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HIGH TEMPERATURE RADIATION DAMAGE TO GRAPHITE

Part I.

PREPARATION OF GRAPHITES FOR IRRADIATION

J. T. MEERS

J. F. DOAR

APRIL 15, 1964

HANFORD LABORATORIES

HANFORD ATOMIC PRODUCTS OPERATION
RICHLAND, WASHINGTON

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FOREWORD

This report summarizes the work on sample fabrication and pre-irradiation evaluation of graphites submitted to Hanford Atomic Products Operations for high temperature irradiation testing. Part I covers the period from April 1, 1960, to June 30, 1962, and represents the fabrication and preliminary evaluation of the materials selected for irradiation.

The work described herein was supported by the United States Atomic Energy Commission under Contract No. AT-(45-1)-1603.

ABSTRACT

The graphites selected and prepared for irradiation tests are described and the method of sample preparation is discussed. All preirradiation test data are tabulated by sample set. This includes purity, electrical and thermal conductivity, coefficient of thermal expansion, lattice spacings, density, and the sonic moduli.

TABLE OF CONTENTS

	<u>Page</u>
I. SUMMARY	1
II. INTRODUCTION	3
III. OBJECTIVE	6
IV. SELECTION OF SAMPLE MATERIAL.	7
V. DESCRIPTION OF CARBONS AND GRAPHITES SELECTED FOR IRRADIATION.	8
A. Single Crystals	8
B. Madagascar Flakes	9
C. Canadian Natural Graphite	9
D. Monolithic Continental Coke.	9
E. Carbon Black Series	10
F. Hot Worked Graphite (ZT 4130, Z, and ZT Samples).	10
G. Anthracite Base Material.	11
H. Controlled Orientation Series	11
I. Conventionally Processed Graphite	12
J. Controlled Density Series.	12
K. Superfine Series	13
L. Laboratory Impregnation Series	13
M. Synthetic Coke-Pitch Series.	15
N. Impregnation-Binder Series.	15
O. R. Series-Isotropic Graphite	16
P. Calcine-Binder Series	16
Q. Special Samples	18
1. In Pile Creep	18
2. In Pile Creep Apparatus	18
3. Miscellaneous Samples	18

Table of Contents (Cont'd)

	<u>Page</u>
VI. PREPARATION OF SAMPLES	19
A. Identification of Samples	19
B. Orientation	19
C. Sample Inspection	21
D. Purification and Annealing	21
VII. PREIRRADIATION MEASUREMENTS	22
A. Purity	22
B. Linear Coefficient of Expansion	24
C. X-ray Measurements	24
D. Diamagnetic Susceptibility	25
E. Dimensional Measurements	27
F. Electrical Resistivity	27
G. Room Temperature Thermal Conductivity	27
H. Sonic Moduli	28
I. Dislocations in Graphite	28
VIII. DATA TABULATION	30
IX. ACKNOWLEDGMENTS	31
X. REFERENCES	32
XI. APPENDIX "A"	33

FIGURE CAPTIONS

		<u>Page</u>
Figure 1.	Typical Graphite Single Crystals.	8
Figure 2.	Preferred Orientation of Formed Graphite	20
Figure 3.	Dislocations in Unirradiated Graphite	29

TABLE CAPTIONS

		<u>Page</u>
Table I.	Dimensional Stability of AGOT and GBF Graphites . . .	5
Table II.	Binder and Impregnant Carbon Contents of Laboratory Impregnation Series	14
Table III.	Impregnation Binder Series	16
Table IV.	Description of Calcine-Binder Series.	17
Table V.	Graphite Springs for In Pile Creep Tests	18
Table VI.	Impurities Contained in Irradiation Samples.	23
Table VII.	Analysis of 1400°C Carbon Black Stock.	23
Table VIII.	Lattice Constants of Test Graphites	25
Table IX.	Total Mass Susceptibility of Graphite.	27
Table X.	Continental Coke Series.	33
Table XI.	1400°C Lampblack Series.	33
Table XII.	3000°C Lampblack	34
Table XIII.	3500°C Lampblack (With Grain)	35
Table XIV.	ZTA Series (Across Grain)	36
Table XV.	ZTA Series (With Grain)	36
Table XVI.	ZT-4130 Series	37
Table XVII.	Anthracite Series (With Grain).	37
Table XVIII.	Controlled Orientation Series, T/L Ratio = 0.78. . . .	38
Table XIX.	Controlled Orientation Series, T/L Ratio = 2.39. . . .	39

Table Captions (Cont'd)

	<u>Page</u>
Table XX. Controlled Orientation Series, T/L Ratio = 6.18 . . .	40
Table XXI. Conventional Graphite Series, Particle Size $\leq 0.016''$.	41
Table XXII. Conventional Graphite Series, Particle Size $\leq 0.035''$.	42
Table XXIII. Conventional Graphite Series, Particle Size $\leq 0.055''$.	43
Table XXIV. Controlled Density Series, B.D. ~ 1.87 g/cc.	44
Table XXV. Controlled Density Series, B.D. ~ 1.97 g/cc.	45
Table XXVI. Controlled Density Series, B.D. ~ 2.05 g/cc.	46
Table XXVII. Controlled Density Series, B.D. ~ 2.10 g/cc.	47
Table XXVIII. High Temperature Controlled Density, B.D. ~ 2.10 g/cc	48
Table XXIX. Superfine Series (With Grain).	49
Table XXX. Laboratory Impregnation Series, Particle Size $\leq 0.016''$	50
Table XXXI. Laboratory Impregnation Series, Particle Size $\leq 0.035''$	51
Table XXXII. Laboratory Impregnation Series, Particle Size $\leq 0.055''$	52
Table XXXIII. Synthetic Coke-Pitch Series (With Grain)	53
Table XXXIV. Impregnation-Binder Series, 11.8 w/o Impregnant Carbon	54
Table XXXV. Impregnation-Binder Series, 9.9 w/o Impregnant Carbon	55
Table XXXVI. Impregnation-Binder Series, ~ 14.5 w/o Impregnant Carbon	56
Table XXXVII. Impregnation-Binder Series, ~ 11 w/o Impregnant Carbon	57
Table XXXVIII. R Series, Across Grain Samples	58
Table XXXIX. R Series, With Grain "A" Samples	59
Table XL. R Series, With Grain "B" Samples	60
Table XLI. Calcine-Binder Series, Across Grain.	61
Table XLII. Calcine-Binder Series, Averages.	61

High Temperature Radiation Damage to Graphite

PART I.

Preparation of Graphites for Irradiation

USAEC Contract No. AT-(45-1)-1603
Summary Report

I. SUMMARY

Neutron bombardment of graphite is known to produce marked changes in the physical and mechanical properties of graphite. The most serious of these effects are the changes in dimension. The dimensional changes which have been noted in graphite are related to the temperature of the graphite when exposed to the neutron flux; at low temperatures ($\leq 250^{\circ}\text{C}$), graphite exhibits a volumetric growth; at higher temperatures ($>300^{\circ}\text{C}$) graphite contracts in volume.

In order to obtain an increased understanding of the damage mechanisms, a series of special graphites, having a wider range of properties than is normally found in moderator graphite, have been fabricated for an irradiation test program. When possible, graphites were selected which would exaggerate a particular parameter.

The parameters selected for observation were those that could be controlled by manufacturing techniques and selection of raw materials. These parameters, which formed an interdependent set, included: anisotropy of the formed piece, crystallite size and perfection, residual strain, binder type and content, heat treatment temperature, filler particle size, filler particle type, and density.

For irradiation tests, sixteen sample sets of the following general types were prepared for irradiation:

- (1) Single crystals and Madagascar flake graphite
- (2) Monolithic coke
- (3) Conventional graphite of several filler sizes
- (4) Hot worked graphite
- (5) Controlled density and controlled anisotropy graphite

- (6) Carbon black base graphite
- (7) Graphites containing either nongraphitizing impregnants or graphitizing impregnants
- (8) Isotropic graphite
- (9) Special types containing one of these fillers: anthracite, micronized Ceylon flake, and laboratory prepared coke.

Samples from each type were machined to ~ 0.426 " diameter and 4.00" length and given a combined chlorine gas purification and anneal at 3000°C to remove impurities, which can be activated by the neutrons, and to relieve residual strains incurred in previous processing.

The preirradiation evaluation consisted of measurements of density, thermal and electrical conductivity, and the sonic moduli of each sample. The coefficient of thermal expansion was measured and used where appropriate as the index of anisotropy of each sample set. The measurements of lattice constants and dislocation density were made on selected Madagascar flakes. Diamagnetic susceptibility was measured on cubes of carbon black, hot worked, and single crystal graphite.

A number of post-irradiation measurements have been made but these will be reported in Part II of the Summary Report.

II. INTRODUCTION

The effectiveness of graphite as a moderator for fast neutrons was first demonstrated in 1942 with the construction and operation of the world's first self-sustaining nuclear reactor, CP-1. Almost simultaneously, Wigner⁽¹⁾ suggested that fast neutrons would have a deleterious effect, both physically and mechanically, upon the graphite; however, the seriousness of these effects was unknown. As experience was gained from reactor operation, the cumulative changes caused by neutron bombardment of the moderator graphite soon became known as the Wigner effect. Today, with many graphite moderated reactors operating at temperatures as high as several hundred degrees centigrade, neutron bombardment is known to produce marked changes in the physical and mechanical properties of graphite. The most serious of these effects is the change in dimension.

The graphites which have been used extensively during the past 20 years have, at low reactor temperature, exhibited a volumetric growth. The preferred c-direction expands and the a-direction contracts, the net change in volume being positive. These dimensional changes are caused by the interstitial accumulation of knock-on carbon atoms within the crystallites. This mechanism accounts for the gross features of the damage, but work has continued on the details so that, at the present time, the problem has been resolved in a more quantitative way. Much of the damage incurred at low temperatures can be removed by annealing at temperatures of 250-300°C.

Neutron damage to graphite at higher temperatures, >300°C, results in either a small expansion or, in most cases, a small contraction along the preferred c-direction accompanied by a larger shrinkage in the preferred a-direction, the net result being a volumetric decrease. In contrast to the annealability of low temperature damage, high temperature damage is not so susceptible to annealing; only a fraction of the total dimensional changes is recoverable.

During the past decade, emphasis has been placed upon power generating reactors; hence, new reactors are being designed to operate at temperatures as high as the present material's technology will permit. Therefore, the behavior of graphite when exposed at high temperatures to high neutron fluxes has been of primary concern to reactor designers.

At the inception of the cooperative program between Hanford and Carbon Products Division of Union Carbide Corporation (formerly National Carbon Company), emphasis had been placed only upon defining the problem, and only qualitative explanations of possible mechanisms had been advanced.

Because shrinkage occurs at temperatures at which annealing of interstitial atoms proceeds simultaneously with irradiation, it was believed that a new set of mechanisms was operative. Furthermore, because the shrinkage per unit neutron dose was much smaller at high temperatures than the expansion at lower temperatures, larger neutron doses were required to clearly define all aspects of the problem.

A number of experiments had been completed which were to serve as a basis for further work in this area. Four observations which helped guide the initial planning were:

- (1) Early work at North American Aviation⁽²⁾ demonstrated that lampblack base graphites shrunk in volume when irradiated at a temperature of 30°C.
- (2) For a given formed graphite (raw materials and forming conditions constant), the shrinkage is inversely proportional to the heat treating temperature.⁽³⁾
- (3) Those graphites which were made from the most anisotropic and crystalline cokes expanded the most when exposed at low temperature to a neutron flux, whereas graphites made from more isotropic cokes were the most stable at these temperatures.
- (4) The dimensional stability of the graphites described in the preceding paragraph reversed when these graphites were exposed at high temperatures to neutron bombardment.

An illustration of the reversal of stability of anisotropic and less anisotropic graphites is given in Table I. The principal difference between these graphites is that the AGOT-KC was made from Kendall coke, a highly crystalline anisotropic coke, whereas CS-GBF was made from a less anisotropic coke.

TABLE I

Dimensional Stability of AGOT and GBF Graphites⁽⁴⁾

	Irradiation Exposure (MWD/AT)	Irradiation Temperature (°C)	Length of Change		Volume Change (%)	C _o Change (%)
			$\perp$ (%)	$\parallel$ (%)		
AGOT-KC	5 x 10 ³	450	+0.0062	-0.6	-0.11	+1
	5 x 10 ³	30	+5.3	-1.50	+9.0	+15
CS-GBF	5 x 10 ³	450	-0.03	-0.08	-0.2	+1
	5 x 10 ³	30	+3.0	-0.8	+5.5	+15

III. OBJECTIVE

The objective of this program was set forth in an initial proposal to the Hanford Atomic Products Operation, General Electric Company, Richland, Washington, dated May 28, 1959.⁽⁵⁾ It is repeated here for convenience.

"The objective of this program outlined in the following paragraphs will be the production of a graphite dimensionally stable under high temperature neutron irradiation. It is believed that this end can be served best [by an] (a) elucidation of the damage mechanisms [through] a research program; and [by] (b) implementing a parallel development program utilizing the efforts of (a) specifically aimed at the fabrication of a dimensionally stable graphite in production quantities. "

This ambitious objective has been met only in part; but as the irradiation of the several sample sets proceed, many of the perplexing aspects of irradiation damage will have been defined and this knowledge will be of great value in the selection of the best available graphites for reactor application.

IV. SELECTION OF SAMPLE MATERIAL

High temperature irradiation data were meager when materials were selected, but, as outlined in the Introduction, several important observations had been made which have been used as guides in the selection of samples for surveying the effect of neutrons upon graphite at high temperatures.

The irradiation program was designed to include samples which introduced a wider range of graphite properties than were available in the graphites normally used as moderator material. In fact, where possible, graphites were selected which would exaggerate a particular parameter, thus permitting a clearer correlation of that parameter with irradiation damage. As a result, the principal effort has been to irradiate graphites of types which were not normally used in reactors. For purposes of control, samples of AGOT were included as one of the irradiation sets. With the exception of three sample sets prepared in the laboratory, all other graphites were prepared in quantity so that neither the number of samples nor the type of measurement would be limited by size. At the beginning of the program, it was decided to use only Continental coke as a filler for all samples made with coke. As the program progressed, other fillers were substituted in special sample sets.

The parameters selected for observation were those that could be controlled by manufacturing process, forming techniques, and selection of raw materials. These parameters which formed an interdependent set included: anisotropy of the formed piece, crystallite size and perfection, low residual strain, binder type, heat treatment temperature, filler particle size, filler particle type, and density.

In addition to formed graphites, single crystals, Madagascar natural graphite (both whole flakes and micronized flakes which were either annealed or unannealed), pieces of lump coke, and natural graphite were included. It was expected that the measurements made upon these samples would be limited to X-ray analysis, susceptibility measurements, and electron microscope observations.

V. DESCRIPTION OF CARBONS AND GRAPHITES SELECTED FOR IRRADIATION

A. Single Crystals

Eight single crystals were selected for irradiation, four of which were obtained from Essex County, New York, marble and four precipitated from a molten iron melt containing an excess of carbon. Impurities were removed by a double fluorine treatment of 3000°C . These crystals were of high quality, although some twin lines were visible on the surface of the natural crystals. The double purification was used because these samples were intended for susceptibility measurements, and the presence of any magnetic materials was highly undesirable. Shown below are photomacrographs of typical graphite single crystals.

(50 X Linear)

N-4007

(50 X Linear)

N-4011

Figure 1. Typical Graphite Single Crystals

B. Madagascar Flakes

Three kinds of Madagascar graphite were selected for irradiation: whole flakes, micronized flakes, and micronized annealed flakes. These flakes were used for X-ray measurements and electron microscope observation. The unannealed micronized flakes were selected to provide a source of rhombohedral graphite.

C. Canadian Natural Graphite

Several lumps of Canadian natural graphite were cut into 0.050 inch cubes for susceptibility measurements. In addition, pieces $\frac{1}{8} \times \frac{1}{8} \times 1$ " long were cut for electrical resistivity measurements. Unfortunately, both prior to and after irradiation, these samples were so fragile that handling became a severe problem. Only the susceptibility cubes were retained for extended irradiations.

D. Monolithic Continental Coke

A large lump (approximately one-half cubic foot) of green Continental coke was selected as the parent stock for samples. The lump was examined after having been sawed on three sides, but it was not possible to identify any extensive area having a particular orientation. Samples were cut from each exposed face and calcined to 1000°C, but differential shrinkage caused cracking and severe curvature in several pieces. Fifteen samples survived a 3000°C heat treatment in a relatively uniform crack-free condition. After resurfacing to rectangular prisms, the samples were weighed and the bulk dimensions were recorded. It was recognized that precise measurement of the small dimensional changes induced by irradiation would be very difficult because gross pores intercepted all surfaces. However, the samples did appear to be sufficiently sound to permit at least preliminary evaluation by irradiation.

This same procedure was used to prepare samples from lump coke which was of poor quality, i. e., coke which upon graphitization produced a less crystalline graphite. Unfortunately, the gross structure was such that all the calcined samples warped and cracked to a degree necessitating the abandonment of this series of samples.

E. Carbon Black Series

Samples were prepared by molding a mix containing pitch and carbon black in proportions which yielded ~ 50 per cent binder coke and 50 per cent carbon black in the finished product. X-ray analysis of this material showed that the pitch coke had assumed the character of the carbon black after graphitization at 3000°C. It was also highly turbostratic, and the average crystallite size in the mass was of the order of 150 Å, which is the same value as obtained from 3000°C graphitized carbon black which has no added binder. Part of the lampblack stock was baked to only 1400°C, at which time the average crystallite size was of the order of 90 Å. A third set of samples was baked to ~ 3550°C, the temperature being in doubt by $\pm 50^\circ\text{C}$.

The total thermal history of the samples baked to ~3550°C was as follows: after graphitization to 3000°C, the carbon black stock was cooled to room temperature in ~ 36 hours. At this time, samples were prepared and a part of the sample lot was packed into a graphite susceptor and inductively heated in argon to 3200°C, the maximum temperature attained in that attempt; the total lapsed time at temperature above 3000°C was 70 minutes. The samples were then reheated, during which period the rate of rise was 11°C/min from 2800°C to 3250°C; at the latter temperature, carbon vapor began to obscure the internal sight tube. Fortunately, the susceptor could be observed independently, and since its surface continued to rise in temperature, heating was continued for an additional 30 minutes. The final internal temperature was approximately determined by extrapolating the temperature time curve of the sample zone yielding a final temperature of 3550°C $\pm 50^\circ\text{C}$. At this temperature, the vapor pressure of carbon is approaching one atmosphere, and there is the possibility that vacancies created by evaporating carbon were quenched into the crystal structure when the power was terminated. This anneal caused a shrinkage which increased the bulk density from 1.61 g/cm³ to 1.65 g/cm³. Whether this shrinkage introduced a relatively large amount of strain into the lattice was not determined.

