FOREWORD

The contract for this R & D program was initiated under Project No. 7350, "Refractory Inorganic Non-Metallic Materials," Task No. 735002, "Refractory Inorganic Non-Metallic Materials: Graphitic; "Project No. 7381, "Materials Application," Task No. 738102, Materials Processes;" and Project No. 7-817, "Process Development for Graphite Materials." The work was administrated by the Air Force Materials Laboratory, Research and Technology Division. Major R. H. Wilson, L. J. Conlon and W. P. Conrardy acted as Project Engineers.

The work covered in this report was conducted from May 1, 1960 through April 30, 1963 at the Advanced Materials Laboratory of National Carbon Company, Lawrenceburg, Tennessee, under the management of R. M. Bushong, Director of the Advanced Materials Project, and of R. C. Stroup, Manager of the Advanced Materials Laboratory.

The characterization of seventeen graphite grades has involved the labors of many people. The author is particularly indebted to the following who have supervised the collection or aided in the preparation of the data for this report: Messrs. S. O. Johnson, G. F. Lanning, M. B. Manofsky, E. T. Rose, W. E. Sloka, M. A. Spring, J. H. Turner.

This volume is the twenty-sixth of the series WADD Technical Report 61-72 describing various phases of research and development on advanced graphite materials conducted by National Carbon Company, a Division of Union Carbide Corporation, under USAF Contract No. AF 33 (616)-6915.

Other volumes in this WADD Technical Report 61-72 series are:

Volume I - Observations by Electron Microscopy of Dislocations in Graphite, by R. Sprague.

Volume II - Applications of Anisotropic Elastic Continuum Theory to Dislocations in Graphite, by G. B. Spence.

Volume III - Decoration of Dislocations and Low Angle Grain Boundaries in Graphite Single Crystals, by R. Bacon and R. Sprague

Volume IV - Adaptation of Radiographic Principles to the Quality Control of Graphite, by R. W. Wallouch.

Volume V	-	Analysis of Creep and Recovery Curves for ATJ Graphite, by E. J. Seldin.
Volume VI	-	Creep of Carbons and Graphites in Flexure at High Temperature, by E. J. Seldin.
Volume VII	-	High-Density, Recrystallized Graphite by Hot-Forming, by E. A. Neel, A. A. Kellar and K. J. Zeitsch.
Supplement	-	High-Density Recrystallized Graphite by Hot-Forming, by G. L. Rowe and M. B. Carter.
Volume VIII	-	Electron Spin Resonance in Polycrystalline Graphite, by L. Singer and G. Wagoner.
Volume IX	-	Fabrication and Properties of Carbonized Cloth Composites, by W. C. Beasley and E. L. Piper.
Volume X	-	Thermal Reactivity of Aromatic Hydrocarbons, by I. C. Lewis and T. Edstrom.
Supplement	-	Thermal Reactivity of Aromatic Hydrocarbons, by I. C. Lewis and T. Edstrom.
Volume XI	-	Characterization of Binders Used in Fabrication of Graphite Bodies, by E. deRuiter, A. Halleux, V. Sandor and H. Tschamler.
Supplement	-	Characterization of Binders Used in Fabrication of Graphite Bodies, by E. deRuiter, J. F. M. Oth, V. Sandor and H. Tschamler.
Volume XII	-	Development of an Improved Large-Diameter, Fine-Grain Graphite for Aerospace Applications, by C. W. Waters and E. L. Piper.
Supplement	-	Development of an Improved Large-Diameter, Fine-Grain Graphite for Aerospace Applications, by R. L. Racicot and C. W. Waters.
Volume XIII	-	Development of a Fine-Grain Isotropic Graphite for Structural and Substrate Applications, by R. A. Howard and E. L. Piper.
Supplement	-	Development of a Fine-Grain Isotropic Graphite for Structural and Substrate Applications, by R. A. Howard and R. L. Racicot.

ABSTRACT

This report presents the physical properties which were measured on the graphites developed and/or evaluated under this program. Methods of and equipment for making these measurements are described. The physical properties are reported for 17 newly developed graphite grades which include six high-density, recrystallized graphites designated as ZT grades; six graphites in which the fillers are shredded or woven carbonized cloths designated as PT grades; and five pressure-cured and/or impregnated grades designated as RVA, RVC, RVD, CFZ, and CFW. Similar properties of ATJ graphite are presented as a basis for comparing the newly developed grades with a well established, premium grade of graphite.

This technical documentary report has been reviewed and is approved.

W. G. RAMKE
Chief, Ceramics and Graphite Branch
Metals and Ceramics Division
Air Force Materials Laboratory

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D)

TABLE OF CONTENTS (CONT'D)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF TABLES

LIST OF TABLES (CONT'D)

1. INTRODUCTION

Twelve properties were selected for measurement to characterize the graphite grades developed and/or evaluated under Contract AF 33(616)-6915. These are:

Bulk Density

Specific Resistance (electrical resistivity) at room temperature

Young's Modulus at room and elevated temperatures

Flexural Strength at room temperature

Compressive Strength at room and elevated temperatures

Tensile Strength at room and elevated temperatures

Shear Strength at room and elevated temperatures

Thermal Expansion at room and elevated temperatures

Thermal Conductivity at room temperature

Permeability or Admittance at room temperature

Porosity (mercury porosimetry)

Ash Content (quantitative)

Eight graphite grades have been completely characterized by being tested for all properties as outlined above, and nine grades partially characterized by being tested for only part of the listed properties. Tensile and shear strengths at room and elevated temperatures and compressive strengths at elevated temperatures are the properties which were not measured for the partially characterized grades. Properties of ATJ graphite are presented in Section 3 to serve as a basis for comparison of the newly developed grades.

Manuscript released by the author April 1964 for publication as an RTD Technical Documentary Report

2. EQUIPMENT AND PROCEDURES

2.1. Bulk Density

Bulk density is determined by measurement of gross volume and weight and, therefore, incorporates both the total porosity of the material and any impregnants added to fill the available pores. Bulk density measurements reported in Section 3 are made on the same $\frac{1}{2}$- by $\frac{1}{2}$- by 5-inch or $1\frac{1}{4}$- by $1\frac{1}{4}$- by 5-inch samples used for determination of specific resistance, Young's modulus, flexural strength, and thermal expansion at elevated temperatures. Width and breadth are measured at three points along the bar (i.e., at the two ends and middle) and averaged. Dimensions are measured to the nearest thousandth of a centimeter and weights to the nearest hundredth of a gram. Bulk density is expressed in grams per cubic centimeter (g/cc).

2.2. Density Profile

No set procedure was followed in establishing the density profile for blocks of graphite evaluated under this program. However, in every case a cross sectional-slab cut in a longitudinal direction from the center of the block was further cut into small pieces for density and other property measurements. One-inch cubes were used for measurement of density profile of blocks fourteen inches in diameter or less. The cubes were later used for compressive tests. Density profiles of some of the larger blocks were obtained from the $\frac{1}{2}$- by $\frac{1}{2}$- by 5-inch or $1\frac{1}{4}$- by $1\frac{1}{4}$- by 5-inch samples mentioned in Section 2.1. Larger samples were used in a limited number of cases.

Bulk density profiles were established for blocks larger than fourteen inches in diameter and apparent density profiles for blocks fourteen inches in diameter or less; i.e., when the samples had been cut into one-inch cubes.

Apparent density is determined by weighing the sample in air and again when it is immersed in distilled water, and using these weights in the following formula:

$$\text{A.D.} = \frac{\text{Weight of sample in air}}{\text{Weight of sample in air minus weight of sample in water}}$$

where:

A.D. = apparent density in g/cc, when weights are in grams.

Water fills some of the large pores when the sample is immersed, thus the volume of water displaced is slightly smaller than the gross volume of the sample. Consequently, densities are approximately 0.02 g/cc higher than bulk densities.

2.3. Room-Temperature Specific Resistance (Electrical Resistivity)

The apparatus for measuring specific resistance at room temperature is shown in Figure 1. Mounted on the left end of the table is a device for positioning the sample. Basically, this device is a jeweller's lathe having such special features as an adjustable positioner for the potential contacts with a span capacity of 5 inches, and current contacts with a span up to 12 inches. The resistance of the sample R_x between the potential contacts is measured by a Kelvin bridge and the specific resistance calculated by means of the formula:

$$\rho = \frac{R_x \cdot A}{L}$$

where:
- ρ = Resistivity in ohm-cm
- R_x = Resistance of the sample in ohms
- A = Cross sectional area of the sample in cm^2
- L = Length of the span in cm over which the resistance R_x is measured

