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RECENT DEVELOPMENTS IN GRAPHITE

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Introduction

As part of the Maritime Gas-Cooled Reactor Materials Program, a review of the developments in graphite during the past 15 months was undertaken. A similar effort was undertaken by Bokros, Dykstra and Merten⁽¹⁾ in May, 1958. This report will concern itself with developments which have taken place since then and will not be concerned with graphite as a fuel bearing material nor the mass transport of graphite.

The material for this report was obtained from the following sources:

- 1) Open literature and reports. Some of the information given in this report has existed for a few years but has only recently been declassified.
- 2) Visits to AEC sites, carbon companies and interested consumers of graphite products as well as manufacturers of specialty graphite products.
- 3) Scientific meetings.
- 4) Limited experimental program at General Atomic.

Radiation Effects

There are two locations where significant efforts are directed toward the study of the effect of irradiation on graphite; Brookhaven National Laboratory and Hanford. The irradiations at Brookhaven are performed at temperatures lower than those of interest to the MGCR. The high temperature irradiations at Hanford⁽²⁾ are directly applicable to the MGCR and will be discussed here.

Hanford is conducting high temperature graphite irradiations at 600 to 1150°C at the Materials Testing Reactor and Preliminary results indicate contractions ranging from .13 to 1.0 per cent for integrated fast fluxes (>1 mev) of 1.9×10^{20} to 2.6×10^{20} respectively. Table I is a summary of the data obtained thus far.

There are several factors, interrelated and interdependent, which should tend to reduce the amount of contraction in graphite. These are increased graphitization, increased density, smaller pore size and larger particle size. Most of these criteria are fulfilled by the low permeability, high density graphites. Thus graphites of this type offer the best immediate hope for improvement in the dimensional stability of reactor graphite. Development work leading to improved graphites is being conducted by all major graphite manufacturers.

Presently, Manford is engaged in an extensive irradiation program on graphite⁽³⁾. The problems being studied are as follows:

- 1) Continuation of high temperature graphite irradiation to further explore the phenomena of contraction. Controlled temperature irradiations of existing and new graphites are in progress at the MTR and the ETR.
- 2) Effect of gamma radiation on the CO_2 -graphite reaction.
- 3) Reaction kinetics of gas-graphite systems using microwave generation of excited molecules to simulate pile radiations.
- 4) Graphite-helium system to determine the effect of ionized helium on graphite.
- 5) Graphite irradiations at 200-400°C.
- 6) Capsule irradiations of graphite - CO_2 at 550°C and 100-400 psi.
- 7) Evaluation of new graphites from the standpoint of purity, mechanical properties and irradiation behavior.

Graphite Outgassing

It is expected that the allowable concentration of oxidizable impurities in the helium stream in the MGCR will be low. One of the main contributors of the impurities is the gas adsorbed by the graphite itself. In support of this, ORNL⁽⁴⁾ is conducting a program on the outgassing characteristics of graphite as

a function of temperature, pressure and types of graphite. The results obtained thus far show that:

- 1) CO is a major fraction of the mass 28 obtained on heating graphite to 1000°C; only below 400°C is N₂ appreciable in comparison with CO.
- 2) The total volume of gas evolved per unit of volume of graphite shows no dependence on sample size over the relatively small range studied and with the considerably long pumping times used in these studies. Step-wise heating of specimens at several temperatures up to 1000°C yields the same total volume and composition of gases as does a single heating at 1000°C.
- 3) AGOT graphite specimens evolve 22 to 32 cm³ of gas/10 cm³ of graphite while TSF specimens evolve somewhat smaller quantities of gas. Very little gas is released above 1400°C; CO is the primary constituent of this small fraction and nitrogen accounts for most of the remainder. In general, the total volume of gas evolved below 1400°C is nearly constant for each of the graphites studied. However, specimens cut from the same section of a graphite bar often show wide variation in the relative proportion of gas evolved at 1000° and at 1400°C.
- 4) AGOT and TSF graphite specimens were outgassed at 1800°C, cooled under vacuum to room temperature and then removed and stored in laboratory air. After 10 days of storage for the AGOT and after 7 days for the TSF, they were again degassed at 1800°C. The second outgassing yielded about 10 fold less gas than the original; rather small volumes of gas are apparently reabsorbed on short exposures.
- 5) Temperature has a marked effect upon the rates of gas release. The rate of release of the gases is extremely rapid as the sample is heated up, making the determination of the rates of evolution very difficult

during the first hour at temperature. The volume of gases measured after one hour give some indication of how rapidly the gases are evolved during this period. Rates of evolution at 300° and 600°C change very slowly after 20-40 hours of heating.

