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PROPERTIES OF ATJ GRAPHITE

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**Astronuclear Laboratory
Westinghouse Electric Corporation**

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ABSTRACT

Selected physical and mechanical properties of ATJ molded graphite were investigated for the 9 X 20 X 24-inch stock in connection with its use for NERVA hardware. Graphite density was found to range from about 1.50 to 1.80 g/cc near the mold surfaces, and 1.69 to 1.76 g/cc near the block's center. Both flexure strength and hardness were found to increase with density, while electrical resistivity decreased. In the case of tensile and compressive strength, dependence on density was not evident. Thermal expansion and tensile strength were studied between room temperature and 2800°C (5070°F), while the remaining properties were determined at room temperature only. All properties exhibited considerable scatter, even when measured on specimens of comparable density.

Thermal expansion coefficient in the room-temperature to 1090°C (2000°F) range was 1.70 microinches per inch per Fahrenheit degree in the with-grain direction and 2.40 in the across-grain direction. At lower temperatures the manufacturer's results showed large scatter and poor agreement with WANL results.

Electrical resistivity of ATJ was 1.12 milliohm-centimeters in the with-grain direction and 1.54 across the grain for a specimen density of 1.73 g/cc, in fair agreement with the manufacturer's data.

Graphite hardness was measured on the Rockwell "B" Scale with a 1/8-inch steel ball and 60 kg load. Indentation readings were converted to linear scale hardness values. A rapid increase of hardness with density was observed. The sub-surface damage below the indentation was found to be of localized extent. Values of graphite hardness showed good correlation with its flexure strength.

Tensile tests were made on thread and shoulder-loaded specimens having gage diameters of 0.25 and 0.50 inches respectively. The large discrepancies observed for the ATJ tensile strength values in the literature can be explained in terms of specimen design. Tensile strength of ATJ graphite (approximately 1.72 to 1.78 g/cc density range) in the with-grain direction was 4020 psi for the shoulder-loaded specimen-4370 and 3580 psi for thread-loaded specimen. Across-grain values for the latter specimen were 3020 and 2710 psi. At 1720°C (3125°F), the average with-grain strength was 5290 psi compared to 3900 psi across the grain; at 2390°C (4335°F) the average strength values were 6830 and 4750 psi, respectively. All high-temperature tests were made on thread-loaded specimens. The lowest with-grain tensile results were comparable to across-grain strength values.

Flexure strength was found to depend on density. For 1.73 g/cc specimens, the average values were 4300 psi with grain and 3800 psi across the grain. All tests were made using four-point loading on bars with rectangular cross-section. Flexure strength averages reported in the literature showed a large scatter due to differences in specimen densities and possibly geometries. The flexure strength was found to be sensitive to irregularities on the tensile face, but not to simulated defects within the specimen.

Compressive strength values were nearly independent of orientation and density, although the number of tests was too small for rigorous conclusions. The average compressive strength was 9530 psi; the literature survey showed large variations in the reported results.

Finally, the stress-strain behavior of ATJ graphite was investigated at room temperature with resistance strain gages. Permanent set was observed to occur in tension, flexure, and compression. In addition, the tensile elongation was determined at elevated temperatures by comparing specimen length before and after fracture.

INTRODUCTION

Due to the fine-grained particle mix, relatively flaw-free structure, and good strength properties, ATJ graphite has found wide acceptance in both nuclear and aerospace applications. This grade has achieved an informal status as the standard of comparison for newly developed graphites. It is used in the NERVA engine for a number of applications demanding high reliability during the reactor's operation.

This report surveys the physical and mechanical properties of ATJ graphite as an aid to both the engineer concerned with the hardware's performance, and the designer seeking to improve this hardware. An extensive effort has been made to summarize the test results published by the previous investigators. WANL test data has been aimed primarily at confirming and extending these results and answering certain problems not covered in the literature.

ATJ graphite is a molded grade produced by the Carbon Products Division (formerly the National Carbon Company division) of the Union Carbide Corporation.⁽¹⁾ The maximum size of coke particles is 0.006 inch. These particles are bonded together with the carbonaceous residue from a pitch-based binder. The final bake temperature of about 2800°C (5070°F) serves to graphitize this composite structure.

ATJ is produced in the following sizes:	<u>Block</u>	<u>Cylinder</u>
	9 x 20 x 24"	13"D x 14" L
		14"D x 15" L
		16.5"D x 14" L

The most common product is the 9 x 20 x 24-inch block, formed by applying the molding pressure on the 20 x 24-inch faces; this results in a preferential coke grain orientation parallel to these faces, with the across-grain direction being parallel to the 9-inch thickness. The preferential grain orientation subsequently determines the directionality and anisotropy effects for the graphite's properties.

WANL tests have been limited to ATJ graphite stock fabricated in the 9 X 20 X 24-inch size. Such stock was obtained from two sources:

(1) Hardware trimmings: When ATJ is purchased for NERVA hardware per WANL Purchasing Specification 30008, the original 9 X 20 X 24-inch block is trimmed to roughly 5 X 20 X 24 inches, providing 2-inch thick slabs of near-surface material for testing. Each slab is roughly 2 X 10 X 20 inches in size; some of this material is used by the manufacturer for the qualification tests, and the remainder is shipped to WANL.

(2) Regular blocks: A number of untrimmed ATJ blocks were procured to supplement the above test slabs by providing hardware-grade material from the central portion of the block.

In generating the test data for this report, various specimens were machined from three test slabs and two full-size blocks, believed to have been produced by the manufacturer in the 1962-1963 period. The following specimens were obtained from these materials:

<u>SAMPLE MATERIAL</u>	<u>SPECIMENS</u>		
	<u>TENSILE</u>	<u>FLEXURAL</u>	<u>OTHERS</u>
Slab T-1	None	105 WG Bars	None
Slab T-2	30 WG Specimens (609B073 type)	None	None
Slab T-3	20 WG Specimens (L-2 type)	None	None
Block H-1	L-2 Specimens 12 AG 4 WG	Flexure Bars 24 WG 36 AG	Compression and Thermal Expansion
Block H-2	L-2 Specimens 15 WG 8 AG	None	None

The flexure specimens were also used to determine the graphite density, electrical resistivity, and hardness properties.

PART I: PHYSICAL PROPERTIES OF ATJ GRAPHITE

During the initial baking of the pitch-bound coke particles, the volatile products given off by the pitch fraction generate small voids in the interstices between various grains. Such voids, termed pores, are usually smaller than the grains, but their aggregate effect is to decrease the density of graphite from the maximum theoretically attainable value of 2.26 g/cc to the nominal density of 1.73 g/cc usually quoted by the manufacturer for ATJ blocks. Accompanying this decrease in density is the reduction in mechanical strength of graphite, and changes in such structure-sensitive properties as heat conduction, electrical resistance, permeability, and others.

Owing to the imperfect structure of the coke grains themselves, the solid-phase density is on the order of 2.20 g/cc. Specimen density measurements in this program gave values in the 1.57 to 1.82 g/cc range, depending on the location in the parent block. The difference between the solid-phase and specimen densities is due to the varying degree of porosity in the graphite. The typical microstructure of ATJ graphite is shown in Figure 1.

Figure 2 shows density profiles across the 9-inch thickness of a 9 X 20 X 24-inch block. These densities were determined by the weight/volume ratio on flexure bars machined from the T-1 and H-1 samples of ATJ graphite. Comparison with specimen densities from other samples confirms these profiles. The density is highest - 1.80 g/cc or higher - at the block's edge. It decreases toward the block's center, becoming about 1.70 g/cc. The large mold faces exhibit densities as low as 1.50 g/cc within about one inch of the mold surface. The trimmed hardware material is estimated to be in the 1.68 to 1.78 g/cc range.

RADIOGRAPHIC INSPECTION AND CHEMICAL ANALYSIS

The 609B073 tensile specimens machined from the T-2 slab were radiographed prior to testing. At the 2% detection sensitivity (based on the graphite thickness) no voids or

cracks were detected in these specimens. Small, radiographically opaque inclusions were found in some specimens; these inclusions had the following distribution by size:

<u>APPROXIMATE DIAMETER (MILS)</u>	<u>DISTRIBUTION (%)</u>
Below 10 mils	Not detectable
10	10.8
15	29
20	51
25	3.5
30	3.5
40	1.2

They ranged from none to six inclusions per specimen. In contrast to these findings, the post-fracture radiography of randomly selected flexure bars machined from the T-1 slab revealed no opaque inclusions or structural deficiencies such as voids or cracks.

Chemical purity of ATJ graphite was ascertained by spectrographic analysis. Small sections had been cut from two 609B073 type tensile specimens to contain three opaque inclusions of 20-mil size in each section. One section of an L-2 type tensile specimen from the T-3 test slab was submitted for comparison; it had not been radiographed. The following chemical analysis was obtained:

<u>ELEMENT</u>	<u>CONCENTRATION, PARTS PER MILLION</u>		
	<u>SLAB T-2</u>		<u>SLAB T-3</u>
	<u>Sample No. 1</u>	<u>Sample No. 2</u>	
Ag	0.02	0.03	(0.3)
Al	78	79	45
B	2.1	1.5	5.0
Ba	6.5	4.1	15
Be	(0.02)	(0.01)	(0.3)
Bi	(0.05)	(0.04)	(3)
Ca	375	260	675
Cd	(2)	(1)	(10)
Co	0.7	0.4	(1)
Cr	10	6.7	(10)

ELEMENT	CONCENTRATION, PARTS PER MILLION		
	SLAB T-2		SLAB T-3
	Sample No. 1	Sample No. 2	
Cs	---	---	(100)
Cu	0.7	0.4	(0.5)
Fe	173	115	10
In	(2)	(1)	(10)
K	---	---	(10)
Li	---	---	(3)
Mg	0.4	1.4	1.0
Mn	0.8	0.5	(1)
Mo	0.7	0.5	(3)
Na	---	---	(3)
Nb	(0.05)	(0.04)	(3)
Ni	3.0	3.3	(3)
P	---	---	(100)
Pb	0.3	0.4	(10)
Rb	---	---	(30)
Sb	(0.5)	(0.4)	(10)
Si	26	18	85
Sn	(0.2)	(0.1)	(10)
Sr	15	11	(10)
Th	---	---	(10)
Ti	220	137	75
Ta	(0.5)	(0.4)	(10)
V	49	35	50
W	11	6	(10)
Zn	23	16	(10)
Zr	1.7	1.3	10
Ash Content	0.163%	0.137%	---

Impurities are given in parts per million with a relative accuracy of $\pm 30\%$, except that the values in parentheses are the limits of detectability, and the actual concentration of the indicated element is lower.