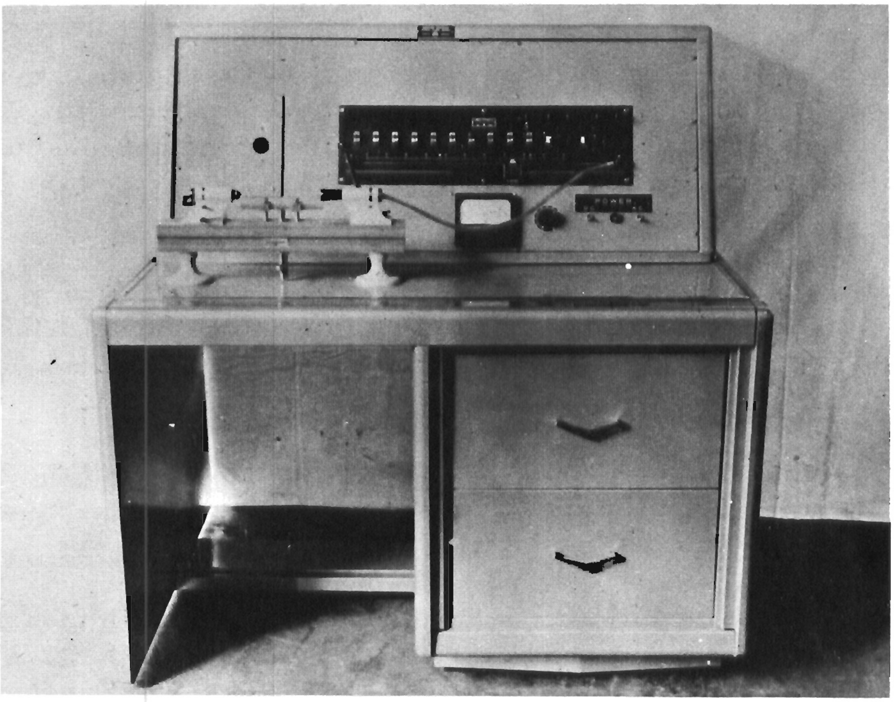


Figure 1. Room-Temperature Specific Resistance Apparatus

Sample dimensions are $\frac{1}{2}$- by $\frac{1}{2}$- by 5 inches from rectangular graphite blocks and cylindrical blocks 14 inches or less in diameter, and $1\frac{1}{4}$- by $1\frac{1}{4}$- by 5 inches from cylindrical blocks larger than 14 inches in diameter.

2.4. Young's Modulus of Elasticity

Young's modulus of elasticity is determined sonically by vibrating a sample in the fundamental flexural mode. It is calculated by the equation:

$$E = \frac{CmF^2}{W}$$

where: E = Modulus of elasticity in lbs/in^2
C = A constant depending upon sample shape, mode, Poisson's ratio, and units
m = Weight of the sample in grams
F = Fundamental frequency, cycles per second
W = Sample width in cm.

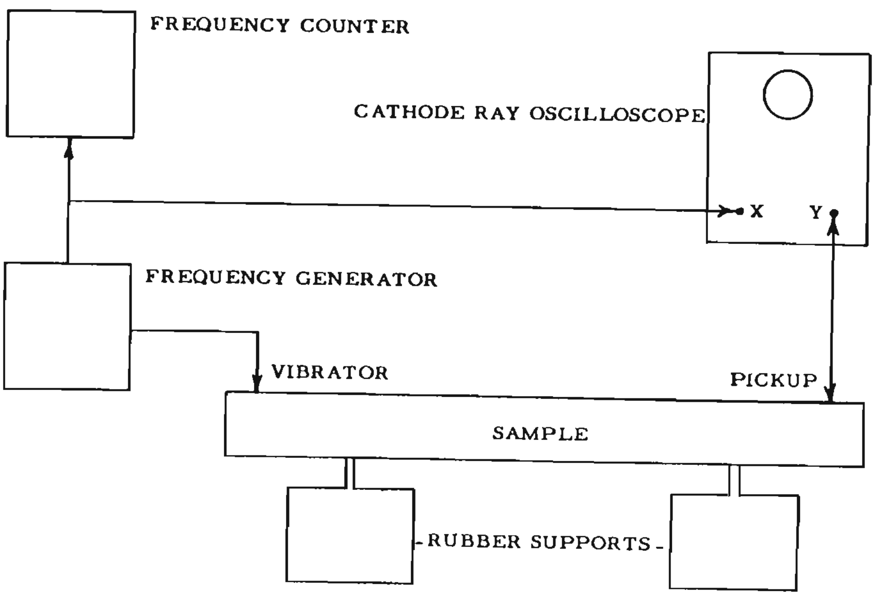
At room temperature, the sample is placed upon two rubber supports 0.56 of the sample length apart, corresponding to the nodal points. A variable (0-20,000 cps) frequency generator supplies a signal to a magnetic recording head, contacting the sample at the top center of one end. The vibration is picked up by a phonograph needle contacting the sample at the top center of the other end. Frequency of the signal is determined by a four-decade frequency counter. The frequency generator is connected to the x-axis of a cathode ray oscilloscope and the pickup to the y-axis. By observing the Lissajous figures thus created on the oscillOscope, the resonant frequency can be measured.

The frequency generator, oscilloscope, and frequency counter are incorporated into a single unit, shown in Figure 2 which also shows the vibrator and the pickup needles in contact with a specimen. Figure 3 is a schematic drawing of the room-temperature equipment.

The method and theory, as well as a description of the equipment and procedures for determining Young's modulus at elevated temperatures, are presented in detail in another report.[1]

The dimensions of samples for room-temperature measurements are the same as those for specific resistance (Section 2.3). Samples for high-temperature measurements are $\frac{1}{2}$- by $\frac{1}{2}$- by 5 inches regardless of the size of the graphite block from which they are cut.

Figure 2. Apparatus for Measuring Young's Modulus at Room Temperature



L-177

Figure 3. Schematic Drawing of Apparatus for Measuring Young's Modulus of Graphite

2.5. Flexural Strength

2.5.1. Equipment and Procedure

Flexural strength (modulus of rupture or transverse strength) is measured by the third-point loading method.[2] The procedure followed in measuring room-temperature flexural strength is described elsewhere.[3] Flexural strength is calculated by the rectangular beam formula:

$$S = \frac{3W(L_2-L_1)}{2bd^2} \tag{1}$$

where: S = Flexural strength in pounds per square inch
W = Maximum applied load (breaking load) in pounds
L_2 = Length of longest span in inches
L_1 = Length of shortest span in inches
b = Width of specimen in inches
d = Depth of specimen in inches

2.5.2. Theory

The flexural strength for a rectangular sample[4] is calculated by the equation:

$$S = \frac{6M}{bd^2} \tag{2}$$

where M is the bending moment or couple, and the other symbols are the same as in Section 2.5.1. It can be shown[5] that for third-point loading the bending moment is:

$$M = \tfrac{1}{4}W\ (L_2-L_1) \tag{3}$$

By substituting M in equation (3) into equation (2):

$$S = \frac{3W\ (L_2-L_1)}{2bd^2} \tag{4}$$

Equation (4) is the same as equation (1) in Section 2.5.1.

Samples used to obtain the flexural strength data given in Section 3 were $\frac{1}{2}$- by $\frac{1}{2}$- by 5 inches from rectangular blocks and cylindrical blocks 14 inches in diameter or less, and $1\frac{1}{4}$- by $1\frac{1}{4}$- by 5 inches from cylindrical blocks greater than 14 inches in diameter.

2.6. Compressive Strength

Equipment and procedures for measuring ultimate compressive strength and stress-strain in compression at room and elevated temperatures have been described in another report.(3)

Graphite is a viscoelastic material which may be considered brittle up to approximately 1500°C, plastic above 2500°C, and in a transition state between 1500°C and 2500°C. The stress applied to a sample may be divided into two parts, one producing elastic deformation and one producing creep or inelastic deformation. The ratio of the stress producing creep to that producing elastic deformation increases rapidly at temperatures exceeding 2000°C, and "ultimate compressive strength" above 2000°C increases rapidly with temperature. In some cases, a sample at 2700°C will not fracture even at extremely high stress. Figure 4 shows a ½-inch diameter by ½-inch length sample of ATJ graphite before testing and after testing at 2700°C. The sample did not break at 33,200 lbs/in^2. The cracks in the compressed sample are surface cracks which appear only on the edge.

In some of the stress-strain curves in compression, and also in tension and apparent shear, stress levels at fracture (ultimate strengths) do not correspond to the values in the tables. This occurs whenever the ultimate strength reported in the table and the stress-strain curve are not obtained from the same sample. It is extremely difficult to adjust the testing machine so stress and strain start recording simultaneously, consequently, many of the stress-strain curves (Figure 26 for example) show an increase in stress near the origin with little or no increase in strain. The strain measurements are subject to question, therefore, absolute values must be used with caution. Stress-strain curves in this report, however, show how strain varies with temperature and from one graphite grade to another.

Figure 4. Compressive Test Samples Before Testing and After Testing at 2700°C, No Break at 33,200 lbs/in^2, ATJ Graphite

2.7. Tensile Strength

Equipment, sample, and procedure used to measure ultimate tensile strength and stress-strain in tension at room and elevated temperatures have been described in another report.[3]

The extensometer rod - differential transformer system for measuring strain was calibrated against strain gauge measurements at room temperature for each graphite grade, and the calibration used in the room-temperature 2000°C range; i.e., until creep became predominate. A calibration method described elsewhere[3] was used when strain measurements were made at 2500 and 2700°C. The strain measurements are subject to question, therefore, absolute values must be used with caution. Stress-strain curves in this report, however, show how strain varies with temperature and from one graphite grade to another.

