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CORRELATION OF RADIATION DAMAGE IN BORONATED GRAPHITE

R. E. DAHL

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CORRELATION OF RADIATION DAMAGE IN BORONATED GRAPHITE

INTRODUCTION

This report presents an analysis of the observed radiation damage caused by fast and thermal neutrons in the boronated graphite used for the shield in the Enrico Fermi Fast Breeder Reactor (EFFBR).

Boronated graphite has excellent potentialities as a fast reactor shield material. Neutrons are moderated and thermalized by the carbon and subsequently captured by boron. Boronated graphite possesses the structural and mechanical properties of nuclear graphite, is readily available, and is relatively inexpensive. However, before using the material in a fast reactor shield, the effects of neutron radiation must be determined.

Radiation damage in boronated graphite is difficult to interpret because two processes operate in parallel to displace atoms and ultimately to damage the material. Displacements are caused by fast neutron collisions with atoms and by the products from the $B^{10}(n,\alpha)Li^7$ reaction which are emitted with a combined energy of 4.7 MeV. This reaction is caused by low energy neutrons and primarily by thermal neutrons. Thus, the extent to which each of these processes contributes to the total radiation effects will depend on the neutron spectrum. The relative effectiveness of each process will have to be understood particularly when one attempts to predict radiation effects in fast reactors from the results of tests conducted in thermal reactors.

Two grades of boronated graphite, black and gray, each containing either 4 or 7 wt% boron carbide (B_4C), were irradiated. Transverse and parallel orientations of each type were studied. The dimensional stability of boronated graphites during irradiation is of particular interest. Tests were conducted in thermal reactors,[1,2] since no fast test reactors were available for materials testing, and because it is believed that data can be applied to the Fermi reactor problems if a careful analysis is made. Thus, if the damaging processes of fast and thermal neutrons can be correlated, the Hanford experiments can be used to predict the behavior of the Fermi shield.

DISCUSSION

Damage Correlations

Correlation of data for graphite irradiation in diverse spectra is based on the assumption that the effects produced in a given material at a given temperature are related to the number of carbon atoms displaced from lattice sites. Cascades of knock-on atoms can be caused in boronated graphite by two processes: the displacement of carbon atoms either by fast neutrons or by helium and lithium atoms formed in the reaction, $B^{10}(n,\alpha)Li^7$. The latter effect is produced almost entirely by thermal neutrons. The relative effectiveness of fast and thermal neutrons in producing displacements is determined from the analysis of these two processes.

Determination of Weighting Functions

Fast Neutrons

Property changes (ie, damage) caused in diverse reactor spectra have been co-related by calculating and equating the lattice atom displacements produced.[3] The number of displacements, D_n, produced per cubic centimeter per second by fast neutrons is given by

$$D_n = \int_0^\infty \phi(E_n)\ \Sigma_s(E_n)\ N(E_n)\ dE \qquad (1)$$

where $\phi(E_n)$ is the neutron spectrum;

$\Sigma_s(E_n)$ is the macroscopic differential elastic scattering cross section of carbon; and

$N(E_n)$ is the number of displacements produced by collision of a neutron of energy (E_n) with an atom.

Data obtained in several diverse spectra have been correlated by normalizing the exposures to neutrons above an energy E_L chosen according to the equation:

$$\bar{\Sigma}_D = \frac{\int_0^{\infty} \phi(E_n) \quad \Sigma_s(E_n) \; N(E_n) \; dE}{\int_{E_L}^{\infty} \phi(E) \; dE} \qquad (2)$$

where $\bar{\Sigma}_D$ is the effective displacement cross section for carbon by neutrons above an energy E_L.

The lower integration limit, E_L, of the exposure normalization is varied until the same or nearly the same value for $\bar{\Sigma}_D$ is obtained in each of the various spectra, $\phi(E)$. When this is accomplished, displacement production per unit exposure to neutrons with energies exceeding E_L is the same regardless of the spectrum. An energy of 0.065 MeV is the optimum value of E_L for carbon.(3) However, the value of 0.18 MeV (corresponding to a lethargy value of 4.0) has been used for several years in graphite studies at Hanford and leads to discrepancies of less than 10%. This value of E_L will therefore continue to be used. Thus, Equation (1) can be conveniently written as $D_n = \Phi(E > 0.18)\bar{\Sigma}_D$ where $\Phi(E > 0.18)$ is the energy integrated flux density from 0.18 to 10 MeV.

$B^{10}(n,\alpha)$ Reaction

Damaged produced by a $B^{10}(n,\alpha)$ reaction can be estimated if two basic assumptions are valid: (1) the observed property change caused by the reaction is proportional to the number of displaced carbon atoms, and (2) the energetic lithium and helium atoms produced by the reaction act as primary knock-on atoms in causing displacement cascades.

The number of displacements caused by a $B(n,\alpha)$ reaction is derived in the Appendix. From this analysis it was estimated that the He^4 atom, emitted with an energy of 0.8 MeV, initiates a cascade which ultimately displaces about 500 carbon atoms and a Li^7 atom, emitted with an energy of 0.45 MeV, ultimately displaces about 800 carbon atoms. Thus, approximately 1300 atoms are estimated to be displaced by each reaction.

The number of carbon atoms displaced per cubic centimeter per second, (D_B), by the $B^{10}(n,\alpha)$ reaction is then calculated by:

$$D_B = N_B \int_0^\infty \phi\ (E)\ \Sigma_a(E)\ dE \qquad (3)$$

where Σ_a is the macroscopic absorption cross section of boron; and N_B, the number of displacements caused by the reaction, has a value of 1300. In this analysis N_B does not vary with neutron energy since the energy of neutrons producing most of the reactions is negligible compared tothe Q value of the reaction.

The degree of boron dispersion in boronated graphite strongly influences the magnitude of produced effects. Boron atoms in the graphite lattice will produce a relatively large number of displaced carbon atoms, and the resulting disorder will be comparable to that caused by a fast neutron collision with a graphite lattice atom. However, damaged produced by boron atoms in B_4C particles will be contained principally within the particles and will have little influence on the bulk properties.

An analysis of damage caused by boron atoms in B_4C particles is made in the Appendix (See section on boron dispersion). It is concluded that the number of displaced atoms produced by reaction of boron atoms in B_4C particles will be less than 5% of the number caused by the same number of boron atoms in solid solution in the graphite crystals. Therefore, in the analysis of radiation effects in boronated graphite, the boron in B_4C particles are assumed to have no effect on the bulk properties during irradiation.

If all the boron were present as B_4C, the bulk material would respond differently to the neutron bombardment than if particulate matter were not present to disturb the structure. Irradiation of a graphite containing inert particles (eg, SiC) having a size relative to that of B_4C would be helpful in analyzing radiation effects in boronated graphite.

Phase diagrams[4] indicate that the maximum amount of boron that can go into solid solution at the manufacturing temperature of the Fermi boronated graphite is approximately 2% if equilibrium were obtained. During cooling, some boron remains in solution while the excess precipitates as B_4C. Thus, the amount of boron in solid solution will depend on the temperature history of the specimen.

Therefore, boron dispersion should be considered in the damage analysis by modifying Equation (3) to include a term which would effectively reduce displacement production by an amount proportional to the fraction of boron as boron carbide particles. Thus, displacements are calculated as

$$D_B = AN_B \int \phi(E) \Sigma_a(E)\, dE$$

where A is the effective boron fraction and $0 \leq A \leq 1$.

The fraction of "effective" boron in solid solution will be evaluated empirically. Values of A vary significantly across sample bars because of processing variations; thus, the values which have been calculated represent gross averages.

Correlation of Irradiation Test Data

Irradiation test data can be correlated if the preceding analysis is valid. Damage from fast neutrons can be estimated if the flux of neutrons with energies exceeding 0.18 MeV can be determined; and damage from the reaction, $B^{10}(n,\alpha)Li^7$, can be estimated if the value of A is evaluated for each type of material. Estimation of damage from the $B^{10}(n,\alpha)$ reaction will be simplified initially by assuming that the reaction is caused only by thermal neutrons.