According to the above analysis, the specimens from Slab T-2 (with three known inclusions each) are higher in iron and titanium than the specimen of unknown radiographic

quality from Slab T-3. The latter contains more calcium and silicon. The ash content of T-2 Slab's samples is comparable to the 0.158% value reported for ATJ graphite by the manufacturer.⁽¹⁾

HARDNESS

The hardness of graphite is generally defined as its ability to resist indentation and abrasion. A variety of test methods are available for its measurement. All such methods are relatively simple, requiring a minimum of specimen preparation, and, therefore, may be considered as an aid in routine inspection of graphite stock. The test results may be correlated with graphite's density and strength.

The hardness measurements in this study were performed on the conventional Rockwell Hardness Tester by indenting broken flexure bars with a 1/8-inch diameter steel ball at 60 kg load, and measuring the size of the residual impression on the Rockwell "B" scale. The Rockwell "B" hardness numbers were then converted to a linearized hardness scale (units in kilograms per square millimeter) according to MacPherson's proposed formula⁽²⁾

$$LSH = \frac{52.8 (kg-8)}{130-N} = \frac{2745}{130-N}$$

where N is the Rockwell "B" number and the load is 60 kg. The test results are summarized in Table 1, and plotted as a function of specimen density in Figure 3.

Figure 3 shows that there is a large scatter in the hardness measurements on flexure specimens of comparable densities. The size of a flexure specimen is much smaller than the volume affected by the hardness test, and hence the local density variations are expected to influence the hardness values. Average hardness shows a substantial increase with density. The hardness values from Slab T-1 are uniformly higher by roughly 10% than those from block H-1, indicating some difference between the two graphite samples.

Figure 4 shows the sub-surface microstructure changes underneath the residual

indentation remaining on the specimen's surface after a hardness test. Immediately under this indentation the coke grains have been crushed and brought into closer contact, thereby eliminating much of the original porosity. At a depth exceeding one indentation diameter, the microstructure does not seem to have been altered.

THERMAL EXPANSION

The expansion behavior of graphite with increasing temperature is governed by its raw materials, their processing during fabrication, and the preferential grain orientation in the final product. Thermal expansion is lowest in the with-grain (WG) direction, but increases in the across-grain (AG) direction. The manufacturer reports the following values from measurements on 5-inch long samples⁽³⁾:

<u>TEMPERATURE</u>		<u>ORIENTATION</u>	<u>ELONGATION</u>	<u>AVERAGE COEFFICIENT OF THERMAL EXPANSION</u>
(°C)	(°F)		(%)	$\left(\frac{\text{Microinches}}{\text{inch}^\circ\text{F}}\right)$
A. Measurements in the low-temperature apparatus, starting from 20°C (68°F)				
100	212	WG	---	1.22 (Std. dev.=10%)
100	212	AG	---	1.90 (Std. dev.=6.5%)
B. Measurements in the high-temperature apparatus, starting from 20°C (68°F)				
500	932	WG	0.117	1.36
		AG	0.168	1.95
1000	1832	WG	0.292	1.65
		AG	0.411	2.33
1500	2732	WG	0.507	1.90
		AG	0.684	2.56
2000	3632	WG	0.772	2.17
		AG	1.029	2.88
2400	4352	WG	1.020	2.38
		AG	1.379	3.22
2800	5072	WG	1.291	2.58
		AG	1.754	3.50

Expansion values from the high-temperature apparatus are the averages of three specimens machined from a single block of ATJ graphite. The number of room-temperature

tests is considerably larger, permitting standard deviations to be calculated.

One across-grain thermal expansion measurement was made for this survey on a 5-inch long tabular specimen machined from the H-1 block. Specimen density was 1.746 g/cc. The following results were obtained:

TEMPERATURE		AVERAGE COEFFICIENT OF THERMAL EXPANSION
(°C)	(°F)	($\frac{\text{Microinches}}{\text{inch } ^\circ\text{F}}$)
20	68	Base Temperature
100	212	1.91
200	392	2.01
300	572	2.11
400	752	2.19
500	932	2.28
600	1112	2.34
700	1292	2.36
800	1472	2.37
900	1652	2.38

The average coefficient reported above is taken between room temperature (20°C or 68°F) and the test temperature; it is calculated by the relationship

$$\bar{\alpha} = \frac{\Delta L}{L_o} \times \frac{1}{T - T_o}$$

where L_o = specimen length at room temperature T_o

ΔL = elongation at the test temperature T

$\bar{\alpha}$ = average coefficient of linear thermal expansion

The resulting values of $\bar{\alpha}$ are plotted in Figure 5 as a function of temperature. Data for 100°C (212°F) are separated from those at higher temperatures because of the differences in apparatus, test stock, and the number of specimens. The thermal expansion coefficient increases with temperature.

ELECTRICAL RESISTIVITY

The degree to which ATJ graphite conducts electric current provides significant

information concerning its preferential grain orientation and structure. Room-temperature electrical resistance measurements were made on selected flexure bars in a four-point Kelvin bridge arrangement. The span between inner electrodes was 2.5 inches, compared to the total specimen length of 3.5 inches. Electrical resistivity was calculated from these data according to the conventional equation

$$\rho = \frac{RA}{L} = R \times \frac{bh}{L}$$

where R = specimen's resistance

L = inter-electrode span

= 2.50 inches

b = width of the flexure bar

h = thickness of the flexure bar

The variation of electrical resistivity with density is shown in Figure 6. The density versus resistivity relationship derived from this data is

$$\log_{10} \rho = k_1 + \frac{k_2}{d}$$

in the 1.69 to 1.76 g/cc density range. Here ρ denotes electrical resistivity, and d, the density. Quantities k_1 and k_2 are the intercept and slope constants, respectively. As the graphite's density increases, electrical resistivity decreases in both the with-grain and across-grain orientations. The values shown in Figure 6 are in fair agreement with those reported by the manufacturer.⁽³⁾

The data in Figure 6 indicate that the intercept constant is not single valued, but denotes a band of values as a result of statistical variation in the coke grain alignment and interface contact geometry. The test results may be summarized by the following relationships:

Across-grain specimens (1.69 to 1.76 g/cc range, 24 specimens)

$$\log_{10} \rho = -1.255 (\pm 0.010) + \frac{2.50}{d}$$

With-grain specimens (1.715 to 1.76 g/cc range, 7 specimens)

$$\log_{10} \rho = -1.405 (\pm 0.005) + \frac{2.52}{d}$$

with electrical resistivity expressed in milliohm-centimeters, and the density in g/cc. Extrapolation of these equations beyond the given density ranges is not recommended.

PART II: MECHANICAL PROPERTIES OF ATJ GRAPHITE

GENERAL

Graphite materials are characterized by a large scatter in mechanical property measurements, with the magnitude of one standard deviation being as high as 10-20% of the average property value. This situation makes it difficult to design graphite structures with good performance and high reliability. Large safety factors are required, amounting to 500% or more of the peak working stress acting on the component. In order to permit reasonably high working stress, it is therefore necessary to seek graphites which possess high average strength and a flaw-free structure. ATJ graphite is one of the grades that is promising in this respect.

Mechanical properties of ATJ have been extensively investigated, notably in connection with possible aerospace applications (3, 7, 9, 11, 12, 13, 14). There is consequently a large volume of published data available on this grade - a situation not frequently found among structural graphites. Mechanical tests at WANL have been aimed at clarifying and supplementing the published data. These tests consisted of tensile, flexural, and compressive strength measurements, together with the supplementary determination of stress-strain curves.

TENSILE STRENGTH

Being a brittle material, ATJ graphite exhibits the lowest strength in tension and the highest in compression. Owing to the preferential alignment of the coke particles during fabrication, the tensile strength must be investigated separately for the with-grain and across-grain directions.

Table 2 summarizes the principal tensile test results reported in the literature for ATJ graphite. Most of the reported tests were performed on specimens of circular cross-section, with diameters ranging between 0.11 and 0.25 inch. Since the maximum grain size of ATJ is 0.006 inch, these diameter values cover 20 to 50 large coke particles (in linear alignment), or 40 to 100 small ones, thereby providing a specimen whose tensile strength should be insensitive to the number of coke particles present in the cross section.

SPECIMEN PREPARATION AND TESTING

The tensile test results for this study were obtained on the L-2 and 609B073 specimen designs. These specimens were selected previously from eight alternate types through comparison tests on an extruded grade of graphite.⁽⁴⁾ The 609B073 specimen was loaded on the outer shoulders by means of a split-ring support fixture, while the L-2 specimen's loading was applied to threaded ends. These specimens are illustrated in Figure 7.

With-grain tensile specimens were machined parallel to either the 20-inch or 24-inch dimensions of the 9 X 20 X 24-inch ATJ stock. Across-grain specimens were parallel to the 9-inch dimension. All graphite stock samples from which these specimens were machined had been trimmed by removing a near-surface layer about one inch in thickness. The 609B073 specimens were radiographed prior to testing, while the smaller L-2 specimens were not.

Tensile tests were conducted using a cross-head rate of 0.02 inch per minute. Room-temperature tests were performed in the ambient atmosphere, while the high-temperature tests were made in either argon or helium inert atmospheres. Strength measurements in hydrogen, the propulsion gas for NERVA reactors, were highly desirable in order to include the physico-chemical effects on both the tensile strength and elongation, but could not be performed due to present equipment limitations.

Supplementary measurements of density, permanent elongation, and electrical

resistivity were made on some specimens to facilitate interpretation of the tensile data. Results of the tensile strength and associated measurements are summarized in Tables 3-a through 3-d.

A simulation of the L-2 specimen's geometry was attempted by combining a cylindrical ATJ gage section with stainless steel threads and collars. The graphite parts could be readily machined in large numbers, while metal parts were re-useable for a large number of tests; the specimens were assembled utilizing an epoxy cement. Initial tests on such specimens gave low tensile strength values (about 40-50% of those from conventional tests) and large scatter, due to the alignment difficulties. Because of these inferior results, the composite specimen was dropped from further consideration.

Selected 609B073 specimens were equipped with resistance strain gages, and their stress-strain curves determined at room temperature. Four 609B073 specimens were prepared by cutting a circumferential groove at their mid-length. Two specimens were made with a shallow V-shaped groove cut into the specimen to a depth of roughly 3 mils with a knife blade. Two more specimens were prepared with a 6-mil deep U-shaped groove. These specimens fractured through the notch plane in all cases. Their tensile strength was substantially lower than the average tensile strength for the regular specimens.