2.8. Shear Strength

A clevis method for measuring shear strength and apparent stress-strain in shear was adopted for use in this program and the reasons for its adoption as well as a description of the apparatus, sample, and procedure are presented elsewhere[3] The clevis method applies both a bending stress and a shearing stress to the sample. At room temperature a bending break occurs in the approximate center of the sample gauge length before the sample breaks in shear at the ends of the gauge length. Multiple bending breaks usually occur at elevated temperatures; however, on rare occasions there have been single bending breaks or none at all. Figure 5 shows a sample which has been broken in shear at 2700°C, with a single bending break in the center of the gauge length. The bending breaks are disregarded and "apparent ultimate shear strength"

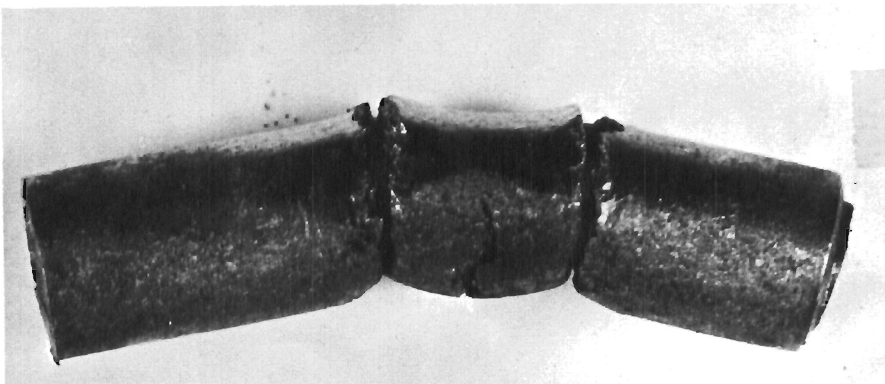


Figure 5. Graphite Sample Showing Typical Shearing and Bending Breaks, 2700°C

is calculated[6] by the equation:

$$S = \frac{L}{2A}$$

where: S = Apparent ultimate shear strength in lbs/in^2
L = Shearing load in pounds
A = Cross-sectional area of the specimen in square inches.

The term "apparent ultimate shear strength" is used because the sample is not subjected to a pure shearing stress, but to a combination of shearing and bending stresses. The apparent shear stress-strain curves presented throughout Section 3 are not intended to be used for design purposes, but rather to show what happens to a sample during the clevis test.

2.9. Coefficient of Thermal Expansion at Room Temperature

2.9.1. Equipment

Coefficient of thermal expansion (CTE) at room temperature involves the determination of thermal expansion of a graphite sample relative to the known expansion of an Invar bar between 20° and 100°C. Figures 6 and 7, respectively, are a photograph and a schematic diagram of the apparatus.

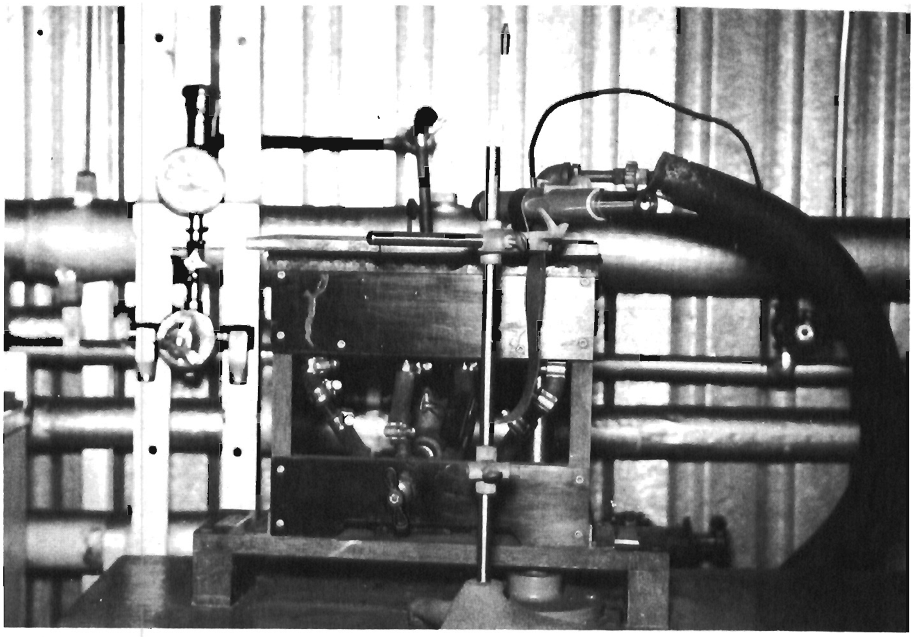
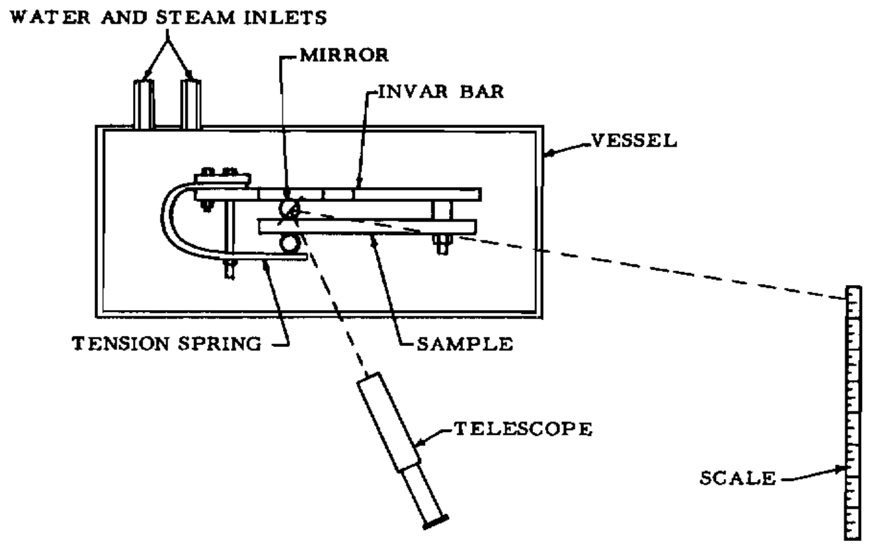


Figure 6. Room-Temperature Thermal Expansion Apparatus



L-178

Figure 7. Schematic Diagram of Room-Temperature Thermal Expansion Apparatus

One end of the sample is fastened to a stud on the Invar bar. A graphite rod with a plain mirror attached to one end is placed between the sample and the Invar bar, which are kept parallel by means of a spring and roller. The two temperature limits (20 and 100°C) are maintained with carefully controlled water and steam. The difference in expansion of the sample and the Invar bar causes the mirror rod to rotate. The amount of rotation is measured by viewing the mirror image of a scale located 200 inches from the mirror. The optical lever permits the observance of very small differences between the expansions of the sample and the Invar bar. Expansion coefficient of the sample is calculated by the formula:

$$CTE = I \pm \frac{2.54\ rs}{(2.54)^2 dL \Delta t} \tag{1}$$

where: CTE = Coefficient of thermal expansion of sample per °C
I = Coefficient of thermal expansion of Invar bar per °C
r = Radius of mirror rod in inches
d = Distance from rod to scale in inches
L = Distance between center of stud on on Invar bar and center of mirror rod in inches
s = Difference in scale readings at 20°C and 100°C
Δt = Temperature increase (80°C).

Thermal expansion data reported in Section 3 were obtained with 0.3- by $\frac{3}{8}$- by 5-inch samples.

2.9.2. Theory

The coefficient of linear thermal expansion of a solid is defined as the fraction of its own original length by which any body of that material will expand when its temperature is raised one degree; that is:

$$\alpha = \frac{\Delta L}{L \Delta t} \qquad (2)$$

where: α = Coefficient of linear thermal expansion of sample
L = Original length of sample
ΔL = Increase in sample length when temperature is increased Δt degrees.

For the equipment described in Section 2.9.1:

$$\alpha = I \pm \frac{\Delta L^*}{L \Delta t} \qquad (3)$$

where: I = Coefficient of thermal expansion of the Invar bar
ΔL^* = Difference between the expansion of the Invar bar and the sample.

As the Invar bar and sample expand, the mirror rod rotates except when $\Delta L^* = 0$. The rod rotates counterclockwise when expansion of the Invar bar is greater than that of the sample, and the term $\frac{\Delta L^*}{L \Delta t}$ is negative. The mirror rod rotates clockwise when the expansion of the sample is greater than that of the Invar bar, and the term $\frac{\Delta L^*}{L \Delta t}$ is positive.

Then: $\Delta L^* = \theta\, r$ radians $\qquad (4)$

where: R = Radius of the mirror rod
θ = angle of rotation of mirror rod.