With the above approximations and the further assumptions that: (1) a displacement from the $B^{10}(n,\alpha)$ reaction, D_B, causes the same property change as a displacement from fast neutrons in D_n; and (2) helium gas formation does not contribute substantially to property change, the property changes should be proportional to the number of displacements as calculated by

$$D = D_n + D_B \qquad (5)$$

where

$$D = [\phi(E > 0.18)\ \bar{\Sigma}_D + \phi_{th}\ A\Sigma_a\ N_B]t. \qquad (6)$$

In order to apply Equation (5), its terms must be evaluated. Displacement production from fast neutron collisions with carbon atoms can be calculated if the flux above 0.18 MeV is determined. The effective displacement cross section, $\bar{\Sigma}_D$ (Equation 2), has a value of 244 for boronated graphite having a density of 1.7 g/cm and has been found to be nearly constant for neutron spectra in light water and graphite moderated reactor which have been studied to date.

The bulk damage contribution of the displacements caused by $B^{10}(n,\alpha)$ reaction will be estimated from Equation (5). For boronated graphite with a density of 1.7 g/cm^3 and 6 wt% natural boron, the absorption cross section (reaction cross section) is

$$\Sigma_a = \sigma_a N_o \rho \qquad (7)$$

where $\sigma_a = 775 \times 10^{-24}$ cm^2, and

$$N_o = \frac{6.023 \times 10^{23} \times 1.7 \times 0.06}{11} = 5.58 \times 10^{21} \text{ atoms/cm}^3.$$

The number of displacements per reaction of boron N_B which is in solution is approximately 1300. Therefore,

$$N_B = (755 \times 10^{-24})(5.58 \times 10^{21})(1.3 \times 10^3)$$

$$\approx 5500 \ \frac{\text{displacements}}{\text{neutron-cm}}. \qquad (8)$$

Thus,

$$D_B = [(240)\phi(E > 0.18) + 5500\ A\ \phi_{th}]t\ \frac{\text{displacements}}{\text{cm}^3}. \qquad (9)$$

Evaluation of $B^{10}(n\alpha)$ Damage

Data can be correlated between diverse neutron spectra if values of A can be determined for the boronated graphites studied. In this investigation, the irradiation tests conducted in the 2C facility(1) in a graphite moderated reactor and those conducted in the ETR(2) provided a means to determine a value of A and apply the data to the EFFBR. The ratio of thermal-to-fast flux in the Hanford 2C test facility(1) was about 8.3. This ratio in the ETR shielded tests(2) (GEH-23-13 and 23-16) was 0.08. Thus, very different ratios of fast-to-thermal neutron induced damage are produced. The GEH-23-8 experiment was an unshielded experiment in the ETR in which the thermal-to-fast ratio is approximately 1.0 thus providing a third spectral variation. Data were correlated by assuming that equal numbers of lattice displacements are produced in samples exhibiting the same dimensional change when irradiated at the same temperature. $B^{10}(n,\alpha)$ damage was estimated in the 2C and ETR tests for each type of boronated graphite, black and gray, by calculating the value of A according to

$$[240\ \phi(E > 0.18) + 5500\ A\ \phi_{th}]_{2C} = [240\ \phi(E > 0.18) + 5500\ A\ \phi_{th}]_{ETR}.$$

Thus,

$$A = 0.04 \left[\frac{\phi(E > 0.18)_{ETR} - \phi(E > 0.18)_{2C}}{\phi_{th\ 2C} - \phi_{th\ ETR}} \right].$$

Data yield values for A of about 0.039 for the gray material and 0.016 for the black. These yields indicate that 2 1/2 times as much effective boron is in the gray material as in the black.

The value of A for black material was calculated from 5% transverse data (Figure 1) from the 2C and GEH-23-16 samples and then was applied to 5% parallel (Figure 2), 7% transverse (Figure 3), and 7% transverse (Figure 4) samples from the remainder of the tests. The value of A was similarly obtained for gray material; ie, 5% transverse (Figure 5), 5% parallel (Figure 6), 7% transverse (Figure 7), and 7% parallel (Figure 8). Thus the value of A was obtained from one set of data and tested on the other sets for both black and gray material.

The relative damaging ratio of fast neutron displacements to those caused by $B^{10}(n,\alpha)$ reaction in the 2C and ETR experiments can be deduced from Equation (6). For black material, the number of displacements is

$$D = [244_{\phi f} + 76\ _{\phi th}]$$

and for gray it is

$$D = [244_{\phi f} + 188\ _{\phi th}].$$

In the 2C facility the ratio of thermal-to-fast flux is 8.3:1; thus, for the black boronated graphite, the number of displacements is

$$D = 244\phi_f + 76(8.3)\phi_f,$$

or the ratio of the number of displacements caused by thermal neutrons to that caused by fast neutrons is