- 6) The rate of evolution is also affected by the pressure of the evolved gases in contact with the graphite specimen. Except for the initial heating period during which the evolution is very rapid, the partial pressures of the gases over the specimen are relatively low and decrease as the rate of evolution decreases. These conditions yield quite different results than the case where the evolved gases are not removed but rather equilibrium conditions are attained.

Some representative data thus far obtained are given in Table 2⁽⁴⁾.

New Graphite Products

I. Impermeable Graphite

The NTGR Materials Group has been actively engaged in testing the permeability of graphites manufactured by various companies. This group also has an active program in developing an "impervious" graphite.

Some of the most interesting graphite specimens thus far have been obtained from the British GEC, Hawker-Siddeley, and Raytheon. Table 3 summarizes the measurements⁽⁵⁾ made on these and other graphites. Subsequently, permeation constants⁽⁶⁾ were determined for helium permeation at room temperature on Hawker-Siddeley graphite samples No. 141-1 and 143-4 and found to be 3×10^{-8} and 4×10^{-9} cm²/sec respectively.

Some recent British work⁽⁷⁾ shows that appreciable attack and increase in permeability of EY.9 graphite occurs on passing argon with 100-200 vpm of impurities containing reactive oxygen atoms through the graphite at 900° - 1000°C for one month. The impurity content in vpm in the argon was: oxygen 40-260, carbon dioxide 0-30,

hydrogen 0-170, water vapor 0-300. Since this is a preliminary report, more information on this problem should be forthcoming.

II. Graphite Fibers

Graphite fibers and yarns could be of interest to the MGCR as an insulating material. Some of the properties of graphite fibers and fabrics can best be described in terms of well-established data on manufactured graphite itself:

Thermal Expansion - at room temperature, the coefficient of thermal expansion for typical grades of manufactured graphite is approximately $1 \text{ to } 4 \times 10^{-6} \text{ cm/cm per degree Centigrade}$. The mean coefficient of thermal expansion from room temperature to about 3000°C is approximately 3 units higher, or from $4 \text{ to } 7 \times 10^{-6} \text{ cm/cm}^{\circ}\text{C}$.

Thermal Conductivity - at room temperature, it is approximately 0.3 calorie-centimeters/second-centimeter-degree Kelvin. At elevated temperatures, this value is reduced to about 1/5 at from 2200° to 3000°C .

Electrical Resistance - typical room-temperature electrical resistance for manufactured graphite is 700 micro-ohm centimeters. This figure drops off to about 4/5 of that as temperatures reach 500° to 600°C , and the value then increases until it is somewhat higher at elevated temperatures than at room temperature.

Chemical Resistance - manufactured graphite is resistant to practically all acids, alkalies, and organic compounds except those of a highly oxidizing nature. It is unreactive with many metals, such as zinc, aluminum, magnesium, copper and its alloys, and metal producing slags at their melting points. Average threshold oxidation temperatures for general purpose manufactured graphite are: in air, 400°C ; in steam, 700°C ; in CO_2 , 900°C .

In addition to the foregoing properties of manufactured graphite itself, specific information on the material in the form of fibers and fabrics follows:

Tensile Strength - the room-temperature tensile strength of graphite textiles will naturally vary with the type of fiber and fabric. Individual yarns of graphite have shown tensile strengths as high as 15,000 psi.

Bulk Density - bulk density of graphite fabrics obviously is related to the fiber and type of weave of the fabric. In general, the real density of the fiber itself is comparable to that of manufactured graphite, but the bulk density of textile forms is much less.

Chemical Analysis - most graphite textiles have less than 0.1 per cent ash. For special purposes, it appears feasible to produce graphite textile forms of spectroscopic purity, that is with no determinable ash.