Figure 8 is a schematic diagram of the optical lever. Before expansion, point 0 on the scale is imaged by the mirror M, and after expansion, point A is imaged by the mirror. If d is the distance from the mirror rod to the scale and S is the difference in scale readings at points A and 0, then:

$$\tan \theta = \frac{S}{d} \qquad (5)$$

But θ is very small, therefore;

$$\theta = \frac{S}{d} \text{ approximately.} \tag{6}$$

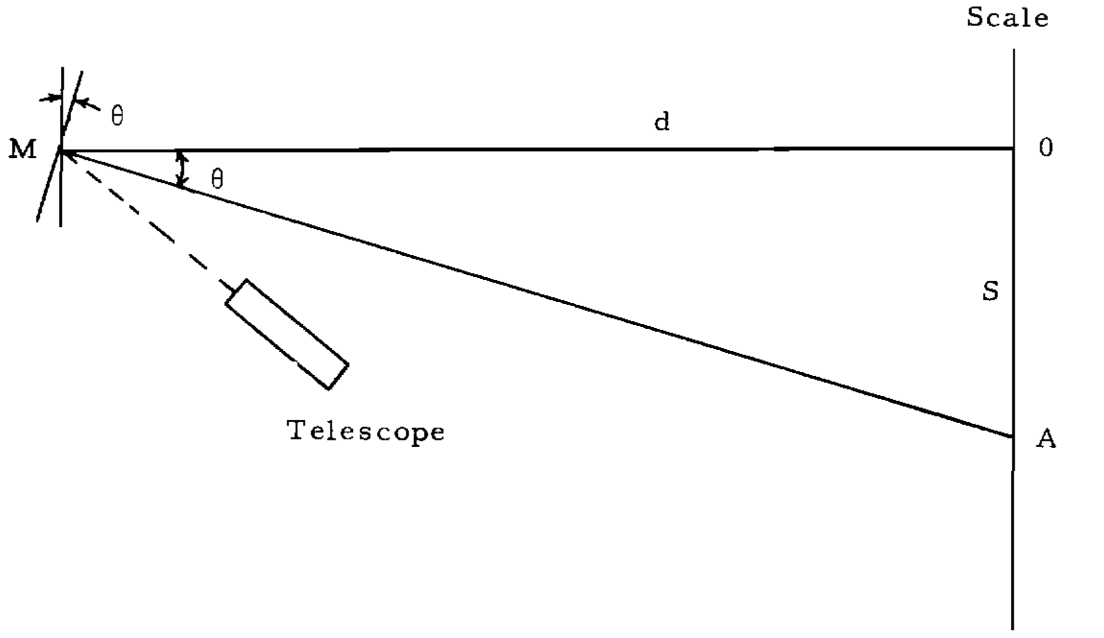


Figure 8. Schematic Diagram of Optical Lever, Thermal Expansion Measurements

By substituting the value of θ in equation (6) into equation (4):

$$\Delta L^* = \frac{rS}{d} \tag{7}$$

and
$$\alpha = I \pm \frac{rs}{dL\,\Delta t} \tag{8}$$

or
$$\alpha = I \pm \frac{2.54\ rs}{(2.54)^2\, dL\,\Delta t} \tag{9}$$

where: α = CTE of sample per °C
I = CTE of Invar bar per °C
r = Radius of mirror rod in inches
d = Distance from mirror rod in inches
L = Distance between center of stud on Invar Bar and center of mirror rod in inches

S = Difference in scale readings at 20° and 100°C in centimeters

Δt = Temperature increase (80°C)

Equation (9) is the same as equation (1) in Section 2.9.1.

2.10. Thermal Expansion at Elevated Temperatures

High-temperature thermal expansion measurements are made with the apparatus and graphite horizontal tube furnace shown in Figure 9. For these measurements, the cross hairs in the micrometer eyepieces of two telescopes are focused one on each end of the sample at room temperature and at specified elevated temperatures. Elongation of the sample at a specific temperature is the sum of the shifts in cross hairs of the two telescopes. Thermal expansion is expressed as $\frac{\Delta L}{L}$, where L is the length of the sample at room temperature and ΔL is the change in length between room and elevated temperature. Figure 10 is a schematic drawing of the equipment.

All high-temperature thermal expansion data reported in Section 3 were obtained from $\frac{1}{2}$- by $\frac{1}{2}$- by 5-inch samples. Two samples can be run at the same time by placing one on top of the other.

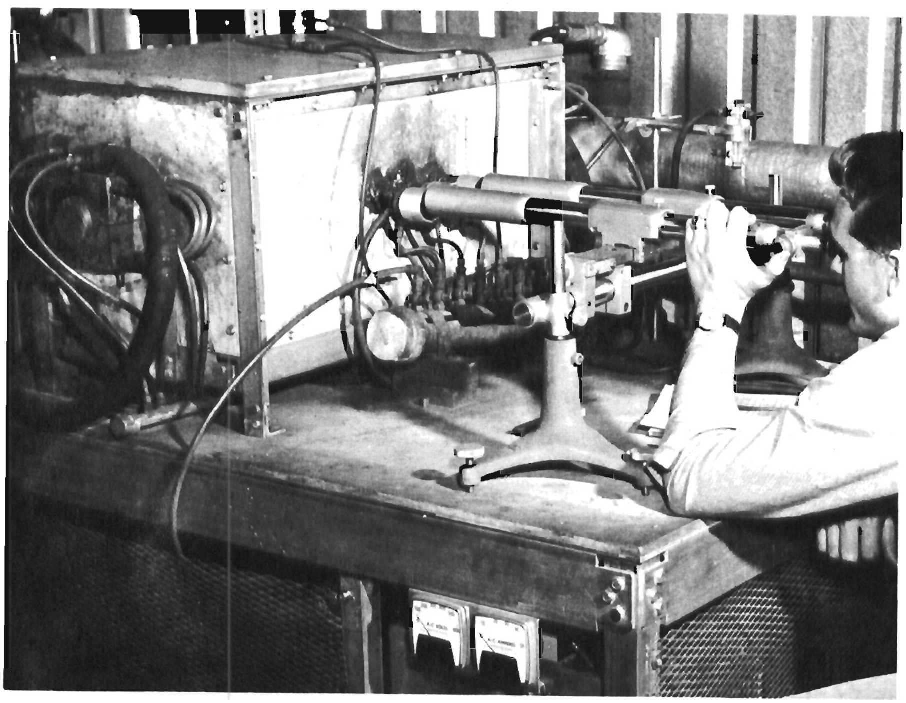
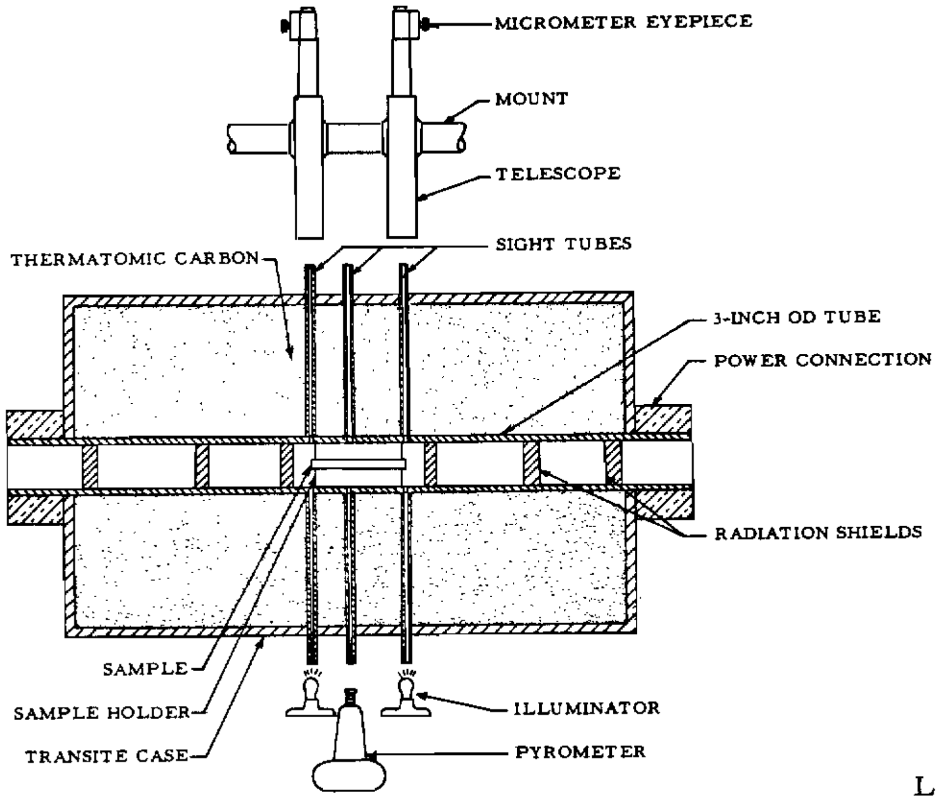


Figure 9. High-Temperature Thermal Expansion Apparatus



L-179

Figure 10. Schematic Drawing of High-Temperature Thermal Expansion Apparatus

2.11. Thermal Conductivity at Room Temperature

2.11.1. Meers Method

2.11.1.1. Equipment

Equipment for measuring longitudinal heat flow in a cylindrical sample by an absolute method [7] is shown in Figure 11. The apparatus can hold as many as six $\frac{1}{2}$-, $\frac{3}{4}$-, or 1-inch diameter samples which can range from 3 to 6 inches in length. The samples are mounted upright in sample holders attached to a copper plate heat sink, maintained at a constant temperature (within 0.1°F) by a circulating water bath system. Heat is applied at the top ends of the samples by individual electric heaters. Solder is used to hold the samples firmly in their holders and to attach the heaters to the samples. The temperature gradient between two points along a sample length is measured by a differential thermocouple. Measurements are made in a vacuum to minimize heat losses. The mounted samples, with the bell jar removed, are located at the lower right end of Figure 11. A schematic drawing of a mounted sample is shown in Figure 12.