F. Hot Worked Graphite (ZT 4130, Z, and ZT Samples)

ZT graphite, with its remarkable anisotropy and crystallinity, had just become available in experimental quantities when sample preparation began; thus, inclusion of ZT graphite permitted immediate irradiation of a type which

had been contemplated but had not been processed. Ultimately, this series was to fit quite naturally into the sequence of the controlled density series described in a later section. The ZT types were prepared by hot working a fine grain graphite at high temperature. Specifically, the graphite was heated to 2400°C, at which point hydraulic pressure was applied. The body was heated to ~3000°C and the hydraulic pressure uniformly increased at a rate to match the creep rate of the graphite billet. A more complete description of this type of material has been given both by Neel, et al., ⁽⁶⁾ and by Rowe and Carter. ⁽⁷⁾

Hot working produces a volume reduction (increase in density) and a marked increase in the anisotropy of the finished graphite. Although the original starting material contained about 36 per cent binder coke, its identity was lost during the hot working. The pore structure has been altered so that the void volume of the samples is contained by pores of 0.2 micron diameter or less. The role of the binder has been minimized, and the irradiation effects upon the graphite crystallites should be enhanced. At the same time, the samples have retained the polycrystalline character of the coke together with a large portion of its microporosity.

G. Anthracite Base Material

At Hanford's request, a set of rods were extruded from a mix of de-ashed graphitized anthracite flour and 28 pph 30 medium pitch binder. The filler flour contained a maximum particle size of 0.015 inch. After extrusion, the rods were graphitized at 3000°C for one hour. As judged by the X-ray pattern, these rods were highly graphitic, having a c_0 spacing of 3.35 Å; however, based on other physical properties, the material was inferior to coke base materials.

H. Controlled Orientation Series

These samples were made by either molding, extruding, or a combination of both. The green mix was made from Continental coke flour having a maximum particle size of 0.016 inch and 30 medium pitch as binder. The mix was extruded as 5 1/8" diameter rounds and cut into short lengths. Several of these extrusions were graphitized as formed, and the remaining green stock was reformed by molding with the force applied parallel to the extrusion axis. The molding pressure was adjusted to yield a series of plugs with a graded

reversal of the orientation which had resulted from the extrusion. A final set of plugs were molded as $6 \frac{1}{8}$ " diameter rounds directly from the green mix. The stock was then graphitized at 3000°C ; the quantity of binder carbon was determined to be 16 per cent of the total carbon present. The anisotropies were determined by the ratio of the transverse-to-longitudinal coefficient of thermal expansion which ranged from 7.3 (extruded) to 0.7 (molded). Although some nearly isotropic graphites were formed in this manner, the low expansion characteristics of Continental coke dominated the volume expansion which remained low.

I. Conventionally Processed Graphite

Three lots of graphite were extruded with a $4 \frac{1}{2} \times 4 \frac{1}{2}$ " square cross section from a mix of Continental coke filler and 30 medium pitch binder. The maximum filler particle size was 0.015 inch for the first lot, 0.030 inch, and 0.060 inch for the other two lots, respectively. The change in filler particle size was reflected in the binder carbon content, which decreased slightly with increasing particle size (12 per cent, 11.2 per cent, and 10.5 per cent for the order given above). These bars were pitch impregnated and the impregnant carbon added by this step was 6.5 per cent, 6.8 per cent, and 1 per cent for the 0.015, 0.030, and 0.060 inch particle size lots, respectively. These graphites were representative of production type graphite and served as controls for other sample sets.

J. Controlled Density Series

A mix of Continental coke flour (maximum particle size 0.015 inch) and pitch was hot molded to form cylindrical billets of graphite 5 inches diameter and 3 to 4 inches long which contained about 12 per cent binder carbon. The densities ranged from 1.80 g/cm^3 to 2.10 g/cm^3 in steps of $\sim 0.05 \text{ g/cm}^3$; in addition, a wide variation in the anisotropy occurred. At the higher densities, the coefficient of thermal expansion parallel to the molding plane was negative for the range 30° to 100°C .

The controlled density series form a sequence of samples in which, at the lower density, the binder carbon should retain the characteristics of conventionally molded graphites; but at high density the binder carbon's identity is lost, and the crystallinity of the mass is greatly enhanced. The high density

samples of this series provide even higher anisotropy than the ZT type samples, being intermediate between the ZT samples and single crystals.

One of these high density pieces was reannealed at $3550^{\circ}\text{C} \pm 50^{\circ}\text{C}$ in the same manner as described in the section for the carbon black samples. This graphite was used for the high temperature controlled density samples. The samples from this stock are also subject to the possibility of vacancy formation due to the high vapor pressure of carbon over graphite at this temperature. The possibility of a large accumulation of strain energy caused by the rapid cooling of the graphite from 3550°C exists, but the plasticity of graphite in this temperature range should minimize this effect.

K. Superfine Series

Ceylon flake graphite was milled to an average particle size of four microns and mixed with a nongraphitizing resin binder. Rods $\frac{3}{8}$ " diameter were extruded, cured, and graphitized at 3000°C . The bulk density of these rods was 1.81 g/cm^3 and the finished rods contained ~ 24 per cent binder carbon. Since the filler is extremely graphitic and the binder is a cross-linking carbon, the role of the binder should be accentuated in this graphite.

L. Laboratory Impregnation Series

An important part of the description of the irradiation behavior of an artificial graphite is the determination, qualitatively if not quantitatively, of the relative importance of the roles played by the binder and filler carbons. Without even considering the complications added by irradiation effects, it is exceedingly difficult to identify quantitatively the location of binder carbon within and its effects upon bulk graphite.

Investigators de Halas and Yoshikawa⁽⁸⁾ proposed a damage model in which the graphite is represented as a two phase system: a graphitic component consisting principally of the filler; and a lesser or nongraphitic component consisting of binder coke. The radiation-induced shrinkage is attributed to a pseudo ordering effect occurring in the less graphitic parts, principally the binder coke.

The samples of this series were prepared to increase the amount of less-graphitic carbon in the selected filler system so that irradiation effects

originating in the nongraphitic portions could be more easily perceived. The most convenient method by which carbon may be added to a particular filler system is by impregnating previously formed graphite with either pitch or resins and then coke the impregnant in situ. In addition to being the most practical approach, impregnation permits the evaluation of pitch cokes versus thermosetting resin cokes which are cross-linking and nongraphitizing. The latter material is of immediate interest for application in gas cooled reactors in which low permeability graphite serves both as moderator and as high temperature plumbing.

The graphite stock described in section H was used as the base graphite for this series. Three sample sets each consisting of a particular filler sizing were prepared by each of the following processes: (1) a pitch impregnation, (2) an impregnation with a thermosetting resin, and (3) a sequence of two nongraphitizing thermosetting impregnations. The average content of binder and impregnant carbon was given previously, but the total binder and impregnant carbon content is given in Table II.

TABLE II
Binder and Impregnant Carbon Contents of Laboratory
Impregnation Series

Maximum Particle Size (Inches)	Sample No.	Per Cent [*] Binder and Impregnant Carbon	Additional Treats	Per Cent Carbon Added	Total Per Cent Carbon as Binder and Impregnant
0.015	A-1 to A-10	18.5	pitch (1)	3.7	22.2
0.030	B-1 to B-10	18.0	pitch (1)	3.3	21.3
0.060	C-1 to C-10	11.0	pitch (1)	3.0	14.0
0.015	A-11 to A-20	18.5	nongraphitizing (1)	7.5	26.0
0.030	B-1 to B-20	18.0	nongraphitizing (1)	7.0	25.0
0.060	C-11 to C-20	11.0	nongraphitizing (1)	6.0	17.0
0.015	A-21 to A-30	18.5	nongraphitizing (2)	10.0	28.5
0.030	B-21 to B-30	18.0	nongraphitizing (2)	9.6	27.6
0.060	C-21 to C-30	11.0	nongraphitizing (2)	8.8	19.8

* These carbon contents were based on measurements of the bulk stock, consequently they are presented as averages for individual samples cut from this stock.

After the impregnations were performed, the samples were graphitized at 3000°C.

M. Synthetic Coke-Pitch Series

These samples were formed using an extremely anisotropic coke prepared from a commercial decant oil by Carbon Products Division Research Laboratory. The three-dimensional structure of graphite from this coke is developed to a high degree by graphitization, and relatively large crystallites are produced. This graphite represents an upper bound in anisotropy which can be attained in a conventional process.

The coke was milled to 0.006 inch maximum particle size and mixed with 30 medium pitch as binder. Because a limited amount of coke was available, the mix was extruded as $\frac{7}{8}$ inch diameter rods to provide as much "with grain" length as possible. By keeping a mass balance during the process, the binder carbon content of the 3000°C graphitized rods was found to be 20 per cent by weight.

The anisotropy of the filler coke was reflected in the negative with-grain expansion coefficient of the formed rods when measured at near room temperatures. It is unfortunate that the size limitation prevents convenient measurements of the against-grain properties. However, the effects of irradiation upon with-grain samples should serve as a connecting link between commercially available coke base graphites and pyrolytic and/or single crystals.

N. Impregnation-Binder Series

Four bars of the all-flour conventional graphite described in Section H were used as the base stock for this series. Moreover, whole bars were processed in production equipment rather than being prepared as small samples, as was the case with the laboratory impregnation series. The total binder carbon and impregnant carbon is given in Table III. These samples were prepared to enhance the amount of "less graphitic" carbon present. These samples can be compared in terms of stability with the control set as well as with other sets containing lesser amounts of either graphitizing or nongraphitizing impregnant carbon. The final heat treatment was 3000°C.

TABLE III
Impregnation Binder Series

Sample No.	Binder + One Pitch Imp. Per Cent Carbon	Type and No. of Additional Impregnations	Per Cent Impregnant Carbon	Per Cent* Total Binder and Impreg- nant Carbon
I-1-1 to I-1-37	18.5	nongraphitizing (1)	11.8	30.3
I-2-1 to I-2-38	18.5	nongraphitizing (1)	9.5	28.0
I-3-1 to I-3-28	18.5	nongraphitizing (2)	14.5	33.0
I-4-1 to I-4-28	18.5	nongraphitizing (2)	11.0	29.0
* The total binder and impregnant carbon was computed from a mass balance of the whole bars; hence, these values represent average values for the samples cut from the bars.				

O. R. Series - Isotropic Graphite

This graphite was developed under Contract AF 33(616)-6915 for application as a substrate for ceramic coatings. The process is fully described by Piper and Howard.⁽⁹⁾

The filler material consists of Gilso carbon, fluid coke, and carbon black which is combined with 175°C melting point pitch. The formed body has a thermal expansion of $5.1 - 5.2 \times 10^{-6}/^{\circ}\text{C}$ for the range 400° to 1000°C. It is known from previous experiments that the filler materials are relatively unstable to irradiation when taken individually. However, the process yields an isotropic bulk graphite which has a fair degree of crystallinity. The criteria for crystallinity presently proposed by the British investigators⁽¹⁰⁾ as a necessary quality of the filler has not been defined clearly. As a result, the classification of this material meets the British criterion of isotropy, but the crystallinity may or may not be adequate, depending upon the specific definition one applies.

P. Calcine-Binder Series

The calcine-binder series was prepared to demonstrate the effects of coke calcination temperature upon the dimensional stability of graphite when exposed to neutron irradiation.

Calcination of coke has long been employed by the carbon and graphite industry to preshrink the coke and thereby increase the processability of the green stock. This preshrinking of the filler coke, although increasing the yield of graphite, reduces the surface activity of the filler coke, thereby reducing the ability of the binder carbon to establish chemical bonds with adjacent coke particles. Hence, if both the filler coke and the binder are chemically active and shrink together, the resulting stock is a more coherent graphitic body than produced when calcined filler cokes or graphitized particles are used.

Plugs one inch in diameter and two inches long were prepared by molding several mixes of Continental coke or synthetic coke fillers with 30 medium pitch or acenaphthylene pitch binder. An outline of the several combinations of coke and binder used are given in Table IV.

TABLE IV
Description of Calcine-Binder Series

Coke	Calcine Temp. (°C)	Maximum Particle Size (inch)	Binder	Sample Code
Continental	600	.016	Conventional Pitch	6 pf
	900			9 pf
	1300			13 pf, 10 pfr, 5 pfr
Continental	600	.006	Conventional Pitch	6 pm
	900			9 pm
	1300			13 pm
Synthetic	600	.016	Acenaphthylene Pitch	6 fap
	900			9 fap
	1300			13 fap
Synthetic	600	.006	Acenaphthylene Pitch	6 map
	900			9 map
	1300			13 map

The last digit in the sample number indicates the block from which it was cut and the Xs are merely to distinguish between the two samples cut from the same block. The samples labeled 10 pfr and 5 pfr differ from those labeled 13 pf only in that the molding pressure was reduced by one-third and two-thirds

from the 15,000 psi used for the remainder of the samples. All samples were cut across grain. The synthetic coke is the same as that used in the synthetic coke-pitch series.

Q. Special Samples

1. In Pile Creep

At Hanford's request, a number of samples in the form of springs $\frac{3}{4}$ inch diameter x $\frac{3}{4}$ inch long were cut from ZTA graphite, TSX (New Production Reactor core graphite) and from AGOT produced for the Experimental Gas Cooled Reactor. Under the time schedule required, sufficiently small grinding wheels could not be procured and the springs were machined with conventional tools on a lathe. As a result, considerable chipping occurred at the edges of the lands. The quantities and pertinent dimensions of the springs are given in Table V.

TABLE V

Graphite Springs for In-Pile Creep Tests

Grade	No. of Pieces	Length (inches)	Diameter (inches)	Lands (inches)
AGOT	8	0.75	0.75	0.125 x 0.178
TSX	10	0.75	0.75	0.125 x 0.178
ZTA (FE 1714)	8	0.75	0.75	0.125 x 0.178

2. In Pile Creep Apparatus

Thirty-six carbon black blocks, 3.75" x 5.25" x 6.25", baked to 1400°C were supplied for in-pile creep test apparatus.

3. Miscellaneous Samples

- (a) 20 pcs ZTA graphite 0.75" diameter x 1.0" long
- (b) 20 pcs ZTA graphite 0.375" diameter x 1.0" long
- (c) 4 pcs of 3000°C baked carbon black 1.50" diameter x 6.0" long
- (d) 1 piece 3000°C baked carbon black 3.75" x 5.25" x 6.25" long
- (e) 1 block of EGCR graphite 6" x 6" x 10" long

VI. PREPARATION OF SAMPLES

Once a particular type of graphite is selected for irradiation, samples are prepared in a size and quantity dictated by either the type of measurement planned or the size of the facility to be used for the irradiations. Because of space limitations, most irradiation studies are conducted with samples which are small when compared with either the bulk graphite as it is produced or the finished graphite parts of the reactor. When stock size permitted, the samples submitted for irradiation under this program conformed to the Hanford standard sample, which is 0.426 inch in diameter and 4 inches long.

There are several considerations of importance in the preparation of samples for irradiation. Among these are: sample identification, i. e., type of stock and grain orientation; the mechanical effects of machining upon the sample; identification of flaws within samples and impurities which can be activated by the irradiation.

A. Identification of Samples

A method for positive identification of each sample was a necessary part of the sample preparation. The most efficient way to prevent loss of sample identification was a step-at-a-time process in which rough samples of only one orientation were cut from the stock and immediately enscribed with a code for that stock and orientation. The rough sample blanks were stored individually in properly marked bags and transported to the final machining area, where the finish machining was done either by a lathe or by a surface grinder. Again, one sample was finished and re-marked by scribing the proper code on the lateral surface of the sample before a second sample entered the process. When the sample lot was complete, batch processing, i. e., radiography and annealing, was accomplished without sample confusion.

B. Orientation

It is instructive to illustrate possible orientations occurring in artificial graphite and the nomenclature used in the carbon industry. Simplified illustrations of several orientations are given in Figure 2, and one can, in a similar way, construct other possible orientations which may be of interest.

N-5029

Figure 2. Preferred Orientation Resulting from Forming Conditions

It is evident that the anisotropy of bulk polycrystalline graphite results from both the forming conditions and the raw materials used in the process. It is also evident that sampling procedures must be developed which keep these possible orientations clearly identified. Sampling at the surface of an "as formed billet of graphite" should be considered in terms of orientation effects caused by the trowelling action of the die surface; therefore, samples cut from the surface layer of the stock may not be representative of the bulk volume.

C. Sample Inspection

All sample lots were examined by radiography to determine if there were flaws which might affect sample behavior. The X-ray examination, when cross checked by preirradiation sonic moduli measurement, formed an efficient method of nondestructive screening for sample integrity. The surviving samples were subjected to a combined gas purification and anneal for one hour at 3000°C.

D. Purification and Annealing

Purification removed much of the residual ash contained within the sample and the surface contamination which resulted from tool wear and handling. Removal of impurities greatly reduces the post-irradiation activity of the samples and permits more efficient post-irradiation handling. Once the purification was completed, all subsequent handling of the samples was done with clean, white, cotton gloves to prevent contamination.

Even if impurities had not been present, the annealing step was necessary to stabilize sample dimensions. First, it is known that a small sample of graphite excised from a larger piece will relax when annealed, and small but measureable dimensional changes will occur. Second, machining introduces mechanical stresses in graphite which can be removed by annealing. Insofar as possible, the changes due to the relaxation of stresses are removed prior to irradiation. This treatment is not perfect since it is confirmed by observation that there is nearly always an initial expansion of the graphite during the first few hundred megawatt days of exposure at temperatures. Neutron-induced relaxation of residual stresses are probably the cause of this small but consistent expansion.

VII. PREIRRADIATION MEASUREMENTS

The interpretation of the effects of radiation damage upon graphite frequently has been hampered by numerous factors which have not always been properly evaluated. The three factors which are most often neglected or misunderstood are the variability of the: (1) raw materials, (2) process conditions, and (3) physical properties of the different graphites which have been used in previous reactor applications.

