~~RESTRICTED~~
UNCLASSIFIED

ORNL-4276

C-91 - Nuclear Reactors for Rocket Propulsion

Contract No. W-7405-eng-26

REACTOR DIVISION

ROOM-TEMPERATURE MECHANICAL PROPERTIES
OF PHOEBUS SUPPORT-ELEMENT GRAPHITE

G. T. Yahr
R. S. Valachovic
J. E. Smith

Classification cancelled (or changed to) **UNCLASSIFIED**
by authority of **SANDIA CLASS. REVIEW (TID-1387)**
by **GG** DTIC, date **3/29/73** **Suppl.**

NOVEMBER 1968

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
UNION CARBIDE CORPORATION
for the
U. S. ATOMIC ENERGY COMMISSION

This report
States, nor
A. Mat
racy, comp
of any info
privately o
B. Ass
use of any
As use
such emplo
disseminat
with the Com
NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

~~RESTRICTED~~
This document contains restricted data as defined in the Atomic Energy Act of 1954. Its transmittal is limited to those persons, in any manner, who are authorized to receive it. It is to be excluded from automatic downgrading and declassification.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

CONFIDENTIAL

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

~~CONFIDENTIAL~~

CONTENTS

ABSTRACT	1
INTRODUCTION.....	1
DESCRIPTION OF TESTS.....	2
General.....	2
Parallel Tensile Tests.....	3
Parallel Compressive Tests.....	7
Special Compressive Tests.....	7
Tube Tests	11
Microspecimens.....	14
DATA-REDUCTION METHODS.....	15
MATERIAL VARIABILITY.....	18
Batch-to-Batch Variation	18
Element-to-Element Variation	20
Axial Variation.....	20
Radial Variation.....	23
CHARACTERISTIC MECHANICAL PROPERTIES FOR DESIGN AND ANALYSIS.....	24
Statistical Presentation of Data.....	24
Analytical Representation of Mean Stress-Strain Curves	31
SUMMARY AND CONCLUSIONS.....	33
ACKNOWLEDGMENTS.....	34
APPENDIX.....	34

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

ROOM-TEMPERATURE MECHANICAL PROPERTIES OF PHOEBUS SUPPORT-ELEMENT GRAPHITE

G. T. Yahr

R. S. Valachovic

J. E. Smith

ABSTRACT

Uniaxial tensile and compressive tests were performed on Phoebus central-support-element graphite at room temperature. It was assumed that the material was transversely isotropic and that the monotropic axis coincided with the axis of the element. Stress-strain curves and strain ratio vs axial strain curves were determined for loading both parallel and perpendicular to the axis of the elements. Several specimen geometries were employed, and numerous specimens of each geometry were tested to obtain reliable average mechanical-properties data and to characterize the variability in mechanical properties.

Special testing techniques were necessary because of the shape of the elements. A gripping technique was developed that permitted tensile tests on specimens with no reduced section, that is, on specimens of uniform cross section along the entire length of the specimen. This technique made tensile tests on full-cross-section lengths of the elements and of 1/16-in.-diam microspecimens possible. The 1/16-in.-diam specimens were used to determine tensile stress-strain behavior both parallel and transverse to the axis of the elements. Thin-walled tubes, subjected to internal pressure in such a manner that no net axial force existed, were also employed to determine transverse mechanical properties.

INTRODUCTION

The core of a Phoebus reactor consists of seven-rod fuel-element assemblies. The central element in each assembly is an extruded 3/4-in. hexagonal graphite rod with a 3/8-in.-diam concentric hole and a length of approximately 54 in. Elements from three different batches manufactured at Los Alamos Scientific Laboratory were tested. These batches were designated as 01-1661, 1719-AA, and 1809.

Mechanical behavior of central-support-element graphite subjected to uniaxial load at room temperature has been thoroughly examined (1) to elucidate its behavior under uniaxial stress and (2) to provide quantitative data for design analyses. In consequence, various testing techniques were developed, notably a method for performing tensile tests on full-cross-section pieces of elements and on tiny 1/16-in.-diam specimens (microspecimens). A method for determining transverse tensile behavior from tube tests was also developed.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Stress-strain curves were obtained for tensile and compressive specimens tested parallel to the element axis and for tensile specimens tested perpendicular to the axis. The ratio of induced lateral strain to axial strain was also recorded. A number of specimens of each type were tested so that property variations could be examined statistically. Effects of testing procedure and specimen geometry were investigated, and properties variations were correlated with position in the elements. Variability from element to element and batch to batch was also examined.

Test procedures and specimen geometries are described in the following section. Methods used in reducing the data are then explained. Next, systematic material variations are discussed; and finally, the most representative data are presented in tabular, graphical, and equation form.

DESCRIPTION OF TESTS

General

In all cases except for reduced-cross-section tensile specimens, elements were cut according to the cutting scheme shown in Fig. 1. The 2-in.-long pieces were used for compressive specimens, the 6- and 8-in.-long pieces were used for tensile specimens, and the 9-in.-long pieces were used for tubular test specimens and microspecimens.

Strains were measured with epoxy-backed foil strain gages attached to the specimens with Eastman 910 cement. A variety of gages and attachment methods were tested, and this particular combination gave the best first-cycle results. Precise first-cycle results are vital when testing graphite because the stress-strain curve is not the same upon reloading as upon initial loading. The use here varies from normal strain-gage procedure, in which materials such as steel are cycled at low stress levels several times before data are recorded to achieve accuracy. Identical gages mounted on unstressed graphite blocks located near the test specimens completed Wheatstone bridge circuits. The strain was then proportional to the voltage output of the bridge.

Loads were also measured with electrical strain gages. Commercial strain-gage-based load cells were used to measure tensile and compressive loads and hydraulic pressure.

Fig. 1. General Cutting Scheme for Graphite Elements.

~~CONFIDENTIAL~~
~~RECORDED~~

~~CONFIDENTIAL~~

All measuring circuits were energized by floating dc solid-state power supplies and were calibrated with precision shunt resistors immediately prior to each test. Data were recorded continuously on X-Y plotters. The data from the X-Y plots were punched on computer cards to accommodate reduction via digital computer. In subsequent tests, data were digitized and recorded on magnetic tape by a central Beckman-Dextir data acquisition system while tests were in progress.

Parallel Tensile Tests

The first tensile specimens were tested on a 120,000-lb-capacity hydraulic Baldwin-Lima-Wiedemann Universal Testing Machine. A model TT-C-L Instron testing machine was subsequently obtained and used for the remaining tensile tests.

When this test program was begun, techniques for testing full-cross-section pieces of the elements in tension had not been developed. The first tensile specimens were therefore machined with a reduced-cross-section gage length as shown in Fig. 2. The central hole was bored out to a larger size, and a portion at the midlength of the piece was turned to a circular cross section, thus forming a tubular cross section in the gage section of the specimen. Both the mean diameter and the wall thickness of those initial specimens were varied, so that the effects of wall thickness and radial position within the element could be examined. Table 1 shows the combinations of mean diameters and wall thicknesses that were tested. The specimens were gripped by braided-wire cable-pulling grips similar to novelty Chinese finger pullers. These tests indicated an effect of radial position within the element, but there was no apparent effect on mechanical properties due to variations in wall thickness. A later series of tests on reduced-cross-section specimens, utilizing only specimens with a 0.040-in. wall thickness but with the three different mean diameters, was run to examine the radial variation of properties in more detail. In this series of tests the load was applied by carefully aligned flexible cables, and a more uniform stress state was achieved, resulting in 25% higher fracture stresses.

