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IRRADIATION-INDUCED DIMENSIONAL CHANGE IN BORONATED GRAPHITE CONTROL ROD ABSORBERS FOR THE FORT ST. VRAIN HTGR

by

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SUMMARY

Dimensional change in neutron-irradiated boronated graphite is probably due primarily to a complex interaction of effects from fast-neutron damage, thermal-neutron capture by B^{10} , and swelling of B_4C particles. A model for B^{10} burnup and dimensional change in a typical absorber compact was developed taking into account effects of a B^{10} burnup gradient and interaction of resulting damage zones. Use of the model in conjunction with irradiation data made possible an estimate of dimensional change in a Fort St. Vrain absorber compact (40 wt-% boron) for 6 years service at 50% and 100% duty factors. In both hot-molded and extruded compacts, expansion is more probable than contraction in any direction at 6 years of continuous exposure. For hot-molded compacts, expansion of 5.0% and 0.5% may occur in the axial and radial directions, respectively. With extrusions, 1.0% and 2.0% expansion can be expected in the axial and radial directions, respectively. At 50% duty factor, there will be less expansion in all cases, and perhaps some radial contraction for hot-molded compacts.

IRRADIATION-INDUCED DIMENSIONAL CHANGE IN BORONATED GRAPHITE
CONTROL ROD ABSORBERS FOR THE FORT ST. VRAIN HTGR

1. INTRODUCTION

The reference neutron absorber configuration for the Fort St. Vrain reactor is a hollow cylinder of boronated graphite containing 0.63 g B/cm^3 ($\approx 40 \text{ wt-\% boron}$). The boron will be present in the form of B_4C particles (100 to 400 μm in diameter) dispersed in the graphite matrix. Neutron irradiation will result in burn-out of the B^{10} isotope and other effects that lead to dimensional changes. These irradiation-induced dimensional changes are of importance in control rod design.

The purpose of this work is first to discuss damage mechanisms and dimensional change effects in boronated graphite, and second, by correlation of experimental data, to estimate irradiation-induced dimensional change in absorber materials under Fort St. Vrain reactor conditions.

2. DAMAGE MECHANISMS AND DIMENSIONAL CHANGE

2.1 FAST-NEUTRON DAMAGE

Collisions of energetic neutrons with graphite matrix atoms will cause displacement of carbon atoms from their original lattice site. The number of atom displacements is proportional to the energy of the colliding neutrons and is significant for energies of 0.1 MeV or greater.⁽¹⁾ In practice, neutrons with energies of 0.18 MeV or greater are considered "fast" and are assumed to produce most of the displacements. The displaced carbon atoms cause distortion of graphite crystallites, and this distortion produces expansion in the c-direction and contraction in the a-direction of the graphite crystals.⁽²⁾

Boronated graphite is relatively transparent to fast neutrons; therefore, the matrix graphite will be exposed to a fast-neutron flux very similar to that in the adjacent fuel graphite of an HTGR. Fast-neutron irradiation damage in nonboronated graphite and in the matrix of boronated graphite should be similar provided that the material compositions, structure, and exposure conditions are the same. Dimensional changes in the matrix material will determine the dimensional changes of the entire body if there is negligible interaction of matrix and the inclusions. The degree of interaction of the B_4C inclusions and the graphite matrix is not known, but it seems possible that fast-neutron damage to the graphite matrix could be a significant parameter in determining dimensional changes.

2.2 B^{10} FISSION PRODUCT DAMAGE

The B^{10} isotope comprises about 20 wt-% of natural boron. The $B^{10}(n,\alpha)Li^7$ reaction absorbs neutrons and makes boron a good control material. It is the low-energy neutrons and, primarily, the thermal neutrons that take part in this reaction. The He and Li atom produced by the reaction have significant kinetic energy, and they may produce some displacement of carbon atoms in the matrix (Ref. 3). If B^{10} fission takes place on the surface of a B_4C particle or at the site of a B^{10} atom in solution in the carbon, the greatest matrix damage occurs. When fission occurs within the particle, some fission products do not escape, and thus matrix damage is reduced or eliminated. The path length of the Li^7 and He^4 particles from a typical B^{10}