$$(76)(8.3)/244 = 2.6:1.$$

For gray boronated graphite the corresponding number would be

$$D = 244 + 188(8.3);$$

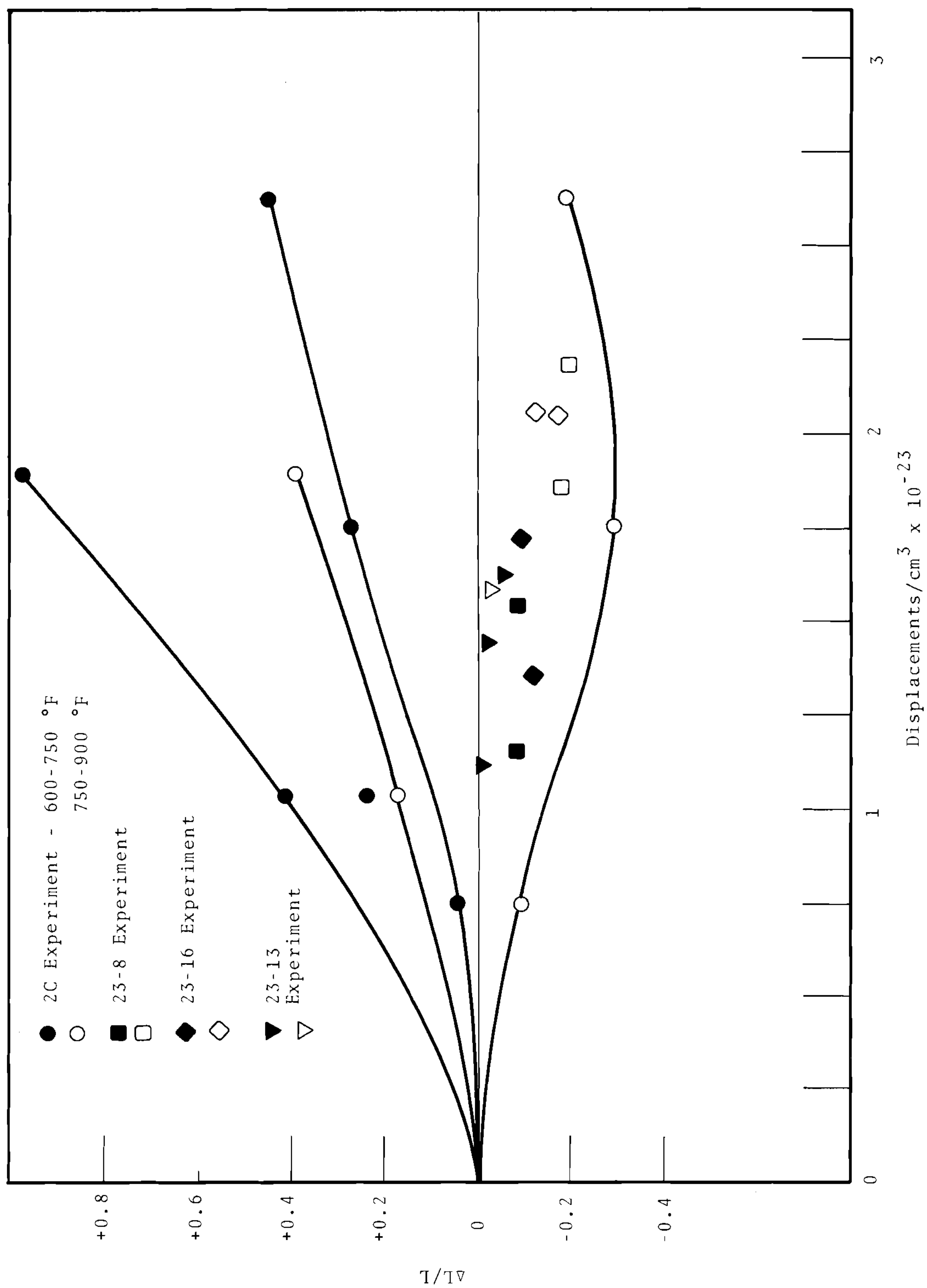

FIGURE 1

Boronated Graphite 5% Black Transverse

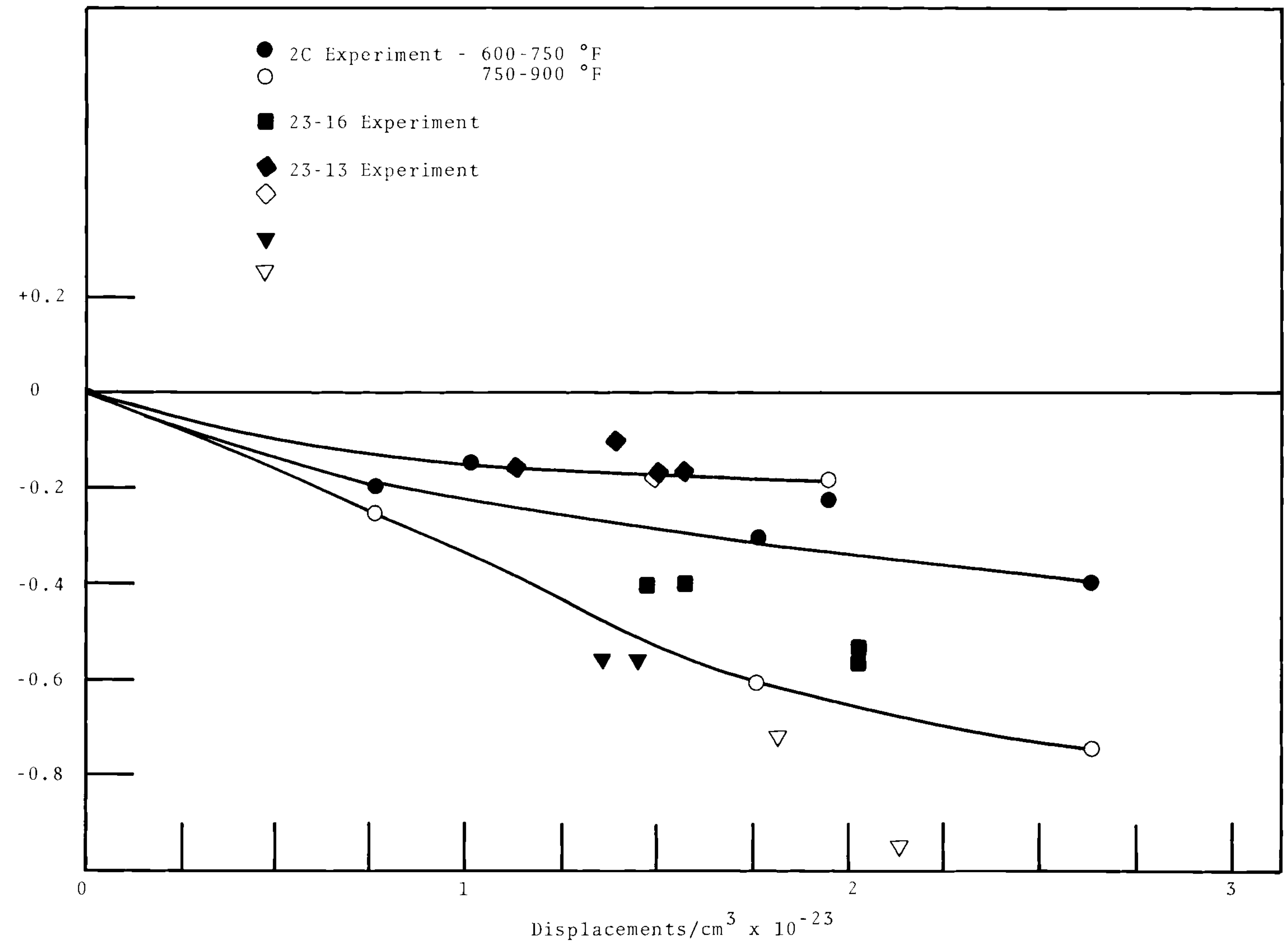

FIGURE 2

Boronated Graphite 5% Black Parallel

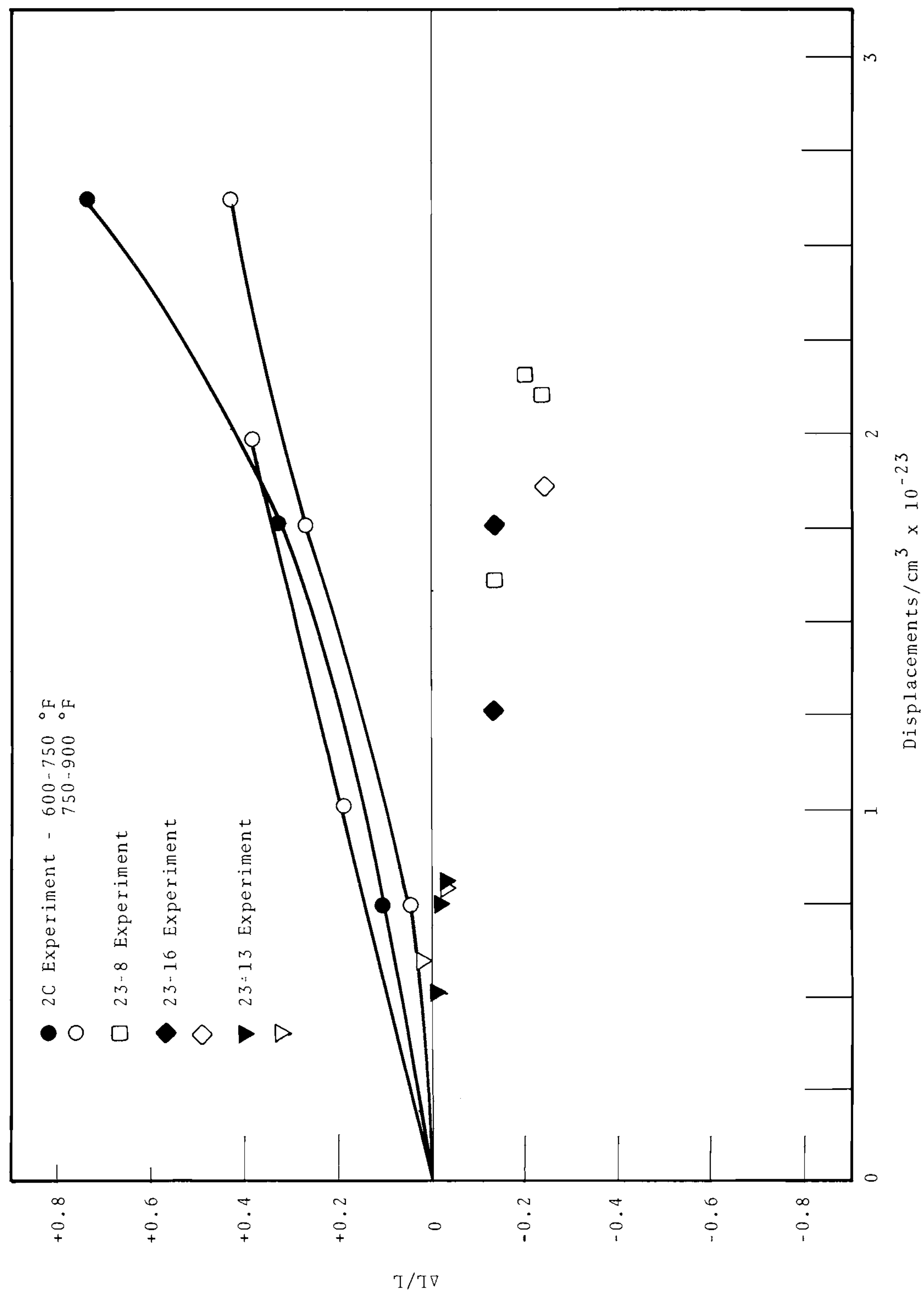

FIGURE 3

Boronated Graphite 7% Black Transverse

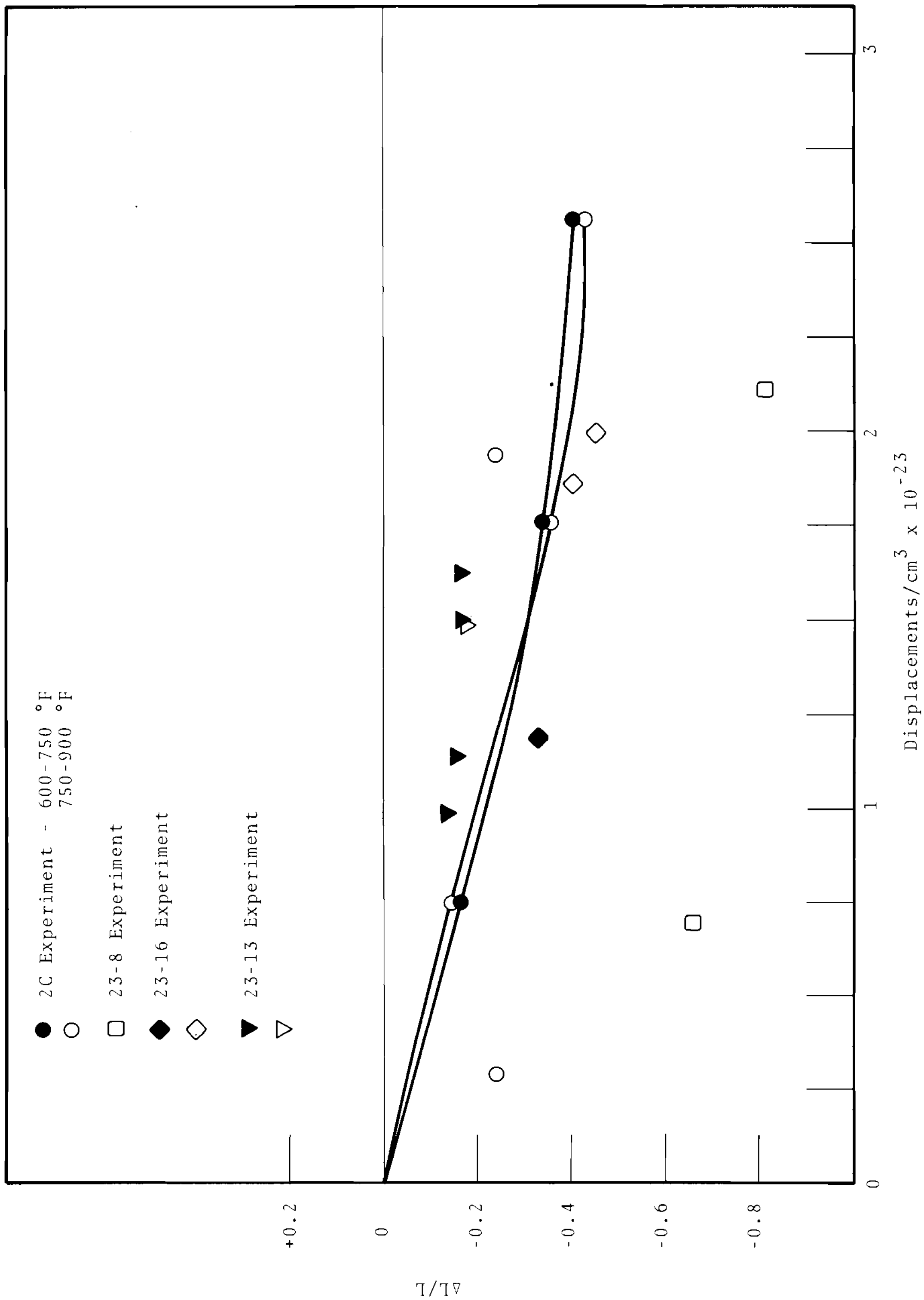

FIGURE 4

Boronated Graphite 7% Black Parallel

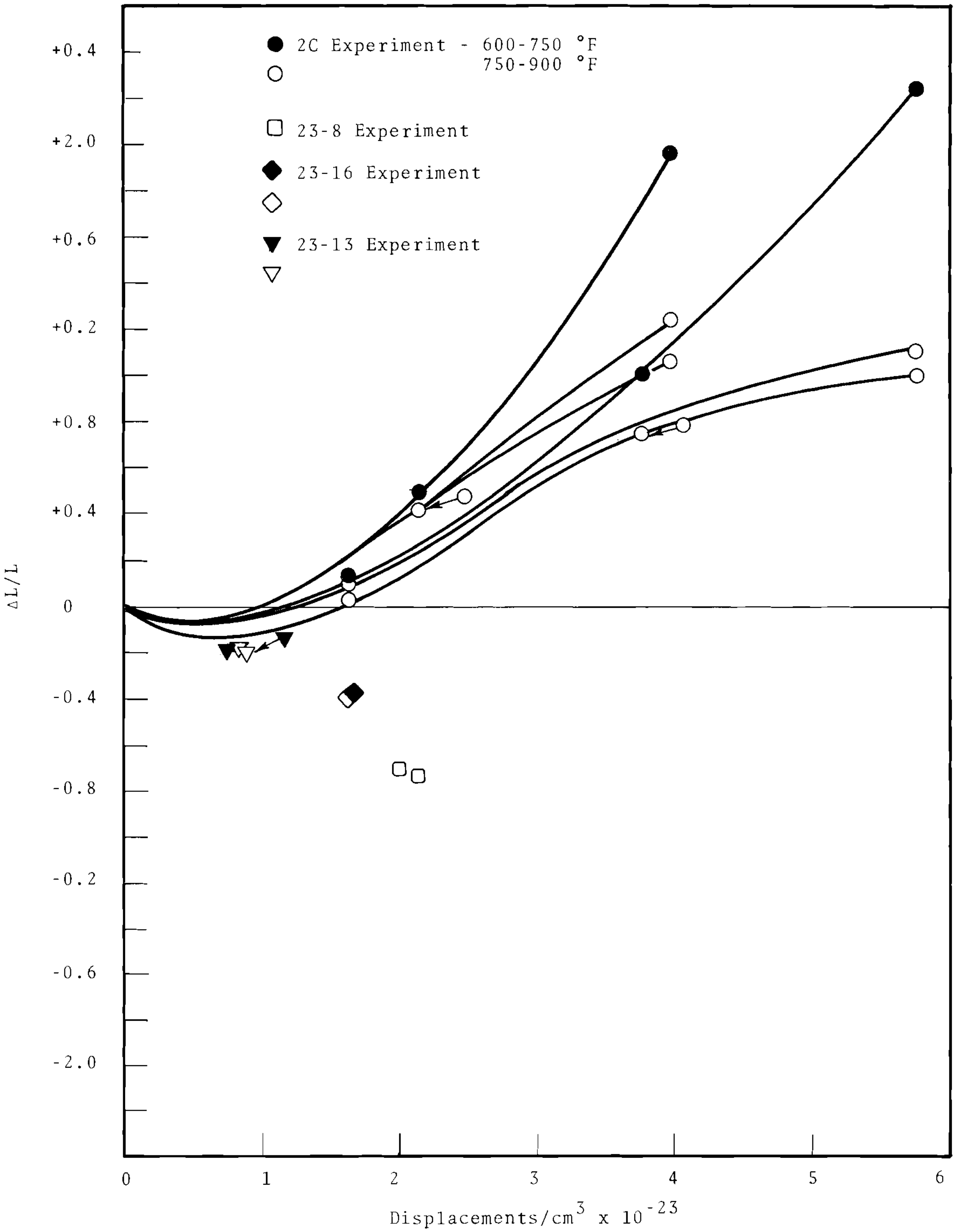

FIGURE 5

Boronated Graphite 5% Gray Transverse

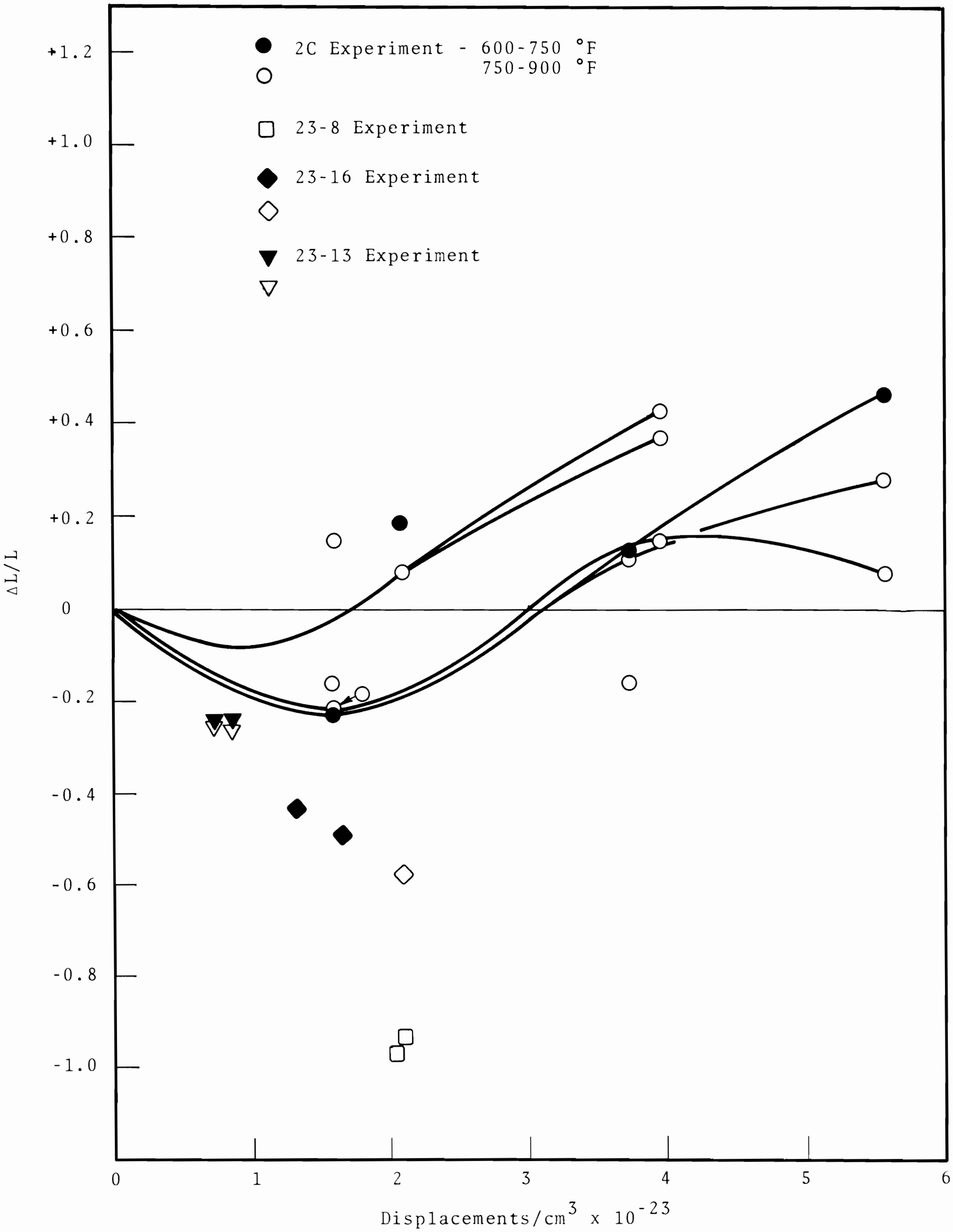

FIGURE 6

Boronated Graphite 5% Gray Parallel

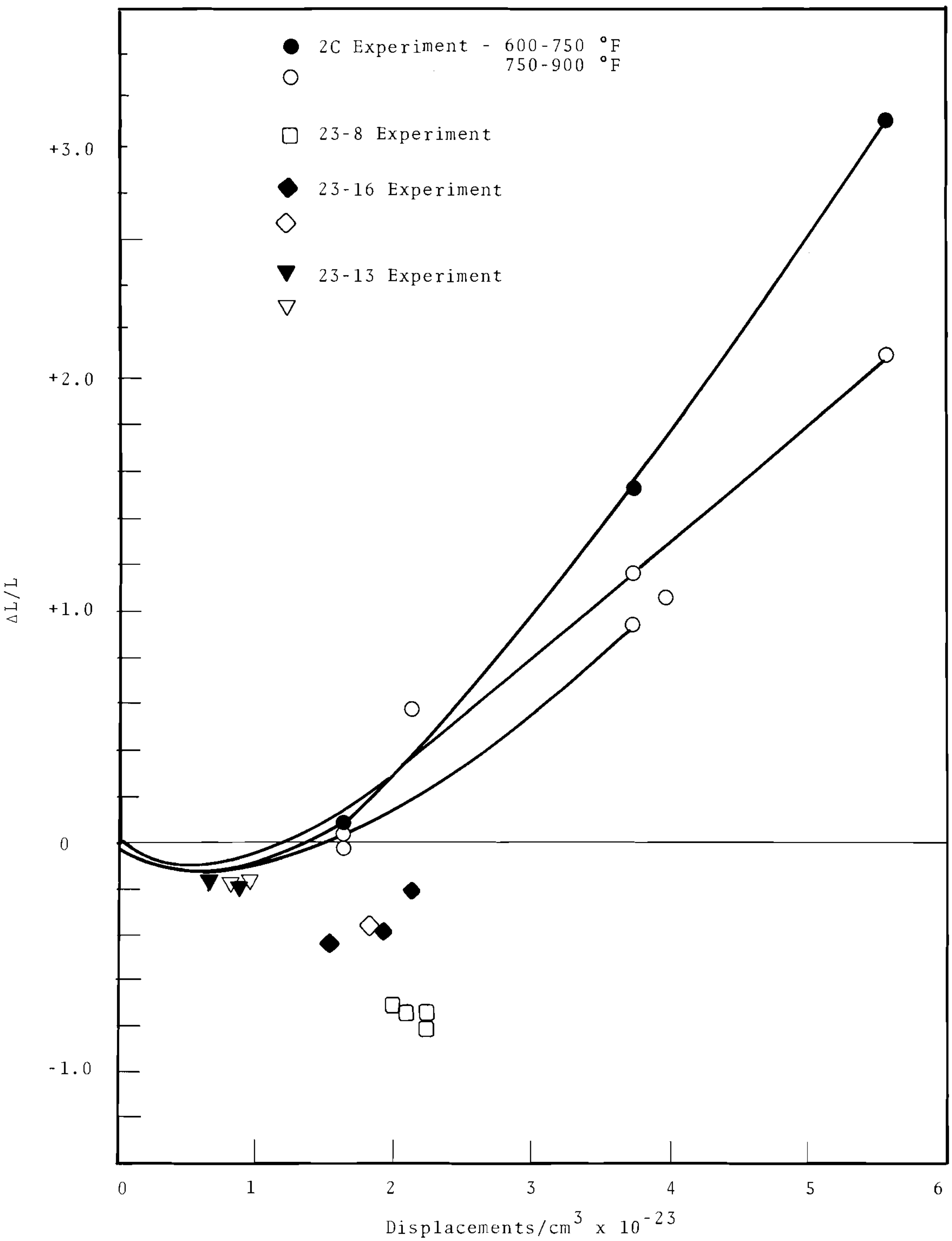

FIGURE 7

Boronated Graphite 7% Gray Transverse

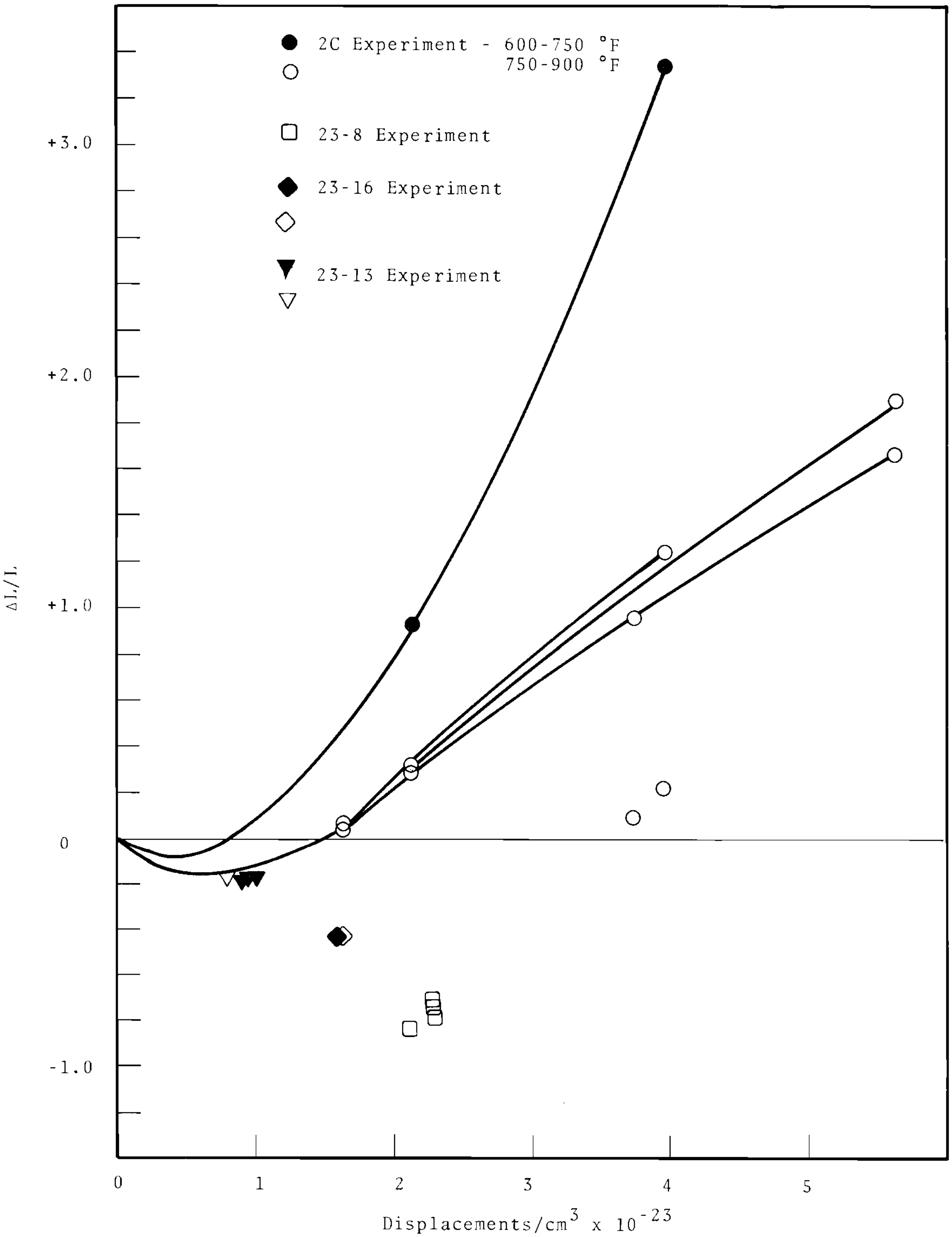

FIGURE 8

Boronated Graphite 7% Gray Parallel

thus, the corresponding ratio of number of displacements would be

$$188(8.3)/244 = 6.4:1.$$

These calculated ratios are in satisfactory agreement with the ratios determined experimentally in the Hanford 2C facility in which a right cylindrical boronated graphite sample was fitted into a sleeve of the same material.[6] The ratio of expansion of the sleeve to that of the cylinder was 2:1 for black graphite and 8:1 for gray.