The unique gripping method illustrated in Fig. 3 was devised, after considerable development, to facilitate tensile tests on full-cross-section specimens. Steel rings were cemented to the ends

Fig. 2. Reduced-Cross-Section Tensile Specimen.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

CONFIDENTIAL
PHOTO 68463A

Fig. 3. Tensile Test of Full-Cross-Section Specimen.

~~CONFIDENTIAL~~
~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Table 1. Dimensions of Reduced-Cross-Section Tensile Specimens

Mean Diameter (in.)	Wall Thickness (in.)	Cross-Sectional Area (in. ²)
0.460	0.020	0.029
0.460	0.040	0.058
0.460	0.060	0.087
0.560	0.020	0.035
0.560	0.040	0.070
0.560	0.060	0.106
0.660	0.020	0.041
0.660	0.040	0.083
0.660	0.060	0.124

of the test specimens with a special epoxy cement as shown in Fig. 3a. These rings were attached to small flexible cables through which the load was applied by a clamshell device shown in Fig. 3b. The cables were just large enough so that the specimen would fail before the cables and were flexible enough so that appreciable bending moments would not be transmitted to the specimen. The entire end-cap assembly was carefully machined and assembled so that the center lines of the cables coincided with the center line of the specimen. The specimen is shown in the test machine in Fig. 3c, and a broken 19-hole element is shown in Fig. 3d.

A detailed drawing of the steel end cap is shown in Fig. 4. The internal taper was of particular importance because it prevented the specimens from consistently failing near the end cap.

Fig. 4. Tensile End Cap.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

CONFIDENTIAL
PHOTO 72102

Fig. 5. Broken Full-Cross-Section Tensile Specimens.

~~CONFIDENTIAL~~
DECLASSIFIED

~~CONFIDENTIAL~~

The void between the end cap and the specimen was filled with epoxy cement, as can be seen in Fig. 5. The portion of the central hole within the end caps was also filled with epoxy cement, which was a special formulation consisting of four parts by volume of Shell Epon 815 resin, one part Cabosil, and one part aluminum powder. Addition of one part by volume of Ciba Hardener 951 to nine parts of the mixture just before use completed the formulation. Completed specimens were left at room temperature overnight. They were then placed in an oven at 150°F for 1 hr before being tested.

The completed specimens had gage lengths of $2\frac{3}{8}$ in. Fracture occurred randomly throughout the gage length, as in the typical specimens shown in Fig. 5, where typical strain-gage installations are visible. Two identical gages were attached halfway around the specimen from those shown in the photograph so that there were an axial gage and a transverse gage on each side of the specimen. The axial and the transverse gages were each wired in series to form one leg of their respective Wheatstone measuring bridge. Such an arrangement provided an average output for each set of gages and canceled any differences in strain due to bending.

Parallel Compressive Tests

The compressive specimens were tested in a commercial compression sub-jig, which assured uniform loading, and the BLW Universal Testing Machine was used to apply load to the compression sub-jig. Specimens were 2-in. lengths of full-cross-section elements with the ends ground parallel. The ends of the specimens were lapped with the compression sub-jig to ensure uniform load distribution. Four strain gages were cemented to each specimen in the same manner as described previously for tensile specimens. A specimen in the sub-jig ready to be tested is shown in Fig. 6.

Special Compressive Tests

End Restraint

A major problem in compression tests is end restraint.^{1,2} After the ends of the compression specimens had been lapped with the compression sub-jig, each end was covered with a 0.003-in.-thick piece of Teflon tape. The purpose of the tape was to reduce friction between the ends of the specimen and the sub-jig and to even out the load on the specimen. Two special tests were run without the Teflon tape to investigate the effectiveness of the tape. These two stress-strain curves are shown in Fig. 7 with the envelope of the stress-strain curves for specimens from the same batch tested with Teflon tape. The average strain ratio vs axial strain curves for the specimens tested with and without the Teflon tape are shown in Fig. 8. Even though the tape apparently had little effect on the recorded mechanical behavior of the specimens, it was used in all compression tests except these two.

¹A. Nadai, *Theory of Flow and Fracture of Solids*, vol 1, 2d ed., pp. 328-346, McGraw-Hill, 1950.

²J. G. Tweeddale, *The Mechanical Properties of Metals, Assessment and Significance*, pp. 205-6, American Elsevier, 1964.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

CONFIDENTIAL
PHOTO 75099

Fig. 6. Compression Specimen in Compression Sub-Jig.

~~CONFIDENTIAL~~
DECLASSIFIED

Fig. 7. Effect of Teflon at Ends of Specimens on the Compressive Stress-Strain Curve.

Fig. 8. Effect of Teflon at Ends of Specimens on Compressive Strain Ratio.

Strain-Rate Effect

Special compressive tests were run to investigate the effect of strain rate. Two specimens were tested at very low strain rates of approximately 0.0004 min^{-1} . Each test lasted longer than 30 min. One specimen was tested at the fastest possible strain rate, which was approximately 0.2 min^{-1} . The stress-strain curves from the two slow tests and the stress-strain curve from the fast test are compared with the envelope of the stress-strain curves for specimens from the same batch tested at the normal strain rate of approximately 0.02 min^{-1} in Fig. 9. The strain ratio vs axial strain curves are compared in Fig. 10. The fast-strain-rate specimen was more deformation resistant than the slow-strain-rate specimens, but the difference is well within the envelope of curves at the regular strain rate. The strain rate apparently has no significant effect on either the stress-strain curve or the strain ratio vs axial strain curve at this temperature.

Cyclic Loading

One compressive specimen was loaded to 8000 psi, and the load was then released and re-applied ten times. On the tenth cycle the load was increased to 10,000 psi, and the load was cycled from 0 to 10,000 psi ten times. Finally, the specimen was loaded to failure. The resultant stress-strain curve is plotted in Fig. 11 together with the mean compressive stress-strain curve for the specimens from the same batch of elements. When loaded to higher loads after cycling, the cyclic curve apparently returned to the stress-strain curve that it would have followed if the specimen had not been cycled.

Fig. 9. Effect of Strain Rate on Compressive Stress-Strain Curves.

Fig. 10. Effect of Strain Rate on Compressive Strain Ratio.

Fig. 11. Cyclic Compressive Stress-Strain Curve.

~~CONFIDENTIAL~~

G. M. Jenkins³ proposed a set of equations to describe the stress-strain curves of graphite upon application, release, and reapplication of load. His equation for describing initial loading is

$$\epsilon = A\sigma + B\sigma^2. \quad (1)$$

The removal of this stress is governed by

$$\epsilon_m - \epsilon = A(\sigma_m - \sigma) + \frac{1}{2}B(\sigma_m - \sigma)^2, \quad (2)$$

and reloading is governed by

$$\epsilon - \epsilon_0 = A\sigma + \frac{1}{2}B\sigma^2, \quad (3)$$

where ϵ and σ are stress and strain, respectively, the subscripts m and 0 refer to the maximum load before unloading and the minimum load before reloading, respectively, and A and B are constants. These equations are quite convenient for plasticity analyses, which require the assumption that the total strain is the sum of an elastic component and a plastic component. The first term on the right side of each of Eqs. (1), (2), and (3) is the elastic strain component, and the second term on the right side of each is the plastic strain component. The initial tangent modulus is the reciprocal of A . These three equations define the dashed curve in Fig. 11. The principal discrepancy between Jenkins's theory and the behavior of the central-support-element compression specimen was in the amount of residual strain. Jenkins's equation predicted 50% more residual strain at zero load than actually occurred in this test.