It is now generally recognized that, although these variations cannot be eliminated, careful selection and characterization of the graphites which are intended for irradiation experiments are prime factors in the understanding of the observed effects. The physical and mechanical properties which are used to characterize the graphite should define the variability of parameters within a sample set and insofar as possible, permit correlation of pre- and post-irradiation data with the results from other sample sets made with either different raw materials or by a different process.

A. Purity

One of the first considerations in the selection of graphite for application in a nuclear reactor was the type and concentration of impurities. Neutron economy dictates that high purity graphite be used in critical areas within the reactor. Because of the low concentration, the impurities contained in moderator graphite have not been considered as an important factor associated with the mechanical problems of radiation damage in graphite. For purposes of record, however, a spectrographic analysis of all but two sample sets was made prior to irradiation. The principal impurities are given in Table VI. The elemental concentrations quoted are estimated as parts per million.

The wet analysis of the 1400°C carbon black stock is given in Table VII. By comparing the chlorine analysis of purified samples with that of the 1400°C carbon black series, one notes the effectiveness of the chlorine treatment. One can expect that the latter samples will be very radioactive after extended exposure to the neutron flux.

TABLE VI
Impurities Contained in Irradiation Samples
(ppm)

Impurity	First Run	Z T	Anthracite	Controlled Orientation Series	High Temperature Controlled Density Series	Controlled Density Series	R-Series	Standard Graphite Series	Impreg-nation Series	Super-fine Series
	A	B	C	D						
Al	2	2	2	3	-	1		2	-	-
ag	3	-	-	-	8	-			-	-
B	0	1	3	1	4	2	trace	0	1	-
Ca	1	2	1	1	-	-		0	0	-
Cu	-	0	2	-	4	2	trace	-	1	-
Fe	2	3	2	2	1	2	trace	2	1	1
Pb	-	0	-	-	-	0		-	-	-
Mg	4	6	5	6	2	3		6	2	1
Mn	1	2	1	1	-	-		-	-	-
Na	-	4	-	-	-	-		0	-	1
Si	3	2	3	3	-	6	trace	2	2	1
	-	-	-	-	-	-		5	-	-

TABLE VII
Analysis of 1400°C Carbon Black Stock

I. Spectroscopic Analysis					II. Wet Analysis	
Major	+	Minor	-	+ Trace	Ash = 0.78 % B = 10 ppm Fe = .06 % V = 5 ppm	
C	Si	←mg	Cr→	B		
		mn→	M'	Ag		
		al	V			
			Ti			
			←Cu			

B. Linear Coefficient of Expansion

Measurements of a particular physical or mechanical property in the parallel and perpendicular directions with respect to the preferred grain orientation yields a measure of the anisotropy of the formed graphite. However, the degree of orientation as determined by the ratio of the measurements made in these two directions varies with the property.

The linear coefficient of thermal expansion of graphite has been most frequently and successfully used as an anisotropy index for graphite. The extreme anisotropy of the linear thermal expansion of the single crystal is partially lost to the formed graphite by (1) disordered arrangement of the crystallites within the filler coke particles, (2) random orientation of the filler particles within the formed volume, and (3) void volume which is composed of the microporosity of the filler coke particles and the gross pores between particles. The first two factors account for the possibility of achieving isotropy in a formed body in spite of the anisotropy of the single crystal. The contained void volume when considered with the weak van de Waals' forces between planes permits one to form a satisfactory explanation of the discrepancy between the volumetric thermal expansion of artificial graphite and that of the single crystal as calculated from X-ray data.

The coefficient of thermal expansion of an artificial graphite is an average of the effect of the voids, crystallites, and amorphous regions, and hence it yields a value which is characteristic of the bulk piece. It is, therefore, possible to characterize a selected graphite stock with relatively few measurements. The thermal expansion coefficients reported in the appendix for individual sample sets are for the temperature range 30-100°C unless otherwise noted.

C. X-ray Measurements

The a_0 and the c_0 lattice constants of the graphite single crystals and Madagascar graphite, both whole flakes and micronized flakes, were measured prior to irradiation. These samples were chosen because the variation in lattice spacings from sample to sample was small; therefore, it was possible to make representative measurements from a random sampling. Thus, neutron-induced dimensional and volume changes of relatively perfect graphite can be measured

on a microscopic scale. This change in volume, which is positive, can be utilized in the analyses of macroscopic changes induced by neutron bombardment of polycrystalline graphites.

The lattice constants of the graphites were measured from Debye powder patterns obtained with a Norelco 114.6 mm diameter camera. The c_0 was determined from the 008 line using NiK α radiation and the a_0 was determined from the 510 line using CuK α radiation. For poorer graphites, CuK α radiation was used. The 006 line or, if necessary, the 004 line was used for c_0 and the 110 line for a_0 . The preirradiation spacings are given in Table VIII.

TABLE VIII
Lattice Constants of Test Graphites

Sample	Exposure	Lattice Spacing (Å)	
		a_0	c_0
Micronized annealed Madagascar flakes	0	2.4599	6.7101
ZT-4130	0	2.458	6.708
Anthracite	0	2.460	6.708

The lattice spacings of coke base graphites vary within a sample as much as one per cent. In order to obtain meaningful comparative data, remeasurement of the exact sample volume must be made after each irradiation. The average spacings of sample sets, when measured, were used to yield a relative index of the crystallinity of that particular material.

D. Diamagnetic Susceptibility

The susceptibility of polycrystalline graphite provides information about the (1) relative amount of the total carbon present which is in the crystalline state, (2) anisotropy of the sample, and (3) position of the Fermi level. The total mass susceptibility of the polycrystalline graphite is compared with the best value for single crystal graphite and the deficiency in the susceptibility of the polycrystalline graphite is interpreted to result from the presence of carbon in either the amorphous state or that contained in crystallites of very small dimensions.

When the susceptibility of a graphite is used to determine the relative orientation, one measures it in mutually perpendicular directions of a sample so oriented that one component is parallel to the forming force. Thus, the ratio of any two susceptibility components yields a measure of anisotropy for those two directions which, in turn, can be related to anisotropy introduced by the forming force. In general, the susceptibility yields an anisotropy ratio for a polycrystalline graphite which is much lower than one obtains from thermal expansion measurements. This difference is caused by the extreme sensitivity of the susceptibility to the position of the Fermi level, whereas the coefficient of thermal expansion is a thermally induced mechanical change which remains quite insensitive to lattice defects and to small inter- and intramisorientations of the crystals.

If the structure is nearly perfect, as in the best single crystals, the susceptibility is a very sensitive measure of the disorder produced by neutron bombardment; but, unless the damage is held to a low level, the susceptibility saturates and, hence, does not appear to be a very promising method of following extensive damage. Susceptibility may prove to be a very useful method of following the recovery of graphite as induced by thermal annealing, particularly as an aid in interpreting the annealable versus unannealable changes in the bulk graphite.

The susceptibility was measured with a Faraday balance which had been calibrated using high purity gold and silver.⁽¹¹⁾ The effectiveness of the purification in removing ferromagnetic impurities from the graphite was checked by measuring the susceptibility as a function of field H . Under such conditions, $\chi^i m$, the mass susceptibility, includes contributions of the ferromagnetic impurities. For large magnetic fields

$$\chi^i m = \chi_m + \frac{C I}{\rho H}$$

where C is the concentration, I is the saturation magnetization of the impurities, $\chi^i m$ is the true mass susceptibility of the graphite, and ρ is the density of the sample. A Honda-Owen plot, $\chi^i m$ versus H^{-1} extrapolated to $H^{-1} = 0$, gives the true susceptibility χ_m . Magnetic impurities contained in the samples submitted for irradiation were found to be ≤ 1 ppm. The total susceptibilities of each of the several sample types are given in Table IX.

TABLE IX

Total Mass Susceptibility of Graphite

Sample	Density (g/cm ³)	χ_1	χ_2	χ_3	χ_T	Anisotropy Ratio
Carbon black	1.61	-1.09	-.703	7.02	-21.1*	~1
Canadian Natural Graphite	1.96				-20.1	>6
ZTA	2.01	-5.6	-6.2	-11.5	-23.3	~2
Z	2.01				-21.9	~2
Single Crystal**	2.26	-0.32	-0.32	-21.5	-22.1	~67

* This figure is a corrected value of the susceptibility quoted in NCC News Letter No. 3, February 1, 1961.

** D. E. Soule, private communication.

E. Dimensional Measurements

The preirradiation dimensions of all the samples were measured for density calculations. However, the sophistication of these measurements does not approach that necessary to detect the length changes caused by irradiation. Therefore, the task of precise measurement of length for computing changes induced by irradiation was relegated, by mutual agreement, to Hanford where they were made on site by Hanford personnel

F. Electrical Resistivity

The electrical resistivity of all samples was measured prior to irradiation, using the standard four probe technique with a Leeds and Northrup K-2 potentiometer as the detector. Although electrical resistivity is a simple measurement to make and provides a measure of the initial thermal conductivity of graphite, the resistivity saturates at very low neutron exposure and is not very useful in interpreting extensive damage. For the sake of completeness, the resistivity should be monitored to note possible trends with extended irradiations.

G. Room Temperature Thermal Conductivity

The thermal conductivity of all graphitized samples was computed from the electrical resistivity using the relationship⁽¹²⁾

$$K\rho = 0.00031 \quad ,$$

where ρ is in ohm-cm and K is in cal/cm sec°C. Since this particular relationship does not hold for either ungraphitized or irradiated samples, an independent measurement of the thermal conductivity must be made in these cases. For example, the 1400°C annealed carbon black samples were measured at room temperature by an absolute method in which a known quantity of heat was introduced at the free end of a sample attached to a heat sink and the resulting thermal gradient along the sample was measured. From these data and the sample dimensions one can compute the thermal conductivity.

H. Sonic Moduli

Measurement of the sonic moduli was added as a further characterization of irradiation samples when it became apparent that the electrical properties were saturating at radiation doses of $< 1000 \frac{\text{MWD}}{\text{AT}}$.

The resonant bar technique was employed in these measurements and, in each case, positive identification of the excited mode was accomplished by establishing the nodal pattern. The apparatus was standard for this type measurement except that the pickup and driving mechanisms were carefully balanced stereo cartridges.

These measurements are reproducible to less than one-half per cent, and small changes in the moduli are easily detected. The largest contributing errors to the measurement are density and orientation variations within the sample. The effects of orientation are most noticeable in ZT type samples, where the orientation is very high and small changes cause mixing of modes.

I. Dislocations in Graphite

In a program not supported under USAEC Contract No. AT (45-1)-1603, dislocations present in thin foils stripped from graphite crystals have been observed with the aid of an electron microscope.⁽¹³⁾ Certain defects are always visible; these are observed directly, and a photographic record is made of interesting areas. By direct observation, dislocations can be seen moving about the crystal under the influence of heat absorbed from the electron beam. Repeated careful observation of the same general area of a sample enables

one to distinguish between certain types of dislocations and interference effects such as Moire' fringes. In Figure 3, a sequence of three frames shows dislocation lines at different depths in the crystal. These are distinguished by the fact that although one set of line dislocations has interacted with a second set at an angle, no interaction is noted with a third set which is located in a crystallite plane below the interacting sets. These photographs illustrate the clarity with which dislocations may be observed in graphite.

N-5396

Figure 3. Dislocations in Unirradiated Graphite
(3100 X)

VIII. DATA TABULATION

With the exception of those data previously given, the results of all other preirradiation measurements of individual samples are tabulated by sample set and presented as Table X in the Appendix.

IX. ACKNOWLEDGMENTS

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D. E. Soule, G. N. Wrights, and R. Sprague.

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XI. APPENDIX "A"

TABULATION OF PREIRRADIATION MEASUREMENTS

TABLE X

Continental Coke Series

Sample	Nominal Length (inch)	Cross Section (inch ²)	Weight (g)	B. D. (g/cc)
1	3.38		25.2609	
2	3.06		21.8041	
3	2.86		20.1199	
4	2.45	0.356	15.0347	1.05
5	2.21	0.356	13.5324	1.05
6	1.96	0.356	11.4176	1.00
7	1.86	0.356	11.4013	1.05
8	1.71	0.356	9.8486	.99
9	1.69	0.356	9.8954	1.00
10	1.69	0.356	9.3878	.95
11	1.67	0.356	10.2499	1.05
12	1.47	0.356	8.6138	1.00
13	1.44	0.356	8.5722	1.02
14	1.42	0.356	8.4482	1.01
15	1.31	0.356	7.5562	1.02
			Average:	1.02

TABLE XI

1400°C Lampblack Series

With Grain			Across Grain		
Sample	Weight (g)	B. D. (g/cc)	Sample	Weight (g)	B. D. (g/cc)
CL-1	14.4500	1.546	AC-1	9.8910	1.565
CL-2	14.4240	1.545	AC-2	9.9120	1.566
CL-3	14.3840	1.539	AC-3	9.8160	1.550
CL-4	14.4802	1.549	AC-4	9.9154	1.566
CL-5	14.5826	1.558	AC-5	9.8973	1.563
CL-6	14.6085	1.562	AC-6	9.8418	1.553
CL-7	14.4250	1.545	AC-7	9.8478	1.553
CL-8	14.4130	1.543	AC-8	9.9120	1.566
CL-9	14.4765	1.548	AC-9	9.8906	1.562
CL-10	14.4764	1.548	AC-10	9.9050	1.565
CL-11	14.5761	1.548	AC-11	9.9050	1.565
CL-12	14.4622	1.566	AC-12	9.8043	1.550
CL-13	14.4734	1.548	AC-13	9.8990	1.562
CL-14	14.5847	1.558	AC-14	9.8685	1.560
CL-15	14.3970	1.540	AC-15	9.9070	1.565
CL-16	14.5904	1.561	AC-16	9.7816	1.546
Average		1.550	Average		1.560

Length= 4.004"

Diameter=0.425"

 $\bar{\rho}_0 = 61.1 \times 10^{-4} \text{ g/cm}$ $\bar{K}_0 = 0.0507 \text{ Cal/sec cm deg}$ $\bar{E}_0 = 1.84 \times 10^6 \text{ LBS/in}^2$

Length= 2.720"

Diameter= 0.425"

 $\bar{\rho}_0 = 63.3 \times 10^{-4} \text{ g/cm}$ $\bar{K}_0 = 0.0490 \text{ Cal/sec cm deg}$ $\bar{E}_0 = 1.91 \times 10^6 \text{ LBS/in}^2$

TABLE XII
3000°C Lampblack

Sample	Orientation	Length (in.)	Weight (g)	B. D. (g/cc)	P_0 (10^{-4} cm)	K_0 (cal/sec.cm.deg)
LB-1	With	3.92	15.0836	1.640	44.0	0.0705
LB-2	With	3.89	14.7231	1.610	42.8	0.0725
LB-3	With	3.91	14.5435	1.585	44.8	0.0692
LB-4	With	3.89	14.6813	1.605	43.4	0.0714
LB-5	With	3.87	14.7923	1.625	43.2	0.0718
LB-6	With	3.90	14.8348	1.618	43.2	0.0718
LB-7	With	3.92	14.8275	1.610	43.6	0.0711
LB-8	With	3.89	14.5777	1.590	43.2	0.0718
LB-9	With	3.92	14.9152	1.620	42.7	0.0726
LB-10	With	3.78	14.2700	1.610	42.8	0.0725
L-1	With	2.00	7.5360	1.595	44.0	0.0705
L-2	Across	2.00	7.5559	1.600	48.4	0.0641
L-3	Across	2.00	7.5618	1.610	48.1	0.0644
L-4	With	2.00	7.5015	1.590	43.9	0.0706
L-5	Across	2.01	7.5311	1.590	50.8	0.0610
L-6	With	2.01	7.5606	1.600	45.7	0.0678
L-7	With	2.21	8.2620	1.590	45.0	0.0689
L-8	Across	2.01	7.5560	1.600	48.2	0.0643
Average: With Grain				1.606	43.7	0.0709
Across Grain				1.600	48.9	0.0634

Diameter of all samples = 0.427"

$\bar{E}_0 = 1.22 \times 10^6$ lbs/in² with grain; 1.02×10^6 lbs/in² across grain

$\bar{G}_0 = 0.486 \times 10^6$ lbs/in² with grain; 0.464×10^6 lbs/in² across grain

TABLE XIII
3500°C Lampblack (With Grain)

Sample	Diameter (in.)	Weight (g)	B.D. (g/cc)	ρ_0 ($10^{-4} \Omega \text{cm}$)	K_0 (cal/sec.cm.deg)	E_F (10^6lbs/in^2)	E_L (10^6lbs/in^2)	G (10^6lbs/in^2)
LHT-1	0.422	14.7610	1.648	48.5	0.0639	1.24	1.24	0.488
LHT-2	0.422	14.7530	1.651	47.5	0.0652	1.27	1.27	0.486
LHT-3	0.422	14.7155	1.644	47.2	0.0657	1.28	1.29	0.500
LHT-4	0.423	14.7835	1.648	47.4	0.0654	1.28	1.29	0.499
LHT-5	0.422	14.7225	1.643	48.1	0.0644	1.24	1.25	0.486
LHT-6	0.423	14.7520	1.643	48.2	0.0643	1.23	1.24	0.483
LHT-7	0.422	14.7280	1.644	48.5	0.0639	1.22	1.24	0.483
LHT-8	0.422	14.7366	1.645	47.6	0.0651	1.28	1.28	0.498
LHT-9	0.422	14.6750	1.644	47.8	0.0648	1.25	1.27	0.491
LHT-10	0.423	14.7410	1.652	48.8	0.0635	1.22	1.24	0.480
LHT-11	0.422	14.7892	1.651	47.0	0.0660	1.28	1.29	0.533
LHT-12	0.423	14.7860	1.647	48.7	0.0637	1.22	1.24	0.519
LHT-13	0.422	14.6660	1.640	48.3	0.0642	1.22	1.24	0.483
LHT-14	0.422	14.9352	1.667	45.8	0.0677	1.31	1.33	0.552
LHT-15	0.422	14.7620	1.649	48.6	0.0638	1.24	1.26	0.486
LHT-16	0.422	14.7600	1.647	48.1	0.0644	1.27	1.27	0.492
LHT-17	0.422	14.7368	1.645	48.4	0.0640	1.29	1.31	0.498
LHT-18	0.422	14.8404	1.656	47.5	0.0652	1.34	1.32	0.518
LHT-19	0.423	14.8065	1.649	47.8	0.0648	1.29	1.29	0.505
LHT-20	0.423	14.8060	1.649	47.2	0.0657	1.29	1.29	0.505
LHT-21	0.423	14.9030	1.637	47.0	0.0660	1.32	1.32	0.517
LHT-22	0.422	14.7448	1.646	47.5	0.0652	1.29	1.26	0.493
LHT-23	0.423	14.8533	1.655	46.4	0.0668	1.32	1.30	0.515
LHT-24	0.422	14.7470	1.646	48.7	0.0637	1.29	1.26	0.493
LHT-25	0.422	14.7487	1.646	47.5	0.0652	1.29	1.29	0.503
LHT-26	0.422	14.7354	1.648	46.9	0.0661	1.30	1.30	0.513
LHT-27	0.423	14.8290	1.649	46.7	0.0664	1.31	1.31	0.516
LHT-28	0.422	14.7133	1.642	49.1	0.0631	1.24	1.24	0.485
LHT-29	0.422	14.7170	1.643	48.8	0.0635	1.28	1.25	0.494
LHT-30	0.423	14.7075	1.638	46.7	0.0664	1.29	1.29	0.503
		Average	1.647	47.7	0.0650	1.27	1.28	0.501

All samples 4.00" long.