RESULTS: ROOM TEMPERATURE TENSILE STRENGTH

The 609B073 specimens were tested only at room temperature. They exhibited many undesirable fractures at the loaded shoulder, with the fracture surface passing under the specimen's head. The peak loads sustained by the specimen tended to be higher for such failures, indicating that the stronger specimens were selectively involved:

<u>FRACTURE SITE</u>	<u>OCCURRENCE</u>	<u>FRACTURE LOAD (LBS)</u>		
		<u>Low</u>	<u>Average</u>	<u>High</u>
Gage Section	8/15 = 53%	630	774	821
Sub-head	7/15 = 47%	714	803	867

Since the dimensions of individual specimens were substantially the same, the specimens with sub-head fractures were stronger than those with the regular fracture in the gage section. This implies that the test results are divided into two populations by strength, and should be considered with some caution.

All of the 609B073 tensile specimens were machined in the with-grain direction from test slab T-2. The individual test results are presented in Table 3-a. The following results had been obtained on the 609B073 specimens:

<u>TYPE AND NO. TESTED</u>	<u>FRACTURE SITE</u>	<u>AVERAGE TENSILE STRENGTH</u>	<u>STANDARD DEVIATION</u>
Regular, 8	Gage section	3960 psi	330 psi
Regular, 7	Sub-head	2610 psi*	155 psi
Regular, 15	Both types	4020 psi	308 psi
V-notched, 2	Notch plane	3425 psi	(+ 35 psi)
U-notched, 2	Notch plane	2400 psi**	(+ 60 psi)
Water-soaked, 1	Sub-head	2630 psi*	----

*Calculated from the outer fillet's cross section.

**Tensile strength corrected for the reduced cross section.

Tests on the L-2 specimens were made on both the slab trimmings and regular block material; the latter data are expected to be characteristic of the trimmed ATJ blocks used for NERVA hardware. All fractures occurred either in the gage section or at the fillet tangency. Room-temperature tests on the with-grain specimens gave the following results:

<u>SOURCE</u>	<u>NUMBER TESTED</u>	<u>AVERAGE TENSILE STRENGTH</u>	<u>STANDARD DEVIATION</u>
Slab T-3	3	4370 psi	---
Block H-2	8	3580 psi	394

The block's average strength is significantly less than that of the slab, since the difference amounts to two standard deviations. The agreement between average strength of the L-2 and 609B073 specimens is fairly good; the difference is about one standard deviation.

Across-grain L-2 specimens exhibited lower tensile strength values at room temperature than the with-grain specimens. Some over-lapping was observed between the lowest with-grain strength values and the highest across-grain values. The following results were obtained:

<u>SOURCE</u>	<u>NO. TESTED</u>	<u>AVERAGE TENSILE STRENGTH (psi)</u>	<u>STANDARD DEVIATION (psi)</u>
Block H-1	4	2710	est. 70
Block H-2	4	3020	est. 185

The 310-psi difference between the two blocks appears to be significant, although the number of tests is too small to make a definite conclusion.

RESULTS: TENSILE STRENGTH AT ELEVATED TEMPERATURES

The L-2 specimens were tested in argon or helium atmosphere. They tended to exhibit multiple fractures, often breaking into three rather than two fragments. The second fracture was probably initiated by a back-lash in the load train from the initial fracture. Figure 8 summarizes the elevated temperature tests conducted on L-2 specimens from both block and test slab material. If all results are considered together, it is evident that the with-grain strength tends to be higher than the across-grain strength, with some minor overlapping. The scatter in with-grain results was much greater than in the across-grain data.

Since the scatter in with-grain results in Figure 8 exceeds the change in strength with temperature even for relatively large temperature intervals, the average strength may be determined by combining the test results over such intervals. The following results were obtained:

<u>NO. OF TESTS</u>	<u>TEST TEMPERATURES</u>		<u>WG TENSILE STRENGTH</u>		
	<u>INTERVAL</u> (°C)	<u>AVERAGE</u> (°C) (°F)	<u>LOW</u> (psi)	<u>AVERAGE</u> (psi)	<u>HIGH</u> (psi)
10	1500-2000	1720 3125	4500	5290	6585
9	2100-2600	2390 4335	4310	6830	8130

The standard deviations are 610 for the lower temperature range and 1160 psi for the higher;

in the latter case the standard deviation drops to 750 psi if one unusually low strength value is discarded. These deviations are roughly twice as large as those from the room-temperature tests, due in part to combining the data from three different samples of ATJ graphite.

TENSILE STRESS-STRAIN CURVES

Selected 609B073 specimens were tested with resistance strain gages to define the stress versus strain curve and Poisson's ratio. Figure 9 shows the typical tensile curve for a specimen subjected to multiple loading to fracture. The stress strain behavior for a specimen initially loaded in tension and then compression is shown in Figure 10. Both specimens exhibited some permanent set upon unloading.

Additional measurements of permanent strain were made by comparing the L-2 tensile specimen length before and after a test. This technique was not sensitive for tests performed under 1000°C (1830°F). In the case of tests at a higher temperature, the elongation within a specimen was sufficient to be accurately measured. Most of the total elongation presumably occurred within the 1.0-inch gage length with only a small contribution by the inner fillet regions. The strain to fracture may thus be defined in terms of measured elongation per unit gage length. Figure 11 shows the variation of fracture strain with tensile strength and test temperature.

FLEXURAL STRENGTH

Investigation of the flexural strength of ATJ graphite was concerned primarily with the effect of density. The secondary aspects of this investigation included the following features:

1. Effect of inhomogeneous density within the specimen
2. Influence of simulated defects on the strength
3. Effects of pre-loading

4. Stress-strain relationship on the tensile and compressive surfaces of the specimen
5. Relation between flexure strength and electrical resistivity to define the possibilities for non-destructive testing utilizing electrical resistivity

Table 4 summarizes the flexure test results reported for ATJ graphite in the literature. The tests were made either on simple flexure bars with a square or rectangular cross section, or on more complex bars having a reduced central cross section analogous to that found in tensile specimens. Flexure strength averages are plotted in Figure 12 as a function of temperature.

SPECIMEN DESIGN, PREPARATION, AND TESTING

The flexure test specimen chosen for this study was a 3.5-inch bar having a 0.43-inch square cross section. The bar was loaded by rounded steel pins in a fixture providing a 3.0-inch outer span and 1.0-inch inner span. All fractures occurred within the inner span. The flexure strength was calculated by the conventional modulus-of-rupture formula for a beam in four-point loading.

The with-grain flexure tests were based on 105 bars machined from the T-1 test slab and 5 bars from the H-1 block. Across-grain tests were made on 25 bars machined from the H-1 block. The specimens were generally oriented in the test rig with the least dense face in tension, resulting in somewhat lowered values of flexure strength than would have been obtained on homogeneously dense specimens. Comparison tests were carried out by placing the denser face in tension. This distinction was applicable only to those specimens whose density did not exceed about 1.70 g/cc (See Figure 2).

For the regular flexure tests (designed to study the influence of density on flexure strength) each specimen was loaded to fracture at a platen rate of 0.02 inch per minute. The

load was applied on the low density face originally nearest the 20" x 24" mold surface; for specimens located within one inch of this surface this was also the low-density face. For the remaining specimens, the density gradient was negligible and the results were not markedly influenced by the specimen orientation in the fixture.

Several specimens were step-loaded in cumulatively increasing 500-psi increments of flexure stress, with complete unloading between cycles. These tests were intended to define the effects of preloading on flexure strength.

A few specimens were modified by various means to re-distribute the conventional stress profile within the flexure bar. These modifications included grooving the surface, drilling bore-holes within the inner span, applying dummy strain gages on the tensile face, and scratching this surface face to introduce small irregular stress-raisers.

FLEXURE TEST RESULTS

Flexure strength of ATJ graphite was found to increase with density for tests in both the with-grain and across-grain directions. Test results within a narrow density range, however, were characterized by a large scatter, making it difficult to evaluate the influence of previously listed secondary aspects of the flexure strength study. Owing to the peculiar density distribution within a test slab, the with-grain flexure bars machined from slab T-1 had two peaks in the 1.57-1.59 and 1.70-1.73 g/cc intervals, with only a small number of specimens between these peaks. The low-density peak corresponded to flexure bars machined near the slab's mold surface. As shown in Figure 2, the near-surface density has a pronounced variation across the specimen thickness, and the strength will hence depend partly upon whether the low-density or high-density face is loaded in tension, where the fracture originates. The higher density peak corresponds to the graphite located one or two inches below the mold surface, and approximates the quality of material within the regular block (hardware grade material).

The principal with-grain flexure strength results are given in Table 5. In addition,

the following values were obtained on the miscellaneous specimens:

1. Specimens with irregular scratches on the tensile face

1.589 g/cc	1804 psi
1.714 g/cc	2670 psi
1.719 g/cc	3310 psi

2. Specimen with a deep inherent crack on the tensile face

1.752 g/cc	647 psi
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Specimens with a machined groove on the tensile face (groove diameter 36 mils, depth 18 mils)

1.717 g/cc	2856 psi
1.738 g/cc	3085 psi

3. Specimen with a machined groove on compressive face (same dimensions)

1.734 g/cc	4816 psi
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4. Specimen with a 36-mil borehole oriented normal to the neutral plane and located in the middle of the inner span

1.712 g/cc	3200 psi
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5. Specimen with a 36-mil borehole oriented parallel to the neutral plane and located at the indicated depth below the tensile face mid-point

<u>DEPTH</u>	<u>DENSITY</u>	<u>FLEXURE STRENGTH</u>
21%	1.716 g/cc	3620 psi
24%	1.713 g/cc	4015 psi
26%	1.735 g/cc	4220 psi
46%	1.720 g/cc	4342 psi
50%	(Site of the neutral plane)	
76%	1.706 g/cc	3412 psi

6. Specimens with cured strain gage cement on the tensile and compressive face within the inner span

1.592 g/cc	3435 psi
1.714 g/cc	4003 psi
1.722 g/cc	4850 psi

7. Specimens with both the above cement and dummy strain gages:

1.631 g/cc	3250 psi
1.718 g/cc	4660 psi
1.722 g/cc	4750 psi

Results for the across-grain measurements are listed in Table 6. The average flexure strength is below the with-grain data, but the standard deviation is also lower. In addition to the regular tests, two specimens with a machined groove on the tensile face (diameter 36 mils, depth 18 mils) were tested; the following results were obtained:

1.697 g/cc	1980 psi
1.709 g/cc	2870 psi

The with-grain and across-grain results are summarized in Figure 13 where both the average values and the calculated statistical limits (plus or minus three standard deviations) have been plotted as a function of density, and the data trends determined.