Jenkins⁴ subsequently showed that the dynamic modulus of elasticity of graphite decreased after prestressing. If it is assumed that the modulus of our specimen decreased from an initial value of 2.75×10^6 psi to 2.29×10^6 psi at 8000 psi, the loop shown as double-dashed lines is obtained from Jenkins's theory. This loop is in excellent agreement with the data.

Tube Tests

Transverse tensile properties were obtained from thin-walled tubes subjected to internal pressure. The specimens were 3-in.-long tubes that had an inside diameter of 0.50 in. and an outside diameter of 0.52 in.; the wall thickness of each individual tube was uniform, and each tube was measured individually.

A specimen is shown in the test rig prior to pressurization in Fig. 12. O-ring seals were held in each end of the specimen so that the pressure force in the axial direction was absorbed

³G. M. Jenkins, "Analysis of the Stress-Strain Relationship in Reactor Grade Graphite," *Brit. J. Appl. Phys.* 13, 30 (1962).

⁴G. M. Jenkins, "Fracture in Reactor Graphite," *J. Nucl. Mater.* 5(3), 280-86 (1962).

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

12

Fig. 12. Tubular Test Specimen Mounted in Test Rig.

by the test rig. Thus the only axial stress in the specimen resulted from restriction of the axial contraction of the specimen by the test rig. The specimen contracted axially when subjected to a tensile hoop stress because of the Poisson's-ratio effect. The O-ring was sized so that the axial restriction was as small as possible. There was a radial stress in the tube that went from the value of the internal pressure at the inside to zero at the outside, but this was small in comparison with the hoop stress. Since the hoop stress was the only appreciable stress, the tube was essentially under uniaxial stress in the circumferential direction. One axial and one circumferential strain gage were attached in the center of each specimen on the outside, as shown in Fig. 12. No liner was used in the specimens.

Figure 13 shows two specimens that have been tested. The axial crack in the specimen on the right is a typical failure. In a few instances, the axial crack extended one-third to two-thirds the length of the tube, then turned and stopped, as in the specimen on the left.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Fig. 13. Broken Tube-Test Specimens.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Microspecimens

Very small tensile specimens, 1/16 in. in diameter, were tested to compare the results with the transverse properties obtained from tube tests and the axial properties obtained as functions of radius from the reduced-cross-section tensile specimens. These miniature specimens, which are called microspecimens, are shown in Fig. 14. They were tested in much the same manner as the larger tensile specimens, utilizing end caps and small flexible cables.

The parallel microspecimens were obtained from two radial locations, one 0.230 in. and the other 0.330 in. from the element's center line. These particular radial locations were selected to conform with the mean radii of the reduced-cross-section tensile specimens that had tubular cross sections and mean diameters of 0.460 in. and 0.660 in. The mean stress-strain curves from the microspecimens are compared with the mean stress-strain curves from reduced-cross-section and full-cross-section specimens in Fig. 15. The microspecimens indicated the same trend regarding effect of radial position on the stress-strain curve as was indicated by the reduced-cross-section specimens. Specifically, the material near the element's center was stronger and more deformation resistant than the material near the outside. The microspecimens were less deformation resistant and slightly stronger than their reduced-cross-section counterparts. The

Fig. 14. Microspecimens Before and After Testing.

~~CONFIDENTIAL~~
DECLASSIFIED

~~CONFIDENTIAL~~

Fig. 15. Comparison of Mean Parallel Tensile Stress-Strain Curves from Microspecimens with Those from Reduced-Cross-Section Specimens.

Fig. 16. Comparison of Mean Transverse Tensile Stress-Strain Curves from Microspecimens with Those from Tube-Burst Specimens.

microspecimens were almost as strong as the full-cross-section specimens. These tests indicate the stress-strain curve can be determined from the microspecimens. There is apparently no effect of specimen size on the stress-strain curve of this graphite in the range of sizes tested.

The transverse microspecimens were machined from the radial position corresponding to the mean radius of the tube-test specimens. The transverse stress-strain curves obtained from the two types of specimens are compared in Fig. 16. Tube-test results for specimens from batches 1719AA and 1809 are shown. The microspecimens came from batch 01-1661. The average stress-strain curve for the tube tests from batch 1809 is almost identical to the average stress-strain curve obtained from microspecimens up to the fracture point for the tube tests. The microspecimens display considerably higher tensile strength, however.

DATA-REDUCTION METHODS

Graphite exhibits unique mechanical behavior that requires special methods for analysis of the data. Mechanical properties measured parallel to the extrusion axis are not the same as those measured normal to the extrusion axis. Mechanical properties are approximately the same for all directions normal to the extrusion axis, however. Thus this graphite is assumed to be transversely isotropic. An elastic transversely isotropic material can be represented by five

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

independent elastic constants.⁵ Consider a three-dimensional rectangular coordinate system imposed on the graphite body so that axis 1 and axis 2 lie in the plane of isotropy and axis 3 is normal to the plane of isotropy. Using subscripts to denote the direction of stresses σ and τ and strains ϵ and γ , the five independent elastic constants are as follows:

$$E_1 = \sigma_1/\epsilon_1 = \sigma_2/\epsilon_2,$$

the modulus of elasticity in the plane of isotropy;

$$E_3 = \sigma_3/\epsilon_3,$$

the modulus of elasticity normal to the plane of isotropy;

$$\nu_{12} = -\epsilon_2/\epsilon_1 = -\epsilon_1/\epsilon_2,$$

Poisson's ratio in the plane of isotropy, where the strain in the denominator corresponds to the direction in which the stress is applied;

$$\nu_{13} = -\epsilon_3/\epsilon_1 = -\epsilon_3/\epsilon_2,$$

Poisson's ratio when the specimen is being stressed in the isotropic plane;

$$G_4 = \tau_{13}/\gamma_{13} = \tau_{23}/\gamma_{13},$$

the shear modulus for the planes normal to the plane of isotropy. There is a third Poisson's ratio, $\nu_{31} = -\epsilon_1/\epsilon_3 = -\epsilon_2/\epsilon_3$, pertaining to a specimen stressed in the direction normal to the plane of isotropy. It is related to the other material constants by the following relationship:

$$\nu_{31} = (E_3/E_1) \nu_{13}. \quad (4)$$

The six constants discussed above pertain to an elastic material, and since graphite exhibits nonelastic behavior even at very low stress values, they can only describe the behavior of graphite in the limit of zero strain on initial loading. At finite values of stress Hooke's law alone is not valid, and the stress-strain behavior is characterized by more complex constitutive equations.

The modulus of elasticity, defined as the slope of the stress-strain curve at the origin, was obtained in each case by least-squares fitting the stress-strain curve with the parabola, that is, Jenkins's equation for initial loading,

$$\epsilon = (\sigma/E) + B\sigma^2, \quad (5)$$

where E is the modulus of elasticity. The entire tensile stress-strain curves were used in determining the tensile modulus of elasticity. The compressive stress-strain curves below 0.28%

⁵S. G. Lekhnitskii, *Theory of Elasticity of an Anisotropic Elastic Body*, transl. by P. Fern, pp. 24-25, Holden-Day, San Francisco, 1963.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

strain were used to determine the compressive moduli. A discussion of why this particular definition of the modulus of elasticity was selected is presented in the Appendix.