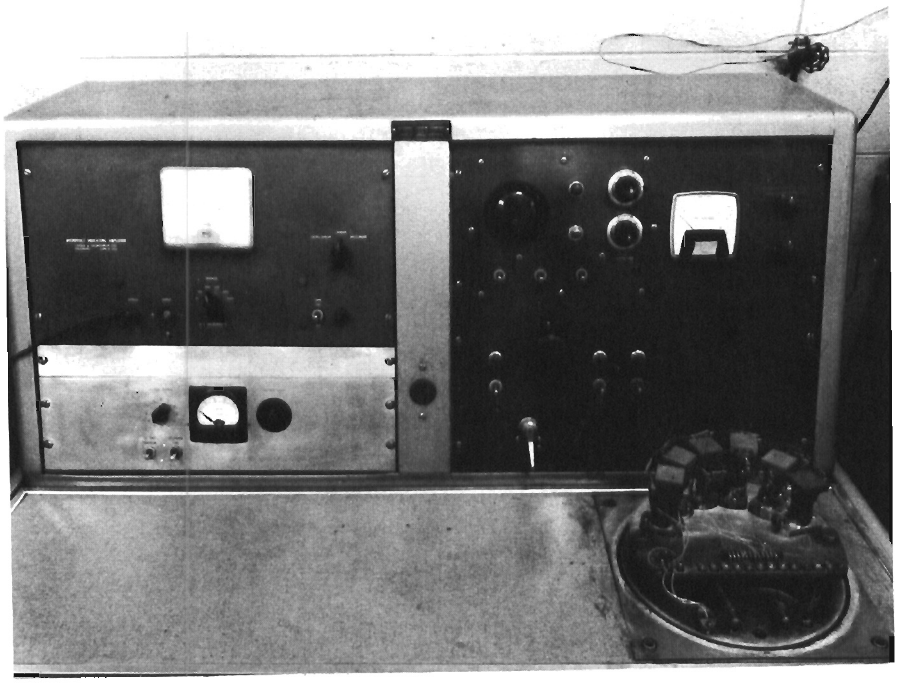
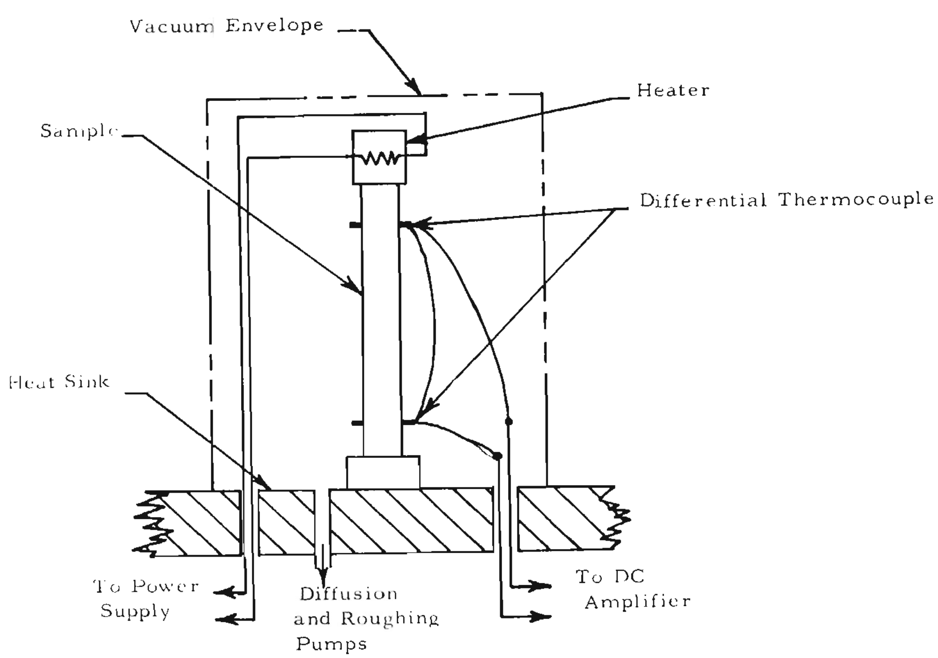


Figure 11. Room-Temperature Thermal Conductivity Apparatus, Meers Method



L-180

Figure 12. Schematic Drawing of Mounting of Thermal Conductivity Sample, Meers Method

Varied power inputs are applied to the upper end of the sample and a plot of heater power input versus the thermocouple voltage output should yield a straight line. The thermal conductivity of the sample is calculated by the equation:

$$K = \frac{CL\Delta P}{A\Delta T^*} \tag{1}$$

where: K = Thermal conductivity, cal-cm/sec/cm^2/°K

L = Distance between the differential thermocouple points in cm

A = Cross sectional area of the sample in cm^2.

$\frac{\Delta P}{\Delta T^*}$ = Slope of the heater power input versus thermocouple voltage output plot in watts/microvolts (μ v)

C = A constant (14.20) for converting watts/μ v to calories/sec/°K

Thermal conductivities as low as 0.004 cal-cm/sec/cm^2/°K were measured by the Meers method.

2.11.1.2. Theory

The fundamental differential equation for heat transfer by conduction is given by Fourier's law: [8]

$$\frac{dQ}{dt} = -KA \frac{dT}{dx} \tag{2}$$

where: $\frac{dQ}{dt}$ = Quantity of heat per unit time

$\frac{-dT}{dx}$ = Temperature gradient in direction of flow of heat

A = Area of sample perpendicular to direction of heat flow

K = Thermal conductivity of sample.

For steady flow, $\frac{dQ}{dt}$ is constant and may be replaced by q, thus equation (2) may be written in the form: [9]

$$q = K\frac{A}{L} \Delta T \tag{3}$$

or

$$K = \frac{L}{A} \cdot \frac{q}{\Delta T} \tag{4}$$

where: ΔT = Temperature differential established between two points in the sample

L = Distance between the two points at which the temperature is measured.

The heat introduced at the top of the sample is the power input of the heater; therefore, $q = P$ watts. The voltage (microvolts) output of the differential thermocouple is proportional to the temperature differential ΔT; therefore ΔT may be expressed in microvolts. The slope of the P versus ΔT plot is $\Delta P/\Delta(\Delta T)$ or $\Delta P/\Delta T^*$, where $\Delta T^* = \Delta(\Delta T)$ in microvolts (μv).

Equation (4) may now be expressed as:

$$K = \frac{L}{A} \quad \frac{\Delta P}{\Delta T^*} \tag{5}$$

where: K = Thermal conductivity in watt-cm/μv/cm^2

L = Distance between the thermocouple points in cm

A = Cross sectional area of the sample in cm^2

$\frac{\Delta P}{\Delta T^*}$ = Slope of the heater power input versus thermocouples voltage plot in watts/microvolts (μv).

Equation (5) may also be expressed as:

$$K = C_1 C_2 \frac{L}{A} \circ \frac{\Delta P}{\Delta T^*} \tag{6}$$

or

$$K = \frac{CL \; \Delta P}{A \Delta T^*} \tag{7}$$

where: C_1 = 59.4 microvolts/°K, the thermoelectric power of the differential thermocouple

C_2 = 0.239, conversion factor for converting watts to calories per second

C = C_1C_2 = 14.19

K = Thermal conductivity in cal-cm/sec/cm^2/°K

Equation (7) is equation (1) in Section 2.11.1.1.

The Fitch method[10] was used to measure thermal conductivities below 0.004 cal-cm/sec/cm^2/°K. It was necessary to use the method for only one graphite grade, PT-0110; however, it might have been possible to use the Meers method had the PT-0110 block ($\frac{1}{2}$- by 6- by 6 inches) been sufficiently thick for a 1-inch diameter by 3-inch length sample.

2.11.2. Fitch Method

2.11.2.1. Equipment

Figure 13 is a schematic diagram of the Fitch apparatus, modified slightly to insure unidirectional heat flow in the sample. Heat is applied to one side of the sample by a flat-bottom metal vessel containing boiling water. The bottom of the vessel is nickel-plated copper. The receiver is a copper cylinder, nickel plated on the end in contact with the sample. The heat source, sample, and receiver are held firmly together by means of a pneumatic press. The temperature differential between the heat source and receiver is measured by a differential thermocouple. As heat flows from the constant temperature heat source through the sample and into the receiver, the temperature of the latter slowly rises. The relationship between time and voltage output of the differential thermocouple is expressed by the equation:[10]

$$t = \frac{2.303\ McL}{KA} (\log V - \log Vo) \qquad (1)$$

where: V = Voltage output of differential thermocouple at time t
Vo = Voltage output of differential thermocouple at zero time
M = Mass of receiver
c = Specific heat of receiver
A = Cross-sectional area of sample in contact with receiver
K = Thermal Conductivity of sample.