TABLE XIV
ZTA Series (Across Grain)

Sample	Cross Section (in x in)	Weight (g)	B. D. (g/cc)	ρ_0 ($10^{-4} \Omega \text{cm}$)	K_0 (cal/sec.cm.deg)
Z-1	0.163x0.163	3.3715	1.940	15.5	0.200
Z-2	0.148x0.148	2.7804	1.943	15.1	0.205
Z-3	0.163x0.163	3.3696	1.945	15.4	0.202
Z-4	0.163x0.163	3.3696	1.944	15.8	0.196
Z-5	0.163x0.163	3.3888	1.960	15.0	0.206
Z-6	0.148x0.148	2.7874	1.950	15.6	0.199
Z-7	0.128x0.128	2.0864	1.960	15.3	0.202
		Average	1.949	15.4	0.201

$E_0 = 0.789 \times 10^6 \text{ lbs/in}^2$
 $G_0 = 0.579 \times 10^6 \text{ lbs/in}^2$

TABLE XV
ZTA Series (With Grain)

Sample	Diameter (in)	Length (in)	Weight (g)	B. D. (g/cc)	ρ_0 ($10^{-4} \Omega \text{cm}$)	K_0 (Cal/sec cm deg)
ZT-1	0.428	2.04	9.4438	1.955	3.57	0.868
ZT-2	0.425	2.02	9.7297	2.030	2.72	1.140
ZT-3	0.425	2.02	9.7278	2.030	2.72	1.140
ZT-4	0.427	2.02	9.2937	1.960	4.19	0.740
ZT-5	0.428	2.02	9.3986	1.975	3.42	0.906
ZT-6	0.426	2.02	9.2202	1.945	4.40	0.705
ZT-7	0.426	2.05	9.3887	1.963	4.21	0.736
ZT-8	0.426	2.01	9.5446	<u>2.035</u>	<u>3.01</u>	<u>1.030</u>
		Average:	1.987	3.53	0.878	

$E_0 = 2.83 \times 10^6 \text{ lbs/in}^2$
 $G_0 = 0.813 \times 10^6 \text{ lbs/in}^2$

TABLE XVI
ZT-4130 Series

Sample	Cross Section (in. x in.)	Length (in.)	Weight (g)	B. D. (g/cc)	ρ_0 ($10^{-4} \Omega \text{cm}$)	K_0 (cal/sec. cm. deg)
1A	0.252 x 0.251	4.17	8.4110	1.945	16.5	0.188
2A	0.251 x 0.251	4.17	8.4955	1.965	15.9	0.195
3A	0.250 x 0.250	4.17	8.4125	1.970	15.5	0.200
4A	0.251 x 0.252	4.17	8.4110	1.945	17.1	0.181
5A	0.251 x 0.250	4.17	8.3697	1.950	16.9	0.183
6A	0.252 x 0.252	1.83	3.7108	1.953	15.2	0.204
7A	0.252 x 0.252	1.83	3.7188	1.955	15.8	0.196
8A	0.252 x 0.252	1.83	3.7273	1.963	15.6	0.199
9A	0.252 x 0.252	1.83	3.7084	1.950	15.1	0.206
10A	0.252 x 0.252	1.83	3.7175	1.965	15.4	0.202
Average				1.956	15.9	0.195
1W	0.252 x 0.252	2.58	5.2048	1.935	7.69	0.403
2W	0.252 x 0.252	2.58	5.1980	1.930	7.42	0.418
3W	0.252 x 0.252	2.58	5.2162	1.940	7.96	0.389
4W	0.252 x 0.252	2.58	5.2052	1.940	7.85	0.395
5W	0.252 x 0.252	2.58	5.2070	1.940	7.99	0.388
6W	0.252 x 0.252	2.19	4.4054	1.933	8.10	0.383
7W	0.252 x 0.252	2.19	4.4133	1.935	8.11	0.382
8W	0.252 x 0.252	2.19	4.3926	1.930	7.98	0.388
9W	0.252 x 0.252	2.19	4.3951	1.932	7.54	0.411
10W	0.252 x 0.252	2.19	4.3885	1.920	7.75	0.400
Average				1.934	7.84	0.395

$\bar{E}_0 = 2.83 \times 10^6 \text{ lbs/in}^2$ with grain; $0.789 \times 10^6 \text{ lbs/in}^2$ Across grain

$\bar{G}_0 = 0.813 \times 10^6 \text{ lbs/in}^2$ with grain; $0.579 \times 10^6 \text{ lbs/in}^2$ Across grain

TABLE XVII
Anthracite Series (With Grain)

Sample	Length (in.)	Diameter (in.)	B. D. (g/cc)	ρ_0 ($10^{-4} \Omega \text{cm}$)	K_0 (cal/sec. cm. deg)
AN-1	4.002	0.426	1.38	27.0	0.115
AN-2	3.998	0.426	1.38	24.7	0.126
AN-3	4.002	0.426	1.37	22.0	0.141
AN-4	4.000	0.426	1.36	19.3	0.161
AN-5	4.000	0.426	1.38	25.8	0.120
AN-6	4.000	0.426	1.38	22.7	0.137
AN-7	4.002	0.426	1.38	23.7	0.131
AN-8	4.002	0.426	1.37	21.0	0.148
AN-9	3.998	0.426	1.37	21.8	0.142
AN-10	4.000	0.426	1.41	29.9	0.104
AN-11	4.000	0.426	1.39	26.6	0.117
AN-12	3.967	0.426	1.36	20.2	0.154
AN-13	4.000	0.426	1.40	28.1	0.110
AN-14	3.999	0.426	1.36	20.0	0.155
AN-15	4.002	0.426	1.34	21.9	0.142
Average			1.37	23.6	0.131

$\bar{E}_0 = 0.783 \times 10^6 \text{ lbs/in}^2$

$\bar{G}_0 = 0.198 \times 10^6 \text{ lbs/in}^2$

TABLE XVIII
Controlled Orientation Series
T/L Ratio = 0.78

Sample	Diameter (in.)	Length (in.)	Weight (g)	B. D. (g/cc)	ρ_0 (10^{-4} cm)	K_0 (cal/sec.cm.deg)	E_F (10^6 lbs/in ²)	E_L (10^6 lbs/in ²)	G (10^6 lbs/in ²)
1A1	0.427	4.009	14.476	1.541	11.4	0.272	0.803		
1A2	0.426	4.007	14.381	1.539	11.1	0.279	0.770		
1A3	0.426	4.007	14.391	1.537	11.6	0.268	0.789		
1A4	0.426	4.007	14.395	1.537	11.8	0.263	0.753		
1A5	0.426	4.005	14.421	1.541	11.8	0.263	0.791		
1A6	0.426	4.008	14.479	1.545	11.5	0.270	0.794		
1A8	0.426	4.006	14.418	1.544	11.4	0.272	0.772		
1A9	0.426	4.008	14.536	1.552	11.5	0.270	0.807		
1A10	0.426	4.006	14.447	1.543	11.7	0.265	0.841	0.853	0.374
1A11	0.426	4.007	14.412	1.538	12.0	0.258	0.826	0.840	0.372
1A12	0.426	4.007	14.467	1.545	11.9	0.260	0.842	0.853	0.381
Across grain average				1.542	11.6	0.268	0.799	0.849	0.376
1C1	0.425	4.005	14.357	1.541	12.9	0.240	0.655		
1C2	0.425	4.004	14.384	1.544	12.6	0.246	0.665		
1C3	0.426	4.005	14.355	1.537	12.8	0.242	0.655		
1C4	0.426	4.005	14.400	1.538	13.1	0.237	0.649		
1C5	0.426	4.009	14.429	1.540	13.2	0.235	0.650		
1C6	0.426	4.006	14.277	1.528	13.2	0.235	0.644		
1C7	0.426	4.008	14.389	1.536	13.2	0.235	0.648		
1C8	0.426	4.005	14.423	1.544	12.7	0.244	0.658		
1C9	0.425	4.005	14.328	1.538	13.0	0.238	0.699	0.710	0.358
1C10	0.425	4.006	14.344	1.539	13.1	0.237	0.706	0.711	0.357
1C11	0.426	4.008	14.571	1.555	12.8	0.242	0.717	0.731	0.370
1C12	0.426	4.009	14.383	1.538	13.1	0.237	0.691	0.710	0.356
With grain average				1.540	13.0	0.238	0.670	0.716	0.360

CTE = $1.76 \times 10^{-6}/^{\circ}\text{C}$ across grain; $2.26 \times 10^{-6}/^{\circ}\text{C}$ with grain

TABLE XIX
Controlled Orientation Series
T/L Ratio = 2.39

Sample	Diameter (in.)	Length (in.)	Weight (g)	B. D. (g/cc)	ρ_0 (10^{-4} cm)	K_0 (cal/sec. cm. deg)	E_F (10^6 lbs/in ²)	E_L (10^6 lbs/in ²)	G (10^6 lbs/in ²)
2A1	0.426	4.006	13.621	1.454	16.1	0.193	0.487		
2A2	0.426	4.007	13.935	1.489	14.3	0.217	0.542		
2A3	0.424	4.007	13.752	1.482	14.1	0.220	0.535		
2A4	0.427	4.006	13.725	1.462	15.1	0.206	0.534		
2A5	0.425	4.007	13.800	1.484	15.1	0.206	0.500		
2A6	0.427	4.006	13.801	1.471	14.9	0.208	0.522		
2A7	0.426	4.008	13.912	1.489	14.3	0.217	0.526		
2A8	0.426	4.005	13.815	1.476	14.3	0.217	0.537		
2A9	0.426	4.007	13.804	1.474	14.5	0.214	0.575	0.570	0.295
2A10	0.426	4.004	13.804	1.475	14.0	0.222	0.582	0.574	0.300
2A11	0.426	4.007	13.831	1.477	15.1	0.206	0.561	0.570	0.297
2A12	0.427	4.004	13.974	1.489	14.0	0.222	0.589	0.586	0.305
Across grain average				1.477	14.7	0.211	0.541	0.575	0.299
2C1	0.426	4.006	13.734	1.469	10.36	0.299	0.789		
2C2	0.426	4.006	13.699	1.467	10.41	0.298	0.823		
2C3	0.426	4.005	13.828	1.481	9.99	0.310	0.803		
2C4	0.426	4.006	13.635	1.459	10.02	0.309	0.819		
2C5	0.425	4.005	13.600	1.460	10.70	0.290	0.737		
2C6	0.427	4.005	13.759	1.467	9.95	0.312	0.790		
2C7	0.426	4.007	14.028	1.498	9.81	0.316	0.834		
2C8	0.426	4.006	13.815	1.479	10.73	0.289	0.821		
2C9	0.426	4.007	13.722	1.465	10.33	0.300	0.978	0.992	0.346
2C10	0.426	4.004	14.429	1.542	8.38	0.370	1.22	1.24	0.419
2C11	0.426	4.006	13.779	1.471	9.70	0.320	1.02	1.04	0.360
With grain average				1.478	10.00	0.310	0.876	1.09	0.375

CTE = $2.37 \times 10^{-6}/^{\circ}\text{C}$ across grain; $0.99 \times 10^{-6}/^{\circ}\text{C}$ with grain

TABLE XX
Controlled Orientation Series
T/L Ratio = 6.18

Sample	Diameter (in.)	Length (in.)	Weight (g)	B. D. (g/cc)	ρ_0 (10^{-4} cm)	K_0 (cal/sec.cm.deg)	E_F (10^6 lbs/in ²)	E_L (10^6 lbs/in ²)	G (10^6 lbs/in ²)
3A1	0.426	4.006	14.251	1.522	16.7	0.186	0.424		
3A2	0.427	4.010	14.458	1.539	15.2	0.204	0.502		
3A3	0.426	4.008	14.274	1.523	16.4	0.189	0.452		
3A4	0.425	4.008	14.208	1.524	15.6	0.199	0.486		
3A5	0.426	4.009	14.538	1.552	16.7	0.186	0.475		
3A6	0.425	4.007	14.172	1.520	16.1	0.192	0.477		
3A7	0.426	4.007	14.300	1.527	15.0	0.201	0.503		
3A8	0.426	4.007	14.175	1.513	16.4	0.189	0.470		
3A9	0.427	4.009	14.237	1.517	16.6	0.187	0.494		
3A10	0.425	4.008	14.225	1.527	15.8	0.196	0.522	0.543	0.293
3A11	0.426	4.006	14.353	1.533	14.8	0.210	0.543		
3A12	0.426	4.006	14.245	1.522	15.8	0.196	0.516		
Across grain average				1.527	16.0	0.194	0.497	0.543	0.298
3C1	0.426	4.003	14.035	1.504	8.24	0.376	1.33		
3C2	0.426	4.002	14.027	1.499	8.32	0.372	1.33		
3C3	0.426	4.003	14.221	1.520	8.07	0.384	1.35		
3C4	0.425	4.004	14.065	1.510	8.36	0.371	1.29		
3C5	0.426	4.003	14.052	1.502	8.28	0.374	1.36		
3C6	0.426	4.003	14.094	1.519	8.36	0.371	1.28		
3C7	0.427	4.004	14.526	1.549	7.18	0.432	1.51		
3C8	0.426	4.003	14.229	1.521	7.77	0.399	1.39		
3C9	0.426	4.004	14.086	1.505	8.21	0.378	1.38	1.46	0.392
3C10	0.426	4.003	14.039	1.504	8.08	0.384	1.39	1.43	0.379
3C11	0.425	4.003	14.066	1.511	8.36	0.371	1.41	1.46	0.390
3C12	0.426	4.003	14.452	1.544	7.95	0.390	1.63	1.64	0.447
With grain average				1.516	8.10	0.383	1.39	1.50	0.402

CTE = $3.03 \times 10^{-6}/^{\circ}\text{C}$ across grain; $0.49 \times 10^{-6}/^{\circ}\text{C}$ with grain

TABLE XXI
Conventional Graphite Series
Particle Size $\leq 0.016''$

Sample	Diameter (in.)	Length (in.)	Weight (g)	B. D. (g/cc)	ρ_0 ($10^{-4} \Omega \text{cm}$)	K_0 (cal/sec.cm.deg)	E_F (10^6lbs/in^2)	E_L (10^6lbs/in^2)	G (10^6lbs/in^2)
11	0.426	4.004	15.043	1.610	12.2	0.254	0.594		
12	0.425	4.002	15.236	1.641	12.7	0.244	0.391		
13	0.426	4.003	15.099	1.617	12.5	0.248	0.563		
14	0.426	4.003	15.001	1.607	11.8	0.263	0.548		
15	0.426	3.999	15.121	1.621	13.0	0.238	0.343		
16	0.426	4.002	15.188	1.628	13.4	0.232	0.489		
17	0.426	4.003	15.082	1.612	13.7	0.226	0.456		
18	0.425	4.002	15.093	1.621	12.2	0.254	0.538		
19	0.425	4.004	15.095	1.626	10.5	0.296	0.757	0.763	0.370
110	0.424	4.003	14.818	1.600	12.0	0.258	0.664	0.671	0.362
111	0.426	4.003	14.799	1.587	11.4	0.272	0.734	0.735	0.364
112	0.425	4.006	14.898	1.600	11.7	0.265	0.641	0.632	0.332
Across-Grain Average				1.614	12.2	0.254	0.560	0.700	0.357
113	0.425	4.002	14.604	1.570	8.07	0.384	1.17		
114	0.425	4.004	14.644	1.577	7.95	0.390	1.19		
115	0.424	4.002	14.447	1.560	8.07	0.384	1.17		
116	0.424	4.003	14.568	1.573	7.95	0.390	1.22		
117	0.425	4.002	14.581	1.567	8.18	0.379	1.14		
118	0.426	4.002	14.601	1.566	8.06	0.384	1.19		
119	0.425	4.002	14.508	1.559	7.96	0.390	1.18		
120	0.425	4.003	14.569	1.566	8.15	0.380	1.16		
121	0.424	4.003	14.590	1.575	7.95	0.390	1.26		0.444
122	0.425	4.002	14.590	1.568	8.10	0.383	1.24	1.27	0.437
123	0.425	4.004	14.698	1.579	7.98	0.388	1.27	1.30	0.442
124	0.425	4.003	14.538	1.566	7.95	0.390	1.23	1.26	0.435
With-Grain Average				1.569	8.03	0.386	1.20	1.28	0.440

CTE = $2.54 \times 10^{-6}/^\circ\text{C}$ across grain; $0.44 \times 10^{-6}/^\circ\text{C}$ with grain
T/L Ratio = 5.8