Because of variability in graphite, several samples were tested in each instance so that the data could be examined on a statistical basis. The stress and the strain ratio were determined at specific values of longitudinal strain for each specimen. These data from each particular test series were averaged at each strain value, and statistical measures of variation were computed. The stress, strain, and strain ratio at fracture were similarly treated.

As was pointed out, the data are reduced in a discontinuous point-to-point manner. However, it is often advantageous to have the stress-strain curve represented by an equation when calculations are performed. The mean stress-strain curves were therefore fitted with the following equations:

$$\epsilon = A\sigma + B\sigma^2, \quad (1)$$

$$\epsilon = (\sigma/E) + D\sigma^n, \quad (6)$$

$$\sigma = (E/C) [1 - \exp(-C\epsilon)], \quad (7)$$

$$\sigma = C_1[1 - \exp(-C_2\epsilon)], \quad (8)$$

where ϵ , σ , and E are strain, stress, and tangent modulus of elasticity as defined previously; A , B , D , n , C , C_1 , and C_2 are all fitting parameters.

Equation (1) is based on a mechanical model for graphite behavior consisting of a series of elements, each made up of a spring and friction block, arranged in series. The model was designed to account for the unloading and reloading behavior as well as the initial loading. It should be noted that this equation applies only for the lower stress levels (i.e., up to about 50% of the fracture stress in compression). Hence it usually fits the entire curve in tension and the above-stated portion of the compressive curve.

Equation (6) is similar to Eq. (1), except that the exponent in the second term is not restricted to a value of 2 and the value of E is fixed at the value obtained from Eq. (5). Because of the additional latitude given by the variable exponent, Eq. (6) fits the compressive data better than Eq. (1). Equation (1) and Eq. (6) can be separated into elastic and plastic components of strain as discussed under "Cyclic Loading." In both equations, the first term on the right is the elastic strain component, and the second term on the right is the plastic strain component.

Equation (7), developed by Woolley⁶ from a dislocation-theory model of graphite, can be easily inverted:

$$\epsilon = \frac{1}{C} \ln \left(\frac{E}{E - \sigma C} \right). \quad (9)$$

⁶R. L. Woolley, "The Yield Curve and the Compressive Strength of Polycrystalline Graphite," *Phil. Mag.* 11(112), 799-807 (1965).

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

The elastic and plastic components of strain may now be separated. The elastic component of the strain (ϵ^E) is given by

$$\epsilon^E = \sigma/E, \quad (10)$$

and the expression for plastic strain (ϵ^P) is

$$\epsilon^P = \frac{1}{C} \ln \left(\frac{E}{E - \sigma C} \right) - \frac{\sigma}{E}. \quad (11)$$

Note that C is the only fitting parameter in this equation, as the modulus is fixed at the value given by Eq. (5).

Equation (8) is the same as Eq. (7), except the modulus of elasticity is no longer fixed at a predetermined value. Thus Eq. (8) has two fitting parameters, C_1 and C_2 . Equation (8) can be written explicitly in ϵ as follows:

$$\epsilon = \frac{1}{C_2} \ln \left(\frac{C_1}{C_1 - \sigma} \right). \quad (12)$$

The elastic and plastic strain components are given by

$$\epsilon^E = \sigma/C_1 C_2 \quad (13)$$

and

$$\epsilon^P = \frac{1}{C_2} \left[\ln \left(\frac{C_1}{C_1 - \sigma} \right) - \frac{\sigma}{C_1} \right] \quad (14)$$

respectively. Note that the product of the two fitting parameters, $C_1 C_2$, is the tangent to the stress-strain curve at zero stress and is thus equivalent to a modulus of elasticity.

MATERIAL VARIABILITY

The mechanical behavior of each specimen was somewhat different, as indicated by the spread in fracture points. A study was made to reveal any systematic variation within each element and to determine variations among elements and batches.

Batch-to-Batch Variation

Three batches of central support elements, designated as 01-1661, 1719AA, and 1809, have been tested. Comparison of data from these three batches indicates the amount of batch-to-batch variation in mechanical properties to be expected.

Parallel tensile specimens from all three batches were tested. From batch 01-1661, only the reduced-cross-section tubular-type tensile specimens and microspecimens were tested. Due to induced bending caused by the gripping method, strengths of reduced-cross-section specimens

~~CONFIDENTIAL~~

NO DISSEM

Fig. 17. Batch-to-Batch Variation of Tensile Stress-Strain Curve.

Fig. 18. Comparison of Compressive Stress-Strain Curves from Two Batches of Central Support Elements.

from batch 01-1661 were low. Reduced-cross-section tensile specimens from batch 1809 and full-cross-section tensile specimens from batches 1719AA and 1809 were also tested. The average stress-strain curve from each group is shown in Fig. 17. There was very little variation in deformation resistance among the three different batches, and the fracture points of the full-cross-section specimens were in good agreement. The significantly lower fracture points of the reduced-cross-section specimens are felt to be a result of induced bending in the specimens rather than batch-to-batch variations.

Parallel compressive stress-strain curves from batches 1719AA and 1809 are compared in Fig. 18. The mean stress-strain curve and the envelope containing the 18 individual stress-strain curves from batch 1719AA are shown in dashed lines. The mean stress-strain curve and the envelope containing the eight individual stress-strain curves from batch 1809 are shown as solid lines. Again, little batch-to-batch variation was evidenced.

Figure 19 displays similar graphic information for the tube-test specimens from batch 1719AA and batch 1809 and for the microspecimens from batch 01-1661. The higher strength exhibited by the microspecimens was due to the specimen design rather than to materials variation.

It is concluded that the three batches tested indicate a fairly small batch-to-batch variation of mechanical properties.

Element-to-Element Variation

The reduced-cross-section tensile specimens were not taken from the elements according to the standard cutting plan shown in Fig. 1. The 36 reduced-cross-section tensile specimens from batch 1809 were machined from three elements, 12 specimens per element. Twenty-seven reduced-cross-section tensile specimens from batch 01-1661 were taken from four elements. The two sets of specimens provided the largest number of measurements per element for calculating average stress-strain curves of elements.

The average tensile stress-strain curves for the three elements from batch 1809 are shown in Fig. 20, and the average tensile stress-strain curves for four elements from batch 01-1661 are given in Fig. 21. The differences among the three stress-strain curves from batch 1809 were small. Although there was a fairly large variation in average fracture points for the four elements from batch 01-1661, the differences are insignificant in comparison with the variation of individual fracture points, shown in Fig. 22. It is concluded from these data that the element-to-element variation within a single batch is negligible.

Axial Variation

A small, but systematic, variation of mechanical properties with axial position was found to exist in the central support elements. Hardness, density, and tensile strength are plotted as

Fig. 19. Comparison of Transverse Tensile Stress-Strain Curves from Three Batches.

Fig. 20. Comparison of Mean Stress-Strain Curves from Three Elements from Batch 1809.

~~CONFIDENTIAL~~

Fig. 21. Comparison of Mean Stress-Strain Curves from Four Elements from Batch 01-1661.