Graphite Cloth (Square Weave, 28 by 28 Construction):

Specific data on a typical form of graphite fabric, square weave, 28 by 28 construction:

Typical Surface Area - 260 square feet per square foot.

Weight Per Square Foot - 0.04 pounds (approximately 1/5th that of a sheet of lightweight magnesium of the same size and thickness).

Tensile Strength, Room Temperature - 10 to 15 pounds per inch width.

Electrical Resistance, Room Temperature - 1/2 ohm per inch width per inch length.

Typical Ash and Spectrographic Analysis - ash: 0.09 per cent. No major impurities. High minor impurities - magnesium. Low minor impurities - aluminum. High trace impurities - calcium, iron, manganese and silicon. Minor trace impurities - boron, copper, nickel, and sodium.

III. Other Products

Information on graphite cements, graphite support structures, TSF graphite and maximum dimensions of graphite has been reported previously⁽⁸⁾.

Properties of Graphite

Recently the National Carbon Co. has released a book entitled, "Industrial Graphite Engineering Handbook" which contains much useful information on various grades of graphite and the products manufactured by the National Carbon Co. Several copies of this handbook will soon be available at GA. Some of the information on the nuclear graphites will be treated here. For additional information on graphite manufacture, grades, graphite applications, common properties, mechanical, thermal, electrical, and chemical properties, the reader is referred to the above mentioned handbook.

The desirable characteristics of a moderator graphite are reasonably high density, structural strength, freedom from gross flaws, and good thermal conductivity. For natural uranium fuel reactors, however, the overriding criterion is purity - specifically, freedom from large capture cross-section materials. Only a limited degree of improvement in purity and quality of material can be attained by careful selection of the raw materials. Gross and consistent improvement can be guaranteed only by one of two procedures; graphitizing at very high temperatures for an extended period of time, or purification by drastic chemical means. Grade AGOT is the result of purification by the first means; and Grades GBF and TSF are examples of the second.

Grade AGOT

Grade AGOT is high purity nuclear graphite of controlled structure. Boron content is carefully controlled and averages 0.4 ppm. Total ash is less than 0.1 per cent. To prevent contamination during storage and shipment, special packaging and handling is employed. This grade machines easily and sharp details can be maintained. Its widespread acceptance to date has literally established it as a standard for the industry.

Grade AGOT is recommended for those applications requiring low neutron capture cross section such as nuclear reactor moderators, reflectors, thermal columns,

exponential piles and structural parts.

Typical Average Properties (Room Temperature)

Sizes Produced	Max. Grain Size	Forming Method	Bulk Density (g/cc)	Flexural Strength with Grain (lbs/in ²)	Resistivity with Grain (ohm-cm)	Ash
4-3/8 x 4-3/8 x 51"	0.03"	Extruded	1.70	2400	7.34x10 ⁻⁴	0.07
6 x 6 x 51"	0.03"	Extruded	1.70	2400	7.10	0.07
8 x 8 x 51"	0.03"	Extruded	1.69	2300	7.10	0.08
12 x 12 x 51"	0.03"	Extruded	1.69	2300	7.10	0.09
16-3/8 x 16-3/8 x 51"	0.03"	Extruded	1.65	2200	8.90	0.09

Grade TSF

Grade TSF is a premium material produced for nuclear applications requiring extremely high purity graphite. Boron and total ash content are extremely low. TSF is gas purified to remove those impurities which cannot be removed entirely by temperature and time. Structure and density are similar to AGOT and CS. Special packaging is also used to prevent contamination during storage and shipment.

Grade TSF has been provided for those reactor applications requiring very low neutron capture cross section and low gas evolution.

Typical Average Properties (Room Temperature)

Sizes Produced*	Max. Grain Size	Forming Method	Bulk Den. (g/cc)	Flexural Strength with grain (lbs/in ²)	Resistivity with grain (ohm-cm)	Ash
4-3/8 x 4-3/8 x 51"	0.03"	Extruded	1.70	2400	8.1x10 ⁻⁴	0.002

*Other sizes available on request.