In the ETR shielded tests (23-13 and 23-16), fast neutrons cause nearly all of the displacements. According to the analysis for black boronated graphite, the number of displacements is

$$D = [244] \times 1 + 76(0.08)]$$

or $D_n/D_B = 40:1$,

and for the gray samples:

$$D = (244 \times 1) + (188 \times 0.08)$$

or $D_n/D_B = 17:1$.

Reasonably good correlation between the 2C experiments and the shielded ETR experiments was obtained for the black material. Parallel samples of both 5 and 7% black showed the same behavior on an exposure scale normalized to displacements. However, behavior of 7% black transverse could not be satisfactorily normalized since all irradiated samples in the ETR contracted while those irradiated in the 2C facility expanded.

In the gray samples irradiated in the Hanford 2C experiments, the length passed through a minimum at relatively low exposures and then expanded rapidly with increasing exposure. All of the gray samples irradiated in the shielded ETR experiments contracted. The dimensional changes are comparable in magnitude to the contractions of the samples, irradiated in 2C, before they began to expand. The method of correlation would be substantiated if further irradiation in the ETR facility caused the samples to expand. Some evidence of this is seen in the 7% gray transverse data. However, if contraction continued with increased exposure, the predominance of another damage mechanism would be established.

Mechanisms which cause damage to boronated graphite other than disorder from displacement cascades are probable. Generation of helium pressure from the $B^{10}(n,\alpha)$ reaction is one possible cause why samples irradiated in a high thermal flux expand while those irradiated in a fast flux contract. However, this possibility seems remote since graphite is very permeable to helium.

Another possibility may be that lattice displacements may nucleate and anneal differently if they are produced randomly throughout the specimen rather than in a highly disordered "buffer" zone surrounding boron-carbide particles.

<u>Application of Analysis to EFFBR shield</u>

Neutron spectra, rates of fast neutron displacement production, and displacements from $B^{10}(n,\alpha)$ reactions were calculated for the EFFBR shield and for samples irradiated in the Hanford 2C facility.

A profile of displacement production for a specimen irradiated in the 2C facility which has no burnout of boron (Figure 9) demonstrates that the principal damaging process is the $B^{10}(n,\alpha)$ reaction. The ratio of total displacements produced in the sample by boron reactions to those produced by fast neutrons, D_B/D_n, is 14. The displacement gradient is very steep because the $B^{10}(n,\alpha)$ damage predominates and self-shielding within the boronated graphite specimen is very important. There is no gradient in fast neutron damage across the specimens because the diameter of the sample is much less than the mean free path of a fast neutron. As this analysis includes cross sections for the $B^{10}(n,\alpha)$ reaction is therefore, overestimated. However, when the effect of nonuniform boron dispersion is included