TABLE XXII
Conventional Graphite Series
Particle Size $\leq 0.035''$

Sample	Diameter (in.)	Length (in.)	Weight (g)	B. D. (g/cc)	ρ_0 ($10^{-4}\Omega\text{cm}$)	K_b (cal/sec.cm.deg)	E_F (10^6lbs/in^2)	E_L (10^6lbs/in^2)	G (10^6lbs/in^2)
31	0.426	4.000	14.457	1.550	13.2	0.235	0.524		
32	0.426	4.002	14.395	1.543	12.0	0.258	0.568		
33	0.426	4.002	14.409	1.544	12.5	0.248	0.522		
34	0.426	4.001	14.484	1.551	12.2	0.254	0.587		
35	0.426	4.001	14.451	1.548	12.6	0.246	0.539		
36	0.426	4.002	14.485	1.552	11.3	0.274	0.653		
37	0.426	4.002	14.520	1.552	11.5	0.270	0.654		
38	0.425	4.002	14.516	1.560	11.6	0.267	0.663		
39	0.427	4.002	14.503	1.536	12.4	0.250	0.591	0.605	0.343
310	0.426	4.001	14.481	1.548	12.9	0.240	0.566	0.572	0.336
311	0.426	4.002	14.410	1.549	12.9	0.240	0.595	0.589	0.341
312	0.426	3.996	14.563	1.562	11.7	0.265	0.631	0.646	0.347
Across-Grain Average				1.550	12.2	0.254	0.591	0.603	0.342
313	0.426	4.002	14.154	1.513	8.84	0.351	1.03		
314	0.426	4.001	14.311	1.540	8.33	0.372	1.14		
315	0.426	4.002	14.402	1.542	8.35	0.371	1.17		
316	0.426	4.002	14.363	1.538	7.95	0.390	1.17		
317	0.426	4.002	14.306	1.530	8.18	0.379	1.16		
318	0.426	4.002	14.358	1.535	8.15	0.380	1.17		
319	0.426	4.002	14.355	1.534	8.11	0.382	1.14		
320	0.426	4.002	14.470	1.547	8.00	0.388	1.23		
321	0.426	4.001	14.329	1.532	8.15	0.380	1.22		0.404
322	0.426	4.001	14.597	1.561	7.72	0.401	1.27	1.30	0.449
323	0.426	4.001	14.450	1.548	8.08	0.384	1.24	1.26	0.431
324	0.425	4.002	14.470	1.555	8.18	0.379	1.25	1.26	0.407
With-Grain Average				1.537	8.17	0.380	1.18	1.27	0.423

CTE = $2.25 \times 10^{-6}/^\circ\text{C}$ across grain; 0.65×10^{-6} with grain
T/L ratio = 3.5

TABLE XXIII
Conventional Graphite Series
Particle Size $\leq 0.055''$

Sample	Diameter (in.)	Length (in.)	Weight (g)	B. D. (g/cc)	ρ_0 ($10^{-4} \Omega \text{cm}$)	K_0 (cal/sec.cm.deg)	E_F (10^6lbs/in^2)	E_L (10^6lbs/in^2)	G (10^6lbs/in^2)
51	0.425	4.001	14.382	1.549	10.8	0.287	0.648		
52	0.427	4.002	14.566	1.551	10.6	0.292	0.682		
53	0.426	4.001	14.545	1.558	10.7	0.290	0.672		
54	0.426	4.001	14.419	1.545	11.0	0.282	0.633		
55	0.427	4.002	14.576	1.555	11.1	0.280	0.640		
56	0.426	4.001	14.390	1.542	11.6	0.267	0.599		
57	0.427	4.001	14.578	1.555	10.7	0.290	0.683		
58	0.427	4.001	14.517	1.546	11.7	0.265	0.613		
59	0.426	4.002	14.443	1.544	11.4	0.272	0.646	0.654	0.341
510	0.427	4.001	14.524	1.546	11.4	0.272	0.659	0.661	0.345
511	0.424	4.002	14.384	1.555	10.7	0.290	0.695	0.708	0.357
512	0.426	4.001	14.488	1.549	11.0	0.282	0.665	0.665	0.348
Across grain average				1.550	11.1	0.280	0.653	0.672	0.348
513	0.427	4.002	14.592	1.553	7.78	0.398	1.12		
514	0.426	4.002	14.589	1.560	7.98	0.388	1.10		
515	0.425	4.002	14.611	1.569	7.70	0.403	1.09		
516	0.428	4.004	14.639	1.555	7.81	0.396	1.12		
517	0.426	4.003	14.625	1.562	7.77	0.399	1.12		
518	0.427	4.002	14.606	1.558	7.44	0.417	1.14		
519	0.426	4.002	14.554	1.558	7.48	0.415	1.17		
520	0.427	4.003	14.607	1.555	7.85	0.395	1.11		
521	0.425	3.997	14.577	1.565	7.47	0.415	1.18	1.23	0.423
522	0.426	4.003	14.579	1.558	7.82	0.396	1.11	1.17	0.405
523	0.426	4.002	14.629	1.564	7.70	0.403	1.13	1.20	0.418
With grain average				1.560	7.71	0.402	1.12	1.20	0.415

CTE = $2.05 \times 10^{-6}/^\circ\text{C}$ across grain; $0.54 \times 10^{-6}/^\circ\text{C}$ with grain
T/L ratio = 3.8

TABLE XXIV
Controlled Density Series
B. D. ~ 1.87 g/cc

Sample	Diameter (in.)	Length (in.)	Weight (g)	B. D. (g/cc)	ρ_0 ($10^{-4}\Omega\text{cm}$)	K_0 (cal/sec.cm.deg)	E_F (10^6lbs/in^2)	E_L (10^6lbs/in^2)	G (10^6lbs/in^2)
D-1-1	0.430	4.008	17.813	1.868	10.6	0.292	0.986	0.983	0.317
D-1-2	0.430	4.010	17.449	1.829	13.3	0.233	0.698	0.715	0.233
D-1-3	0.431	4.009	17.555	1.832	12.8	0.242	0.878	0.782	0.245
D-1-4	0.430	4.007	17.540	1.839	11.4	0.272	0.890	0.875	0.294
D-1-5	0.430	4.010	17.308	1.814	13.7	0.226	0.669	0.667	0.218
D-1-6	0.430	4.005	17.720	1.859	11.0	0.282	0.928	0.946	0.304
D-1-7	0.430	4.008	17.600	1.845	12.3	0.252	0.810	0.822	0.264
D-1-8	0.431	4.006	17.388	1.815	13.2	0.235	0.682	0.703	0.232
D-1-9	0.431	4.011	17.336	1.808	14.5	0.214	0.663	0.668	0.221
With grain average				1.834	12.5	0.248	0.800	0.796	0.259
D-1-21	0.428	2.021	8.958	1.880	27.3	0.114	0.328	0.321	0.251
D-1-22	0.428	2.024	9.045	1.895	25.2	0.123	0.359	0.346	0.263
D-1-23	0.428	2.021	8.881	1.864	27.6	0.112	0.318	0.311	0.241
D-1-24	0.428	2.022	9.043	1.897	24.4	0.127	0.369	0.357	0.273
D-1-25	0.428	2.021	9.054	1.900	24.8	0.125	0.359	0.351	0.265
D-1-26	0.428	2.022	8.941	1.876	25.6	0.121	0.330	0.321	0.248
D-1-27	0.428	2.021	9.040	1.897	26.8	0.116	0.344	0.331	0.267
D-1-28	0.428	1.990	8.833	1.883	30.1	0.103	0.296	0.290	0.229
D-1-29	0.428	2.023	8.911	1.868	27.0	0.115	0.320	0.312	0.237
D-1-30	0.428	2.020	9.094	1.910	26.9	0.115	0.346	0.346	0.278
D-1-31	0.428	2.023	8.846	1.855	28.2	0.110	0.305	0.295	0.227
D-1-32	0.428	2.022	8.954	1.878	30.1	0.103	0.294	0.290	0.238
Across grain average				1.884	27.0	0.115	0.331	0.323	0.251

CTE = $8.28 \times 10^{-6}/^\circ\text{C}$ across grain; $1.42 \times 10^{-6}/^\circ\text{C}$ with grain
T/L Ratio = 5.8

TABLE XXV
Controlled Density Series
B. D. ~ 1.97 g/cc

Sample	Diameter (in.)	Length (in.)	Weight (g)	B. D. (g/cc)	ρ_0 ($10^{-4}\Omega\text{cm}$)	K_0 (cal/sec.cm.deg)	E_F (10^6lbs/in^2)	E_L (10^6lbs/in^2)	G (10^6lbs/in^2)
D-2-1	0.429	4.006	18.559	1.956	7.51	0.412	1.41	1.42	0.439
D-2-2	0.429	4.007	18.448	1.944	8.22	0.377	1.34	1.33	0.405
D-2-3	0.429	4.005	18.671	1.968	7.14	0.434	1.61	1.64	0.448
D-2-4	0.429	4.004	18.781	1.980	6.58	0.471	1.81	1.82	0.452
D-2-5	0.429	4.003	18.728	1.975	6.95	0.446	1.60	1.65	0.465
D-2-6	0.429	4.009	18.440	1.942	7.66	0.405	1.40	1.39	0.405
D-2-7	0.429	4.008	18.539	1.953	7.06	0.439	1.56	1.55	0.446
D-2-8	0.429	4.005	18.628	1.964	7.36	0.421	1.55	1.54	0.460
D-2-9	0.429	4.007	18.600	1.960	6.68	0.464	1.63	1.61	0.459
D-2-10	0.429	4.007	18.613	1.961	6.77	0.458	1.64	1.66	0.455
D-2-11	0.429	4.008	18.484	1.947	7.73	0.461	1.36	1.33	0.408
D-2-12	0.429	4.010	18.494	1.947	8.06	0.384	1.46	1.43	0.420
D-2-13	0.429	4.004	18.797	1.982	6.62	0.468	1.75	1.78	0.445
D-2-14	0.429	4.003	18.844	1.987	6.50	0.477	1.83	1.86	0.468
D-2-15	0.429	4.007	18.510	1.950	7.66	0.404	1.41	1.40	0.429
D-2-16	0.429	4.005	18.676	1.959	7.06	0.439	1.66	1.67	0.463
With grain average				1.961	7.22	0.429	1.56	1.57	0.442
D-2-21	0.429	4.030	18.643	1.958	24.0	0.129	0.415	0.397	0.309
D-2-22	0.428	4.029	18.527	1.950	20.8	0.149	0.453	0.421	0.324
D-2-23	0.428	4.030	18.715	1.970	22.0	0.141	0.443	0.420	0.337
D-2-24	0.426	4.030	18.458	1.960	18.4	0.168	0.490	0.473	0.351
D-2-25	0.428	4.030	18.630	1.961	19.4	0.160	0.480	0.456	0.344
D-2-26	0.428	4.030	18.460	1.943	20.2	0.153	0.423	0.405	0.313
D-2-27	0.428	4.031	18.554	1.952	20.7	0.150	0.441	0.419	0.304
D-2-28	0.428	4.030	18.645	1.962	19.0	0.163	0.466	0.440	0.342
D-2-29	0.428	4.028	18.720	1.971	19.3	0.161	0.475	0.448	0.351
D-2-30	0.428	4.033	18.634	1.960	19.9	0.156	0.467	0.448	0.330
D-2-31	0.428	4.029	18.690	1.968	20.2	0.153	0.460	0.439	0.339
D-2-32	0.429	4.032	18.577	1.950	22.2	0.140	0.434	0.410	0.315
D-2-33	0.428	4.031	18.623	1.960	19.6	0.158	0.460	0.436	0.333
D-2-34	0.428	4.031	18.600	1.957	18.3	0.169	0.470	0.447	0.343
D-2-35	0.428	4.031	18.491	1.946	19.7	0.157	0.457	0.422	0.319
D-2-36	0.424	3.993	18.268	1.977	19.0	0.163	0.515	0.476	0.343
Across grain average				1.959	20.1	0.154	0.459	0.435	0.331

CTE = 9.34×10^{-6} / °C across grain; 1.48×10^{-6} / °C with grain
T/L Ratio = 6.3

TABLE XXVI
Controlled Density Series
B. D. ~ 2.05 g/cc

Sample	Diameter (in.)	Length (in.)	Weight (g)	B. D. (g/cc)	P ₀ (10 ⁻⁴ Ωcm)	K ₀ (cal/sec.cm.deg)	E _F (10 ⁴ lbs/in ²)	E _L (10 ⁴ lbs/in ²)	G (10 ⁴ lbs/in ²)
D-3-1	0.430	3.998	19.544	2.054	5.86	0.529	2.45	2.53	0.593
D-3-2	0.430	3.999	19.587	2.058	5.97	0.519	2.33	2.38	0.610
D-3-3	0.430	3.996	19.599	2.061	6.10	0.509	2.25	2.32	0.607
D-3-4	0.430	3.999	19.506	2.050	5.86	0.529	2.21	2.29	0.578
D-3-5	0.430	4.001	19.496	2.048	6.07	0.511	2.25	2.34	0.574
D-3-6	0.430	3.998	19.555	2.055	5.48	0.565	2.60	2.62	0.578
D-3-7	0.430	3.999	19.510	2.050	5.54	0.560	2.29	2.33	0.593
D-3-8	0.430	3.999	19.486	2.048	5.69	0.545	2.43	2.48	0.592
D-3-9	0.430	4.000	19.472	2.046	6.51	0.476	2.06	2.08	0.573
D-3-10	0.430	3.999	19.486	2.048	6.06	0.511	2.25	2.31	0.598
D-3-11	0.430	4.000	19.470	2.045	5.50	0.564	2.41	2.48	0.573
D-3-12	0.430	3.996	19.430	2.043	6.70	0.463	1.98	2.01	0.568
D-3-13	0.430	4.000	19.508	2.049	5.68	0.546	2.37	2.40	0.593
D-3-14	0.430	3.999	19.469	2.046	5.92	0.524	1.99	2.08	0.568
With grain average				2.050	5.93	0.523	2.28	2.33	0.586
D-3-21	0.427	2.022	9.738	2.053	25.0	0.124	0.494	0.496	0.392
D-3-22	0.427	2.024	9.705	2.045	20.6	0.150	0.550	0.546	0.399
D-3-23	0.427	2.023	9.744	2.054	21.3	0.146	0.518	0.518	0.405
D-3-24	0.427	2.023	9.727	2.050	22.1	0.140	0.529	0.521	0.408
D-3-25	0.427	2.025	9.685	2.040	17.5	0.177	0.577	0.587	0.412
D-3-26	0.427	2.023	9.719	2.048	20.1	0.154	0.539	0.543	0.411
D-3-27	0.427	2.024	9.681	2.040	22.4	0.138	0.521	0.513	0.397
D-3-28	0.427	2.021	9.695	2.044	21.3	0.146	0.535	0.544	0.400
D-3-29	0.428	2.024	9.748	2.054	25.1	0.124	0.493	0.488	0.385
D-3-30	0.427	2.025	9.740	2.052	20.6	0.150	0.532	0.534	0.405
D-3-31	0.427	2.024	9.756	2.056	21.6	0.144	0.527	0.517	0.408
D-3-32	0.427	2.024	9.739	2.052	22.3	0.139	0.522	0.527	0.408
D-3-33	0.427	2.024	9.744	2.053	22.7	0.137	0.505	0.515	0.405
D-3-34	0.427	2.024	9.712	2.046	20.6	0.150	0.526	0.526	0.391
Across grain average				2.049	21.7	0.143	0.526	0.527	0.401

CTE = $8.71 \times 10^{-6}/^{\circ}\text{C}$ across grain; $0.66 \times 10^{-6}/^{\circ}\text{C}$ with grain
T/L ratio = 13.2

TABLE XXVII

Controlled Density Series
B. D. ~ 2.10 g/cc

Sample	Diameter (in.)	Length (in.)	Weight (g)	B. D. (g/cc)	ρ_0 (10^{-4} g/cm)	K_0 (cal/sec.cm.deg)	E_F (10^6 lbs/in ²)	E_L (10^6 lbs/in ²)	G (10^6 lbs/in ²)
D-4-1	0.428	3.998	19.978	2.12	3.84	0.807			
D-4-2	0.428	3.995	19.671	2.09	4.46	0.695			
D-4-3	0.428	3.996	19.813	2.10	4.56	0.679			
D-4-4	0.428	3.994	19.781	2.10	4.35	0.712			
D-4-5	0.428	3.996	19.809	2.10	3.94	0.786	4.15	4.16	0.713
D-4-6	0.429	3.996	19.833	2.10	4.60	0.674	3.68	4.03	0.697
D-4-7	0.429	3.995	19.806	2.10	4.07	0.762	4.11	4.24	0.703
D-4-8	0.428	3.998	19.899	2.12	4.15	0.747	4.29	4.42	0.718
D-4-9	0.428	3.996	19.903	2.11	3.94	0.786	4.18	4.32	0.718
D-4-10	0.428	3.994	19.772	2.10	4.68	0.662	3.66	3.76	0.692
With grain average				2.10	4.26	0.727	4.01	4.16	0.707
D-4-21	0.426	2.804	13.711	2.09	25.9	0.120			
D-4-22	0.426	2.799	13.733	2.10	27.7	0.112			
D-4-23	0.426	2.794	13.690	2.10	27.1	0.114			
D-4-24	0.426	2.776	13.606	2.10	25.7	0.121			
D-4-25	0.426	2.801	13.720	2.10	25.7	0.121	0.497	0.482	0.436
D-4-26	0.426	2.803	13.765	2.10	25.7	0.121	0.500	0.482	0.436
D-4-27	0.426	2.795	13.690	2.10	23.7	0.131	0.487	0.487	0.436
D-4-28	0.426	2.800	13.757	2.10	25.4	0.122	0.507	0.481	0.436
D-4-29	0.426	2.803	13.734	2.10	24.7	0.126	0.506	0.487	0.436
Across grain average				2.10	25.7	0.121	0.499	0.484	0.436

CTE = $11.3 \times 10^{-6}/^{\circ}\text{C}$ across grain; $-0.19 \times 10^{-5}/^{\circ}\text{C}$ with grain
T/L ratio = -59.5