Fig. 22. Mean Stress-Strain Curve, Range of Data, and Fracture Points for Reduced-Cross-Section Parallel Tensile Specimens from Batch 01-1661.

functions of axial position in Fig. 23. The hardness was determined on a Rockwell superficial hardness tester using a 1/8-in.-diam ball and a 15-kg major load (15 W scale). The density was determined by weighing the specimen on an analytical balance and measuring the length and the width across flats with micrometers. The holes were assumed to be as specified on manufacturing drawings. Hardness and density of the parallel tensile and compressive specimens obtained from batch 1719AA were determined. Data for specimens from the same axial location in the rods were averaged, and the average values of hardness and density are plotted in Fig. 23. The material was harder at the ends than at the middle, and the numbered end was slightly harder than the other end. The density was lower near the ends than in the center and was higher in the half rod near the numbered end. The average fracture stresses at each axial position in the rods for the full-cross-section tensile specimens and reduced-cross-section tensile specimens are also plotted in Fig. 23. The average fracture stresses were higher at the ends than in the middle of the rod. Also, average stress values were highest near the numbered end.

The variation with axial position, though small, definitely exists. Data from full-cross-section tensile specimens at both ends were averaged, as were the data from the specimens from the two sections near the center. These two average curves are plotted in Fig. 24. A similar plot for compressive data is shown in Fig. 25. The letters A, B, D, E, F, G, I, and J used in the figure

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

22

Fig. 23. Property Variations as Functions of Axial Position.

Fig. 24. Comparison of Mean Tensile Stress-Strain Curves from the Middle and Ends of Central Support Elements.

Fig. 25. Comparison of Mean Compressive Stress-Strain Curves from the Middle and Ends of Central Support Elements.

~~CONFIDENTIAL~~

conform to the letter designations of specimen locations given in Fig. 1. These two figures give a clear illustration that the variation with axial position is of minor importance.

Radial Variation

Discussions with personnel experienced in machining central support elements revealed that there is a radial variation of mechanical properties in central support elements. This phenomenon was investigated by testing (1) reduced-cross-section tensile specimens that had tubular gage sections with three different mean diameters and (2) tensile microspecimens from two different radial locations. In addition, hardness measurements were made at five radial locations on several full-cross-section tensile and compressive specimens before they were broken.

The average fracture stress at each radial location for three sets of specimens and the average hardness at five radial locations are plotted vs radial position in Fig. 26. The material was harder and stronger at the center than at the outside of the element.

Mean stress-strain curves obtained from reduced-cross-section specimens from batch 1809 are compared in Fig. 27. The radial variation exceeded the axial variation discussed above. At 0.15%

Fig. 26. Tensile Strength and Hardness vs Radial Position in Central Support Elements.

~~CONFIDENTIAL~~

24

Fig. 27. Tensile Stress-Strain Curves from 0.040-in.-thick Tubes.

strain, the coefficient of variation of the stress from the full-cross-section tensile specimens was 2.8%, while the mean stress from the 0.460-in. reduced-cross-section tensile specimens was 8.4% higher than for the 0.660-in. reduced-cross-section tensile specimens. Thus it is concluded that the radial variation is significant.

CHARACTERISTIC MECHANICAL PROPERTIES FOR DESIGN AND ANALYSIS

The data most representative of central support elements' mechanical behavior are presented in this section in graphical, tabular, and equation form. The parallel data were determined from full-cross-section specimens. The transverse tensile stress-strain curve was obtained from tests on microspecimens, and the corresponding strain ratio was measured on tubular test specimens.

Statistical Presentation of Data

The data are summarized in Table 2. The batches from which the elements tested were selected, the number of specimens tested, the average stress, strain, strain energy, and strain ratio at fracture, the average modulus of elasticity, and the average initial strain ratio are listed. The coefficient of variation of each property is given as a percentage.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Table 2. Mechanical Properties of Graphite Central Support Elements

Type of Test	Batch Numbers	Number of Specimens	Stress at Fracture (psi)	Strain at Fracture (%)	Modulus of Elasticity (psi)	Strain Energy (in.-lb/in. ³)	Initial Strain Ratio	Final Strain Ratio
<hr/>								
					$\times 10^6$			
Parallel tensile	1719AA, 1809	27	4,200 (6) ^a	0.24 (7)	2.37 (4)	5.6 (13)	0.17 (11)	0.08 (9)
Parallel compressive	1719AA, 1809	31	12,000 (4)	1.18 (8)	2.79 (11)	90.8 (13)	0.17 (15)	0.17 (6)
Transverse microspecimens	01-1661	9	2,200 (11)	0.22 (13)	1.27 (7)	2.7 (23)		
Tube tests	1719AA, 1809	25			1.47 (13)		0.06 (34)	0.05 (29)
Tube tests and transverse microspecimens	01-1661, 1719AA, 1809	34	1,800 (22)	0.16 (29)	1.41 (13)	1.56 (51)		

^aNumbers in parentheses are the coefficients of variation in percent.

As was stated earlier, the tube tests and microspecimen tests yielded comparable stress-strain curves up to the fracture point of the tubular specimens. Therefore the most representative modulus of elasticity is the average from both the tubes and the transverse microspecimens. The appropriate transverse tensile stress, strain, and strain energy at fracture should be obtained from microspecimen data only, however. Since strain-ratio data were not obtained from microspecimens, the strain-ratio values are from the 25 tube tests. The high coefficients of variation in transverse tensile data are due, at least in part, to the small sample size.

Note that initial strain ratio from parallel tests is about the same in tension and compression, as would be expected. The initial strain ratio obtained from transverse tube tests, ν_{13} , should be related to the initial strain ratio from parallel tests, ν_{31} , by Eq. (4). The value of $(E_1/E_3)\nu_{31}$ is 0.093, based on tensile data, and is about 50% higher than the value of ν_{13} . This disagreement is probably a result of end restraint in the tube tests near zero strain. This is discussed further below.

The modulus of elasticity for the parallel compressive specimens is 18% more than the modulus of elasticity for the parallel tensile specimens. The average tensile stress-strain curve and the first part of the average compressive stress-strain curve are plotted together in Fig. 28. The portion of the compressive stress-strain curve plotted in Fig. 28 is the portion used in calculating the modulus of elasticity. The "one-sided normal test"⁷ was used to determine whether it could be shown statistically that the modulus of elasticity in compression is greater than the tensile

⁷M. G. Natrella, *Experimental Statistics, National Bureau of Standards Handbook 91*, pp. 3-37, U.S. Government Printing Office, Washington, D.C., 1963.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Fig. 28. Comparison of Average Parallel Tensile and Compressive Stress-Strain Curves.

modulus. The average stress in the compression test at a strain of 0.01% was compared with the average stress in the tension test at the same strain using the "one-sided normal test." Both the null hypothesis that the average compressive modulus is greater than the average tensile modulus and the null hypothesis that the average compressive stress at 0.01% strain is greater than the average tensile stress at 0.01% strain could not be rejected at the 0.1% significance level. It was therefore concluded that the central-support-element graphite does have a higher modulus in compression than in tension.