fission is about 0.85 and 5.8 μm , respectively. Under these conditions, it can be shown that for boron concentration of 0.63 g B/cm³ (nominal 40 wt-% boron) and B₄C particles with diameters of 100 μm or greater, about 12% or less of the graphite matrix is damaged by fission products.⁽⁴⁾ The relationship is shown in Fig. 1. With decreasing particle size, the extent of damage increases rapidly so that with 20 μm particles, the entire matrix is subject to damage. The importance of maximizing B₄C particle size is indicated by these examples. For each B₄C particle, most of the B¹⁰ fission that results in matrix damage must take place early in the burn-out process. Shielding of the inner B¹⁰ atoms by those near the particle surface would bring this about. Results of irradiation tests on YB₆ and YB₁₂ are interesting in this regard. After neutron exposure, no crystalline structure was detectable by X-ray diffraction on the outer surface of the specimens. In contrast, only minor damage to crystalline structure was measured in the inner portions of the specimens.⁽⁵⁾

2.3 SWELLING OF B₄C PARTICLES

There is considerable experimental evidence that B₄C particles will expand when irradiated with neutrons.⁽⁵⁻⁸⁾ Swelling apparently takes place as a result of crystal lattice damage from B¹⁰ fission and the generation of interstitial Li⁷ and He⁴ atoms.⁽⁵⁾ Significant quantities of foreign atoms can be retained in the B₄C crystal. For example, 82% of the theoretically generated helium was retained by B₄C powders (~ 10 μm size) irradiated to 85% B¹⁰ burnup at 400°C.⁽⁸⁾ During this irradiation experiment, 6% volume expansion of powder compact was observed, and considerable sintering took place. In another experiment, a vacuum hot-pressed B₄C compact of 100% theoretical density was restrained radially by a metal container and underwent 35% B¹⁰ burnup at about 250°C. In that case, 89% of the theoretically generated helium was retained, and a volume expansion of 36% was measured.⁽⁸⁾ When B₄C was not restrained by metal holders, complete granulation took place at 36% B¹⁰ burnup.⁽⁹⁾ In general, it appears that volume changes will be related to B¹⁰ burnup, temperature, fraction of fission products retained, and degree of restraint afforded by the container or matrix material.⁽⁷⁾

Analysis of B₄C expansion data from the diverse irradiation experiments referenced above suggests that at a B¹⁰ burnup approaching 100%, B₄C volume

Fig. 1. Effect of B_4C particle size on volume of matrix damaged by fission fragments resulting from the $B^{10}(n,\alpha)Li^7$ reaction. Conditions for two boron concentrations are shown: 0.47 g B/cm^3 (Peach Bottom absorbers) and 0.63 g B/cm^3 (Fort St. Vrain absorbers). The alpha particle (He^4) produces most of the damage. The extent of damage decreases rapidly with increasing particle size. With $20 \mu m$ particles, the entire matrix would be subjected to damage at a B concentration of 0.47 g B/cm^3 . (Data derived from Ref. 4.)

expansion on the order of 60% can be expected. In that case, a 30 wt-% boronated graphite containing B_4C particles with 100% B^{10} burnup might exhibit a 6% linear dimensional expansion. Expansions of irradiated 30 wt-% boronated graphite on the order of several percent have been measured at high B^{10} burnup, and it seems likely that swelling B_4C particles may have contributed strongly to the volume increase.^(10,11) The fact that dimensional expansions did not reach 6% and that contraction was observed in some cases may be the result of compensating and restraining conditions in the boronated graphite which operate to reduce the effect of particle swelling.

2.4 THERMAL NEUTRON SHIELDING

With 5 wt-% and 7 wt-% boronated graphite, most thermal neutrons are absorbed within about 0.2 cm of the surface.⁽³⁾ For 30 wt-% boronated graphite, the depth of the maximum absorption zone will probably be about the same. Irradiated bodies with wall thicknesses several times greater than 0.2 cm will develop a severe B^{10} burnup and damage gradient because of this thermal-neutron shielding effect.