TABLE XXVIII
High Temperature Controlled Density Series
B. D. ~ 2.10 g/cc

Sample	Diameter (in.)	Length (in.)	Weight (g)	B. D. (g/cc)	ρ_0 ($10^{-4} \Omega \text{cm}$)	K_0 (cal/sec.cm.deg)	E_F (10^6lbs/in^2)	E_L (10^6lbs/in^2)	G (10^6lbs/in^2)
R-81	0.4173	3.998	16.6417	1.869	12.6	0.246	1.58	1.58	0.647
R-82	0.4043	4.002	15.3660	1.825	12.5	0.248	1.59	1.58	0.630
R-83	0.4242	3.997	17.1719	1.855	12.5	0.248	1.58	1.60	0.636
R-84	0.4243	3.998	16.9063	1.827	12.4	0.250	1.55	1.54	0.613
R-85	0.4252	3.997	17.2000	1.850	12.8	0.242	1.53	1.51	0.621
R-86	0.4267	3.998	17.3320	1.850	12.6	0.246	1.52	1.50	0.618
R-87	0.4265	3.998	17.4084	1.860	12.4	0.250	1.58	1.60	0.640
R-88	0.4260	3.997	17.3904	1.859	12.1	0.256	1.60	1.62	0.648
R-89	0.4245	3.995	17.2490	1.862	12.2	0.254	1.60	1.59	0.642
R-90	0.4267	3.998	17.5134	1.869	12.0	0.258	1.65	1.66	0.658
R-91	0.4249	3.998	17.4140	1.875	11.9	0.261	1.67	1.69	0.667
R-92	0.4262	3.998	17.3286	1.854	12.3	0.252	1.59	1.60	0.636
R-93	0.4245	3.998	17.2092	1.856	12.4	0.250	1.58	1.59	0.647
R-94	0.4256	3.998	17.2418	1.850	12.4	0.250	1.57	1.58	0.629
R-95	0.4250	3.998	17.2300	1.854	12.5	0.248	1.60	1.61	0.639
R-96	0.4263	3.884	16.5884	1.826	12.3	0.252	1.58	1.56	0.626
R-97	0.4270	3.998	17.3252	1.847	12.5	0.248	1.51	1.52	0.620
R-98	0.4262	3.998	17.3283	1.854	12.3	0.252	1.54	1.55	0.628
R-99	0.4261	3.999	17.3713	1.859	12.1	0.256	1.57	1.58	0.637
R-100	0.4263	3.999	17.4326	1.864	12.1	0.256	1.61	1.62	0.648
R-101	0.4267	3.999	17.4185	1.859	12.3	0.252	1.58	1.57	0.636
R-102	0.4190	3.999	16.8557	1.871	12.0	0.258	1.68	1.66	0.660
R-103	0.4269	3.997	17.5439	1.866	12.2	0.254	1.63	1.64	0.653
R-104	0.4113	3.999	16.0690	1.846	12.7	0.244	1.53	1.56	0.622
R-105	0.4262	3.987	17.2010	1.845	12.4	0.250	1.54	1.56	0.624
R-106	0.4241	3.999	17.1192	1.849	12.4	0.250	1.57	1.58	0.625
R-107	0.4210	3.998	16.8142	1.844	12.7	0.244	1.55	1.56	0.618
R-108	0.4264	3.998	17.1878	1.837	12.4	0.250	1.50	1.51	0.600
R-109	0.4114	3.999	16.0154	1.839	12.3	0.252	1.51	1.52	0.605
R-110	0.4218	3.999	16.8698	1.842	12.4	0.250	1.52	1.53	0.610
R-111	0.4114	3.998	16.0953	1.848	12.4	0.250	1.53	1.54	0.621
R-112	0.4115	3.998	16.1723	1.856	12.3	0.252	1.57	1.58	0.628
R-113	0.4277	3.998	17.4685	1.856	12.2	0.254	1.59	1.59	0.639
R-114	0.4247	3.999	17.2885	1.862	12.3	0.252	1.62	1.63	0.654
R-115	0.4217	3.999	17.0436	1.862	12.5	0.248	1.63	1.63	0.650
Average:				1.853	12.4	0.250	1.58	1.58	0.634

CTE = $2.48 \times 10^{-6}/^{\circ}\text{C}$; T/L Ratio = 1.32

TABLE XXIX

Superfine Series
(With Grain)

Sample	Diameter (in.)	Weight (g)	B. D. (g/cc)	ρ_0 ($10^{-4}\Omega\text{cm}$)	K_0 (cal/sec.cm.deg)	E_F (10^6lbs/in^2)	E_L (10^6lbs/in^2)	G (10^6lbs/in^2)
SFL-1	0.322	9.6246	1.802	9.01	0.344	3.59	3.57	0.712
SFL-2	0.323	9.7240	1.812	8.84	0.351	3.61	3.67	0.812
SFL-3	0.317	9.3703	1.812	9.18	0.338	3.36	3.51	0.776
SFL-4	0.320	9.5955	1.819	9.12	0.340	3.47	3.57	0.793
SFL-5	0.322	9.6813	1.818	8.87	0.350	3.59	3.55	0.793
SFL-6	0.322	9.6808	1.809	8.70	0.356	3.59	3.65	0.810
SFL-7	0.323	9.7350	1.797	8.80	0.352	3.58	3.63	0.808
SFL-8	0.322	9.7430	1.820	8.74	0.355	3.63	3.61	0.811
SFL-9	0.324	9.7887	1.807	8.72	0.356	3.59	3.65	0.812
SFL-10	0.324	9.7319	1.805	8.58	0.361	3.68	3.73	0.942
SFL-11	0.320	9.5640	1.811	9.01	0.344	3.40	3.51	0.898
SFL-12	0.324	9.7588	1.801	8.62	0.360	3.74	3.76	0.874
SFL-13	0.317	9.3394	1.804	9.24	0.336	3.29	3.49	0.862
SFL-14	0.323	9.7070	1.811	8.54	0.363	3.60	3.62	0.949
SFL-15	0.317	9.3248	1.808	9.33	0.332	3.37	3.49	0.854
SFL-16	0.320	9.6360	1.834	8.84	0.351	3.53	3.62	0.917
SFL-17	0.322	9.7062	1.822	8.68	0.357	3.70	3.64	0.946
SFL-18	0.324	9.7920	1.812	8.62	0.360	3.70	3.73	0.956
Average:			1.811	8.86	0.350	3.56	3.61	0.851

All samples 4.00" long

TABLE XXX
Laboratory Impregnation Series Particle Size $\leq 0.016''$

Sample	Diameter (in)	Weight (g)	Impregnant (w/o)	B. D. (g/cc)	ρ_0 (10^{-4} cm)	K_0 (Cal/sec cm deg)	E_F (10^6 lbs/in 2)	E_L (10^6 lbs/in 2)	G (10^6 lbs/in 2)
A-1	0.426	15.5913	3.59	1.671	7.12	0.435	1.57	1.53	0.524
A-2	0.426	15.4720	3.38	1.658	7.57	0.409	1.44	1.44	0.505
A-3	0.426	15.7682	3.26	1.686	7.09	0.437	1.61	1.59	0.537
A-4	0.426	15.4755	3.87	1.655	7.80	0.398	1.37	1.39	0.498
A-5	0.426	15.4747	4.05	1.653	7.91	0.382	1.35	1.37	0.490
A-6	0.426	15.8093	3.32	1.689	7.08	0.438	1.59	1.60	0.542
A-7	0.426	15.7198	3.33	1.680	7.06	0.439	1.61	1.60	0.533
A-8	0.426	15.4305	3.70	1.649	8.09	0.384	1.29	1.33	0.484
A-9	0.426	15.3650	3.83	1.646	8.22	0.377	1.30	1.34	0.480
A-10	0.426	15.4448	4.23	1.653	7.64	0.406	1.42	1.43	0.500
Average:			3.66	1.664	7.56	0.410	1.45	1.46	0.509
A-11	0.427	16.6520	9.00	1.778	7.33	0.423	1.63	1.62	0.569
A-12	0.426	15.9735	7.50	1.707	7.93	0.391	1.30	1.15	0.440
A-13	0.426	15.9768	7.55	1.709	7.55	0.411	1.38	1.40	0.508
A-14	0.426	15.9993	7.59	1.712	7.46	0.415	1.41	1.42	0.515
A-15	0.426	16.1948	7.23	1.730	7.01	0.442	1.66	1.65	0.549
A-16	0.427	16.2748	6.91	1.736	7.09	0.438	1.61	1.59	0.551
A-17	0.426	16.1605	7.18	1.727	7.33	0.423	1.50	1.53	0.537
A-19	0.426	16.2797	6.73	1.739	7.04	0.440	1.67	1.67	0.561
A-20	0.426	16.0431	7.41	1.714	7.23	0.429	1.45	1.47	0.522
Average:			7.45	1.728	7.33	0.423	1.51	1.50	0.528
A-21	0.427	16.7613	9.44	1.790	6.18	0.502	2.11	2.13	0.694
A-22	0.427	16.6805	9.94	1.781	6.47	0.479	1.99	2.00	0.672
A-23	0.426	16.6330	10.79	1.779	6.45	0.480	2.00	1.98	0.676
A-24	0.427	16.6042	9.53	1.773	6.42	0.482	1.98	1.95	0.664
A-25	0.427	16.8663	9.25	1.795	6.37	0.487	2.17	2.13	0.688
A-26	0.427	16.5977	10.40	1.770	6.88	0.451	2.04	1.99	0.677
A-27	0.427	16.6680	10.29	1.778	6.64	0.467	1.94	1.91	0.665
A-28	0.427	16.7151	9.98	1.783	6.21	0.499	2.15	2.16	0.699
A-29	0.427	16.6718	10.12	1.778	6.57	0.472	2.00	2.00	0.676
A-30	0.427	16.6494	10.59	1.786	6.66	0.465	2.07	2.03	0.701
Average			10.03	1.781	6.49	0.478	2.04	2.03	0.681

All Samples 4.00" Long

HW-80752

TABLE XXXI
Laboratory Impregnation Series Particle Size $\leq 0.035''$

Sample	Diameter (in.)	Weight (g)	Impregnant (w/o)	B. D. (g/cc)	ρ_0 ($10^{-4}\Omega\text{cm}$)	K_0 (cal/sec.cm.deg)	E_F (10^6lbs/in^2)	E_L (10^6lbs/in^2)	G (10^6lbs/in^2)
B-1	0.426	15.2603	2.75	1.636	7.24	0.428	1.46	1.48	0.512
B-2	0.426	15.2965	2.93	1.636	7.38	0.420	1.42	1.44	0.507
B-3	0.426	15.2670	3.06	1.636	7.23	0.429	1.42	1.46	0.497
B-4	0.426	15.0620	3.84	1.614	7.79	0.398	1.34	1.36	0.463
B-5	0.426	15.2109	3.44	1.628	7.46	0.415	1.45	1.46	0.506
B-6	0.426	15.1236	3.59	1.616	7.79	0.398	1.37	1.37	0.481
B-7	0.426	15.0794	3.72	1.614	7.74	0.401	1.35	1.35	0.457
B-8	0.426	15.1943	3.39	1.623	7.58	0.409	1.40	1.39	0.483
B-9	0.426	15.5340	3.25	1.663	6.75	0.459	1.60	1.62	0.552
B-10	0.426	15.3825	2.91	1.647	7.10	0.437	1.53	1.54	0.531
Average:			3.29	1.631	7.41	0.419	1.43	1.45	0.499
B-11	0.426	15.6789	7.10	1.677	7.50	0.413	1.38	1.40	0.481
B-12	0.426	15.8624	7.01	1.697	7.08	0.438	1.56	1.54	0.542
B-13	0.426	15.9007	6.58	1.701	6.86	0.452	1.61	1.63	0.550
B-14	0.426	15.6332	7.29	1.673	7.63	0.406	1.26	1.38	0.389
B-15	0.426	15.6802	7.04	1.675	7.69	0.403	1.40	1.39	0.474
B-16	0.426	16.0543	7.52	1.715	7.53	0.412	1.37	1.36	0.521
B-17	0.426	15.9005	6.77	1.699	6.89	0.450	1.61	1.68	0.550
B-18	0.426	15.7713	6.82	1.685	7.13	0.435	1.49	1.59	0.576
Average:			7.02	1.690	7.29	0.425	1.46	1.50	0.510
B-21	0.427	16.1983	9.61	1.727	6.56	0.472	1.83	1.86	0.628
B-22	0.426	16.3537	8.86	1.750	6.36	0.487	1.92	1.95	0.668
B-24	0.426	16.2005	9.64	1.733	6.83	0.454	1.80	1.82	0.622
B-25	0.426	16.2588	9.49	1.739	6.26	0.495	2.03	1.99	0.696
B-26	0.426	16.2017	9.94	1.731	6.61	0.469	1.88	1.87	0.654
B-27	0.426	16.4880	9.02	1.762	5.98	0.519	2.04	2.01	0.683
B-28	0.426	16.3233	9.58	1.744	6.35	0.488	2.05	2.02	0.701
B-29	0.427	16.1510	10.34	1.722	6.65	0.466	1.91	1.91	0.655
B-30	0.426	16.2785	10.12	1.739	6.49	0.478	2.03	2.01	0.697
Average:			9.62	1.739	6.45	0.481	1.95	1.94	0.664

All samples 4.00" long

HW-80752

TABLE XXXII
Laboratory Impregnation Series
Particle Size $< 0.055''$

Sample	Diameter (in.)	Weight (g)	Impregnant (w/o)	B. D. (g/cc)	ρ_0 ($10^{-4} \Omega \text{cm}$)	K_0 (cal/sec.cm.deg)	E_F (10^6lbs/in^2)	E_L (10^6lbs/in^2)	G (10^6lbs/in^2)
C-1	0.426	15.3370	3.04	1.644	6.84	0.453	1.44	1.48	0.496
C-2	0.426	15.3620	2.67	1.646	6.64	0.467	1.55	1.55	0.515
C-3	0.426	15.2280	3.13	1.632	7.43	0.417	1.30	1.30	0.459
C-4	0.426	15.3052	3.17	1.640	6.78	0.457	1.43	1.45	0.498
C-5	0.426	15.2710	2.57	1.635	6.87	0.451	1.47	1.47	0.494
C-6	0.426	15.1333	2.34	1.620	7.31	0.424	1.34	1.36	0.456
C-7	0.426	15.4230	3.03	1.651	6.60	0.470	1.57	1.58	0.523
C-8	0.426	15.3637	3.16	1.645	7.19	0.431	1.57	1.53	0.508
C-9	0.426	15.2650	2.82	1.634	7.49	0.414	1.20	1.35	0.460
C-10	0.424	15.2693	3.70	1.647	7.27	0.426	1.41	1.45	0.500
Average:			2.96	1.639	7.04	0.441	1.43	1.45	0.491
C-11	0.426	15.7025	6.11	1.685	6.90	0.449	1.46	1.44	0.510
C-12	0.426	15.7583	6.10	1.689	7.02	0.441	1.44	1.45	0.509
C-13	0.426	15.7960	6.14	1.693	6.81	0.455	1.44	1.50	0.512
C-14	0.426	15.7750	6.09	1.691	6.80	0.456	1.45	1.52	0.516
C-15	0.426	15.7483	6.11	1.686	6.97	0.445	1.44	1.47	0.514
C-16	0.426	16.0142	6.02	1.711	6.31	0.491	1.77	1.75	0.525
C-17	0.426	15.7930	5.69	1.687	6.54	0.474	1.55	1.55	0.529
C-18	0.426	15.9410	5.87	1.703	6.65	0.466	1.63	1.61	0.552
C-19	0.426	15.8714	5.84	1.696	6.48	0.479	1.61	1.63	0.548
Average:			6.00	1.693	6.72	0.461	1.53	1.55	0.524
C-21	0.426	16.3497	8.35	1.749	5.85	0.530	1.97	2.08	0.688
C-22	0.426	16.1900	8.66	1.732	6.14	0.505	1.88	1.90	0.657
C-23	0.427	16.4320	8.15	1.755	6.06	0.511	2.00	2.03	0.665
C-24	0.426	16.3555	8.51	1.750	6.01	0.515	1.98	2.06	0.670
C-25	0.426	16.3164	8.38	1.743	5.81	0.533	2.02	2.10	0.668
C-26	0.426	16.2715	8.51	1.739	5.97	0.519	2.00	1.98	0.658
C-27	0.426	16.2972	8.44	1.741	6.23	0.498	1.96	1.97	0.668
C-28	0.426	16.1360	8.18	1.724	6.02	0.515	1.86	1.85	0.629
C-29	0.426	16.2582	8.64	1.737	5.88	0.527	2.09	2.10	0.666
C-30	0.419	15.6390	11.94	1.734	6.29	0.493	1.87	1.79	0.611
Average:			8.77	1.740	6.03	0.514	1.96	1.99	0.658

All samples 4.00" long

HW-80752

TABLE XXXIII

Synthetic Coke-Pitch Series
(With Grain)

Sample	Diameter (in.)	Length (in.)	Weight (g)	B. D. (g/cc)	ρ_0 ($10^{-4} \Omega \text{cm}$)	K_0 (cal/sec.cm.deg)	E_F (10^6lbs/in^2)	E_L (10^6lbs/in^2)	G (10^6lbs/in^2)
14-1	0.4270	4.012	14.4063	1.531	5.03	0.616	2.28	2.34	0.504
14-2	0.4270	4.008	14.3897	1.531	4.89	0.634	2.23	2.29	0.507
21-1	0.4275	4.012	14.3343	1.520	5.12	0.605	2.25	2.27	0.484
21-2	0.4267	4.004	14.2413	1.518	5.25	0.590	2.22	2.26	0.484
30-1	0.4270	4.000	14.4293	1.537	5.23	0.592	2.33	2.41	0.547
30-2	0.4263	4.008	14.2445	1.519	5.22	0.594	2.17	2.24	0.520
31-1	0.4278	4.012	14.3125	1.515	5.20	0.596	2.21	2.26	0.517
31-2	0.4268	4.008	14.2394	1.516	5.48	0.565	2.18	2.24	0.517
38-1	0.4266	4.012	14.2283	1.514	5.45	0.569	2.14	2.21	0.480
38-2	0.4277	4.012	14.2543	1.510	5.23	0.592	2.12	2.23	0.481
39-1	0.4263	4.008	14.1945	1.514	5.46	0.567	2.13	2.21	0.481
39-2	0.4280	4.012	14.2213	1.504	5.39	0.575	2.08	2.15	0.483
41-1	0.4268	4.004	14.2270	1.516	5.36	0.578	2.15	2.21	0.492
41-2	0.4280	4.004	14.2853	1.514	5.21	0.595	2.18	2.20	0.500
46-1	0.4268	4.008	14.2348	1.515	5.57	0.556	2.16	2.24	0.499
46-2	0.4248	4.012	14.0819	1.510	5.22	0.594	2.12	2.21	0.487
47-1	0.4253	4.004	13.9978	1.503	5.57	0.556	2.10	2.21	0.625
47-2	0.4264	4.008	14.1600	1.510	5.49	0.565	2.16	2.23	0.478
48-1	0.4275	4.004	14.1136	1.498	5.52	0.561	2.10	2.13	0.476
48-2	0.4268	4.000	14.1348	1.507	5.55	0.559	2.18	2.22	0.484
Average:				1.515	5.32	0.583	2.18	2.24	0.502