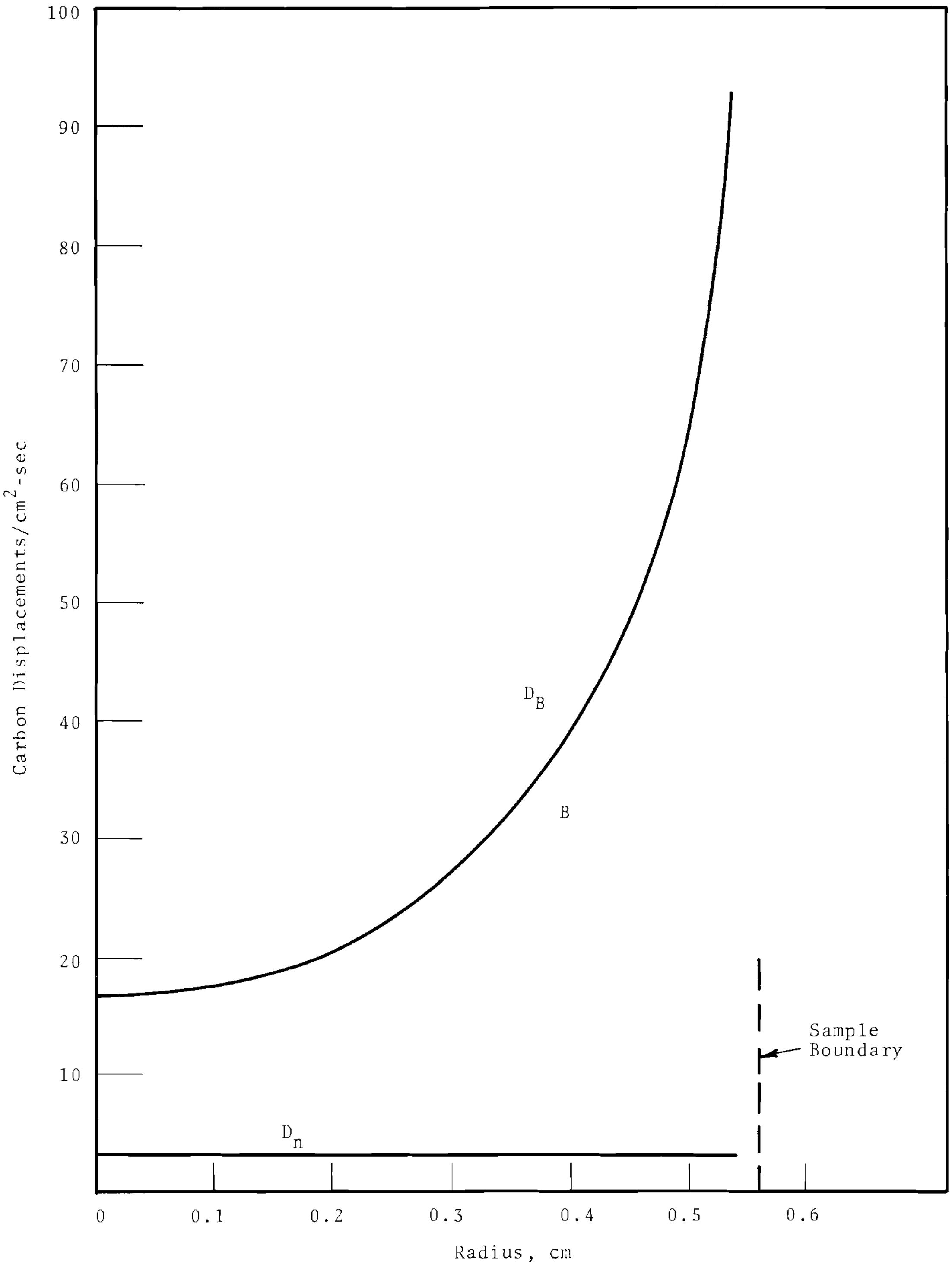

FIGURE 9

Carbon Displacements/cm^2-sec

in the analysis, the two processes cause approximately equal damage.

A similar analysis is made for the inner boronated graphite region of the EFFBR shield, and results are presented in Figure 10. In this case the ratio of displacements, caused by the fast neutrons, to those caused by boron reactions was 113:1 in the boronated graphite region, when the effect of boron dispersion was not considered. When boron dispersion is included, the ratio is nearly 3000:1, thus, indicating that there will be no appreciable effect caused by $B^{10}(n,\alpha)$ reactions. Since this is the case, self-shielding does not produce a damage gradient, and the damage gradient of 14 across the 13 cm region is proportional to the fast flux gradient.

CONCLUSIONS

The method developed in this study is considered adequate to establish limits for dimensional changes which will occur in the EFFBR shield by using radiation effects in boronated graphite observed in irradiation tests. Dimensional changes observed in the tests are at exposures which are calculated to equal or exceed those which will be received in the EFFBR shield.

However, use of the analysis to verify postulates on displacement mechanisms or to extrapolate predictions beyond the present exposure levels is not justified by the data correlations made to date. Additional data at higher exposures would verify or refute the assumption that the samples irradiated in a flux with a low thermal-to-fast ratio would expand after initial contracting. Thereby, these data would correlate with the expansion of samples irradiated in a flux with a low thermal-to-fast ratio.

The analysis performed for the inner boronated region in the EFFBR shield indicates that the fast neutron induced displacements are the predominant damaging mechanism. There is no self-shielding with this process. Hence, there is not the extreme

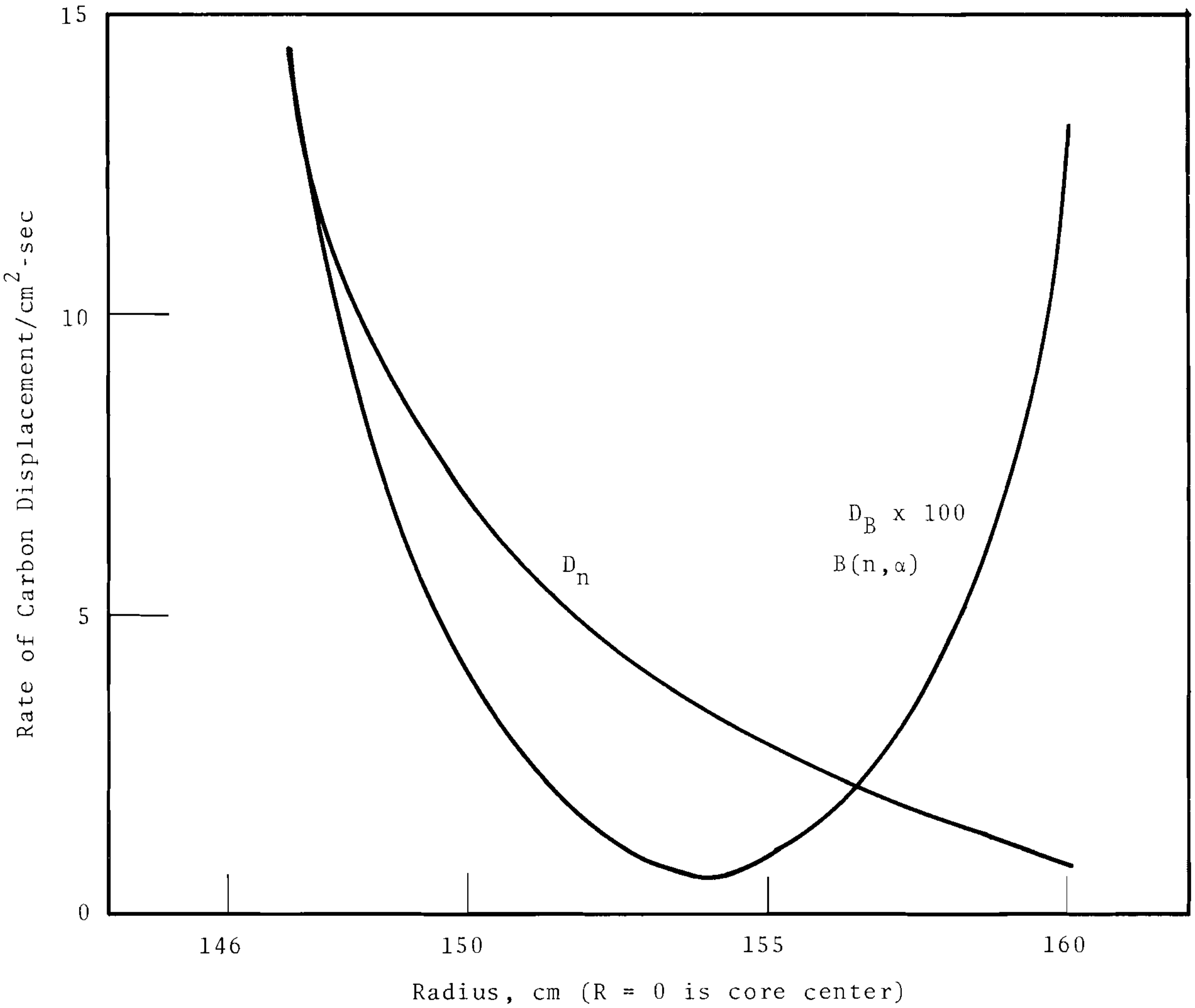

FIGURE 10

Displacements in the Boronated Region of the Fermi Reactor damage gradient characteristic of the $B^{10}(n,\alpha)$ reaction.

ACKNOWLEDGMENTS

The author is grateful for the continued help received from J. A. Ulseth in all phases of this study, and for the help received from J. C. Stouffer and Dr. J. B. Goebel in developing a method and computer program to calculate the affect of particulate B_4C on radiation damage in boronated graphite.