The graph of t plotted against log V is a straight line, therefore:

$$m = \frac{2.303\ McL}{KA} \qquad (2)$$

or

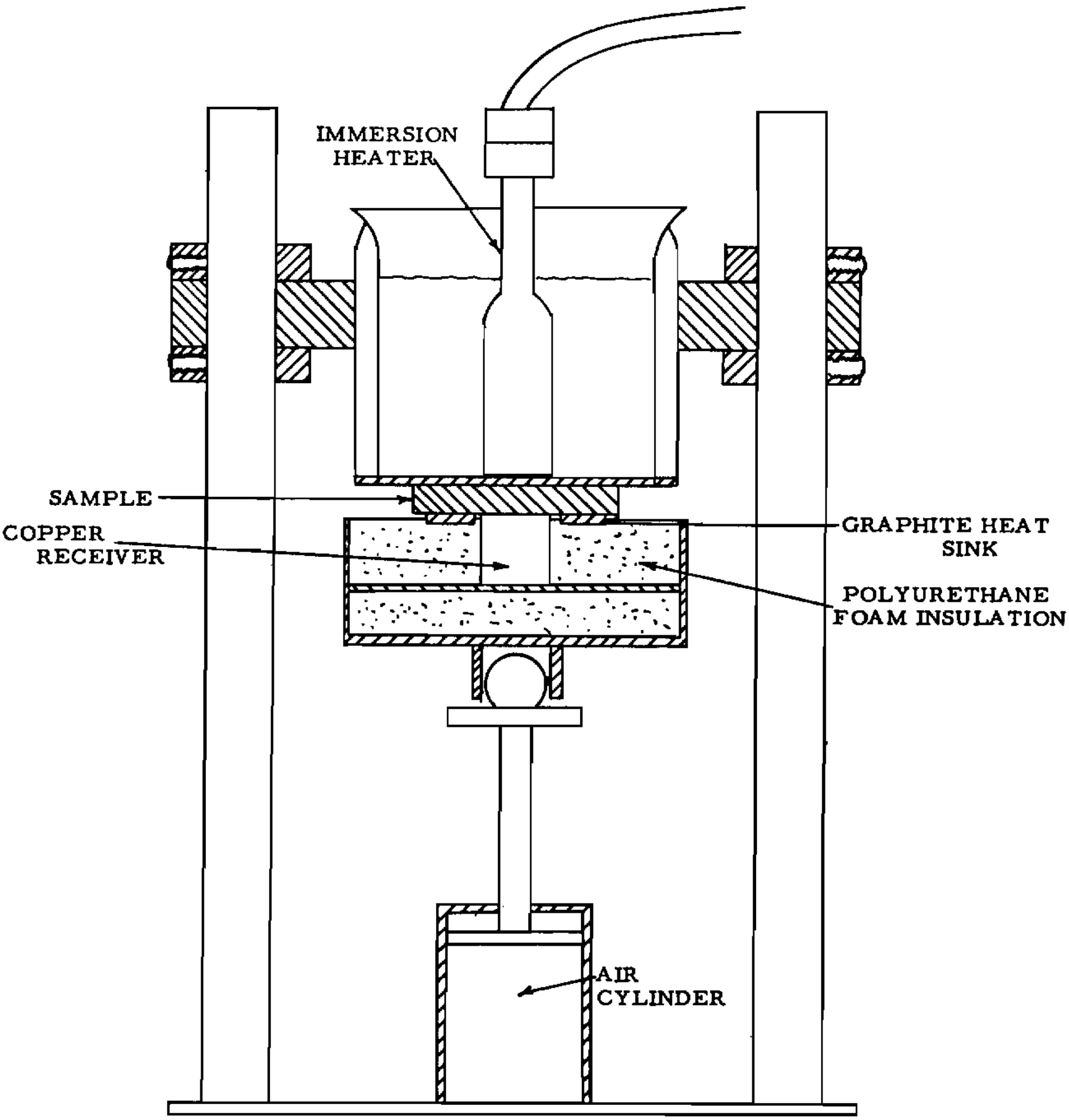
$$K = \frac{2.303\ McL}{mA} \qquad (3)$$

where: m = The slope of the t versus log V plot.

K is in calorie-centimeters per second per square centimeters per degree absolute when M is in grams, c is in calories per gram per degree absolute, L is in centimeters, A is in square centimeters, and m is in seconds.

2.11.2.2. Modification of Equipment

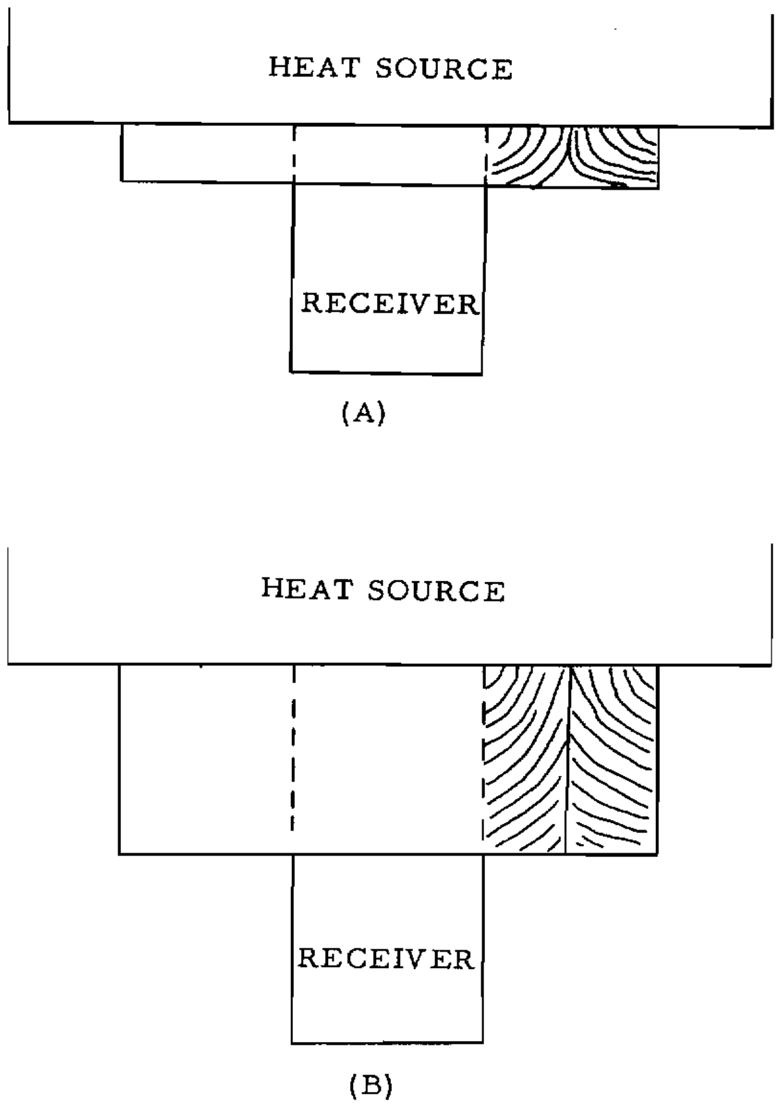
During preliminary trials a problem was observed in that the measured thermal conductivity was a linear function of the sample thickness. Because the heat source and sample are larger in area than the receiver, it was assumed that the phenomenon was the result of multidirectional heat flow within the sample. Figure 14 is a schematic diagram showing a possible heat-flow pattern in the outer portions of the sample.



L-444

Figure 13. Schematic Drawing of the "Fitch" Apparatus for Thermal Conductivity Measurements

As the thickness of the specimen is increased, an increased amount of the heat flowing through the outer portions of the sample reaches the receiver. A sample having the same cross-sectional area as the receiver is not a satisfactory solution to the problem because of radiation losses at the edge of the sample.



L-812

Figure 14. Schematic Diagram Showing Possible Multi-directional Heat Flow into Central Portion of Sample from Outer Portions

The problem was partially solved by surrounding the receiver with a graphite ring, thermally insulated from the receiver (Figure 13). The ring acts as a heat sink and directs the heat in the outer portions of the sample away from the receiver. The introduction of the graphite heat sink permits the measurements of thermal conductivities up to 0.012 cal-cm/sec/cm^2/°K.

The thermal conductivity of PT-0113 graphite was measured by both the Meers and Fitch methods to compare the two methods. Average with- and across-grain values of 0.013 and 0.007 cal-cm/sec/cm^2/°K, respectively, were obtained by the Meers method and 0.010 and 0.005, respectively, by the Fitch method.

All samples used in the Fitch method were 3 inches in diameter with the thickness varying from $\frac{1}{2}$ to $1\frac{1}{2}$ inches.

2.12. Permeability

2.12.1 Equipment

The apparatus for measuring the permeability of graphite is shown in Figure 15. In the left side of the panel is a dial manometer connected to measure the difference between the pressure of the supply gas going into the sample holder and the pressure of the gas leaving the holder, thus indicating the pressure drop across the sample. The manometer is calibrated against a mercury column with an accuracy of one part in one thousand of full scale.

On the right side of the panel are two flowmeters measuring the flow in cubic centimeters per minute after the gas has passed through the sample. The ranges of the flowmeters are 1 to 40 and 1 to 250 cubic centimeters per minute. A third flowmeter, having a range of 10 to 1000 cubic centimeters per minute, is available if higher flow ranges are required. Next to the flowmeters is a silica-gel moisture indicator and a selective porosity filter which removes moisture from the gas stream.