Production

The nuclear grades of graphite are manufactured identically, until the final graphitization. The basic materials, coke particles (in 0.015 to 0.03 inches size range) and coke flour are mixed with pitch, extruded, gas-baked and then pitch impregnated. For the AGOT grade the next, and final, step is graphitization at 2800°-3000°C. With GBF graphite the pitch impregnation is followed by a gas-bake and then a simultaneous purification and graphitization at 2500°C. Essentially, GBF and TSF have the same properties although TSF does have the advantages of being produceable in large sizes and of being more easily machined. Both GBF and TSF are purified by being chemically flushed with chlorine and fluorine gases.

In the early days of reactor construction, rigid control over raw materials gave rise to a variety of supplementary graphite designations: AGOT-KC, -KS, -CS, etc., and CSF, TSF. These designations identified the virgin coke and pitch sources. Subsequently, purification and processing were found to effectively eliminate variations in the initial coke sources. Hence, control over raw materials is no longer critical, and both AGOT and TSF (or GBF) are now produced without these grade-names implying a designation of raw materials.

The use of halogens in purifying graphite evolved from the similar treating of spectroscopic electrodes where ultimate purity was also required. Several impurities in the raw material, especially boron (cross-section 755 barns) and vanadium (5 barns) form extremely stable carbides which are converted to volatile halides in the presence of chlorine or fluorine and flushed from the graphite. Since this purification depends on gaseous and solid state diffusion the time of treatment increases appreciably as the cross-sectional area of the fabricated graphite bars increases.

As an illustration of the results of the above purification treatment the approximate neutron characteristics of these graphite grades are listed in Table 4. For comparison, results for grade CS are also listed. This grade is similar to

AGOT or GBF but has been given only a normal graphitization at 2600°C.

Special Grades of Nuclear Graphite

Although AGOT, TSF and GBF are the only commonly produced moderator grade graphite, several special purpose grades have been produced for specific requirements. For example, grade TSP has been developed for low gas evolution. It is similar to GBF except chlorine, instead of the chlorine-fluorine mixture, was used in the purification, and helium and argon were used as flushing gases instead of nitrogen. The Δ ih is 0.85, indicating the incomplete removal of boron. The gas evolution on heating is 0.3cc STP/100cc graphite at 1500°C, 17cc less than the normal.

For comparison, some of the physical properties of these discussed grades are indicated in Tables 5 and 6. Grade CEQ, lampblack based material, is also included since it has been extensively studied with regard to radiation damage. CEQ is of particular interest in radiation damage studies since it is a material in which the crystallites are extremely small and registry between crystal planes is poorly developed. Consequently, a large amount of cross-bonding occurs.

Additional Information

Considerable information on graphite exists in the classified literature. The classified reports are listed below by number under a general category. The unclassified reports of interest to the MGCR are listed by author and title.

Chemical Properties

Woodley, R.E. - "Promotion of Chemical Reaction Gas-Graphite Systems by Gamma Radiation" - HW-40142.

Tomlinson, M. - "Comparison of Data on the Oxidation of Graphite in Reactors" - AERE C/R 2619.

Kosiba, W.L. - Graphite-Helium System - Quarterly Progress Report (July 1959) - MGCR-M-178.

HW-38300

HW-38519

HW-38924

HW-49128

HW-55798

Graphite Development

HW-44741

Mechanical Properties

Martens, H. E., Jaffe, L. D., and Bulton, D. D. - "High-Temperature Short-Time Creep of Graphite", (Nov. 1958) - Col. Inst. Tech., Jet Prop. Lab. 8921 JPL-EP-583.

Green, Leon - "The Behavior of Graphite Under Alternating Stress" - Jour. of Applied Mech., Vol. 18, No. 4 (Dec. 1951) p. 345.

Green, Leon - Experimental Studies on Heat Transfer and Fluid Flow Systems" - Part 2 of Quarterly Progress Report No. 1, June 22 - Sept. 30, 1956 - Project 6 - (1-9964) Contract AF33(616)-3767.

HW-27443

HW-55048

HW-42498

Graphite Moderator Drying

Kosiba, W. L. - "Graphite Drying" - MGCR-M-79, Nov. 1958.