It seems likely that the outer layer of a boronated graphite body would tend to change dimensions faster than the shielded core because of its more rapid damage rate. An experiment was conducted to measure this effect with 5 wt-% and 7 wt-% boronated graphite.⁽¹²⁾ Concentric cylinders of material were irradiated so that the outer cylinder shielded the inner cylinder. The dimensional change of the inner cylinders was 1.3 and 2.0 times less than that of the outer cylinder for 5 wt-% and 7 wt-% materials, respectively. The inner-cylinder length change was in good agreement with changes found for solid specimens with the same total overall size and shape as the two concentric cylinders. From this experiment, it appears that the relatively undamaged cores of the solid samples provided a restraint on the dimensional changes in the outer volume suffering rapid B^{10} burnup.

3. A MODEL FOR DIMENSIONAL CHANGE EFFECTS IN AN ABSORBER COMPACT

The complex interrelationship of B^{10} burnup, matrix damage, internal strain, and dimensional change in boronated graphite is not well understood. Enough is known, however, to make possible a working model for the purposes of understanding existing radiation data, planning future experiments, and estimating dimensional change under reactor conditions.

In this discussion, the course of radiation damage will be described for a hypothetical hollow cylinder of boronated graphite with a length-to-diameter ratio greater than one. In the model, to simplify the discussion, the cylinder has been shielded from thermal neutrons on the ends. The chronological steps from initial exposure in a typical reactor neutron flux to an advanced state of B^{10} burnup have been divided into four phases. During each phase, a slightly different combination of irradiation damage zones are assumed to exist. Each zone is characterized by a combination of predominant irradiation effects. While in reality the boundaries of the suggested zones may not be distinct, the hypothesis of their existence is a useful device for gaining an initial understanding of the process. A summary and schematic representation of the phases and zones is shown in Table 1.

3.1 PHASE I

Upon onset of irradiation, damage zones 1 and 2 will develop in the hollow cylinder. Zone 1, the "core," will be exposed only to fast neutrons, and hence will primarily suffer damage from neutron collision with graphite matrix atoms. However, the capture cross section of B^{10} for fast neutrons is finite, so there will be some B^{10} fission product damage to the matrix. For instance, it has been estimated that initially about 50% of the B^{10} fission in a Fort St. Vrain control-rod absorber will be distributed throughout the absorber core as a result of fast-neutron capture.⁽¹³⁾ On the basis of this estimate, the ratio of fast-neutron matrix damage to that of B^{10} fission product damage in zone 1 would be about 20 at 25% burnup of B^{10} in a Fort St. Vrain absorber. The technique for calculating this ratio is described later.

Table 1
 B^{10} BURNUP PROCESS IN A BORONATED GRAPHITE HOLLOW-CYLINDER ABSORBER COMPACT

B^{10} Burnup Phase	Zone Number	Primary Irradiation Effect in Zone ^a	Zone Location in Cross Section of Hollow Cylindrical Compact
I	1	$D_N + D_B^1$
	2	$D_N + D_B^2 + D_B^1$	
II	1	$D_N + D_B^1$
	2	$D_N + D_B^2 + D_B^1$	
	3	$D_N + D_B^2 + v_{B_4C}$	
III	1	$D_N + D_B^1$
	2	$D_N + D_B^2 + D_B^1$	
	3	$D_N + D_B^2 + v_{B_4C}$	
	4	D_N	
IV	Zones 1 to 3 are eliminated in sequence as B^{10} burnup completed		