A laboratory press mounted upon the right side of the table has a sample holder attached to its frame. The sample holder chamber has a circular cross section and tapered walls. The sample is placed in a large rubber stopper from which the center has been removed, as illustrated in Figure 16, and the assembly is pressed firmly into the holder. Pressure exerted on the rubber stopper by the tapered walls of the holder provide a pressure seal on the sides of the sample and assures linear gas flow. The bottom of the chamber is sealed by means of an end plate and rubber gasket held firmly in place by a hydraulic jack. The

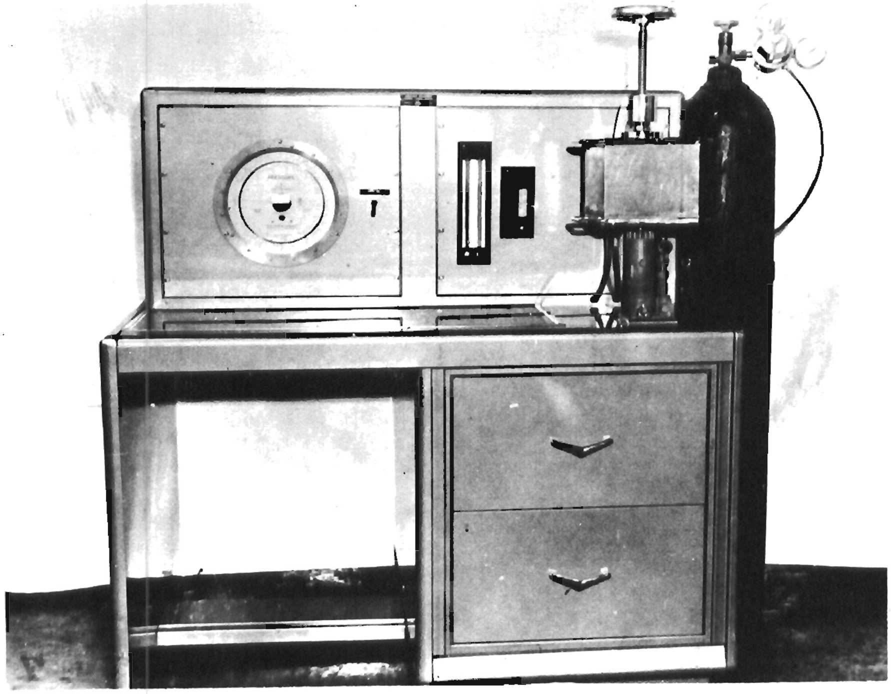


Figure 15. Apparatus for Measuring Permeability of Graphite

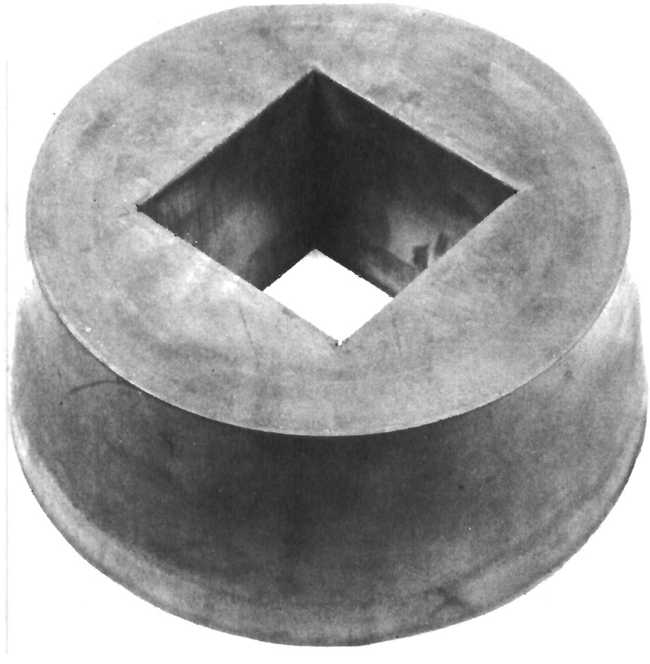


Figure 16. Rubber Stopper Accessory for Mounting Permeability Sample

top is sealed by a similar plate and gasket with pressure applied by a hand operated screw.

Sample sizes used to obtain the permeability measurements presented in Section 3 are:

1) 2- by 2- by 2 inches for 9- by 20- by 24-inch rectangular blocks and for cylindrical stock $8\frac{1}{2}$ inches and larger in diameter

2) 1- by 1- by 1 inch for 5-inch diameter cylindrical stock.

3) $\frac{1}{2}$- by 1- by 1 inch for $\frac{1}{2}$- by 6- by 6-inch rectangular blocks.

Permeabilities were calculated by the following formula, using nitrogen (N_2) as the gas:

$$k = \frac{2\mu\, Q_v L}{A\, \Delta p\, (\Delta p + 2)} \qquad (1)$$

where: k = Permeability in Darcy's
μ = Viscosity of nitrogen in centipoises
L = Length of sample in direction of gas flow in cm
A = Area of sample perpendicular to direction of gas flow in cm^2
Qv = Flow rate of gas in cc/sec
Δp = Differential pressure in atmospheres

2.12.2. Theory

Gas flow through graphite can be described by Darcy's law, one differential form [11] of which is represented by the equation:

$$-\frac{k}{\mu} = \frac{V}{(\text{grad } p)} \qquad (2)$$

where: k = Permeability
μ = Viscosity of the gas
p = Pressure of the gas
V = Velocity of the gas.

Gas flow through a graphite sample is a polytropic expansion and is presented by the general formula pV^n = a constant or:

$$\frac{p}{p_o} = \left(\frac{\rho}{\rho_o}\right)^n \qquad (3)$$

where: ρ = Density of gas at pressure p
ρ_o = Density of gas at pressure p_o
n = Polytropic exponent.

Using the principle of mass continuity:

$$Q_m = \rho V A \tag{4}$$

where Q_m is the mass flow of gas. When V from equation (4) and ρ from equation (3) are substituted into equation (2):

$$-\frac{k}{\mu} = \frac{Q_m}{A\rho_o}\left(\frac{p_o}{p}\right)^{\frac{1}{n}} \frac{1}{(\text{grad } p)} \tag{5}$$

Since the gas flow through the sample is linear:

$$\text{grad } p = \frac{dp}{dx}$$

and equation (5) becomes:

$$\frac{dp}{dx} = -\frac{\mu Q_m}{kA\rho_o}\left(\frac{p_o}{p}\right)^{\frac{1}{n}} \tag{6}$$

By integration of equation (6) over the sample length L:

$$\frac{n}{n+1}\left(p_1^{\frac{1+n}{n}} - p_2^{\frac{1+n}{n}}\right) = \frac{\mu Q_m p_o L}{k A \rho_o} \tag{7}$$

Assuming isothermal conditions (n = 1) for the gas flow (small velocities), equation (7) becomes:

$$\frac{1}{2}(p_1^2 - p_2^2) = \frac{\mu Q_m p_o L}{k A \rho_o} \quad \text{or}$$

$$k = \frac{2\mu Q_m p_o L}{A\rho_o(p_1^2 - p_2^2)} \tag{8}$$

where: p_1 = Pressure of gas going into sample
p_2 = Pressure of gas leaving sample.

Since $p_1^2 - p_2^2 = (p_1 - p_2)(p_1 + p_2) = \Delta p\,(p_1 + p_2)$

and $p_1 + p_2 = p_1 - p_2 + 2p_2 = \Delta p + 2p_2$

equation (8) becomes:

$$k = \frac{2\mu Q_m \rho_o L}{A\rho_o \; \Delta p(\Delta p + 2p_2)} \tag{9}$$

But $p_2 = p_o = 1$ atm

and $\dfrac{Q_m}{\rho_o} = Qv$

where Q_v = volume gas flow.

Therefore:

$$k = \frac{2\mu Q_v L}{A \Delta p (\Delta p + 2)} \tag{10}$$

Equation (10) is equation (1) in Section 2.12.1.

2.13. Admittance Factor

2.13.1 Equipment

The admittance factors which are presented in Section 3 were obtained by a pressure decay method, using a tubular sample $1\frac{1}{2}$-inch O. D. by $\frac{3}{4}$-inch I. D. by 4-inch length. The apparatus and sample are illustrated in Figure 17.

The ends of the sample are sealed by rubber gaskets attached to two end-plates which are held firmly in place by four pull-rods. A pressure gauge is connected to the sample through the top end plate. The sample is filled with nitrogen gas to a pressure p_o through a valve attached to the bottom end-plate. The value of p_o depends upon the permeability of the sample. Pressures of fourteen and five pounds per square inch were adequate for measuring the admittance of all low permeability graphites reported in Section 3.