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APPENDIX

An analysis of radiation effects in boronated graphite depends on determining the number of displacements caused by collisions of fast neutrons with carbon atoms relative to the number of displacements causec by $B^{10}(n,\alpha)$ reactions. For the analysis the following assumptions will be made:

1. Damage (dimensional changes) induced by neutron irradiation may be related to the total number of displaced carbon atoms.
2. The helium and lithium atoms which are the products of the $B^{10}(n,\alpha)$ Li^7 reaction will act as primary knock-on atoms in initiating displacement cascades of carbon atoms. The magnitude of the cascades can be calculated from carbon displacement models with appropriate corrections for atomic charge, mass, and energy.

The basic data to be used in this analysis are

	Li^7	He^4	C^{12}
Initial energy (E_p) MeV	0.45	0.8	-
Path length (ρ), microns	0.85	5.8	-
Atomic mass (M)	7	4	12
Atomic charge (Z)	3	2	6
Displacement (E_D) energy, eV	-	-	25

The method outlined by Dienes and Vineyard[(6)] will be used to determine scattering modes and finally to calculate displacement production.

Scattering Mode

It must be determined whether the carbon atom, scattering from He^4 and Li^7, obeys either the Rutherford or the hard-shell scattering laws, and the distinction must be determined.

Elastic collisions are of Rutherford type when the energy of the moving atom, E, is much greater than a critical energy (ie, $E \gg E_A$). These collisions are approximately the hard-sphere type when $E \ll E_A$.

The critical energy, E_A (following the treatment of Dienes and Vineyard) is

$$E_A = E_R \; [2(M_1 + M_2)/M_2] \; Z_1 \; Z_2 \; \sqrt{Z_1 2/3 + Z_2 2/3} \qquad (10)$$

where E_R is the Rydberg Energy = 13.6 eV.

For He^4, C^{12} collisions,

$$E_A = 13.6 \; [2(4 + 12)/12] \; (2) \; (6) \; \sqrt{2 \; 2/3 + 6 \; 2/3} = 1800 \text{ eV}$$

Since the energies of the Li^7 and He_4 atoms are much greater than 1800 eV, the above collisions are of the Rutherford type with low energy transfers probable.

To calculate the mean number of displacements per primary displaced atom collision ($\bar{\nu}$), consider the primary displaced atom which will cause displacements in a carbon matrix:

$$\bar{\nu} = \bar{G}/2E_D$$

where G is that part of the energy of the primary knock-on atom that is expended in elastic collisions.

However, for light elements, a good approximation can be made by setting $\bar{G}$ equal to the ionization energy,

$$\bar{G} = E_1$$

and by determining the ionization energy according to:

$$E_i \doteq M \times 10^3 \text{ eV}.$$

Thus for, He^4: $\bar{\nu} = 4 \times 10^3 2(25) \doteq 80$

Li^7: $\bar{\nu} = 7 \times 10^3/2(25) = 140$

C^{12}: $\bar{\nu} = 12 \times 10^3/2(25) = 240.$

The preceding calculations indicate that the number of displacements will be proportional to the mass of the moving atoms. Therefore, a He^4 atom at a given energy will cause 4/12 as many displacements as a carbon atom of the same energy; similarly, a Li^7 atom will cause 7/12 as many as a carbon atom when both have the same energy.

Carbon displacement production as a function of neutron energy can be estimated using a displacement theory model. The Kinchin and Pease model,[7] which has been used in this analysis, relates energy of the displaced carbon atom to neutron energies by:

$$\bar{T} = f[2M_1 M_2/(M_1 + M_2)] E_\eta \quad (11)$$

where $\bar{T}$ is the mean energy transferred, and

f is a factor correcting for anisotropy and inelastic scattering. (For fast neutron bombardment $f \approx 2/3$.)

Thus, for neutron bombardment of carbon, the mean transferred energy

$$\bar{T} = 2/3\left[\frac{2(1)(12)}{1 + (12)} 2\right] E_\eta$$

$$= 0.095 E_\eta \cong 1/10 E_\eta$$

Thus, a 0.8 MeV carbon knock-on atom would be caused by a neutron of 8 MeV. Similarly a 0.45 MeV carbon knock-on atom would be caused by a 4.74 MeV neutron. According to Kinchin and Pease model, with neutrons with energies of 8.42 MeV, and 4.74 MeV cause about 1500 displacements.

From this relationship the number of displacements produced by carbon atoms with the kinetic energy of the Li^7 and He^4 products of the $B^{10}(n,\alpha)$ reaction can be calculated. The mass differences will be used to calculate the number of displacements actually caused by the He^4 and Li^7 atoms. Therefore, a He^4 atom with 0.8 MeV energy will cause:

(1500)(4/12) = 500 displacements;

and a Li^7 atom with 0.45 MeV energy will cause

(1445)(7/12) = 900 displacements.

The total displacements caused by the $B^{10}(n,\alpha)$ reaction is the sum of the displacement of its products,

500 + 900 = 1400 displacements,

if both fragments interact only with lattice carbon atoms.

<u>Effects of Boron Dispersion</u>

Microscopic examination of boronated graphite specimens has shown that some of the boron exists in discrete B_4C particles. However, in this study, the only concern is with displacements which occur in the graphite lattice and cause bulk damage. Therefore, if a $B^{10}(n,\alpha)$ reaction took place in a B_4C particle at a distance greater than the mean path length of either the He^4 atom or the Li^7 atom from the surface of the particle, the displacements caused would be contained within the particle and would not affect the bulk properties. If boron is concentrated in B_4C particles, the net effect will be a reduction of the contribution of the $B^{10}(n,\alpha)$ reactions.

To analyze the effects of B_4C particles on displacement production, the following assumptions are made:

1. The geometry of the B_4C particles can be approximated as spheres.
2. The B_4C particles will in general have diameters ranging from 10 to 100μ.
3. Displacement production will be proportional to the distance which the energetic atom travels. Thus:

$$-\frac{dE}{dx} = \frac{dD}{dx} = C \text{ or } -dE = Cdx = dD \qquad (12)$$

4. The density of boron atoms within a B_4C particle is constant.

If a $B^{10}(n,\alpha)$ reaction occurs within a B_4C particle, the number of displacements which will be caused in the graphite will depend on the diameter of the particle and the position of the fissioning boron atom within the B_4C particle.

An effectiveness term can be calculated to estimate the damage caused by boron atoms in a particle of assumed average size. This term will depend on the above two variables plus the path length of the reaction products outside the B_4C particle.

The effectiveness can be considered as the product of three probability terms. The first term, P_1, is the probability of a B^{10} atom being within a spherical shell having a volume V_Z:

$$P_1 = \frac{V_Z}{V_T}. \tag{13}$$

This term defines the probability that the reacting B^{10} atom lies within one mean free path of the surface of the B_4C particle. However, the reaction products may not emerge unless they are emitted in a direction which will enable them to penetrate the surface of the particle. Since the products are emitted isotropically, another probability term can be defined as the solid angle of emergence divided by 4 π.

$$P_2 = \frac{\theta}{4\pi}.$$

where θ = the solid angle subtended by the cone whose origin is the fissioning boron atom and whose surface length is the mean path length of the fragment atom. The Li^7 and He^4 atoms will emerge isotropically but can damage the graphite only if they emerge within the solid angle θ.

The third term, P_3, is the mean fraction of the path length of a Li^7 or He^4 particle which lies in the graphite:

$$P_3 = \ell/\rho \tag{15}$$

where ℓ is the distance traveled by the particle in the graphite and ρ is the total path length of the particle.

This mean fractional length can be calculated by dividing the volume of the spherical cap, which is that part of the sphere of influence of the fissioning atom within the graphite, by its surface area, and yields the average radial distance across the segment.

Therefore, the effectiveness index is:

$$A = P_1 \ P_2 \ P_3, \tag{16}$$

and the number of displacements caused in graphite by any B^{10} atom undergoing an (n,α) reaction is

$$D = \frac{A}{\Sigma_D}. \tag{17}$$

The relationship between A and the B_4C particle size was determined by calculating A values for particle sizes ranging between 10 and 100μ in diameter.

The results of these calculations indicate that the function A is 1.0 at r = 0 and approaches an average value of 0.055 for particles with radii between 5 and 50μ. This value of A was determined by integration of the function between these limits of r.

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