HW-24799

HW-33074

Graphite Moderator Stability

HW-38632

HW-58026

Thermal Conductivity

HW-19414

HW-28648

Quality

HW-34415

Radiation Effects

Nightingale, R. E. and Snyder, W. A. - "Radiation Damage in Graphite", HW-49626, June 1957.

Reactor Atmosphere

HW-38580

Reactor Matrices

HW-39924

HW-41224

Properties (Miscellaneous)

Clayton, E. D., - "Summary of Graphite Diffusion Length Studies at Hanford", HW-48891, March 1957.

Kosiba, W. L. - "Graphite Canning Technology", MGCR-M-77, Nov. 1958.

Woodley, R. E. - "A Preliminary Study of the Effect of Neutron Irradiation and Oxidation at Moderate Temperatures on the Structural Characteristics of CSF Graphite" - HW-52375.

HW-33487

References

- (1) Bokros, J. C., L. Dykstra and U. Merten; A Survey of Non-Fuel Bearing Materials for the MGCR - GAMD-316, May, 1958.
- (2) Davidson, J. M., E. M. Woodruff, and H. H. Yoshikawa; High Temperature Radiation Induced Graphite Contraction, HW-57900, Feb. 1959.
- (3) Kosiba, W. L.; Trip Report, Feb. 1959, MGCR-M-111, GA-P-40-81.
- (4) Wallace, W. P., and T. H. Pigford; Trip Report, June 1959, MGCR-M-173, GA-P-40-97.
- (5) HTGR (Project 32) Progress Report for March 1959 (Issued April 20, 1959) - Materials and Chemistry Program.
- (6) HTGR Progress Report for May 1959 - Materials and Chemistry - GA-P-32-113.
- (7) Antill, J. E. K. A. Peakall and E. Smart; Change of Permeability of EY.9 Graphite in Impure Argon - AERE M/M-172, HTGC-CWP/Memo 9.
- (8) Kosiba, W. L.; Trip Report Jan. 18-24, 1959, MGCR-M-100, GA-P-40-77.

TABLE 1

HIGH TEMPERATURE GRAPHITE IRRADIATIONS

Graphite Type and Density, gm/cm ²	Irradiation Temp., °C	Integrated Flux (nvt x 10 ⁻²⁰)					Exposure, MWD/AT		Pct Length Change	
		calculated ^b		measured ^b			minimum ^c	maximum ^d	optical	micro-meter
		0-115 ev	>1mev	<.4ev	.4ev-1mev	>1 mev				
TSGBF 1.6	750	14	1.4				(3125) ^e	7300	-.06	-.03
TSGBF 1.6	750est	12	1.8				(2320) ^e	8420	-.06	
TSGBF 1.6	750	11	1.0	5.6	9.6	.53	2410	5600	-.32	
TSGBF 1.6	975	18	2.6				(5600) ^e	15300	-1.11	-.87
TSGBF 1.6	975	12	1.9	9	16	1.0	4000	11300	-.13	
TSGBF 1.6	1050	14	2	9	16	1.0	4000	11700	-.49	
TSGBF 1.6	750		.4					2200	-.07	-.05
TSF 1.4	750		.3	2.3	1.7	.17	650	1630	+.02	

a. From MTR integrated MWD, and prior flux traverse of L-42.

b. From monitors at samples.

c. Based on 6.5×10^{17} nvt total/MWD/AT.

d. Based on damage correlating factor.

e. Estimated from cross reference with measured positions.