Figure 14 shows the probability of fracture as a function of the maximum surface stress, determined on 46 with-grain specimens in the 1.700-1.730 g/cc range. The flexure strength of these specimens varied from 3360 to 4920 psi. This group represents the combined specimens from the T-1 and H-1 samples of ATJ graphite, with the regular and step-loaded test results combined. As is shown in Figure 13, the average strength and nominal scatter is about the same for all groups in this density range. Table 7 summarizes the test results obtained for the special flexure tests, comparing them to the control strength values obtained from the regular tests.

STRESS VERSUS STRAIN IN FLEXURE

One flexure bar of 1.78 g/cc density was provided with resistance-type strain gages on the tensile and compressive faces, and step-loaded to fracture in 1000-psi cumulative intervals. The variation of surface strains with the stresses calculated from the modulus-of-

rupture formula are shown in Figure 15. The specimen broke at 5560 psi. Young's modulus at the low stress levels was found to be in the range of 1.86 to 2.02×10^6 psi for the as-machined specimen; after pre-loading to high stress level (about 80% of the fracture strength) these values dropped to 1.78 to 1.87×10^6 psi. Young's moduli on the tensile and compressive faces agreed within $\pm 2\%$.

COMPRESSIVE STRENGTH

Graphites in general are stronger in compression than in tension. Compressive strength of ATJ graphite was determined on cylindrical specimens 0.75 inch in diameter and 1.50 inches long*. A typical cylinder was loaded between two steel platens of the testing machine at a cross head rate of 0.02 inch per minute. Specimen failure occurred in two steps: first, a shear-type fracture took place near one of the platens, producing a wedge-shaped fragment, second, this fragment split the remaining portion of the specimen. The following results were obtained for the with-grain specimens:

<u>Specimen Density (g/cc)</u>	1.715	1.717	1.736
<u>Compressive Strength (psi)</u>	9270	9310	9440

Across-grain specimens gave the following results:

<u>Specimen Density (g/cc)</u>	1.686	1.721	1.724	1.744	1.751	1.777	1.785
<u>Compressive Strength (psi)</u>	9070	9910	9030	9700	10,050	8800	10,260
		9960				9250	

There was no appreciable difference between the with-grain and across-grain test values, although the number of tests is too small to draw a rigorous conclusion. The average compressive strength of all specimens was 9530 psi, with a standard deviation of 465 psi. The manufacturer reports the following values (3):

<u>SPECIMEN TYPE AND DIMENSIONS</u>	<u>ORIENTATION AND NUMBER OF TESTS</u>	<u>COMPRESSIVE STRENGTH AND STANDARD DEVIATION (psi)</u>
Cube, 1" x 1" x 1"	WG	8270 (1028)
	AG	8540 (1144)
Cylinder, 1/2" D, 1/2" L	WG (10)	6700 (306)
	AG (10)	5670 (724)

*Machined from the H-1 block in both the with-grain and across-grain orientations

STRESS VERSUS STRAIN IN COMPRESSION

One with-grain cylinder (density 1.733 g/cc) and one across-grain cylinder (1.727 g/cc) with resistance-type strain gages were used to determine the axial and circumferential strains during compressive loading. At stress levels below 1000 psi, the readings were non-linear, presumably because the loaded faces were not plane and parallel. The following data were obtained for Young's modulus and Poisson's ratio above 1000 psi.

	APPLIED COMPRESSIVE STRESS RANGE (psi)	PEAK PRE- LOAD STRESS (psi)	YOUNG'S MODULUS ($\times 10^6$ psi)	POISSON'S RATIO
With-grain specimen:	1250-2260	None	1.24	0.12
	1600-2260	2260	1.33	0.14
	3000-4300	2260	0.87	----
	2700-4300	4500	1.04	0.11
	5900-6800	4500	0.46	0.15
Across-grain specimen:	1350-2250	None	0.70	0.11
	1350-2250	2250	0.91	0.12
	2900-4000	2250	0.54	0.12
	2900-4000	4500	0.65	0.10
	5280-6800	4500	(0.20)	(0.08)

The value in parentheses is probably in error due to the elongation of one strain gage beyond the manufacturer's recommended accuracy range.

DISCUSSION

STRUCTURAL INTEGRITY

The final density of graphite depends on the influence of raw materials and the processing variables. Within a given block of ATJ graphite (size 9 x 20 x 24 inches) the density varies as follows:

1. Density is high (generally in excess of 1.85 g/cc) along all peripheral edges.
2. On the large mold faces (20 x 24 inches) the near-surface density decreases away from the edges, and may be as low as 1.50 g/cc.
3. About two inches below the large mold faces the density reaches an ill-defined peak of about 1.74 g/cc, except near the edges.
4. The central density of the entire block is comparatively uniform, ranging from 1.69 to 1.75 g/cc.

Figure 2 summarizes the density profile across the block's 9-inch dimension. The central densities are relatively uniform, while within one inch of the large mold surface the variation is considerably larger.

ATJ graphite has a high degree of porosity, (Figures 1 and 4) whose value may be calculated from the semi-empirical equation

$$P = \frac{2.22-d}{2.22} \times 100\%$$

with P the intergranular porosity in volume percent, d the specimen's density in g/cc units, and 2.22 g/cc the assumed true density of the coke particles. The theoretical density of graphite (achieved, for example, by the void-free deposits of pyrolytic graphite) is 2.26, but the lower value used here for the coke particles reflects the presence of numerous small imperfections generally associated with their structure (Figure 1).

The individual pores in graphite have varying geometries and orientations. They

are, in general, considerably smaller than the maximum particle size, which for the ATJ graphite is approximately 0.006 inch or 150 microns. According to the published results⁽³⁾ of mercury porosimetry measurements, the pore sizes in ATJ graphite are smaller than 10 microns, with the majority being in the 1 to 10 micron range.

The pores are formed during the volatilization of the pitch binder phase, typically at the interstices between the coke grains. Porosity is therefore a normal feature of the molded graphite grades. These pores are potential stress raisers, particularly if augmented by small cracks in the coke particles that result from differential thermal contraction for the randomly oriented particles during the process cooling cycle. When a suitably oriented stress field is applied, the pore will grow and disrupt the binder phase. Upon continued loading, the active neighboring pores would interconnect to form the failure crack. Graphite with a higher density has a lower concentration of pores, and hence exhibits higher strength than a low-density sample.

Open defects larger than the grain size are quite possible in graphite; they are defined as voids. Their occurrence in ATJ graphite is infrequent due to the fine-grained particle mix and the high molding pressures. None were observed on the machined surfaces of the many specimens used in this study. One large crack was observed in the as-machined flexure bar from test slab T-2; this crack amounted to roughly 50% of the bar's cross section, and was probably present in the slab.

Some x-ray opaque inclusions were revealed by the radiographic inspection of slab T-2. These inclusions were on the order of 4 large coke particle diameters (nominal size 20 mils). None of these inclusions were successfully isolated from the enclosing graphite matrix for further examination. It is not known whether these inclusions are present as dense, single particles, or as a diffuse aggregate consisting of impurity-coated pores. The latter case is possible for those carbides which vaporize at the graphitization temperatures.

TENSILE STRENGTH OF ATJ GRAPHITE

Tensile tests were made with both the shoulder-loaded (609B073) and smaller thread-loaded (L-2) specimens. The following results were obtained at room temperature:

<u>TYPE OF SPECIMEN AND NO. OF TESTS</u>	<u>SOURCE</u>	<u>AVERAGE TENSILE STRENGTH AND STANDARD DEVIATION</u>
Shoulder-loaded (15)	Slab T-2	With-grain: 4020 (308)
Thread-loaded (3)	Slab T-3	With-grain: 4370
Thread-loaded (8)	Block H-2	With-grain: 3580 (394)
Thread-loaded (4)	Block H-1	Across-grain: 2710 (70)
Thread-loaded (4)	Block H-2	Across-grain: 3020 (185)

Specimens machined from the block samples are representative of NERVA hardware grade material. It is evident that a considerable variation exists between different samples for both the with-grain and across-grain orientations. Tensile strength measurements made on one block may not be indicative of the strength of another block.

Upon testing at elevated temperatures, the tensile strength of ATJ graphite was found to increase (Fig. 8) to approximately 2600°C (4710°F). The with-grain strength is both higher and more variable than the across-grain strength throughout the entire temperature range examined. Since the with-grain scatter is larger than a change in strength over a moderate temperature range, the limited high-temperature results may be combined to estimate the magnitude of tensile strength as a function of temperature. Combining results of with-grain tensile tests on the L-2 specimens from slab T-3 and blocks H-1 and H-2, the following are obtained:

<u>AVERAGE TEMPERATURE (°C)</u>	<u>(°F)</u>	<u>NO. OF TESTS</u>	<u>TENSILE STRENGTH AND STD. DEVIATION</u>
1720	3125	10	5290 (610)
2390	4335	9	6830 (750)

The scatter in these results is increased to some extent by the differences in sampled graphite and the spread in temperatures.

The shoulder-loaded 609B073 specimen was not suitable for the high-temperature

and across-grain tests. It was too strong for the existing load train in the former case, and too long to avoid density inhomogeneities in the latter case. Furthermore, the with-grain tests at room temperature resulted in a frequent occurrence of undesirable sub-head fractures at the load-supporting shoulder. The ratio of nominal stress values for the gage section and the sub-head section is 1.54. In order for a sub-head fracture to occur, the stress concentration factor at the load-bearing shoulder must be at least 1.54. Since seven specimens out of fifteen tested had sub-head fractures, the actual stress concentration factor was evidently of the same magnitude as the above stress ratio. The specimen's performance can be readily improved by decreasing the gage diameter from 0.50 inch to 0.40 inch, thereby increasing the stress ratio above the 1.5 stress concentration factor in the loaded shoulder.

The shoulder-loaded specimen was used to evaluate the influence of circumferential notches on tensile strength. Two specimens were provided with a V-notch roughly 3 mils deep, and two with a U-notch 6 mils deep. The following results were obtained:

SPECIMEN	TENSILE STRENGTH (psi)	STRENGTH LOSS (%)
V-notched specimens		
No. 1	3390	15.7
No. 2	3460	13.9
U-notched specimens		
No. 1	2360	41.3
No. 2	2440	39.3
Control Group, Average	4020 (15 tests)	0
Control Group, Average Less three std. deviations	3060	23.1

It is evident that the relatively shallow V-shaped notch did not decrease the strength below the value expected from the spread of the central values. The strength loss from the U-shaped notch was significantly higher, even though the tensile strength had been corrected for the reduced cross section. In all instances, the fracture occurred through the notch plane.