In a previous investigation on EGCR-type AGOT graphite⁸ the compressive modulus was found to be 18% higher than the tensile modulus in uniaxial tests parallel to the extrusion axis and 16% higher in uniaxial tests transverse to the extrusion direction. Flexure tests also indicated that the modulus of elasticity was greater for compressive loading than for tensile loading for EGCR-type AGOT graphite. Seldin⁹ noted in his investigations on ATJ and ZTA graphites that, for a given stress, there is in general slightly greater strain in tension than there is in compression, which is in agreement with our results. He concluded, however, that the initial modulus of elasticity was the same, within the limits of experimental error, for tension and compression. Seldin determined the modulus of elasticity directly from the slope of the initial part of the stress-strain

⁸B. L. Greenstreet et al., *Room-Temperature Mechanical Properties of EGCR-Type AGOT Graphite*, ORNL-3728 (January 1965).

⁹E. J. Seldin, "Stress-Strain Properties of Polycrystalline Graphites in Tension and Compression at Room Temperature," *Carbon* 4, 177-91 (1966).

~~CONFIDENTIAL~~

Fig. 29. Tensile Stress-Strain Curves for Graphite Central Support Elements.

Fig. 30. Parallel Compressive Stress-Strain Curve for Graphite Central Support Elements.

curve, which was plotted to a scale such that full scale on the recorder chart was somewhere between 100 and 200 psi.

The mean tensile stress-strain curves for the two directions are compared in Fig. 29. The parallel tensile curve is the average from 27 full-cross-section tensile tests on elements from two batches of material. The transverse tensile curve is the average from nine microspecimens taken from one element. Both curves are nonlinear. The average parallel compressive stress-strain curve is shown in Fig. 30. It is the average of data from 31 full-cross-section compressive specimens from two batches of elements. Note that the stress and strain at fracture are much higher in compression than in tension.

Figures 31 through 34 statistically summarize the behavior of the central support elements. Each individual fracture point, an envelope encompassing every stress-strain curve, and the mean stress-strain curve are shown at the left in Figs. 31, 32, and 33. On the right, the mean, the 95% confidence interval for the mean, and the standard deviation of the stresses at particular strain values and of the fracture stresses and strains are plotted. The average stress and the coefficient of variation of the stress at particular strain values are tabulated in Tables 3, 4, and 5 for the full-cross-section parallel tensile and compressive specimens and transverse tensile microspecimens respectively.

Fig. 31. Parallel Tensile Stress-Strain Curve and Statistics.

Fig. 32. Parallel Compressive Stress-Strain Curve and Statistics.

Fig. 33. Transverse Tensile Stress-Strain Curve and Statistics Obtained from Microspecimens.

Table 4. Parallel Compressive Stress-Strain Data from 31 Full-Cross-Section Specimens

Strain (%)	Stress (psi)	Coefficient of Variation of Stress (%)
0.010	295	16.98
0.030	809	10.60
0.040	1,032	8.38
0.050	1,270	8.79
0.070	1,680	7.53
0.120	2,619	5.60
0.200	3,948	4.27
0.280	5,103	3.59
0.360	6,123	3.40
0.440	7,028	3.18
0.520	7,838	3.13
0.600	8,554	3.07
0.680	9,211	3.02
0.760	9,793	2.96
0.840	10,320	2.88
0.920	10,797	2.87
1.000	11,242	2.91
1.080	11,596	2.76
1.160	11,933	2.70
1.175 (8.37) ^a	12,041	4.47

Table 3. Parallel Tensile Stress-Strain Data from 27 Full-Cross-Section Specimens

Strain (%)	Stress (psi)	Coefficient of Variation of Stress (%)
0.010	237	6.89
0.030	697	2.42
0.050	1100	2.61
0.070	1470	2.99
0.090	1829	3.31
0.110	2165	3.06
0.130	2505	2.85
0.150	2825	2.78
0.170	3138	2.77
0.190	3446	2.62
0.210	3746	2.69
0.230	4047	2.65
0.243 (7.15) ^a	4233	6.31

^aCoefficient of variation of fracture strain in percent.

^aCoefficient of variation of fracture strain in percent.

Fig. 34. Strain-Ratio Data for Graphite Central Support Elements.

The mean strain ratios μ_{ij} along with their standard deviations and the 95% confidence intervals of their means are plotted as functions of the axial strain in Fig. 34. Here, μ_{ij} is defined as the ratio of the transverse strain in the j direction to the axial strain in the i direction; $\mu_{ij} = -\epsilon_j/\epsilon_i$. Note that the initial strain ratio from the transverse tensile tests was less than the strain ratio at 0.02% strain, whereas it was larger in the parallel tensile test. There is evidence that axial contraction in the tube tests, from which these data were obtained, was inhibited by the O-ring seals at the beginning of each test. The dotted extrapolation of the strain-ratio curve from the transverse

Table 5. Transverse Tensile Stress-Strain Data from Nine Microspecimens

Strain (%)	Stress (psi)	Coefficient of Variation of Stress (%)
0.010	130	8.13
0.030	371	6.08
0.050	596	5.39
0.070	813	5.60
0.090	1019	5.66
0.110	1217	5.57
0.130	1417	5.37
0.150	1602	5.54
0.170	1786	5.82
0.190	1945	5.81
0.210	2114	5.64
0.221 (13.08) ^a	2215	11.17

^aCoefficient of variation of fracture strain in percent.

Table 6. Parameters Obtained by Fitting the Mean Stress-Strain Curves with the Equation

$$\epsilon = (\sigma/E) + B\sigma^{-2}$$

Type of Test	E, Modulus of Elasticity (psi)	B [(psi) ⁻²]
	$\times 10^6$	$\times 10^{-12}$
Parallel tensile	2.37	36
Parallel compressive	2.79	37
Transverse tensile, microspecimens	1.27	99

tensile tests to the value of $(E_1/E_3) \nu_{31}$ calculated above makes the curve more similar to the strain-ratio curve from the parallel tensile tests.

Analytical Representation of Mean Stress-Strain Curves

Data often used by designers, such as modulus of elasticity, fracture stress, and fracture strain, were tabulated, and the stress-strain curves were presented in the preceding section. In plasticity analyses it is often found useful to have the mean stress-strain curves described by analytical expressions. Since it is not known what type of expression will be required in a particular analysis, Eqs. (1), (6), (7), and (8) have each been fitted to the three representative mean stress-strain curves discussed in the previous section.

The parameters of Eq. (1) providing the best fit to the mean stress-strain curves are listed in Table 6. Seldin⁹ fitted Jenkins's equation to compressive stress-strain curves for ATJ graphite, which is a standard high-quality molded graphite produced by Union Carbide Corporation. For comparison, Seldin's values for E and B were the following:

Specimen Orientation	E (psi)	B (psi ⁻²)
With grain	1.72×10^6	43×10^{-12}
Across grain	1.22×10^6	100×10^{-12}

The parameters obtained when Eq. (6) was least-squares fitted to the mean stress-strain curves are given in Table 7. Note that for tensile data n is approximately 2, but the values of D are not the same as the values of B in Table 6. Equation (1) was fitted to the compressive stress-strain curve below 0.28% strain, whereas the entire compressive stress-strain curve was fitted with Eqs. (6), (7), and (8). Hence it should not be expected that the parameters for Eqs. (1) and (6) can be compared for compressive data.