a. D_N = Fast-neutron displacement of matrix atoms

D_B^1 = B^{10} fission fragment damage to matrix from fast-neutron capture

D_B^2 = B^{10} fission fragment damage to matrix from thermal-neutron capture

v_{B_4C} = Volume expansion of B_4C particles due to effects of B^{10} burnup

Within zone 2, there will be damage from fast neutrons as in zone 1, but, in addition, fission products from thermal-neutron capture by B^{10} will contribute heavily to the damage rate. For example, the ratio of fast-neutron matrix damage to that of B^{10} fission product damage would be about 3 at 25% burnup of total B^{10} in a Fort St. Vrain absorber. The initial thickness of the zone will be about 0.2 cm. Most of the B^{10} fission will take place near the B_4C particle surface. The matrix damage rate from B^{10} fission will therefore be greater in this zone than the average during the entire course of B^{10} burnup in the individual B_4C particles. Because of the greater damage rate in zone 2, this zone will tend to change dimensions faster than zone 1, and opposing stresses will develop. The stress level will be lower in zone 1, assuming it has a larger cross section, so it will tend to restrain and control axial dimensional change and also dimensional change in circumference.

3.2 PHASE II

During Phase II, damage zone 2 will move radially inward at the expense of zone 1 because of B^{10} burnup. Zone 3 will develop at the outer surface of the cylinder. In zone 3, there will be graphite matrix damage from fast neutrons and from B^{10} fission products. The B^{10} fission products will be mainly caused by thermal-neutron capture. The B^{10} concentration will be reduced, so capture of fast neutrons is assumed to be insignificant. The B_4C particles will be in an advanced state of burnup. The effect of B_4C swelling will contribute to generation of internal stress and perhaps dimensional change. Zone 1 will still control axial dimensional change assuming its stress level is still much less than that in zones 2 and 3. If zone interface stress levels are not greater than the strength of the material, zone 1 will also control circumference change in zones 2 and 3.

3.3 PHASE III

In Phase III, damage zones 2 and 3 advance inward radially, and zone 4 will appear at the surface of the compact. In zone 4, all B^{10} has been exhausted, and only fast-neutron damage to the carbon matrix remains as a damage mechanism. All four damage zones will exist together provided that the cylinder wall thickness is great enough so that zone 1 does not disappear before zone 4 develops. Axial and circumferential dimensional changes will probably be controlled by the zone with the lowest stress level.

3.4 PHASE IV

Phase IV will be the terminal phase of an absorber compact. Zones 1 through 3 disappear in sequence as the B^{10} is exhausted. Zone 4 becomes the largest zone, and probably controls dimensional change in all directions.

4. CORRELATION OF RADIATION DAMAGE

4.1 WEIGHTING FACTORS

Correlation of irradiation damage has been made for boronated graphite irradiated in different neutron spectra.⁽³⁾ The correlation is based on the assumption that the effects produced in a given material at a given temperature are proportional to the number of displaced carbon atoms produced. In boronated graphite, as discussed previously, carbon atoms can be displaced by fast neutrons or by helium and lithium atoms produced by the $B^{10}(n,\alpha)Li^7$ reaction. The $B^{10}(n,\alpha)Li^7$ reaction is caused mainly by thermal neutrons, although capture of more energetic neutrons can be significant.

The relative effectiveness of fast and thermal neutrons for displacement of carbon atoms in boronated graphite has been calculated by Dahl.⁽³⁾ Fast neutrons ($E > 0.18$ MeV) are estimated to produce an average of 240 displaced carbon atoms per exposure unit (nvt) in graphite containing 5 to 7 wt-% boron and having a density of 1.6 g/cm³. A B^{10} atom in solution in the carbon matrix will fission to yield one He^4 and one Li^7 atom, which will cause about 500 and 800 carbon atom displacements, respectively. When boron is held in the form of B_4C particles, the total fission products impinging on the graphite matrix will decrease with increasing particle size. It has been calculated⁽³⁾ that for B_4C particles of 10 to 100 μ m diameter the effectiveness of fission products in producing displacements is 5% of that for B^{10} in solid solution in the graphite matrix. Therefore, the average number of displaced carbon atoms per B^{10} fission in 10 to 100 μ m B_4C granules would be about 65.