No significant influence of the x-ray-opaque inclusions on tensile strength was found in the case of 609B073 specimens. The predominant inclusion dimension was 20 mils compared with 500 mils for the gage diameter; the area ratio of the specimen's cross section to the typical inclusion was hence on the order of $(500/20)^2 = 625$, and the apparent strength is consequently governed by the graphite. Specimens with up to six inclusions in the reduced section had about the same strength as those without any detectable inclusions. The minimum detection sensitivity achieved with the radiographic technique was 2% of the thickness, and hence inclusions as large as 10 mils in size could have been lost in the background haze produced in the film by scattered x-rays.

Tensile strength measurements in general were performed on specimens machined from relatively dense portions of the original samples. Gage-section densities were measured by the weight-to-volume ratio, generally on those specimens which broke at the point of fillet tangency. The resulting values ranged between 1.73 and 1.78 g/cc for specimens tested at room temperature, and somewhat lower in the case of high-temperature specimens. The typical specimen densities were 1.75 g/cc for the with-grain specimens and 1.74 for across-grain specimens. These typical values are roughly 0.04 g/cc higher than the predominant densities of the flexure bar population; the latter were determined on larger specimens prior to testing, and are considered to be more reliable. Part of the density difference may be associated with structural changes due to testing.

Gage-section densities of the high-temperature specimens were significantly lower than the room-temperature values, indicating that the specimen volume is not conserved during tests at high-temperatures. The following results were obtained in those cases where densities were known for a pair of adjacent specimens:

TEST TEMPERATURE		DENSITY DIFFERENCE	VOLUME INCREASE	ELONGATION
(°C)	(°F)	(g/cc)	(%)	(%)
With-grain Tests				
2000	3632	-0.000	0.0	0.0
2200	3992	-0.013	1.3	0.0
2500	4532	-0.023	2.3	1.2
2500	4532	-0.036	3.6	3.6
2600	4712	-0.090	9.0	9.2
2800	5072	-0.246	24.6	28.4
Across-grain Tests				
2500	4532	-0.011	1.1	0.20

It appears, therefore, that during tensile tests at temperatures above 2500°C (4530°F) the with-grain specimens undergo considerable axial elongation, with only a minor change in their cross section. These results confirm those reported for ATJ graphite by Martens et.al.⁽¹⁴⁾

Figure II shows the relationship of test temperature to both the tensile strength and elongation (tensile strain to fracture). The elongation values represent only the plastic portion of the specimen's strain since they were determined by comparing a specimen's length before and after the fracture. It is evident that for a given test temperature, the stronger specimens also possess a somewhat greater capability for elongation. This capability is considerably higher for the with-grain specimens at 2500°C (4530°F), but becomes comparable to the across-grain values at lower temperatures.

TENSILE SPECIMEN DESIGN CONSIDERATIONS

In view of the observed variation in the average tensile strength from one sample to another, the comparison of WANL results with the previously published values (Table 2) should be made with caution. There are four conventional types of tensile specimens:

1. Specimens with inherently high stress concentration and severe alignment problems, such as the dog-bone and button-head types.
2. Specimens with an axially tapered gage section, possessing a minimum cross section near their mid-length. The radius of taper is large enough to avoid major stress concentration effects, and the fracture occurs predictably at the minimal cross section.
3. Specimens with constant gage section and conical ends, loaded on these ends.
4. Same as item 3, with an outer shoulder (type 609B073) or the threaded ends (type L-2) for loading.

The dog-bone specimen (having an approximately 1.0 x 1.0-inch reduced cross section and 1.0-inch gage length) gives the lowest tensile strength values reported in the literature for ATJ graphite at room temperature:

<u>ORIENTATION</u>	<u>TENSILE STRENGTH, psi</u>			
	DOG-BONE	609B073	L-2 (Slab)	L-2 (Block)
WG	1790	4020	4370	3580
AG	1420	----	----	2710 302 ^c

The dog-bone specimen has been routinely used by graphite manufacturers to perform tensile tests intended primarily for quality control purposes. The resulting test values are neither realistic nor applicable for purposes of a critical design.

The button-head specimen ^{(5), (14)} consisted of a 0.25" diameter x 2.0 long gage section, with two integral ends connected to the gage section by a 1/64-inch fillet radius. This design provides an improvement over the dog-bone specimen, but the stress concentration and misalignment problems are still severe. The test results obtained with this specimen are unrealistic, since the across-grain strength of 2570 psi exceeds the with-grain strength of 2510 psi. Over 90% of the fractures occur under the loading head at room temperature. ^{(14).}

These results are entirely unreliable.

The specimen design with conical ends is an improvement over the button-head design; it may be readily machined in large numbers by a suitably shaped carbide cutting tool. Tensile tests on 15 WG specimens of this type (WANL Drawing 609B064) were previously performed at WANL ⁽⁸⁾ in a helium atmosphere pressurized from 15 to 1000 psi. The cross section was 0.177 inch in diameter and 1.50 inches long. Test results were found to be insensitive to the ambient helium pressure, and, averaged as a whole, gave 3540 psi for the with-grain tensile strength, with 248 psi standard deviation. This result is comparable to the 3580 psi average from the H-2 block of ATJ graphite as determined on L-2 specimen, but falls below the 4020 psi average from the 609B073 shoulder-loaded specimen.

Tensile test results obtained by the manufacturer ⁽⁶⁾ on a comparable specimen (gage diameter 0.250 inch) design were in fair agreement with WANL results. Approximately the same strength values were reported for a thread-loaded specimen ⁽⁷⁾ having 0.200-inch diameter gage section 1.0 inch long.

A tensile specimen with a tapered gage section (1.0-inch taper radius, 0.113-inch minimum diameter) and thread-loaded ends has been used in conjunction with a uniaxial loading fixture to determine the with-grain strength of ATJ graphite. ⁽⁹⁾ Test results for 12 specimens gave 4060 psi average with a 360 psi standard deviation. This average is intermediate between WANL's L-2 specimen results for the T-3 and H-2 stock samples (4370 and 3580 psi, respectively).

It is evident from these comparisons that the tensile strength of ATJ graphite, although variable, can be determined with reasonable agreement from tests made on adequately designed specimens.

Results from the L-2 specimen are comparable to those obtained from the other high-performance specimen designs reported in the literature. The original 609B073 shoulder-loaded specimen represents border-line performance owing to the frequent sub-head fractures. Decreasing its diameter somewhat would solve this problem. The modified 609B073 specimen can be used in conjunction with L-2 specimen for volume effect studies. Its large cross section makes this specimen ideal for work with strain gages at room temperature, but not for tensile tests at high temperatures. The major portion of tensile tests on ATJ and related graphites will thus be performed in the future using the L-2 specimen.

FLEXURAL STRENGTH OF ATJ GRAPHITE

All flexure tests in this survey were made on specimens with a square cross section. The bars were tested in four-point loading. At any value of applied load, the peak stresses are found on the loaded faces. The bar's mid-height has ~~approximately~~ no stress acting on it, thereby forming the neutral plane. Fracture in graphite originates in the tensile-loaded portions of the bar (generally on the tensile face itself) presumably under the influence of the miscellaneous stress-raisers. The resulting value of flexure strength is calculated from the fracture load by the conventional modulus of rupture formula for this geometry:

$$S_f = \frac{MC}{I} = \frac{3a}{bh^2} W_{MAX}, \text{ where}$$

S_f = modulus of rupture (generally considered to be the flexure strength, with the small correction due to friction and other effects being neglected)

W_{MAX} = fracture load

a = inner span, 1.00 inch

b = width of the specimens, about 0.43 inch

h = thickness of the specimen, about 0.43 inch

I = moment of inertia for the square cross section about its neutral axis

M = bending moment on the specimen

C = Maximum distance from the neutral axis = half-thickness of the specimen

Figure 13 summarizes the variation of flexure strength with specimen density. The average flexure strength is seen to increase with density for both the with-grain and across-grain orientations. With-grain tests have a considerably higher scatter than across-grain tests. Density inhomogeneity across the flexure bar's thickness is pronounced for the tests on 1.58 g/cc with-grain specimens. From Table 5 it is found that specimens loaded on the low-density face average 2763 psi, (with 140 psi standard deviation for 7 tests), while those loaded on the high-density face average 3153 psi. The density difference between these two faces was estimated to be between 7 and 9% from the density versus thickness profiles of Figure 2. The difference in flexural strength values is 390 psi or 13.2% of the combined average. For the 1.72 g/cc specimens, the density difference was on the order of only 1%, and the flexure strength values were substantially the same. These results demonstrate the need for machining flexure specimens from homogeneously dense graphites samples if closely controlled experiments are to be conducted.

Selected specimens were step-loaded to failure in cumulatively increasing stress increments of about 500 psi, i.e., the specimen was stressed to 500 psi, unloaded, re-loaded to 1000 psi, unloaded again, etc. Such specimens showed no significant difference from the control group. It is therefore inferred that flexure strength is not affected by preloading the specimen.

The flexure behavior of specimens was found to be affected by the nature of the tensile surface. For example, specimens whose tensile and compressive faces were coated within the inner span with strain gage cement tended to be stronger than the average, regardless of density; this behavior was also observed for specimens equipped with dummy strain gages. Specimens coated with strain gage cement and then scratched to expose bare graphite failed considerably below the average, and generally below the minimum expected strength. Those specimens with a semi-circular groove 18 mils deep (compared to about a 430-mil thickness and 6-mil maximum particle size) broke considerably below the average value, exceeding the minimum expected strength in some cases. One specimen with a groove on

the compressively loaded face failed at about the average strength, indicating that the graphite is probably insensitive to major defects in compressive loading. Flexure bars with 36-mil diameter holes drilled parallel to the neutral plane showed no significant weakening, indicating that their strength was controlled by the undisturbed tensile surface. The numerical results of these various tests are summarized in Table 7.

Strength changes within 10% of the control values are not significantly large, since they amount to only one or two standard deviations. Only those changes in excess of three standard deviations are significant. The miscellaneous tests were of an exploratory nature, and the number of tests is not sufficient to obtain rigorous numerical conclusions.