The values of C obtained when Eq. (7) was least-squares fitted to the mean stress-strain curves are tabulated in Table 8. Recall that the elastic moduli were obtained using Eq. (1). The values of the parameters obtained when Eq. (8) was least-squares fitted to the mean stress-strain curves and the products of the parameters are tabulated in Table 9. It is interesting to compare the products of the parameters with the moduli given in Table 2. The products of C_1 and C_2 in Table 9 for parallel tension and compression are equal, whereas the parallel compressive modulus in Table 2 is much higher than the parallel tensile modulus.

All four equations fit the tensile data quite well. Figure 35 compares curves described by the equations with points from the average compressive stress-strain curve. Equations (6) and (8) fit the data almost equally well. The Jenkins equation, Eq. (1), gives a good fit below a stress of 8000 psi, but the data and curve diverge above that point. Equation (7) doesn't fit the compressive stress-strain curve nearly as well as the other equations do.

Table 7. Parameters Obtained by Fitting the Mean Stress-Strain Curves with the Equation

$$\epsilon = (\sigma/E) + D\sigma^n$$

Type of Test	E , Modulus of Elasticity (psi)	D	n
	$\times 10^6$		
Parallel tensile	2.37	81×10^{-12}	1.90
Parallel compressive	2.79	14.2×10^{-14}	2.62
Transverse tensile	1.27	64×10^{-12}	2.06

Table 8. Parameters Obtained by Fitting the Mean Stress-Strain Curves with the Equation $\sigma = (E/C) [1 - \exp(-C\epsilon)]$

Type of Test	E (psi)	C
	$\times 10^6$	
Parallel tensile	2.37	285
Parallel compressive	2.79	227
Transverse tensile	1.27	234

Table 9. Parameters Obtained by Fitting the Mean Stress-Strain Curves with the Equation $\sigma = C_1 [1 - \exp(-C_2\epsilon)]$

Type of Test	C_1	C_2	$C_1 C_2$ (psi)
			$\times 10^6$
Parallel tensile	10,200	219	2.23
Parallel compressive	14,200	156	2.22
Transverse tensile	6,000	207	1.24

~~CONFIDENTIAL~~

Fig. 35. Equations Compared with Mean Parallel Compressive Stress-Strain Curve.

SUMMARY AND CONCLUSIONS

Accurate determinations of stress-strain curves and strain ratios were made for the Phoebus central support elements at room temperature. Several tests of each type were performed in order to determine the variability of material.

A remarkable feature of this graphite is its low variability of mechanical properties as compared with commercial graphites. The strength of the graphite varies in a linear fashion with radial position, being strongest at the center. The Phoebus central-support-element graphite is a strong

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

graphite and has a relatively high modulus of elasticity. The strength and modulus of elasticity perpendicular to the axis are about half as much as they are parallel to the extrusion axis. In the parallel direction, this graphite is slightly more deformation resistant and much stronger in compression than in tension.

A very satisfactory method for testing full-cross-section tensile specimens at room temperature was developed. Techniques were also developed for determining mechanical properties perpendicular to the axis of the element. One-sixteenth-inch-diameter "microspecimens" were found to be very useful for determining the transverse tensile stress-strain curve. Thin-walled tubes subjected to internal pressure in such a way that no axial force was transmitted to the specimen were also used to obtain stress-strain data. It was found that these specimens were most useful in determining strain-ratio values for loading transverse to the extrusion direction.

The data are presented in graphical, tabular, and equation form so that the data will be of maximum utility to the designer.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to the many people involved in the work reported here. Special thanks go to B. L. Greenstreet for his suggestions for data interpretation and support in writing this report and to F. J. Witt, who was in charge of the project while much of this work was done, for his guidance of the work. R. L. Maxwell provided valuable consultation on the tensile-grip development. J. M. Chapman, H. D. Curtis, R. C. Gwaltney, and J. P. Rudd assisted in strain gaging the specimens and in running the tests. S. J. Adamski, D. T. Godwin, and H. A. MacColl helped process the data. R. B. Bullock, H. M. Nicholson, and O. W. Russ wrote the computer programs. S. E. Moore and F. M. O'Hara, Jr., reviewed and edited this report.

We would also like to acknowledge the financial support of the Space Nuclear Propulsion Office (SNPO). This work was carried out in support of the Advanced Graphite Research and Technology Portion of the Nuclear Rocket Program. The cognizant engineers for SNPO are J. E. Morrissey, SNPO, Washington, D.C., and Harold Hessing, SNPO-A, Los Alamos, New Mexico. The Technical Director for USAEC is J. C. Rowley, N-7 Group, N Division, Los Alamos Scientific Laboratory.

APPENDIX

There is no standard method for defining the modulus of elasticity for graphite. ASTM Standard C565 (ref. 10), entitled "Tension Testing of Carbon-Graphite Mechanical Materials," specifies strength measurement only. ASTM Standard E111-61 (1965),¹¹ entitled "Standard Method for Determination of Young's Modulus at Room Temperature," lists four moduli, of which any one may be used

¹⁰"Tension Testing of Carbon-Graphite Mechanical Materials," ASTM Designation: C565.

¹¹"Standard Method for Determination of Young's Modulus at Room Temperature," ASTM Designation: E111-61 (1965).

~~CONFIDENTIAL~~

instead of Young's modulus if the proportional limit is so low that a constant ratio of stress to strain cannot be obtained under the conditions of the test. Those four moduli are illustrated in Fig. A-1. The initial tangent modulus, shown in Fig. A-1a, is the most useful in our studies because our analyses are based upon the premise that the total strain at any stress level consists of an elastic strain component and a plastic strain component.

An accurate determination of the tangent to a nonlinear curve is difficult, particularly at the origin. The slope of the tangent determined by laying a straightedge on the curve and visually determining the tangent to the curve is subject to considerable variation. As an example of the inaccuracy associated with visual determination of the initial tangent modulus of elasticity, three engineers drew what each thought was the initial tangent to the stress-strain curve in Fig. A-2. They obtained values of 2.25×10^6 , 2.42×10^6 , and 2.62×10^6 for the initial tangent modulus. The tangent modulus determined by this visual method will depend, of course, on the scale.

Several equations for representing the stress-strain curve of graphite have been reported. The most widely used of these equations is the one proposed by Jenkins,³

$$\epsilon = (\sigma/E) + B\sigma^2, \quad (A1)$$

Fig. A-1. Stress-Strain Diagrams Showing Straight Lines Corresponding to (a) Initial Tangent Modulus, (b) Tangent Modulus, (c) Secant Modulus, and (d) Chord Modulus.

Fig. A-2. Typical Tensile Stress-Strain Curve.

where E is the modulus of elasticity. This equation may be written as

$$\epsilon/\sigma = (1/E) + B\sigma, \quad (A2)$$

so that this equation produces a straight line that intercepts the ordinate at $1/E$ and has a slope of B , where ϵ/σ is plotted vs σ . Figure A-3 shows such a plot for the same tensile stress-strain curve shown in Fig. A-2 and for a typical compressive stress-strain curve. The tensile data fit a straight line except at low stress levels (below 1000 psi), where the data fall below the straight line. This deviation from the straight line at low stress levels was observed for most of the stress-strain curves for central support elements examined in this manner. This phenomenon was reported previously by Rappeneau, Jouquet, and Guimard.¹² The compressive data fall below the straight line at low stress levels also, and at high stress levels (above 7000 psi) the data lie above the straight line. The deviation of the compressive data at high stress levels was noted by Jenkins when he first presented Eq. (A1), and he hypothesized that the discrepancy between the theory and experimental results at high stresses is due to a decrease in the modulus of the bulk material as the stress is raised to high values. The observed deviations from the straight line indicate that the stress-strain curves are more linear than predicted by the parabolic equation proposed by Jenkins at low stress levels and more nonlinear at high stress levels.