These weighting factors were developed for low wt-% boronated graphite with B_4C particle size somewhat smaller than typical, but they should be useful in making a first-order correlation of other radiation data. In making a correlation between dimensional change data for 30 wt-% boronated graphite, the approach of Dahl⁽³⁾ was modified by taking into account the effect of thermal-neutron shielding and apparent restraint by the inner core.

4.2 HOT-MOLDED GRAPHITE DIMENSIONAL CHANGES -- BORONATED AND NONBORONATED

A correlation between dimensional change in a matrix-type graphite and in a highly boronated graphite was made in an attempt to determine the

importance of B_4C particle swelling. Data were available from two irradiation experiments with hot-molded and sintered 30 wt-% boronated graphite^(10,11) and from four irradiation experiments with nonboronated hot-molded and sintered matrix graphite.⁽¹⁴⁾ The following assumptions were made in correlating dimensional change data for these graphites:

1. The average number of carbon atom displacements per nvt was 240 for fast-neutron ($E > 0.18$ MeV) irradiation.
2. The average carbon atom displacement per B^{10} fission was 65.
3. B^{10} fission density was estimated from chemical analysis; when chemical analysis was not available, the fission density was assumed to be directly proportional to thermal-neutron exposure up to 100% B^{10} burnup.
4. The irradiation experiments resulted in either 100% B^{10} burnup or 50% burnup in the boronated graphite. In the case of the 50% total B^{10} burnup, one half of the B^{10} fissions were assumed to be concentrated in an outer zone in which 100% B^{10} burnup had occurred. The other half of the fissions were assumed to be distributed over the remaining volume of the specimen. The B^{10} fission density of the inner core was used to correlate data since the inner core was assumed to control dimensional change.
5. There was uncertainty and a wide range in irradiation temperatures of the experiments, but temperatures generally were above 300°C.
6. The matrix of the boronated graphite had the same irradiation properties as the nonboronated warm-pressed material.
7. Essentially all B^{10} was in B_4C particles with greater than 10 μm diameter (i.e., no B^{10} in solid solution in the carbon matrix).
8. Discontinuities in the graphite matrix in the form of B_4C particles did not affect the rate of dimensional change due to irradiation damage in the matrix.
9. Helium escaping from B_4C particles diffused rapidly through the graphite matrix without a pressure buildup or distortion of the crystal structure.

Table 2 shows the irradiation data and the results of displacement density calculations. The irradiation-induced dimensional changes in the

Table 2

IRRADIATION DATA FOR HOT-MOLDED NONBORONATED GRAPHITE AND FOR 30 WT-% BORONATED GRAPHITE CONTROL MATERIALS,
AND ESTIMATES FOR FORT ST. VRAIN ABSORBER COMPACT