The large strengthening effect (Table 7) observed for those flexure bars which had strain gage cement on the stresses surfaces (with or without the strain gages) is attributed to the following:

1. A relatively minor strengthening of graphite from the load-carrying capability of the cement.
2. A more significant strengthening due to the impregnation of surface pores by the cement, and the subsequent decrease in their ability to act as stress-raisers.

For a specimen whose tensile surface is completely covered with cement (including the edges), the fracture would be initiated some distance below the surface, where the cement penetration becomes negligible. If, however, a small bare spot remains on the surface itself, the strengthening effect would be absent.

The flexure strength values reported in the literature for ATJ graphite have a large scatter. The lowest average with-grain strength in Table 4 is 3180 psi for average density material (about 1.71 g/cc), while the highest is 7417 psi for material of undefined density. The number of tests for any of the reported averages does not exceed 15 specimens.

Results of this type are valid and useful only for determining the order-of-magnitude flexure strength values for ATJ graphite, while further deductions will be subject to question.

Flexure strength behavior in a statistically large number of tests is demonstrated in Figure 14, which shows how the probability of failure varies with the applied stress. The flexure test results are summarized for 46 with-grain specimens machined from the T-1 and H-1 samples of ATJ graphite. Results from the regular and step-loaded flexure bars have been considered together, since both the average values and the scatter were similar. Only the specimens in the 1.700 to 1.730 g/cc density range were considered, in view of the large increase of average strength with density. The results of Figure 14 are expected to be typical of the trimmed ATJ graphite stock used for NERVA hardware. These results indicate that the analytical determination of the fracture probability in ATJ graphite poses a formidable problem.

STRAIN AND ELONGATION IN FLEXURE

Figures 15-a and 15-b show the stress-strain relationship on flexure bar tensile and compressive surfaces. The density of this bar was 1.78 g/cc, which is above most of the other specimens. The resulting values for the tangent Young's modulus (by definition, the slope of the stress-strain curve) will therefore approximate the upper limit for ATJ graphite. The specimen was step-loaded in approximately 1000 psi stress increments to failure at 5560 psi.

The stress-strain curve consists of both the original and pre-loaded components. A pre-loading effect is evident from the appearance of permanent strain on both the tensile and compressive faces. This strain cannot be attributed to strain gage errors, since their limitations had not been exceeded by the magnitude of strains involved in the test. The permanent strain must therefore be attributed to the material. The mechanism by which it occurs is not well defined at this time. It may possibly be determined from the simultaneous measurements of electrical resistivity which would serve as an index of the micro-structural continuity.

The Young's moduli on the tensile and compressive faces are in agreement within 2%. At low stress levels characteristic of operating structural components, the modulus values are in the range 1.86 to 2.02×10^6 psi. Pre-loading to high stresses (80% of the failure stress in flexure) lowers these values to 1.78 – 1.87×10^6 psi. The Young's modulus is concluded to depend on the magnitude of the highest pre-stress which the specimen has encountered prior to testing. The negligible effect of such pre-loading on the flexure strength has already been demonstrated (Figure 13).

It is evident that graphite may accommodate a certain amount of applied stress by deforming permanently, particularly when such stress is cyclic. On the basis of the 1.78 g/cc specimen, the magnitude of deformation for a stress of 73% of the ultimate is approximately 400 microinches per inch. Once such a peak stress has been applied and the resulting permanent strain induced, the stress-strain relationship for high stress levels is nearly linear to fracture.

In addition to the above strain measurements on the surface, the relative value of peak deflection was determined for the with-grain flexure bars from slab T-1 from the cross-head loading motion of the fixture. The relative deflection of approximately 100 specimens from initial loading to fracture increased only slightly with density in the entire 1.58 to 1.81 g/cc range. The increase amounted to roughly 25%.

STRAIN AND ELONGATION IN TENSION

Figure 10 shows the stress-strain curve for a with-grain 609B073 specimen which was loaded in tension through two 0 to 1500 psi cycles, and then identically loaded in compression. The magnitude of permanent set lost in changing this specimen from the tensile to compressive loading was not determined, but it is believed to be small. The permanent set for equal stress levels was larger in tension than in compression. The specimen was therefore left with a residual set when the tests had been completed.

Figure 9 presents the stress-strain curve for another with-grain 609B073 tensile specimen, step-loaded in tension to failure. The permanent set is seen to be roughly proportional to the maximum applied stress, while the tangent Young's Modulus varies with the preload and applied stress.

The presence of permanent set will influence graphite strength by accommodating a certain magnitude of specimen misalignment in the test fixture. The graphite behavior in this respect is analogous to the plastic flow in the ductile materials. The influence of misalignment is relatively unimportant when making tensile tests on ductile metallic specimens because they respond to the misalignment stresses by localized plastic flow. With the brittle materials such as graphite, however, the misalignment stresses remain superimposed on the tensile stress, thereby decreasing the apparent strength of the graphite and increasing variability of the results. The presence of permanent set would permit the graphite specimen to absorb a certain small magnitude of misalignment; this indicates that a well-designed regular test fixture will give results comparable to those obtained on an identical specimen tested in a uniaxial fixture. A poorly designed test fixture would impose a greater misalignment than the graphite can absorb, and hence lead to erroneously low and variable test results.

Another influence of permanent set is variability of the Young's modulus measurements. Consider two tensile specimens, one of which has been preloaded in tension to 1500 psi. The latter specimen will appear to have a higher Young's modulus than the former. This consideration would also apply to graphite hardware. The preloaded graphite would break with a smaller strain than the virgin graphite, and therefore accommodate a proportionally smaller strain induced because of misalignment and thermal expansion differences.

PREDICTING THE STRENGTH OF ATJ GRAPHITE

Due to the demonstrated variability in the strength of ATJ graphite and the demands on reliability of NERVA hardware under service conditions, it becomes necessary to screen raw material with stringent quality control procedures. Two promising methods not presently employed at WANL have been investigated for this role:

1. Electrical resistivity
2. Surface hardness

The first is suitable for both new material and hardware shapes possessing geometrically simple cross sections. The second is applicable to the raw material shapes and portions of hardware with level surfaces.

Electrical Resistivity Versus Flexure Strength

Electrical resistivity measurements have been described previously in dealing with the physical properties of ATJ graphite. Here only the correlation of resistivity to the flexure strength will be considered. Correlation of the flexure bars' resistivity with their subsequently determined flexure strength resulted in an inverse relationship between the two quantities. That is, flexure bars exhibiting large resistivity values were found to be relatively weak, while the bars with low resistivity were relatively strong. This relationship follows from the observed dependence of electrical resistivity and flexure strength on specimen density. One should keep in mind, however, that the geometrical stress-raisers (generally small cracks) are not expected to affect the passage of electric current to the same extent that they would affect the flexure strength, and hence the large strength scatter observed in Figure 13 cannot be avoided entirely.

Figure 16 shows the variation of resistivity versus flexure strength for specimens in the 1.69 to 1.76 g/cc density range. The following relationships have been determined in this case

$$\begin{aligned}
 &(\text{Flexure strength, psi}) \times (\text{Electrical resistivity, ohm-cm}) \\
 &= 5.0 \text{ (With-grain data)} \\
 &= 5.8 \text{ (Across-grain data)}
 \end{aligned}$$

It should be noted, however, that electrical resistivity of a sample will depend somewhat on the raw material, graphitizing temperature, and chemical impurities, while the strength may remain the same. This may require a separate determination of the above constants for each lot of ATJ graphite.

Surface Hardness Versus Flexure Strength

Graphite hardness (described previously in the Physical Properties Section) is a more attractive index of strength than electrical resistivity, since the sole requirement for its determination is a reasonably flat surface. The hardness measurement results in a small indentation on the surface, with some disrupted graphite underneath. This measurement is therefore not desirable for the finish-machined hardware, but is readily applicable to excluding possible substandard hardware blanks from further processing.

Figure 17 shows the correlation between flexure strength and the Linear Scale Hardness parameter for both with-grain and across-grain specimens. It is seen that flexure strength increases linearly with hardness, exhibiting roughly the same scatter as found for the strength versus density correlation of Figure 13. In view of the large scatter, further evaluation is required on additional samples of ATJ graphite to establish this correlation more precisely. It is possible, however, to reject the weak, low-density graphite hardware blanks by means of the hardness tests. Since hardness tests are easier to carry out than electrical resistivity measurements, the latter is less desirable to apply in practice.

CONCLUSIONS

This report has covered selected physical and mechanical properties of ATJ graphite. One feature common to all of these properties is their variability -- both from specimen to specimen and from one lot to another. Part of this variability is due to the density variations within the as-fabricated stock, while the remainder may be attributed to structural features such as porosity and preferential orientation. Hence, in order to determine the desired property value with a high degree of reliability, it is necessary to test a large number of specimens; this is particularly true if a minimum design value is required, as in the case of graphite strength.

One important consideration not fully answered in this report is the dependence of graphite strength on x-ray-opaque inclusions (generally carbides). For an inclusion effect on strength to become prominent, the cross sectional ratio of specimen to inclusion must be on the order of 10 or less. This implies the use of L-2 tensile specimen in preference to the 609B073 specimen, since the latter's cross section is undesirably large for the general defect sizes (high density) observed. Preliminary results indicate that, because of the inherent variability in graphite properties, neither the strength nor Young's modulus would be significantly affected by x-ray-opaque inclusions when the ash content does not exceed one percent. The major strength reduction factors for graphite are cracks and voids; these undesirable features are not common in ATJ.

The primary objective of any physical or mechanical property studies on ATJ graphite is to define both its general behavior and the magnitude of useful property values in the reactor environment. This implies that the graphite test stock should be fully equivalent to the hardware material. ATJ test slab trimmings are not suitable in this respect since their density is highly variable from one location to another. Future tests should therefore be performed on the trimmed ATJ blocks identical to those used for NERVA hardware.

In order to define the strength of ATJ graphite in the reactor environment, the physico-chemical effect of hydrogen (NERVA propulsion gas) must be considered. Strength tests should be performed in a hydrogen atmosphere, with the effects of hydrogen on strength, elongation, and creep properties being determined.

Hardness testing of ATJ graphite appears to be a promising inspection method for the quality control of ATJ graphite prior to machining hardware. The test is relatively easy to perform, since only a reasonably smooth surface is required. The results show good correlation with flexure strength. Sub-surface damage below the residual indentation appears to be tolerable; the affected region, however, must be machined off. Hardness measurements deserve further consideration as a quality control procedure for graphite.