CTE = $-0.20 \times 10^{-6} / ^\circ\text{C}$ with grain

TABLE XXXIV
Impregnation-Binder Series
11.8 w/o Impregnant Carbon

Sample	Diameter (in.)	Length (in.)	Weight (g)	B. D. (g/cc)	ρ_0 (10^{-6} g/cm)	K_0 (cal/sec.cm.deg)	E_F (10^6 lbs/in ²)	E_L (10^6 lbs/in ²)	G (10^6 lbs/in ²)
I-1-1	0.4265	4.004	16.742	1.786	9.81	0.316	1.195	1.210	0.618
I-1-2	0.4265	4.004	16.787	1.791	9.20	0.337	1.342	1.330	0.643
I-1-3	0.4265	4.004	16.709	1.783	10.15	0.306	1.142	1.169	0.622
I-1-4	0.4265	4.004	16.631	1.775	10.28	0.302	1.130	1.138	0.597
I-1-5	0.4265	4.004	16.673	1.779	9.68	0.320	1.224	1.245	0.619
I-1-6	0.4260	4.004	16.670	1.782	10.19	0.304	1.157	1.162	0.606
I-1-7	0.4265	4.005	16.831	1.795	9.29	0.334	1.325	1.342	0.644
I-1-8	0.4265	4.004	16.809	1.793	9.15	0.339	1.330	1.320	0.649
I-1-9	0.4265	4.004	16.716	1.783	9.88	0.314	1.178	1.200	0.595
I-1-10	0.4265	4.003	16.682	1.780	10.21	0.304	1.158	1.162	0.607
I-1-11	0.4265	4.004	16.644	1.776	10.03	0.309	1.161	1.167	0.610
I-1-12	0.4265	4.004	16.748	1.787	9.77	0.317	1.200	1.220	0.620
I-1-13	0.4265	4.004	16.718	1.784	10.16	0.305	1.156	1.178	0.612
I-1-14	0.4265	4.004	16.681	1.780	10.25	0.302	1.145	1.150	0.598
I-1-15	0.4265	4.004	16.677	1.779	10.38	0.299	1.145	1.145	0.607
I-1-16	0.4265	4.004	16.656	1.777	9.95	0.312	1.192	1.180	0.611
I-1-17	0.4265	4.004	16.680	1.780	10.25	0.302	1.170	1.155	0.608
I-1-18	0.4265	4.004	16.715	1.783	9.37	0.331	1.265	1.285	0.539
I-1-19	0.4265	3.998	16.681	1.783	9.70	0.320	1.222	1.240	0.629
Across grain average				1.779	9.88	0.314	1.202	1.210	0.612
I-1-21	0.4265	4.001	16.694	1.782	7.27	0.426	2.120	2.150	0.713
I-1-22	0.4265	4.001	16.733	1.787	7.18	0.432	2.050	2.030	0.703
I-1-23	0.4265	4.001	16.714	1.783	7.44	0.417	2.030	2.090	0.720
I-1-24	0.4265	4.002	16.665	1.779	7.42	0.418	1.975	2.010	0.699
I-1-25	0.4270	4.002	16.644	1.772	7.60	0.408	1.915	1.945	0.694
I-1-26	0.4265	4.002	16.667	1.779	7.46	0.415	1.972	2.015	0.701
I-1-27	0.4265	4.002	16.675	1.780	7.42	0.418	1.973	2.020	0.702
I-1-28	0.4265	4.002	16.659	1.778	7.55	0.411	1.955	1.977	0.699
I-1-29	0.4265	4.002	16.659	1.778	7.40	0.419	2.010	2.025	0.702
I-1-30	0.4265	4.002	16.651	1.777	7.53	0.412	1.940	1.965	0.694
I-1-31	0.4265	4.002	16.694	1.782	7.44	0.417	1.955	1.985	0.700
I-1-32	0.4265	4.002	16.642	1.776	7.47	0.415	1.875	2.000	0.694
I-1-33	0.4265	4.001	16.614	1.774	7.64	0.406	1.942	1.975	0.698
I-1-34	0.4265	4.001	16.697	1.783	7.38	0.420	1.960	1.970	0.695
I-1-35	0.4265	4.001	16.682	1.781	7.42	0.418	2.005	2.020	0.702
I-1-36	0.4265	4.002	16.660	1.778	7.40	0.419	1.955	2.000	0.695
I-1-37	0.4265	3.954	16.492	1.782	7.35	0.422	1.940	2.000	0.693
With grain average				1.779	7.43	0.417	1.975	2.010	0.700

CTE = $2.13 \times 10^{-6}/^{\circ}\text{C}$ across grain; $0.86 \times 10^{-6}/^{\circ}\text{C}$ with grain
T/L ratio = 2.48

HW-80752

TABLE XXXV
Impregnation-Binder Series
9.9 w/o Impregnant Carbon

Sample	Diameter (in.)	Length (in.)	Weight (g)	B. D. (g/cc)	P_0 (10^{-4} cm)	K_0 (cal/sec.cm.deg)	E_F (10^6 lbs/in ²)	E_L (10^6 lbs/in ²)	G (10^6 lbs/in ²)
I-2-1	0.4260	4.004	16.717	1.788	9.79	0.317	1.215	1.218	0.614
I-2-2	0.4260	4.004	16.705	1.786	9.99	0.310	1.160	1.144	0.597
I-2-3	0.4265	4.004	16.742	1.786	9.99	0.310	1.200	1.200	0.615
I-2-4	0.4265	4.004	16.790	1.791	10.10	0.307	1.270	1.270	0.624
I-2-5	0.4265	4.004	16.719	1.784	10.32	0.300	1.140	1.140	0.601
I-2-6	0.4265	4.004	16.687	1.780	9.94	0.312	1.200	1.190	0.598
I-2-7	0.4265	4.004	16.747	1.787	9.70	0.320	1.220	1.200	0.615
I-2-8	0.4265	4.004	16.711	1.783	10.10	0.307	1.170	1.145	0.591
I-2-9	0.4265	4.004	16.737	1.786	10.03	0.309	1.180	1.200	0.594
I-2-10	0.4265	4.004	16.758	1.788	9.99	0.310	1.195	1.198	0.602
I-2-11	0.4265	4.004	16.759	1.788	9.16	0.338	1.310	1.310	0.580
I-2-12	0.4265	4.004	16.832	1.796	9.20	0.337	1.305	1.232	0.596
I-2-13	0.4265	4.004	16.711	1.783	10.28	0.302	1.160	1.145	0.597
I-2-14	0.4265	4.004	16.648	1.776	10.63	0.292	1.150	1.140	0.595
I-2-15	0.4265	4.004	16.764	1.789	9.69	0.320	1.310	1.298	0.625
I-2-16	0.4265	4.004	16.723	1.784	10.05	0.308	1.173	1.165	0.601
I-2-17	0.4265	4.004	16.783	1.791	9.75	0.318	1.270	1.246	0.593
I-2-18	0.4260	4.004	16.779	1.794	10.01	0.310	1.185	1.148	0.601
I-2-19	0.4265	3.945	16.413	1.777	10.17	0.305	1.190	1.166	0.597
I-2-20	0.4265	4.004	16.743	1.786	9.34	0.332	1.310	1.296	0.629
Across grain average				1.786	9.89	0.314	1.216	1.203	0.603
I-2-21	0.4265	4.000	16.737	1.787	7.42	0.418	1.820	1.865	0.689
I-2-22	0.4265	4.002	16.731	1.786	7.47	0.415	1.940	1.970	0.701
I-2-23	0.4270	4.002	16.755	1.784	7.80	0.398	1.850	1.875	0.697
I-2-24	0.4265	4.002	16.721	1.785	7.46	0.416	1.980	2.010	0.708
I-2-25	0.4265	4.001	16.702	1.783	7.79	0.398	1.810	1.830	0.687
I-2-26	0.4265	4.001	16.721	1.785	7.79	0.398	1.700	1.800	0.680
I-2-27	0.4265	4.001	16.772	1.791	7.55	0.411	1.775	1.770	0.674
I-2-28	0.4265	4.001	16.702	1.783	7.68	0.404	1.800	1.820	0.687
I-2-29	0.4265	3.997	16.703	1.785	7.51	0.413	1.895	1.945	0.701
I-2-30	0.4265	4.002	16.740	1.783	7.24	0.428	2.020	2.060	0.716
I-2-31	0.4265	4.001	16.736	1.787	7.46	0.416	1.795	1.800	0.672
I-2-32	0.4265	4.002	16.681	1.781	8.30	0.374	1.485	1.540	0.630
I-2-33	0.4270	4.002	16.710	1.779	7.47	0.415	1.815	1.880	0.693
I-2-34	0.4265	4.001	16.681	1.781	7.42	0.418	1.815	1.860	0.686
I-2-35	0.4265	3.999	16.744	1.789	7.49	0.414	1.855	1.895	0.703
I-2-36	0.4275	3.999	16.776	1.784	7.38	0.420	1.850	1.890	0.696
I-2-37	0.4280	4.001	16.956	1.797	6.88	0.451	2.010	2.035	0.728
I-2-38	0.4280	4.000	16.969	1.799	7.06	0.439	1.975	2.005	0.712
With grain average				1.786	7.51	0.413	1.844	1.881	0.692

CTE = $2.13 \times 10^{-6}/^{\circ}\text{C}$ across grain; 0.78×10^{-6} with grain
T/L ratio = 2.73

TABLE XXXVI

Impregnation-Binder Series
~ 14.5 w/o Impregnant Carbon

Sample	Weight (g)	B. D. (g/cc)	ρ_0 ($10^{-4} \Omega \text{cm}$)	K_0 (cal/sec.cm.deg)	E_F (10^4lbs/in^2)	E_L (10^4lbs/in^2)	G (10^4lbs/in^2)
I-3-1	16.6000	1.779	11.0	0.282	1.03	1.13	0.590
I-3-2	16.5710	1.776	10.7	0.290	1.17	1.17	0.602
I-3-3	16.6290	1.782	10.9	0.284	1.13	1.13	0.589
I-3-4	16.5337	1.772	10.3	0.301	1.25	1.25	0.611
I-3-5	16.6060	1.780	11.1	0.279	1.10	1.10	0.574
I-3-6	16.5667	1.776	10.1	0.307	1.27	1.27	0.612
I-3-7	16.5673	1.776	10.7	0.290	1.07	1.17	0.598
I-3-8	16.5734	1.776	10.3	0.301	1.26	1.26	0.607
I-3-9	16.5870	1.778	11.0	0.282	1.14	1.13	0.580
I-3-10	16.7562	1.796	10.2	0.304	1.18	1.18	0.579
I-3-11	16.6348	1.783	10.6	0.292	1.12	1.12	0.583
I-3-12	16.4910	1.768	10.6	0.292	1.19	1.19	0.586
I-3-13	16.5558	1.774	10.5	0.295	1.26	1.25	0.611
I-3-14	17.0693	1.829	7.3	0.423	2.29	2.28	0.791
I-3-15	16.6712	1.787	10.7	0.290	1.15	1.14	0.596
I-3-16	16.4518	1.763	10.5	0.295	1.17	1.18	0.591
I-3-17	16.7900	1.797	10.5	0.295	1.29	1.27	0.608
I-3-18	16.5960	1.776	10.8	0.287	1.19	1.19	0.598
I-3-19	16.5370	1.774	11.1	0.279	1.15	1.15	0.538
I-3-20	16.5705	1.774	9.7	0.320	1.27	1.28	0.611
Across grain average 1.781			10.4	0.298	1.23	1.24	0.603
I-3-21	16.8768	1.809	7.51	0.412	2.20	2.19	0.775
I-3-22	16.8497	1.809	7.78	0.398	2.26	2.34	0.827
I-3-23	16.8938	1.811	6.96	0.445	2.35	2.35	0.802
I-3-24	16.7490	1.798	7.60	0.408	2.15	2.19	0.791
I-3-25	16.7903	1.800	8.36	0.371	1.97	2.15	0.768
I-3-26	16.8980	1.814	7.67	0.404	2.41	2.43	0.853
I-3-27	16.7485	1.795	7.96	0.389	2.26	2.25	0.784
I-3-28	16.8425	1.809	7.64	0.406	2.23	2.20	0.796
I-3-29	16.8430	1.805	7.47	0.415	2.00	2.05	0.744
I-3-30	16.8944	1.814	7.59	0.409	2.35	2.33	0.763
I-3-31	16.8900	1.810	7.74	0.401	2.41	2.36	0.836
I-3-32	16.9908	1.824	6.99	0.444	2.39	2.38	0.821
I-3-33	17.1170	1.838	7.28	0.426	2.40	2.40	0.780
I-3-34	16.9210	1.817	7.63	0.406	2.27	2.27	0.821
I-3-35	16.9998	1.825	7.45	0.416	2.06	2.18	0.770
I-3-36	16.8487	1.809	7.71	0.402	2.40	2.42	0.966
I-3-37	16.9792	1.821	7.58	0.415	2.36	2.33	0.809
I-3-38	16.8835	1.811	7.61	0.407	2.27	2.33	0.812
I-3-39	16.9461	1.817	7.58	0.415	2.16	2.22	0.784
I-3-40	16.8822	1.807	7.97	0.389	1.90	1.93	0.710
With grain average 1.812			7.60	0.408	2.24	2.27	0.801

All samples 0.426" diameter by 4.00" long

CTE = $2.23 \times 10^{-6}/^{\circ}\text{C}$ across grain; $0.82 \times 10^{-6}/^{\circ}\text{C}$ with grain

T/L ratio = 2.72

HW-80752

TABLE XXXVII

Impregnation-Binder Series ~11 w/o Impregnant Carbon

Sample	Length (in.)	Weight (g)	B. D. (g/cc)	ρ_0 ($10^{-4}\Omega\text{cm}$)	K_0 (cal/sec.cm.deg)	E_F (10^6lbs/in^2)	E_L (10^6lbs/in^2)	G (10^6lbs/in^2)
I-4-1	3.81	16.1783	1.820	9.32	0.332	1.163	1.037	0.586
I-4-2	3.81	16.0723	1.808	10.20	0.304	0.976	0.949	0.530
I-4-3	3.81	16.0900	1.810	9.70	0.320	1.138	0.946	0.557
I-4-4	3.81	16.0000	1.799	10.29	0.302	1.027	1.089	0.494
I-4-5	3.81	16.1401	1.815	9.12	0.340	1.160	1.159	0.589
I-4-6	3.81	16.1127	1.812	9.17	0.338	1.191	1.217	0.582
I-4-7	3.81	16.0920	1.806	9.28	0.334	0.833	0.806	0.524
I-4-8	3.81	16.1608	1.818	9.21	0.336	1.441	1.255	0.622
I-4-9	3.81	16.0128	1.801	10.23	0.303	1.156	1.016	0.512
I-4-10	3.81	16.1165	1.813	10.18	0.305	0.984	0.961	0.561
I-4-11	3.81	16.1558	1.817	10.62	0.292	1.027	0.997	0.558
I-4-12	3.81	16.0961	1.807	9.67	0.320	1.002	0.958	0.534
I-4-13	3.81	16.0727	1.808	9.55	0.324	1.072	1.086	0.547
I-4-14	3.80	16.1581	1.821	9.08	0.342	1.333	1.216	0.590
I-4-15	3.81	16.1515	1.817	9.13	0.340	1.245	1.228	0.614
I-4-16	3.81	16.1556	1.817	9.54	0.325	1.141	0.997	0.567
I-4-17	3.81	16.0944	1.810	9.84	0.315	0.992	0.877	0.476
I-4-18	3.56	15.0349	1.805	10.80	0.287	1.000	0.837	0.524
I-4-19	3.45	14.6560	1.817	10.23	0.303	0.989	0.998	0.549
Across grain average			1.812	9.75	0.318	1.098	1.033	0.553
I-4-21	4.00	16.7600	1.794	6.04	0.513	2.48	2.51	0.694
I-4-22	4.00	16.8049	1.802	6.07	0.511	2.34	2.38	0.661
I-4-23	4.00	17.0283	1.823	5.76	0.538	2.52	2.55	0.697
I-4-24	4.00	16.7347	1.795	5.98	0.519	2.82	2.45	0.709
I-4-25	4.00	16.8848	1.811	5.86	0.529	2.50	2.52	0.784
I-4-26	4.00	16.7663	1.795	6.04	0.513	2.43	2.48	0.690
I-4-27	4.00	16.7548	1.793	6.06	0.511	2.42	2.47	0.687
I-4-28	4.00	16.9227	1.811	5.71	0.542	2.59	2.66	0.755
I-4-29	4.00	16.9139	1.814	5.76	0.538	2.47	2.55	0.727
I-4-30	4.00	16.6880	1.790	6.05	0.512	2.32	2.40	0.634
I-4-31	4.00	17.0060	1.824	5.71	0.542	2.52	2.54	0.700
I-4-32	4.00	16.9306	1.812	5.76	0.538	2.45	2.50	0.708
I-4-33	4.00	16.9170	1.814	5.79	0.536	2.47	2.51	0.742
I-4-34	4.00	16.9606	1.819	5.66	0.547	2.73	2.80	0.750
I-4-35	4.00	16.8452	1.807	5.72	0.541	2.51	2.54	0.735
I-4-36	4.00	16.7817	1.800	6.04	0.513	2.34	2.38	0.669
I-4-37	4.00	16.7581	1.797	5.77	0.537	2.44	2.49	0.721
I-4-38	4.00	16.7633	1.798	5.76	0.538	2.46	2.50	0.699
I-4-39	4.00	16.8380	1.806	5.71	0.542	2.49	2.52	0.728
I-4-40	4.00	16.8995	1.812	5.81	0.533	2.45	2.49	0.692
With grain average			1.806	5.85	0.530	2.48	2.51	0.708

