after additional exposure, performing in a manner characteristic of nonboronated nuclear graphites. None of the graphites irradiated in this test series exhibited temperature-dependent length changes in the range of 260 to 570 °C.

Weight changes for samples irradiated in the GEH-23 capsules are in general quite low, indicating minimal oxidation within the apparatus. Fractional changes for samples of each material were with few exceptions equal to or less than 0.1% weight loss or gain. Changes larger than this can be attributed to the placement of

thermocouples in samples after weighing had been completed.

CONCLUSIONS

Thermal-neutron-shielded experiments have furnished length-change results which add appreciably to the understanding of radiation-induced dimensional distortion for the black and recrystallized grey grades of 5 and 7 wt% boronated graphite used in the Fermi Reactor. The data presented in this report have been compared with similar data obtained from boronated-graphite irradiations conducted in a Hanford 2-C irradiation facility,⁽¹⁾ and even though the neutron spectra for the two experiments differ radically, similar length-change patterns are observed for identical types of graphite tested in the two irradiation series. Results from the GEH-23 test, in which the fast-neutron component ($E > 0.18 \text{ MeV}$) was a factor of 12 to 14 times larger than the thermal component, correspond approximately to length changes achieved early in the high thermal flux of the Hanford 2-C irradiations. These similarities support the validity of the 2-C experiments and increase confidence in the predictions of boronated graphite behavior after long-term service in in a fast-reactor shield.

The similar behavior of the boronated graphite when irradiated in differing neutron spectra provides a reasonable basis for determining the amount of irradiation damage caused by neutrons of various energies. A correlation of the relative damaging effect of thermal and fast neutrons and the nature of the boron

distribution has been made for the four boronated materials discussed in this report using the 2-C and GEH-23 length-change results. This theoretical study,⁽⁸⁾ furnished a means of estimating the dimensional distortion for a specific fast-reactor exposure from the test results of irradiations conducted in high thermal, or intermediate energy fluxes.

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