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TABLE I

SUMMARY OF THE HARDNESS MEASUREMENTS ON ATJ GRAPHITE

<u>SPECIMEN DENSITY</u>			<u>NUMBER OF TESTS</u>	<u>LINEAR SCALE HARDNESS</u>			<u>SOURCE OF SPECIMENS</u>
<u>Low (g/cc)</u>	<u>Average (g/cc)</u>	<u>High (g/cc)</u>		<u>Low (kg/mm²)</u>	<u>Average (kg/mm²)</u>	<u>High (kg/mm²)</u>	
1.583	1.586	1.591	4	15.3	15.8	16.4	Slab T-1
--	1.689	--	2	17.2	----	17.3	Block H-1
1.696	1.697	1.700	12	16.9	17.3	17.6	Block H-1
1.703	1.706	1.709	6	17.5	17.7	17.9	Block H-1
1.712	1.715	1.720	4	18.4	19.3	20.4	Slab T-1
1.716	1.717	1.718	4	18.1	18.4	19.1	Block H-1
1.722	1.726	1.730	4	20.2	20.4	20.9	Slab T-1
1.722	1.725	1.727	8	17.6	18.8	19.3	Block H-1
1.731	1.734	1.737	8	18.4	19.1	19.9	Block H-1
1.741	1.745	1.750	6	19.6	20.1	20.8	Block H-1
1.753	1.756	1.760	6	19.6	20.4	20.8	Block H-1
1.762	1.763	1.764	4	20.4	21.2	21.6	Block H-1

TABLE 2

ROOM-TEMPERATURE TENSILE STRENGTH REPORTED FOR ATJ GRAPHITE IN THE LITERATURE

<u>REFERENCE AND SPECIMEN DESIGN</u>	<u>DENSITY</u> (g/cc)	<u>ORIENTATION AND NO. OF TESTS</u>	<u>TENSILE STRENGTH AND STD. DEVIATION</u> (psi)	<u>GAGE DIMENSIONS</u> <u>DIAMETER</u> (in.)	<u>LENGTH</u> (in.)
A. Specimens With Inherently High Stress Concentration					
(5), "Dog-bone"	Unknown	WG -- AG --	1790 (225) 1420 (226)	(Reduced Volume = 1.0 x 1.0 x 1.0)	
(5), (14), Button-head	1.59 - 1.86	WG (4) AG (3)	2510 (est. 370) 2570 (est. 315)	0.25 0.25	2.00 2.00
B. Specimens With Inherently Low Stress Concentration					
(6), Conic ends	(9 x 20 x 24-inch Block)	WG (11) AG (10)	3355 (379) 2935 (117)	0.25 0.25	1.50 1.50
(7), Similar to L-2 Design)	Unknown	WG (1) AG (1)	3630 2930	0.20 0.20	1.00 1.00
(8), WANL Dwg. 609B064	Unknown	WG (15)	3540 (248)	0.177	1.50
C. Specimens With Tapered Gage Section					
(9)	Unknown	WG (12)	4060 (360)	0.113 min.	--

TABLE 3a
 ROOM-TEMPERATURE TENSILE TESTS ON THE 609B073
 SHOULDER-LOADED SPECIMENS MACHINED IN THE
 WITH-GRAIN DIRECTION FROM SLAB T-2

SPECIMEN NO. AND TEST CONDITIONS	SITE OF FRACTURE (1)	TENSILE STRENGTH (psi) (3)	NO. OF X-RAY OPAQUE INCLUSIONS	GAGE SECTION DENSITY
A. Regular Specimens Oriented Parallel to the Parent Block's 20-inch Dimension				
7	G. S.	3216	3	-----
13	G. S.	4140	1	1.752 g/cc
15	Sub-head	2515/3980	4	-----
2A2 (2)	Sub-head	3630/4140	0	-----
2A4	G. S.	4100	2	-----
2B4 (3)	Sub-head	2630/4125	4	-----
B. Regular Specimens, Parallel to 24" Block Dimension				
1	G. S.	3690	0	1.757 g/cc
9	Sub-head	2790/4392	0	-----
10	G. S.	4190	4	1.760 g/cc
11	G. S.	3940	0	1.750 g/cc
2A6	Sub-head	2380/3640	0	-----
2A7	Sub-head	2810/4410	1	1.765 g/cc
2B5	G. S.	4100 4190	6	1.752 g/cc
2B6	Sub-head	2520/3930	1	1.761 g/cc
2B8	G. S.	4160	0	1.765 g/cc

C. Notched Specimens: See Text.

NOTES:

- (1) G. S. - Fracture site is in the gage section or at the point of fillet tangency.
- (2) Specimen used to determine the stress-strain curve.
- (3) For specimens with sub-head fractures, the given stresses refer to the outer shoulder and the gage section, respectively.

TABLE 3-b

SUMMARY OF THE TENSILE TESTS CONDUCTED ON
THE WITH-GRAIN L-2 SPECIMENS MACHINED FROM
THE T-3 SLAB OF ATJ GRAPHITE

SPECIMEN NUMBER AND ORIENTATION	TEST TEMPERATURE		TENSILE STRENGTH (psi)	PERMANENT ELONGATION (mils/inch)	POST-FRACTURE DENSITY (g/cc)
	(°C)	(°F)			
B1-1 (Parallel to 20")	Room Temperature		4720	Less than 1	1.753
B1-10 (Parallel to 20")	Room Temperature		4310	Less than 1	1.758
B3-1 (Parallel to 24")	Room Temperature		4085	Less than 1	1.738
B1-2 (Parallel to 20")	1000	1830	4685	Less than 1	1.768
B1-3 (Parallel to 20")	1600	2910	5820	Less than 1	-----
B1-4 (Parallel to 20")	1800	3270	5250	Less than 1	-----
B3-3 (Parallel to 24")	1800	3270	5250	Less than 1	-----
B1-5 (Parallel to 20")	2000	3630	6586	Less than 1	-----
B1-7 (Parallel to 20")	2200	3990	4310	Less than 1	1.745
B3-4 (Parallel to 24")	2200	3990	6465	Less than 1	-----
B4-5 (Parallel to 20")	2200	3990	6150	Less than 1	-----
B1-8 (Parallel to 20")	2400	4350	6815	6	-----
B4-2 (Parallel to 24")	2400	4350	7550	16	-----
B1-9 (Parallel to 20")	2600	4710	7030	92	1.668

TABLE 3-c

SUMMARY OF THE TENSILE TESTS CONDUCTED
ON THE L-2 SPECIMENS FROM THE H-1 BLOCK
OF ATJ GRAPHITE

SPECIMEN NUMBER AND ORIENTATION	TEST TEMPERATURE		TENSILE STRENGTH (psi)	PERMANENT ELONGATION (mils/inch)	POST-FRACTURE DENSITY (g/cc)	NO. OF FRACTURES
	(°C)	(°F)				
B-3, WG, par. 20"	1000	1830	4358	Less than 1	----	2
B-1, WG, par. 20"	2000	3630	4697	Less than 1	1.730	2
B-4, WG, par. 20"	2000	3630	4865	Less than 1	----	2
B-2, WG, par. 20"	2800	5075	3010	284	1.484	1
A-1, AG	Room Temperature		2689	Less than 1	1.732	--
A-6, AG	Room Temperature		2626	Less than 1	----	--
A-9, AG	Room Temperature		2787	Less than 1	1.733	--
A-12, AG	Room Temperature		2727	Less than 1	1.753	--
A-7, AG	1000	1830	3308	---	----	2
A-10, AG	1800	3270	3789	---	----	--
A-8, AG	2000	3630	4158	---	----	--
A-4, AG	2400	4350	5012	---	----	--

TABLE 3-d

 SUMMARY OF TENSILE TESTS CONDUCTED ON L-2
 SPECIMENS FROM THE H-2 BLOCK OF ATJ GRAPHITE

<u>ELECTRICAL RESISTANCE(1)</u> (milli-ohms)	<u>TEST TEMPERATURE</u> (°C) (°F)		<u>TENSILE STRENGTH</u> (psi)	<u>PERMANENT ELONGATION</u> (mils/inch)	<u>POST-FRACTURE DENSITY</u> (g/cc)
A. With-grain Specimens (Parallel to the block's 24-inch dimension)					
14.25	Room Temperature		3620	Less than 1	-----
14.0	Room Temperature		3820	Less than 1	-----
14.0	Room Temperature		3220	Less than 1	1.734
13.8	Room Temperature		3650	Less than 1	1.734
13.8	Room Temperature		3100	Less than 1	1.764
13.5	Room Temperature		3710	Less than 1	1.764
13.5	Room Temperature		3210	Less than 1	1.778
12.8	Room Temperature		4290	Less than 1	-----
14.0	1500	2730	4500	Less than 1	1.737
13.8	1500	2730	5040	Less than 1	-----
13.5	1500	2730	4870	2	1.747
13.5	1500	2730	5240	6	-----
14.0	2500	4530	6900	12	1.711
13.8	2500	4530	8110	43	-----
13.5	2500	4530	8130	36	1.699
B. Across-grain Specimens					
18.75	Room Temperature		3190	Less than 1	1.741
18.6	Room Temperature		3170	Less than 1	1.743
18.5	Room Temperature		2890	Less than 1	1.743
18.4	Room Temperature		2840	Less than 1	1.746
18.6	1500	2730	3750	4	-----
18.5	1500	2730	3800	5	1.749
18.4	1500	2730	3640	1	1.750
18.5	2500	4530	4540	2	1.739

NOTES:

(1) Electrical resistance was determined at room temperature.