Table 2

Volume and Composition of Gases Evolved by AGOT-III Graphite

Specimen Size	Temp. (°C)	Time (hrs)	Volume cm ³ /100 cm ³ graphite	H ₂		Hydro- carbon		H ₂ O		CO ₂		Mass 28		N ₂		CO	
				%	cm ³	%	cm ³	%	cm ³	%	cm ³	%	cm ³	%	cm ³	%	cm ³
3/4"x 2"	300	19	1.9	0.8	-	0.5	-	85	1.6	2.0	-	11	0.2	0.9% H ₂ S			
	600	5.5	6.8	4.4	0.3	1.3	0.1	39	2.6	47	3.2	8.5	0.6				
	600	16	1.5	11	0.2	17	0.2	31	0.5	24	0.4	16	0.2	1.5% H ₂ S			
	1000	4	13.5	12	1.6	0.6	0.1	2	0.3	28	3.8	52	7.1	4.8% SO ₂			
	1000	17	3.7	42	1.5	1.1	-	0.8	-	0.1	-	56	2.1	SO ₂			
Total			27.4		3.6		0.4		5.0		7.4		10.2	0.6			
3/4"x 2"	1000	7	27.3	18	4.8	2.3	0.6	25	7.0	21	5.8	32	8.7	0.5% SO ₂			
	1000	11	2.8	40	1.1	1.6	-	4	0.1	0.5	-	53	1.5	SO ₂			
	Total		30.1		5.9		0.6		7.1		5.8		10.2	0.1			
1 1/4"x 1"	300	2	1.7	1.5	-	4	-	68	1.3	3.5	-	22	0.4	21	0.4	1	-
	600	2.5	6.5	3.5	0.2	14	0.9	47	3.0	23	1.5	13	0.8	5	0.3	8	0.5
	1000	0.5	15.6	14	2.1	3	0.5	3	0.5	32	4.9	48	7.4	1	0.2	47	7.2
	1000	10	6.0	31	1.9	4	0.2	10	0.6	-	-	55	3.3	3	0.2	52	3.1
	Total		29.8		4.2		1.6		5.4		6.4		11.9		1.1		10.8
1 1/2"x 2"	300	1.5	1.1	1.3	-	3	-	83	0.9	1.7	-	12	0.1	11	0.1	1	-
	400	3.5	0.9	1.0	-	3	-	90	0.8	2.0	-	4	-	2	-	2	-
	500	3.25	1.3	2.7	-	14	0.1	43	0.5	26	0.3	15	0.2	6	0.1	9	0.1
	600	2.5	3.6	2.4	0.1	10	0.4	15	0.5	57	2.1	15	0.6	2	0.1	13	0.5
	700	4	3.2	4.0	0.1	5	0.1	16	0.5	58	1.9	13	0.4	4	0.1	9	0.3
	800	5	7.4	1.9	0.1	2	0.1	10	0.7	66	4.9	15	1.1	4	0.3	11	0.8
	900	4.25	3.9	13	0.5	1	-	1	-	8	0.3	78	3.0	1	-	77	3.0
	1000	4.5	5.1	29	1.5	2	0.1	1	-	0.2	-	68	3.5	3	0.2	65	3.3
	Total		26.5		2.3		0.8		3.9		9.5		8.9		0.9		8.0

Table 2 (continued)

Specimen Size	Temp. (°C)	Time (hrs)	Volume cm ³ /100 cm ³ graphite	H ₂		Hydro- carbon		H ₂ O		CO ₂		Mass 28		N ₂		CO	
				%	cm ³	%	cm ³	%	cm ³	%	cm ³	%	cm ³	%	cm ³	%	cm ³
1½"x 2"	300	5.5	0.6	0.5	-	2.7	-	75	0.5	6.2	-	13	0.1	H ₂ S-1.1%; SO ₂ -0.4% " -0.4%; " -0.2%			
	300	19	0.2	1.3	-	6.3	-	56	0.1	9.2	-	26	0.1				
	600	1.5	2.1	1.8	-	4.6	0.1	55	1.1	32	0.7	7.3	0.2				
	600	8.5	3.5	1.6	0.1	2.1	0.1	11	0.4	77	2.7	8.3	0.3				
	600	11.5	0.4	5.2	-	6.5	-	11	-	61	0.2	15	0.1				
	1000	0.75	12.8	5.9	0.8	-	-	1	0.1	31	4.0	59	7.6	SO ₂ - 0.9%			
	1000	20	4.7	24	1.1	0.2	-	1	-	0.2	-	71	3.3	" - 2.2%			
	Total		24.3		2.0		0.2		2.2		7.6		11.7	SO ₂ - 0.3			