All samples 0.426" diameter

CTE = $2.36 \times 10^{-6}/^\circ\text{C}$ across grain; 0.71×10^{-6} with grain

T/L ratio = 3.32

HW-80752

TABLE XXXVIII

R Series
Across Grain Samples

Sample	Diameter (in.)	Length (in.)	Weight (g)	B. D. (g/cc)	ρ_0 ($10^{-4} \Omega \text{cm}$)	K_0 (cal/sec.cm.deg)	E_F (10^6bs/in^2)	E_L (10^6bs/in^2)	G (10^6bs/in^2)
R-1	0.4267	3.970	17.4508	1.876	15.0	0.207	1.29	1.29	0.626
R-2	0.4250	3.997	17.4141	1.874	14.8	0.210	1.28	1.28	0.618
R-3	0.4280	3.996	17.5903	1.867	15.1	0.206	1.24	1.25	0.623
R-4	0.4263	3.998	17.4876	1.870	15.5	0.200	1.27	1.27	0.616
R-5	0.4263	3.997	17.4057	1.862	15.7	0.198	1.25	1.25	0.610
R-6	0.4245	3.998	17.3145	1.867	15.4	0.202	1.27	1.28	0.622
R-7	0.4214	3.929	16.7550	1.866	14.7	0.211	1.25	1.25	0.606
R-8	0.4240	3.998	17.3418	1.875	14.8	0.210	1.29	1.29	0.628
R-9	0.4230	3.998	17.2863	1.878	14.3	0.217	1.28	1.28	0.624
R-10	0.4255	3.998	17.4155	1.869	15.0	0.207	1.30	1.30	0.619
R-11	0.4248	3.998	17.3495	1.869	14.6	0.212	1.33	1.33	0.628
R-12	0.4260	3.998	17.4728	1.871	15.3	0.203	1.33	1.34	0.633
R-13	0.4245	3.998	17.2804	1.864	14.9	0.208	1.26	1.26	0.611
R-14	0.4250	3.998	17.2685	1.858	14.8	0.210	1.23	1.23	0.603
R-15	0.4248	3.998	17.3408	1.868	15.3	0.203	1.25	1.23	0.611
R-16	0.4265	3.998	17.3510	1.854	15.5	0.200	1.22	1.23	0.605
R-17	0.4265	3.998	17.4708	1.867	15.2	0.204	1.24	1.24	0.613
R-18	0.4250	3.998	17.2817	1.859	15.5	0.200	1.23	1.24	0.610
R-19	0.4250	3.997	17.2665	1.858	16.3	0.190	1.24	1.26	0.612
R-20	0.4230	3.998	17.0764	1.855	14.9	0.208	1.25	1.25	0.609
R-21	0.4263	3.998	17.5160	1.873	14.9	0.208	1.26	1.26	0.621
R-22	0.4265	3.998	17.4170	1.862	15.6	0.199	1.26	1.26	0.613
R-23	0.4250	3.998	17.2900	1.860	15.6	0.199	1.25	1.26	0.611
R-24	0.4210	3.997	16.9965	1.863	15.7	0.198	1.27	1.27	0.613
R-25	0.4190	3.998	16.8294	1.864	15.7	0.198	1.22	1.21	0.608
R-26	0.4245	3.998	17.1460	1.849	16.1	0.193	1.15	1.16	0.580
R-27	0.4235	3.998	17.0919	1.852	15.2	0.204	1.15	1.16	0.575
R-28	0.4240	3.998	17.0265	1.841	16.5	0.188	1.14	1.14	0.574
R-29	0.4265	3.998	17.2675	1.845	16.1	0.193	1.12	1.13	0.567
R-30	0.4266	3.998	17.2578	1.843	16.8	0.185	1.11	1.11	0.561
R-31	0.4265	3.998	17.2943	1.848	16.1	0.193	1.17	1.17	0.586
R-32	0.4265	3.998	17.2140	1.839	16.8	0.185	1.07	1.08	0.549
Average:				1.861	15.4	0.201	1.23	1.24	0.606

CTE = $3.27 \times 10^{-6}/^\circ\text{C}$; T/L ratio = 1.32

HW-80752

TABLE XXXIX

R Series With Grain "A" Samples

Sample	Diameter (in.)	Length (in.)	Weight (g)	B. D. (g/cc)	ρ_0 (10^{-4} g/cm)	K_0 (cal/sec. cm. deg)	E_F (10^4 lbs/in ²)	E_L (10^4 lbs/in ²)	G (10^4 lbs/in ²)
R-40	0.4223	3.998	17.0480	1.858	12.3	0.252	1.63	1.63	0.651
R-41	0.4202	3.997	16.8395	1.854	12.5	0.248	1.57	1.56	0.626
R-42	0.4233	3.998	17.1403	1.859	11.8	0.263	1.58	1.59	0.640
R-43	0.4253	3.998	17.3474	1.864	12.4	0.250	1.65	1.63	0.650
R-44	0.4260	3.998	17.3308	1.856	12.1	0.266	1.58	1.59	0.636
R-45	0.4240	3.998	17.1518	1.854	11.8	0.263	1.57	1.58	0.631
R-46	0.4245	3.997	17.1193	1.847	12.2	0.254	1.52	1.53	0.612
R-47	0.4285	3.998	17.5184	1.854	12.1	0.256	1.58	1.60	0.635
R-48	0.4255	3.998	17.3080	1.858	12.0	0.258	1.58	1.60	0.637
R-49	0.4271	3.998	17.5400	1.869	11.9	0.260	1.63	1.64	0.653
R-50	0.4265	3.998	17.5562	1.876	11.8	0.263	1.66	1.67	0.658
R-51	0.4205	3.998	17.1050	1.880	12.3	0.252	1.69	1.69	0.668
R-52	0.4275	3.998	17.4625	1.857	12.2	0.254	1.58	1.58	0.638
R-53	0.4160	3.998	16.5165	1.855	12.0	0.258	1.57	1.58	0.639
R-54	0.4258	3.999	17.3550	1.860	12.3	0.252	1.57	1.58	0.636
R-55	0.4260	3.998	17.3056	1.853	12.5	0.248	1.59	1.62	0.636
R-56	0.4259	3.998	17.2975	1.853	12.0	0.258	1.58	1.59	0.630
R-57	0.4270	3.998	17.3752	1.852	12.2	0.254	1.54	1.55	0.628
R-58	0.4119	3.998	16.2216	1.858	12.1	0.256	1.59	1.59	0.638
R-59	0.4236	3.998	17.1500	1.857	12.2	0.254	1.56	1.58	0.623
R-60	0.4254	3.997	17.3215	1.861	12.0	0.258	1.56	1.58	0.632
R-61	0.4268	3.998	17.4762	1.865	12.3	0.252	1.60	1.61	0.646
R-62	0.4264	3.998	17.5243	1.873	11.8	0.263	1.65	1.67	0.656
R-63	0.4232	3.998	17.2623	1.873	11.8	0.263	1.65	1.67	0.660
R-64	0.4266	3.999	17.3619	1.854	12.2	0.254	1.56	1.57	0.631
R-65	0.4090	3.553	14.1657	1.852	12.3	0.252	1.57	1.58	0.633
R-66	0.4257	3.996	17.3178	1.858	12.4	0.250	1.58	1.58	0.630
R-67	0.4248	3.998	17.2493	1.858	12.4	0.250	1.62	1.61	0.640
R-68	0.4243	3.998	17.1153	1.848	12.1	0.256	1.57	1.58	0.629
R-69	0.4112	3.998	16.0537	1.845	12.3	0.252	1.55	1.55	0.623
R-70	0.4256	3.999	17.2464	1.850	12.0	0.258	1.58	1.58	0.626
R-71	0.4250	3.998	17.2578	1.857	12.1	0.256	1.58	1.59	0.634
R-72	0.4244	3.998	17.2453	1.861	12.0	0.258	1.60	1.61	0.639
R-73	0.4245	3.998	17.2764	1.863	12.3	0.252	1.60	1.60	0.646
R-74	0.4253	3.997	17.4251	1.873	12.1	0.256	1.63	1.65	0.653
R-75	0.4260	3.998	17.4970	1.874	12.2	0.254	1.67	1.68	0.651
Average:				1.859	12.1	0.256	1.59	1.60	0.639

CTE = 2.49×10^{-6} / °C; T/L ratio = 1.32

HW-80752

TABLE XL
R Series With Grain "B" Samples

Sample	Length (in.)	Weight (g)	B. D. (g/cc)	ρ_0 ($10^{-4}\Omega\text{cm}$)	K_0 (cal/sec.cm.deg)	E_F (10^6lbs/in^2)	E_L (10^6lbs/in^2)	G (10^6lbs/in^2)
D-5-2	4.00	19.5210	2.092	4.58	0.677	3.40	3.47	0.696
D-5-3	4.00	19.5140	2.092	4.97	0.624	3.28	3.43	0.716
D-5-4	4.00	19.5960	2.100	4.64	0.669	3.61	3.80	0.722
D-5-5	4.00	19.5243	2.093	4.55	0.681	3.46	3.65	0.698
D-5-6	4.00	19.4775	2.088	4.88	0.635	3.30	3.42	0.696
D-5-7	4.00	19.4610	2.090	5.03	0.617	3.16	3.30	0.676
D-5-8	4.00	19.5635	2.097	4.86	0.638	3.38	3.48	0.705
D-5-9	4.00	19.5368	2.094	5.13	0.605	3.38	3.43	0.680
D-5-10	4.00	19.5470	2.099	4.80	0.646	3.40	3.62	0.684
D-5-11	4.00	19.4757	2.087	4.91	0.631	3.21	3.28	0.705
D-5-12	4.00	19.4900	2.093	4.67	0.664	3.26	3.50	0.678
D-5-13	4.00	19.5109	2.092	4.87	0.637	3.31	3.29	0.699
D-5-14	4.00	19.6392	2.104	4.48	0.692	3.63	3.63	0.702
With grain average			2.094	4.79	0.647	3.37	3.48	0.697
D-5-21	2.81	13.6738	2.089	24.0	0.129	0.534	0.538	0.456
D-5-22	2.81	13.6723	2.089	23.1	0.134	0.534	0.554	0.458
D-5-23	2.81	13.7090	2.095	23.6	0.131	0.480	0.496	0.430
D-5-24	2.81	13.7285	2.098	26.7	0.116	0.473	0.479	0.424
D-5-25	2.81	13.7247	2.097	26.0	0.119	0.481	0.488	0.427
D-5-26	2.81	13.6920	2.092	27.0	0.115	0.497	0.518	0.443
D-5-27	2.81	13.6700	2.089	24.4	0.127	0.504	0.510	0.436
D-5-28	2.81	13.6970	2.093	23.9	0.130	0.492	0.495	0.434
D-5-29	2.81	13.7040	2.094	25.9	0.120	0.497	0.512	0.445
D-5-30	2.81	13.6987	2.093	24.1	0.129	0.501	0.516	0.444
D-5-31	2.81	13.7061	2.094	27.0	0.115	0.489	0.503	0.441
D-5-32	2.81	13.6950	2.093	24.2	0.128	0.513	0.520	0.449
D-5-33	2.81	13.7484	2.097	26.0	0.119	0.477	0.491	0.430
Across grain average			2.093	25.1	0.124	0.498	0.509	0.440

All samples 0.426" diameter

CTE = $10.6 \times 10^{-6}/^\circ\text{C}$ across grain; $0.09 \times 10^{-6}/^\circ\text{C}$ with grain
T/L ratio = 118

HW-80752

TABLE XLI
Calcine-Binder Series Across Grain

Sample	Cross Section (in x in)	Length (in)	Weight (g)	B. D. (g/cc)	Resistivity ($10^{-4}\Omega\text{cm}$)	Conductivity (cal/sec cm deg)	Sonic Moduli		
							E_F (10^6 psi)	E_L (10^6 psi)	E_G (10^6 psi)
X6PF-1	.3027 x .3024	1.6586	3.1064	1.25	21.1	0.142	0.291	0.304	0.146
6PF-1	.3025 x .3025	1.6440	3.0731	1.24	21.9	0.137	0.281	0.286	0.145
X6PF-2	.3024 x .3024	1.8030	3.3962	1.26	22.3	0.135	0.265	0.274	0.144
6PF-2	.3025 x .3027	1.7487	3.2914	1.25	22.6	0.133	0.280	0.282	0.142
X9PF-1	.3023 x .3020	2.0704	4.2087	1.36	18.3	0.164	0.369	0.371	0.202
9PF-1	.3020 x .3014	2.0763	4.2049	1.36	17.9	0.168	0.371	0.371	0.217
X9PF-2	.3020 x .3016	2.0790	4.1938	1.35	18.0	0.167	0.351	0.348	0.200
9PF-2	.3024 x .3023	2.0810	4.2043	1.35	19.7	0.152	0.318	0.318	0.174
X13PF-1	.3024 x .3021	1.8715	3.9805	1.42	18.9	0.159	0.316	0.319	0.178
13PF-1	.3023 x .3023	1.8739	4.0418	1.44	16.5	0.182	0.374	0.376	0.201
X13PF-2	.3027 x .3028	1.8505	3.9537	1.42	19.8	0.152	0.306	0.329	0.169
13PF-2	.3030 x .3028	1.8659	3.9920	1.42	19.8	0.152	0.297	0.295	0.182
X10PFR	.3025 x .3015	1.7945	3.7876	1.41	17.6	0.170	0.364	0.375	0.200
10PFR	.3023 x .3023	1.7738	3.7513	1.42	16.5	0.182	0.388	0.359	0.186
X5PFR	.3025 x .3004	1.8053	3.6920	1.37	18.3	0.164	0.355	0.357	0.187
5PFR	.3028 x .3028	1.7908	3.7407	1.39	19.2	0.156	0.331	0.334	0.187
X6PM-1	.3025 x .3025	1.5478	3.1210	1.34	22.5	0.138	0.304	0.312	0.176
6PM-1	.3024 x .3027	1.4866	2.9851	1.34	21.6	0.144	0.321	0.323	0.176
X9PM-1	.3024 x .3026	1.5100	3.3997	1.50	17.6	0.176	0.544	0.535	0.287
9PM-1	.3020 x .3035	1.5388	3.4613	1.50	16.4	0.189	0.544	0.545	0.270
X9PM-2	.3025 x .3023	1.7855	3.9267	1.47	17.3	0.179	0.506	0.508	0.257
9PM-2	.3027 x .3026	1.7528	3.9754	1.51	17.1	0.181	0.513	0.532	0.273
X13PM-1	.3023 x .3008	1.7340	3.7237	1.44	23.8	0.130	0.331	0.344	0.171
13PM-1	.3018 x .3022	1.7455	3.7807	1.45	24.7	0.126	0.322	0.337	0.174
X13PM-2	.3013 x .3024	1.6676	3.6004	1.45	24.2	0.128	0.317	0.330	0.150
13PM-2	.3023 x .3024	1.6730	3.6294	1.45	23.4	0.133	0.328	0.330	0.152
X6FAP-1	.3025 x .3024	1.6975	3.4189	1.34	11.0	0.282	0.332	0.307	0.181
6FAP-1	.3028 x .3034	1.6933	3.4238	1.35	9.9	0.314	0.356	0.358	0.206
X6FAP-2	.3023 x .3030	1.6128	3.2423	1.34	12.3	0.252	0.307	0.302	0.196
6FAP-2	.3027 x .3036	1.6098	3.2432	1.34	11.5	0.270	0.323	0.323	0.198
X9FAP-1	.3023 x .3025	1.7593	3.5271	1.34	13.3	0.233	0.344	0.372	0.220
9FAP-1	.3025 x .3024	1.7380	3.4864	1.34	16.6	0.187	0.209	0.206	0.176
X9FAP-2	.3029 x .3024	1.6115	3.2269	1.34	14.9	0.208	0.337	0.281	0.173
9FAP-2	.3033 x .3026	1.6545	3.3272	1.34	15.8	0.196	0.231	0.278	0.173
X13FAP-1	.3021 x .3024	1.5178	3.1251	1.38	16.6	0.187	0.227	0.227	0.174
13FAP-1	.3024 x .3021	1.5049	3.1136	1.39	18.8	0.165	0.227	0.220	0.180
X13FAP-2	.3024 x .3028	1.7487	3.6142	1.38	21.1	0.147	-	-	-
13FAP-2	.3029 x .3023	1.7950	3.7157	1.38	17.4	0.178	0.206	0.191	0.168
X6MAP-1	.3031 x .3030	1.5090	3.2613	1.44	8.8	0.352	0.523	0.521	0.282
6MAP-1	.3030 x .3030	1.4946	3.2200	1.43	9.2	0.336	0.492	0.481	0.274
X6MAP-2	.3030 x .3033	1.3265	2.8529	1.43	10.0	0.310	0.469	0.375	0.202
6MAP-2	.3030 x .3033	1.3514	2.9079	1.43	10.2	0.304	0.453	0.457	0.274
X9MAP-1	.3030 x .3030	1.6588	3.4615	1.39	11.3	0.274	0.456	0.462	0.254
9MAP-1	.3030 x .3028	1.4652	3.0555	1.39	13.8	0.225	0.392	0.412	0.238
X9MAP-2	.3027 x .3023	1.4374	2.9872	1.39	14.5	0.214	0.362	0.378	0.247
X13MAP-1	.3025 x .3031	1.2946	2.7902	1.43	14.9	0.208	0.373	0.379	0.245
13MAP-1	.3029 x .3030	1.3114	2.8226	1.43	15.2	0.204	0.320	0.290	0.238
X13MAP-2	.3030 x .3030	1.5610	3.3498	1.43	16.3	0.190	0.323	0.315	0.227
13MAP-2	.3024 x .3022	1.5834	3.3796	1.43	17.0	0.182	0.300	0.294	0.219

TABLE XLII
Calcine-Binder Series Averages

Sample Set	Coke Source	Calcine Temp. °C	Per Cent Binder Carbon	Max. Part. Size (inch)	Binder	B. D. (g/cc)	$\bar{\rho}_0$ ($10^{-4}\Omega\text{cm}$)	E_0 (10^6lbs/in^2)	$\bar{C}_0$ (10^6lbs/in^2)
6PF	Continental	600	14.0	0.016	30 Med. Pitch	1.25	22.0	0.283	0.144
9PF		900	17.5			1.36	18.5	0.352	0.198
13PF		1300	17.8			1.43	18.8	0.327	0.183
6PM	Continental	600	18.0	0.006	30 Med. Pitch	1.34	22.1	0.315	0.176
9PM		900	19.8			1.49	17.1	0.528	0.272
13PM		1300	15.5			1.45	24.0	0.330	0.162
6FAP	Laboratory	600	16.0	0.016	Acenaphthylene	1.34	11.2	0.326	0.195
9FAP		900	17.7			1.34	15.2	0.282	0.186
13FAP		1300	18.5			1.38	18.5	0.227	0.174
6MAP	Laboratory	600	16.4	0.006	Acenaphthylene	1.43	9.6	0.471	0.258
9MAP		900	17.0			1.39	13.2	0.410	0.246
13MAP		1300	18.3			1.43	15.9	0.324	0.232

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