The modulus of elasticity obtained by fitting Jenkins's equation to the data underestimates the true tangent modulus of elasticity. Fitting a smooth curve to the low-stress-value points in Fig. A-3 gives tensile and compressive moduli of 2.64×10^6 psi and 3.52×10^6 psi, respectively,

¹²J. Rappeneau, G. Jouquet, and M. Guimard, "Fluage Thermique et Comportement Non Elastique du Graphite Artificiel," *Carbon* 3, 407-20 (1966).

Fig. A-3. Method for Determining the Modulus of Elasticity for Graphite.

~~CONFIDENTIAL~~

which are appreciably higher than the values of 2.34×10^6 psi and 2.75×10^6 psi obtained by fitting Jenkins's equation to the data. The tangents obtained by these two methods are compared with the stress-strain curves in Figs. A-2 and A-4. As was mentioned above, the initial tangent moduli determined by three engineers by drawing in what they felt was the tangent to the curve in Fig. A-2 varied from 2.25×10^6 psi to 2.62×10^6 psi.

Because of the wide variation in tangent modulus of elasticity values obtained by different methods or, in the case of visually drawing the tangent, the difference in values obtained by different individuals, some definite systematic method for determining the tangent modulus of elasticity must be specified. This method should use data from the same stress range for both tensile and compressive stress-strain curves, so that a valid comparison of tensile and compressive moduli can be made. Figure A-5 shows plots of the coefficients of variation of stress at various strain values plotted vs those strain values for the full-cross-section parallel tensile and compressive specimens and transverse microspecimens. The coefficients of variation for the tensile data are much higher at 0.01% strain than at the higher strain values because of the greater effect

Fig. A-4. Typical Compressive Stress-Strain Curve.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Fig. A-5. Coefficient of Variation of Stress vs Strain.

of accuracy on the small values of stress. The coefficients of variation of stress for the compressive data are high to a considerably higher strain value. This is because the compressive data must be plotted to a smaller scale than the tensile data. Because of these inaccuracies in the compressive data, the data used in determining the modulus of elasticity should cover the complete range of the tensile stress-strain curve.

The tensile moduli in this report were determined by least-squares fitting the entire stress-strain curve with Eq. (A1). The compressive moduli were obtained by fitting the portion of the stress-strain curve below 0.28% strain.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

39

ORNL-4276

C-91 - Nuclear Reactors for Rocket Propulsion

INTERNAL DISTRIBUTION

1. Biology Library	27. C. E. Larson
2-4. Central Research Library	28. R. N. Lyon
5-6. ORNL - Y-12 Technical Library	29. H. G. MacPherson
Document Reference Section	30. G. B. Marrow (Y-12)
7-16. Laboratory Records Department	31. J. G. Merkle
17. Laboratory Records, ORNL R.C.	32. S. E. Moore
18. S. E. Beall	33. J. M. Napier (Y-12)
19. J. P. Callahan	34. C. E. Pugh
20. W. H. Cook	35. M. J. Skinner
21. J. M. Corum	36. J. E. Smith
22. F. L. Culler	37. D. B. Trauger
23. R. W. Derby	38. R. S. Valachovic
24. A. P. Fraas	39. A. M. Weinberg
25. B. L. Greenstreet	40. J. R. Weir, Jr.
26. R. C. Gwaltney	41. G. T. Yahr

EXTERNAL DISTRIBUTION

- 42. H. W. Behrman, RDT Site Office (ORNL)
- 43. Al Boltax, Westinghouse Astronuclear Laboratory, Pittsburgh, Pennsylvania
- 44. S. A. Bortz, IIT Research Institute, Chicago, Illinois
- 45. Jack Cully, SNPO-A, c/o USAEC, P.O. Box 5400, Albuquerque, N.M.
- 46. R. J. Dietz, Los Alamos Scientific Laboratory, Los Alamos, N.M.
- 47. L. L. France, Westinghouse Astronuclear Laboratory, Pittsburgh, Pennsylvania
- 48. Harold Hessing, SNPO-A, c/o Los Alamos Scientific Laboratory, GMB Division, Los Alamos, N.M.
- 49. W. J. Larkin, AEC, ORO
- 50. L. L. Lyon, Los Alamos Scientific Laboratory, Los Alamos, N.M.
- 51. M. Manjoine, Westinghouse Astronuclear Laboratory, Pittsburgh, Pennsylvania
- 52. D. P. MacMillan, Los Alamos Scientific Laboratory, Los Alamos, N.M.
- 53-54. J. E. Morrissey, SNPO, AEC, Washington
- 55. R. E. Nightingale, Pacific Northwest Laboratory, Richland, Washington
- 56. W. G. Ramke, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio
- 57-66. J. C. Rowley, Los Alamos Scientific Laboratory, Los Alamos, N.M.
- 67. W. S. Scheib, SNPO, AEC, Washington
- 68. F. C. Schwenk, SNPO, AEC, Washington
- 69. N. R. Thielke, SNPO, NASA Lewis Research Center, Cleveland, Ohio
- 70. D. E. Thomas, Materials and Fuel Facility, Westinghouse Astronuclear Laboratory, Pittsburgh, Pennsylvania
- 71. M. C. Smith, Los Alamos Scientific Laboratory, Los Alamos, N.M.
- 72. R. G. Lawton, Los Alamos Scientific Laboratory, Los Alamos, N.M.
- 73. Milt Swope, Aerojet-General, Sacramento, California

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

74. V. Kachur, Westinghouse Astronuclear Laboratory, Pittsburgh, Pennsylvania
75. Fred Kirkhart, Westinghouse Astronuclear Laboratory, Pittsburgh, Pennsylvania
76. W. Brussalis, Westinghouse Astronuclear Laboratory, Pittsburgh, Pennsylvania
77. E. A. Henne, Westinghouse Astronuclear Laboratory, Pittsburgh, Pennsylvania
78. C. A. Anderson, Westinghouse Astronuclear Laboratory, Pittsburgh, Pennsylvania
79. E. M. Woodruff, Pacific-Northwest Laboratory, Richland, Washington
80. H. E. Martens, Jet Propulsion Laboratory, Pasadena, California
81. Tu-Lung Weng, Parma Research Center, Cleveland, Ohio
82. E. J. Seldin, Parma Research Center, Cleveland, Ohio
83. J. T. Meers, Parma Research Center, Cleveland, Ohio
84. G. B. Spence, Parma Research Center, Cleveland, Ohio
85. C. W. Funk, Nuclear Rocket Operations, Aerojet-General Corporation, Sacramento, California
86. J. J. Lombardo, SNPO, NASA Lewis Research Center, Cleveland, Ohio
87. R. H. Singleton, Westinghouse Astronuclear Laboratory, Pittsburgh, Pennsylvania
88. J. S. Theilacker, Westinghouse Astronuclear Laboratory, Pittsburgh, Pennsylvania
89. J. A. Swartout, Union Carbide Corporation, New York
90. Laboratory and University Division, AEC, ORO
- 91-191. Given distribution as shown in M-3679 (57th ed.) under Nuclear Reactors for Rocket Propulsion category

~~CONFIDENTIAL~~