TABLE 3

Graphite Specimen Number	Type	Permeation Constant cm^2/sec	Intercept min	Helium Pressure mm Hg	Duration of Test	Previously Reported Permeation Constant
Nat'l Carbon RXLP-1	Low Permeability	5.6×10^{-7} 5.3×10^{-7}	9 9	742 393	155 min 120 min	
Hawker Siddeley No. 1 AAEC 6	Impregnated	1.8×10^{-5}	19	723	120 min	1.6×10^{-6}
General Electric No. 3	Low Permeability	2.7×10^{-5} 2.1×10^{-5} 1.7×10^{-5}	-- 4 3.5	750 158 20	50 min 60 min 95 min	
General Electric No. 1	Impervious	$< 10^{-9*}$	120	754	140 hrs	
Hawker Siddeley No. 4	Impregnated	$< 8 \times 10^{-9}$	--	768	120 min	7.4×10^{-6}
National Carbon CEY	Low Permeability	4×10^{-6}	--	744	90 min	6×10^{-6} Eatherly et. al.
Raytheon	Pyrolytic Carbon	$< 5 \times 10^{-10*}$	--	759	80 min	

* The measured pressure rise was equal to the previously determined outgassing rate.
It was assumed that a permeation rate 15% of the outgassing rate would be detectable.

Table 4

Approximate Neutron Characteristics^(a)

Grade	$\Delta ih^{(b)}$ (in hours)	σ (kT) (millibarns)	Approx. B-Content (ppm)	Approx. Ash Level (%)
CS	-0.85	5.07	2	1.2
AGOT	0.25	4.28	0.4	0.07
GBF	1.00	3.73	< 0.2	< 0.01
"Pure" Carbon	1.7	3.5	0	0

- (a) These absorption cross-sections include the neutron absorption by air in the pores and by surface absorbed gases.
- (b) Δih , which comes from Hanford tests in an actual reactor, has become a common means of expressing graphite neutron capture cross-section. It represents the difference in time-constant of a reactor containing test graphite from one containing standard graphite (AGOT-CS) and has the units of (hours)⁻¹, called inhours. It is directly correlated with the total thermal neutron capture cross-section. See Report, HW-43547 (1956) for a full description and definition.

Table 5

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Room Temperature Properties

	CS-312		GBF		AGOT		CEQ
	Ave.	Std. Dev.	Ave.	Std. Dev.	Ave.	Std. Dev.	Characteristics
Density (g/cc)	1.72	0.028	1.71	0.02	1.70	0.02	~ 1.63
Specific Resistance ($\mu\Omega$ -cm)							
with grain	860	75	932	134	734	59	~ 4830
against grain	1100	130	1190	41	940	111	
Flexural Strength (lbs/in ²)							
with grain	2400	506					~ 4000
against grain	1970	509					
Tensile Strength (lbs/in ²)							
with grain	1440	254					---
against grain	1260	308					
Compressive Strength (lbs/in ²)							
with grain	5990	638					---
against grain	5960	918					
Young's Modulus (10 ⁶ lbs/in ²)							
with grain	1.49	0.142					~ 1.25
against grain	1.11	0.091					
Thermal Expansion Coefficient (10 ⁻⁶ °K ⁻¹)							
with grain	2.22	0.386					~ 3.7
against grain	3.77	0.416					
Δ ih	~-0.85	--	0.96	0.076	0.255	0.075	~ 0.05
Total Ash (wt. %)	0.090	0.034	<0.01	--	0.074	0.013	--
Boron (wt. %)	0.00012	0.00005	0.00002	-	0.00004	0.00002	--
Permeability (Darcys)							
with grain	0.115						--
against grain	0.098						-- 9 020

Strengths, Young's Modulus, and Thermal Expansion for grades AGOT and GBF will be approximately the same as CS-312.

Table 6
Characteristic Room Temperature Properties

	CS-312	GBF	AGOT	CEQ
Hall Constant (emu)				
with grain	-0.5	--	-0.65	-0.01
Thermoelectric Power ($\mu\text{V}/^\circ\text{K}$)				
with grain	--	--	-0.6	9.0
against grain	--	--	-0.2	
Thermal Conductivity (watts/ $^\circ\text{K}$ -cm)				
with grain	1.20	1.30	2.27	0.23
against grain	1.08	0.86	1.38	
Magnetic Susceptibility ($\text{cm}^{-3} \times 10^6$)				
with grain	--	--	4.23	7.18
against grain	--	--	8.41	