Material Type and Ref.	Sample No.	Specimen		Calcu- lated O.D. of Shielded Core (cm)	B^{10} Fission Density of Shielded Core (Fissions/ cm ³) $\times 10^{-21}$	Fast Neutron Exposure (nvt) $\times 10^{-20}$	Fast Neutron Graphite Matrix Atom Displace- ment Density (Disp/cm ³) $\times 10^{-23}$	B^{10} Fission Product Displace- ment Density (Disp/cm ³) $\times 10^{-23}$	Total Displace- ment Density (Disp/cm ³) $\times 10^{-23}$	Dimensional Change (%)		Irrad- iation Temp. (°C)
		O.D. (cm)	I.D. (cm)							Parallel to Forming Direction	Perpen- dicular to Forming Direction	
Boronated graphite, hot-molded (Ref. 11)	44-4-1	2.5	0.6	2.2	2.3	6.0	1.4	1.5	2.9	+0.32	-1.34	330
	12-2-1	2.5	0.6	2.2	2.3	6.0	1.4	1.5	2.9	+0.91	-0.15	300
	44-4-2	2.5	0.6	0	6.8	20.8	5.0	4.4	9.4	+1.21	-0.72	330
	12-2-2	2.5	0.6	0	6.8	20.8	5.0	4.4	9.4	+3.08	-0.57	300
Boronated graphite, extruded and baked (Ref. 11)	255-1	2.5	0.6	2.2	2.3	6.0	1.4	1.5	2.9	-0.04	+0.2	330
	-2	2.5	0.6	2.2	2.3	6.0	1.4	1.5	2.9	-0.14	+0.28	300
	-4	2.5	0.6	0	6.8	20.8	5.0	4.4	9.4	+0.58	+1.29	330
	-5	2.5	0.6	0	6.8	20.8	5.0	4.4	9.4	+0.27	+0.20	300
Boronated graphite, hot-molded ^a (Ref. 10)	310.5-1	2.5	--	0	6.8	9.8	2.3	4.4	6.8	+1.3	-0.2	>330
	-3	2.5	--	0	6.8	9.8	2.3	4.4	6.8	+1.5	-0.2	670-780
	-2	2.5	--	0	6.8	24.0	5.7	4.4	10.2	+2.5	0	>330
	-4	2.5	--	0	6.8	24.0	5.7	4.4	10.2	+2.5	+0.1	670-780
Nonboronated graphite, hot- molded ^a (Ref. 14)	G1 ^b	--	--	--	--	25	6.0	--	6.0	+0.2	-0.8	450±150
	G2	--	--	--	--	25	6.0	--	6.0	+0.1	-1.3	1000-1400
	G3	--	--	--	--	16	3.8	--	3.8	+0.1	-0.4	550±150
	G3	--	--	--	--	88	21.1	--	21.1	+8.2	-1.1	Unknown
	G4	--	--	--	--	16	3.8	--	3.8	+0.2	-0.1	900±150
	G4	--	--	--	--	88	21.1	--	21.1	+0.8	-1.4	Unknown
Typical Fort St. Vrain Absorber (6-yr, 100% duty factor, 25% B^{10} burnup)	--	8.2	5.0	7.8	1.0	60	14.4	0.6	15.0	----	----	500

a. Solid-cylinder specimens.

b. Capsule number.

directions parallel and perpendicular to the molding direction are plotted in Figs. 2 and 3, respectively, as a function of graphite-matrix atom displacement density.

The specimens of both boronated and nonboronated graphites expanded parallel to the molding direction and tended to contract in the other direction. This characteristic could result from preferred orientation of graphite crystallites in a direction determined by the forming process.⁽²⁾

The boronated graphites at the highest exposures were depleted of B^{10} so they were probably well into Phase IV of the B^{10} burn-out process. There was considerable scatter in the data, particularly for nonboronated graphite at high exposure and parallel to the molding direction. In spite of this condition, a trend was evident for the boronated material to undergo more expansion parallel to the molding direction and less contraction in the perpendicular direction than nonboronated graphite. It seems probable that swelling of B_4C particles in boronated graphite may be primarily responsible for this difference.

4.3 PREDICTION OF ABSORBER DIMENSIONAL CHANGE IN THE FORT ST. VRAIN REACTOR

The assumptions listed above were used to treat irradiation data for hot-molded and extruded 30 wt-% boronated graphite reported previously.^(10,11) Dimensional changes were correlated with calculated graphite-matrix atom displacement density. Correlation of data in this manner should make possible an estimate of Fort St. Vrain absorber dimensional change by calculation of its displacement density in the shielded absorber core at a given B^{10} burnup level. The fact that the reference Fort St. Vrain absorber material will contain approximately 40 wt-% boron rather than the 30 wt-% boron of the test data does not preclude use of the test data, for several reasons. First, the maximum absolute difference in percent of damaged matrix volume for the two material types should be less than 3% if the B_4C particle size is 100 μm or greater and the same size distribution exists in both materials (see Fig. 1). Second, some irradiation data that compare materials containing 30 and 40 wt-% boron⁽¹⁰⁾ show no systematic dependence of dimensional change on boron content. This observation tends to minimize the importance of boron content in this range of concentrations because the

Fig. 2. Correlation of irradiation-induced dimensional change in boronated and nonboronated hot-molded graphite; parallel to molding direction

Fig. 3. Correlation of irradiation-induced dimensional change in boronated and nonboronated hot-molded graphite; perpendicular to molding direction