TABLE 4

SUMMARY OF THE FLEXURE TEST RESULTS REPORTED
IN THE LITERATURE FOR ATJ GRAPHITE

REF. NO.	TEMPERATURE		DENSITY (g/cc)	FLEXURE STRENGTH			MISCELLANEOUS
				Low (psi)	Average (psi)	High (psi)	
A. Flexure tests conducted on bar-shaped specimens with rectangular cross section in four-point loading; with-grain orientation							
(10)	Room Temperature		Unknown	---	4010	---	Specimen size 8.0 x 0.50 x 0.50 inches Outer span 6.0 inches, inner span 1.0 inch. Number of tests unknown.
	1000	1830	Unknown	---	4800	---	
	2000	3630	Unknown	---	6300	---	
	2500	4530	Unknown	---	8400*	---	
	Room Temperature		Unknown	---	3580		Across-grain tests.
(11)	Room Temperature		Unknown	6493*	7417*	8987*	Specimen size 5.0 x 0.25 x 0.25 Ten tests with 4.0-inch outer span and 1.0-inch inner span
(12)	21	70	Unknown	---	3520 (589)	---	Five tests each on 1.0 x 2.0 x 10-inch bars; span to depth ratio = 10.
	816	1500	Unknown	---	3900 (542)	---	
	1370	2500	Unknown	---	4020 (616)	---	
	21	70	Unknown	---	4480 (589)	---	Five tests each on 0.25 x 0.50 x 2.50 inch bars; span to depth ratio = 10.
	816	1500	Unknown	---	4310 (645)	---	
	1370	2500	Unknown	---	5570 (287)	---	
B. Flexure tests on specimens with reduced central cross section; with-grain tests							
(13)	Room Temperature		1.769 (0.026)	2790	3520 (460)	4370	12-inches long specimen with an inner span section of 0.80 x 0.80 x 3.14" Thirteen tests each.
	Room Temperature		1.722 (0.043)	2880	3540 (320)	4190	
	Room Temperature		1.708 (0.057)	2170	3180 (560)	4200	

*Questionable results

TABLE 5

SUMMARY OF THE WITH-GRAIN FLEXURE TESTS AT ROOM TEMPERATURE

TYPE OF TEST	NO. OF SPECIMENS	DENSITY RANGE			FLEXURE STRENGTH			STANDARD DEVIATION
		Low (g/cc)	Average (g/cc)	High (g/cc)	Low (psi)	Average (psi)	High (psi)	
Tension on low-density face	7	1.576	1.584	1.594	2512	2763	2904	140
Same, step-loaded	3	1.583	1.587	1.591	2289	2702	2962	---
Tension on high-density face	3	1.580	1.582	1.584	2945	3153	3270	---
Combined data (weighted)	13	1.576	1.584	1.594	2290	2900	3270	259
Tension on low-density face	3	1.604	1.613	1.623	2530	2730	3073	---
Same	3	1.638	1.644	1.654	3140	3300	3463	---
Same	2	1.672	1.680	1.688	3845	3880	3900	---
Same, step-loaded	1	-----	1.680	-----	-----	3905	-----	---
Tension on high-density face	1	-----	1.607	-----	-----	-----	3560	---
Combined data	9	1.604	1.629	1.654	2530	3160	3560	373
Tension on low-density face	6	1.704	1.706	1.708	3620	4060	4373	---
Same	12	1.711	1.715	1.720	3370	4075	4365	---
Same	3	1.723	1.724	1.725	3407	3870	4220	---
Combined data	24	1.704	1.714	1.725	3371	4023	4501	338
Tension on low-density face, step loaded	8	1.712	1.724	1.730	3620	4346	4920	441
Tension on high-density face	11	1.709	1.720	1.730	3480	4248	4835	461
Series II tests; tension on high-density face*	3	1.716	1.719	1.724	4190	4425	4570	---
Tests on uniformly dense bars	8	1.733	1.744	1.760	4220	4670	5010	285
Same, Series II*	2	1.753	1.757	1.760	4460	4750	5040	---
Step-loaded	1	-----	1.742	-----	-----	4850	-----	---
Tests on uniformly dense bars	6	1.765	1.782	1.799	4780	5270	5670	298
Same, step-loaded	1	-----	1.785	-----	-----	5700	-----	---
Tests on uniformly dense bars	4	1.809	1.811	1.816	5825	6100	5420	---

*Series II tests were made on specimens from the H-1 sample; all other tests made on the T-1 specimens.

TABLE 6
SUMMARY OF THE ACROSS-GRAIN
FLEXURE TESTS AT ROOM TEMPERATURE

<u>DENSITY RANGE</u>			<u>NO. OF SPECIMENS</u>	<u>FLEXURE STRENGTH</u>			<u>STD. DEV.</u>
<u>Low</u>	<u>Average</u>	<u>High</u>		<u>Low</u>	<u>Average</u>	<u>High</u>	
(g/cc)	(g/cc)	(g/cc)		(psi)	(psi)	(psi)	(psi)
1.689	1.696	1.700	7	3210	3450	3650	133
1.703	1.709	1.716	4	3540	3605	3690	---
1.722	1.730	1.737	6	3710	3825	4000	115
1.741	1.753	1.764	6	3730	3890	4180	163

TABLE 7

SUMMARY OF THE SPECIAL FLEXURE TESTS

<u>ORIENTATION</u>	<u>TENSILE FACE DATA</u>	<u>SPECIMEN DENSITY</u> (g/cc)	<u>OBSERVED STRENGTH</u> (psi)	<u>CONTROL STRENGTH</u> (psi)	<u>CHANGE (%)</u>
A. Specimens with impaired tensile surface					
WG	Scratched surface	1.589	1804	2673	-32.5
WG	Scratched surface	1.714	2670	4023	-33.7
WG	Scratched surface	1.719	3310	4023	-17.7
WG	Grooved surface	1.717	2856	4023	-29.0
WG	Grooved surface	1.738	3085	4500	-31.4
AG	Grooved surface	1.697	1980	3450	-42.6
AG	Grooved surface	1.709	2870	3605	-20.4
WG	Deep crack	1.752	647	4670	-86.0
B. Specimens with improved tensile surface					
WG	Cement-covered	1.592	3435	2763	+24.3
WG	Cement-covered	1.714	4003	4023	-0.5
WG	Cement-covered	1.722	4850	4023	+20.5
WG	Strain gage	1.631	3250	3000	+8.34
WG	Strain gage	1.718	4660	4023	+15.8
WG	Strain gage	1.722	4750	4025	+18.1
C. Specimens with simulated internal defects					
WG	Borehole, 21%*	1.716	3620	4023	-10.0
WG	Borehole, 24%	1.713	4015	4023	0.0
WG	Borehole, 26%	1.735	4220	4400	-4.1
WG	Borehole, 46%	1.720	4342	4023	+8.0
WG	Borehole, 76%	1.706	3412	4023	-15.2

*The borehole axis is located at the given % of specimen thickness under the tensile face.

(1-a)

0 10 MILS

(1-b)

0 2 MILS = 0.0020 INCH

FIGURE 1

TYPICAL MICROSTRUCTURE OF ATJ GRAPHITE. FIGURE 1-a SHOWS THE GENERAL VIEW OF GRAINS (LIGHTER PHASE) AND PORES (DARK PHASE) AT 100 X. FIGURE 1-b IS A 750X ENLARGEMENT MADE NEAR THE CENTER OF THE PREVIOUS FIGURE TO DEMONSTRATE THE MICROSTRUCTURE WITHIN A GRAIN.

Figure 2 DISTRIBUTION OF DENSITY ALONG THE 9-INCH DIMENSION OF A 9X20X24-INCH ATJ BLOCK, BASED ON THE FLEXURE BAR DENSITY MEASUREMENTS

Figure 3 LINEARIZED HARDNESS OF ATJ GRAPHITE VERSUS DENSITY

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0 5 10 MILS
0 0.005 0.010 INCHES

FIGURE 4

MICROSTRUCTURE OF GRAPHITE AFTER A HARDNESS TEST, SHOWN IN A COMPOSITE PHOTOMICROGRAPH. ORIGINAL STRUCTURE AT THE SURFACE (TOP) HAS BEEN PRESERVED BY MOUNTING THE SPECIMEN IN RESIN; NOTE THAT THIS RESIN HAS PENETRATED INTO OPEN PORES NEAR THE SURFACE. THE LIGHT-GRAY PHASE REPRESENTS THE COKE-GRAIN AND BINDER STRUCTURE, WHILE THE DARK IRREGULAR SPOTS ARE AIR-FILLED VOIDS. NOTE THE FRACTURED GRAINS UNDER THE INDENTATION.

Figure 5 THERMAL EXPANSION OF ATJ GRAPHITE AS A FUNCTION OF TEMPERATURE AND ORIENTATION

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Figure 6 ELECTRICAL RESISTIVITY OF ATJ GRAPHITE AS A FUNCTION OF DENSITY. THE SPECIMENS WERE FLEXURE BARS (7/16 X 7/16 X 3 1/2 INCHES) MACHINED FROM HARDWARE -- GRADE PORTION OF THE H-1 BLOCK. INTERELECTRODE SPAN WAS 71% OF THE SPECIMEN'S LENGTH.

A) TYPE 609B073

B) TYPE L-2

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FIGURE 7 GRAPHITE TENSILE SPECIMENS

FIGURE 8 TENSILE STRENGTH OF ATJ GRAPHITE AS A FUNCTION OF TEMPERATURE.
ALL MEASUREMENTS BASED ON THE L-2 TENSILE SPECIMENS IN THE
1.72 -- 1.78 G/CC DENSITY RANGE

FIGURE 9 STRESS -- STRAIN CURVE FOR THE 609B073 SPECIMEN (0.5 INCH GAGE DIAMETER) MACHINED FROM ATJ GRAPHITE IN THE WITH-GRAIN DIRECTION. THE SPECIMEN WAS LOADED TO FRACTURE AT ROOM TEMPERATURE.

ATJ GRAPHITE

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FIGURE 10 THE STRESS-STRAIN BEHAVIOR OF ATJ WITH-GRAIN 609B073 SPECIMEN WHEN LOADED IN BOTH TENSION AND COMPRESSION

FIGURE 11 PERMANENT ELONGATION VS MAXIMUM TENSILE STRESS FOR ATJ GRAPHITE AT VARIOUS TEMPERATURES

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FIGURE 12 SUMMARY OF ATJ FLEXURE STRENGTH RESULTS REPORTED IN THE LITERATURE.

FIGURE 13 SUMMARY OF THE FLEXURE TESTS ON ATJ GRAPHITE AS A FUNCTION OF DENSITY AND ORIENTATION.

FIGURE 14 DISTRIBUTION OF FLEXURAL STRENGTH VALUES OBSERVED IN 46 WITH-GRAIN FLEXURE BARS IN THE 1.70 - 1.73 G/CC RANGE

FIGURE 15a STRESS-STRAIN CURVE FOR THE TENSILE FACE OF ATJ WITH-GRAIN FLEXURE BAR. VALUES OF YOUNG'S MODULUS ARE INDICATED.

FIGURE 15b STRESS-STRAIN CURVE FOR THE COMPRESSIVELY--LOADED SURFACE OF THE ATJ FLEXURE BAR IN FIGURE 15a.

FIGURE 16

CORRELATION BETWEEN THE ELECTRICAL RESISTIVITY AND FLEXURE STRENGTH OF
ATJ GRAPHITE.

FIGURE 17 CORRELATION BETWEEN THE LINEARIZED HARDNESS PARAMETER
AND FLEXURE STRENGTH OF ATJ GRAPHITE

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