B_4C particle size in those experiments⁽¹⁰⁾ was 20 μm or less and the difference in damaged matrix volume resulting from B^{10} fission should have been significant (see Fig. 1). Third, the experimental data used here include results from material with B_4C particle size less than 20 μm .⁽¹⁰⁾ Such material, although it contains less boron than the Fort St. Vrain reference material, would have experienced more matrix damage and presumably greater dimensional change due to B^{10} fission. (The Fort St. Vrain reference B_4C particle size is 100 to 400 μm .) Use of these data results in conservative predictions of dimensional change in Fort St. Vrain absorbers.

In arriving at a B^{10} fission density for the Fort St. Vrain absorber compact, one half of the predicted burnup was assumed concentrated in an outer cylinder with 100% of the B^{10} burned out. The other half of the predicted burnup was averaged over the remaining core volume. The shielded core was assumed to control axial and radial dimensional change. It was estimated that 25% of the total B^{10} was consumed by the end of 6 years of continuous exposure.⁽¹³⁾ Fast-neutron damage was calculated from estimated exposure levels.⁽¹⁵⁾

The irradiation data and the results of calculations used in this correlation are shown in Table 2. The dimensional change data plotted as a function of displacement density for hot-molded and for extruded material are shown in Figs. 4 and 5, respectively. The estimated Fort St. Vrain absorber core damage density for a 6-year exposure similar to that planned for the central control rod (i.e., 100% duty factor) is also shown in Table 2.

The extruded and hot-molded boronated graphites both showed a tendency to expand at damage densities approaching that equivalent to 6 years in the Fort St. Vrain reactor. Swelling of B_4C particles probably contributed significantly to this effect. At lower exposures, some contraction was exhibited by extruded material in the parallel and by hot-molded material in the perpendicular forming directions. Contraction may be a manifestation of Phase I, while later expansion reflects the complex interactions of other advanced phases of the irradiation.

A prediction of Fort St. Vrain absorber compact dimensional change for the two fabrication methods can be made from Figs. 4 and 5. Table 3 shows estimates for parallel and perpendicular change at 50% and 100% duty factor for 6 years in the Fort St. Vrain reactor. With regard to a typical absorber compact,

Fig. 4. Irradiation-induced dimensional change in hot-molded boronated graphite (30 wt-% boron)

Fig. 5. Irradiation-induced dimensional change in extruded boronated graphite (30 wt-% boron)

Table 3
ESTIMATED DIMENSIONAL CHANGE OF BORONATED GRAPHITE
(40 wt-% boron) ABSORBER COMPACT IN
FORT ST. VRAIN REACTOR

Forming Method	Duty Factor For 6 Yrs (%)	Probable Range of Dimensional Change (%)	
		Parallel to Forming Direction	Perpendicular to Forming Direction
Hot Molding	50	+1.0 to +2.5	-1.0 to 0.0
	100	+2.0 to +5.0	0.0 to +0.5
Extrusion	50	0.0 to +0.5	0.0 to +1.0
	100	+0.5 to +1.0	0.0 to +2.0

the extruded boronated graphite would probably undergo less total axial and radial dimensional change than hot-molded material. The hot-molded compacts probably would expand more in the axial direction and contract more in the radial direction than would comparable extrusions.

One weakness of the correlation technique is the assumption that the rate of dimensional change will be controlled by the center core (zone 1) in all phases of B^{10} burnup. No problem exists if all zones tend to change dimensions at the same rate and in the same direction. It seems likely, however, that the outer zones will tend to expand because of high B^{10} burnup, while the shielded core (zone 1) may either expand at a different rate or contract. Under these conditions, the relative dimensional change of an irradiated specimen with complete B^{10} burnup may be significantly different from a specimen still in Phase I of B^{10} burnup, even though the damage density of the cores may be the same. This situation, if it exists for the data in Figs. 4 and 5, probably would result in prediction of greater expansion or less contraction than may actually take place in the more massive Fort St. Vrain absorber at low B^{10} burnup.

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