The time t required for the pressure inside the sample to decay from its original value of p_o to a value p is measured and the admittance factor calculated, using the formula:

$$F_o = \frac{V_o \ln \frac{r_o}{r_i}}{2\pi \quad h\,t} \cdot \left(\ln \frac{p_o}{p_t}\right) \tag{1}$$

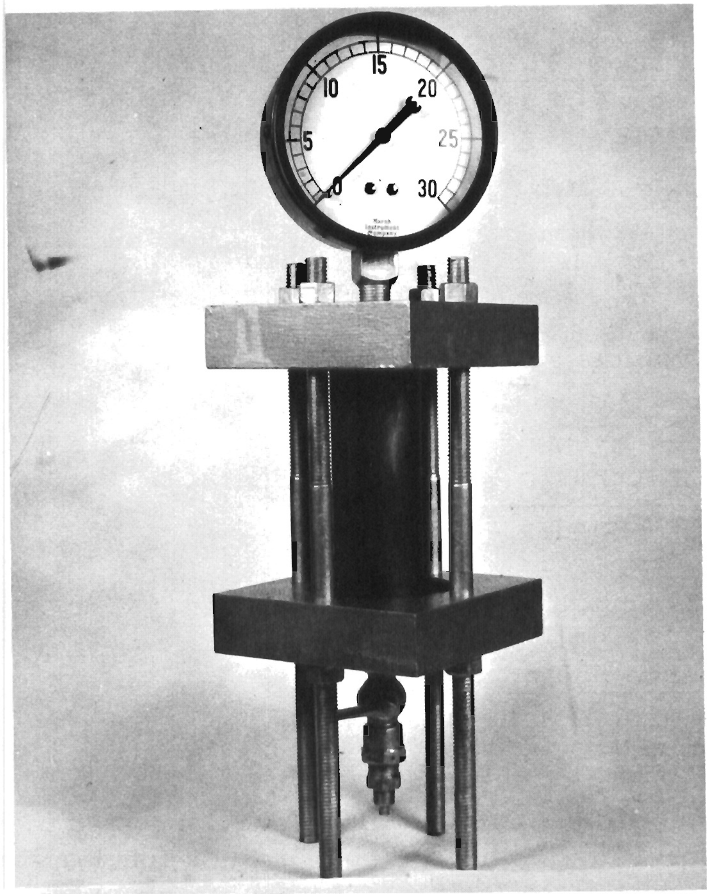


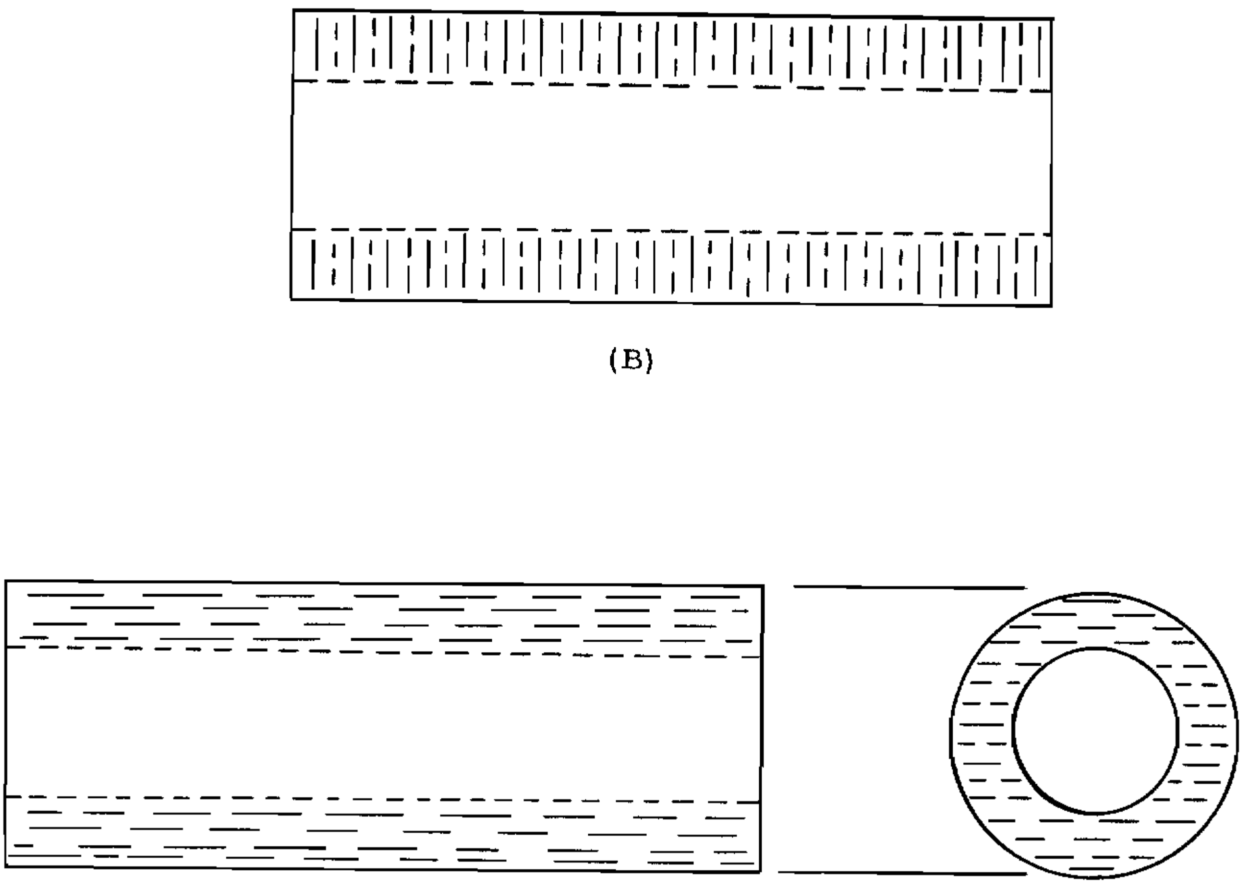
Figure 17. Apparatus for Measuring Admittance Factor of Graphite

where:
V_o = Static volume of the system* in cm^3
r_o = Outside radius of sample in cm
r_i = Inside radius of sample in cm
h = Length of sample in cm
p_o = Original pressure inside sample in lbs/in^2
p_t = Pressure inside sample in lbs/in^2 at time t
F_o = Admittance factor in cm^2/sec.

A pressure decay of two pounds per square inch was used to determine the admittance factors reported in Section 3.

*Note: Static volume of the system is the inside volume of the sample plus the volume of the valve connection and the pressure gauge and its connection.

Figure 18 shows the grain orientation in an admittance sample prepared with its long axis parallel to the grain (A), and perpendicular to the grain (B). Gas diffusion through the sample is in a radial direction. It can be seen in Figure 18A that diffusion is with grain in some sections of the sample, across grain in other sections, and intermediate between with and across grain in still other sections. An admittance factor obtained from a sample having the grain orientation shown in Figure 18A is called "with-grain admittance" because the long axis of the sample is parallel to the grain. Admittance obtained from a sample having the grain orientation shown in Figure 18B is called "across-grain admittance" because the long axis of the sample is perpendicular to the grain direction. Gas diffusion, however, is parallel to the grain in all parts of the sample cut as shown in Figure 18B.



(B)

(A)

Figure 18. Grain Orientation in Admittance Sample, (A) With-Grain, (B) Across-Grain L-811

2.13.2. Theory

Gas flow in low permeability graphites is more complex than that defined by Darcy's law and may be represented [12] by the equation:

$$Q_{pv} = F \frac{A}{L} \Delta p \tag{2}$$

where:
- Q_{pv} = Pressure-volume flow rate in cc atm./sec.
- A = Area of sample perpendicular to direction of flow in cm^2
- L = Length of sample in direction of flow in cm.
- Δp = Pressure differential across the sample in atmosphere
- F = An admittance factor in cm^2/sec.

The admittance factor F consists of two terms: [12]

$$F = F_o + F_1 \overline{p}$$

where:

- F_o = Admittance factor for diffusive flow
- F_1 = Admittance factor for viscous flow
- $\overline{p}$ = Average gas pressure

Since the materials tested by the pressure decay method have many small pores and few, or no, large pores it can be assumed that $F_1 = 0$ and that the gas flow is almost purely diffusive. Equation (2) then becomes:

$$Q_{pv} = F_o \frac{A}{L} \Delta p \tag{3}$$

The flow represented by equation (3) is applicable only to a steady state method. Pressure decay is not a steady state method; therefore, equation (3) must be written:

$$- \frac{d(pv)}{dt} = F_o \frac{A}{L} \Delta p \tag{4}$$

or

$$- \frac{d(p'v)}{dt} = F_o \frac{A}{L} (p' - p_a) \tag{5}$$

where:

- p' = Absolute pressure inside the specimen
- p_a = Pressure outside the specimen (atmospheric)

The term on the left side of equations (4) and (5) is negative because the pressure inside the sample decreases with time.

Since the volume of the system is constant

$$-\frac{d(p'v)}{dt} = -V_o \frac{dp'}{dt}$$

where:

V_o = volume of the system (see foot note on page 26), and

$$-V_o \frac{dp'}{dt} = F_o \frac{A}{L} (p' - p_a). \tag{6}$$

Integrating equation (6) between the limits p'_o and p'_t

$$V_o \ln \left(\frac{p'_o - p_a}{p'_t - p_a}\right) = F_o \frac{A}{L} t \tag{7}$$

where:

p'_o = Absolute pressure inside cylinder at t = o
p'_t = Absolute pressure inside cylinder at time t

If p_o = Gauge pressure at t = o and p_t = gauge pressure at time t, then:

$$p'_o - p_a = p_o + p_a - p_a = p_o \tag{8}$$

and

$$p'_t - p_a = p_t + p_a - p_a = p_t \tag{9}$$

Equation (7) thus becomes:

$$V_o \ln\left(\frac{p_o}{p_t}\right) = F_o \frac{A}{L} t \tag{10}$$

or

$$F_o = \frac{V_o L}{A} \ln \left(\frac{p_o}{p_t}\right) \tag{11}$$

Since the sample is a hollow cylinder an average area must be used in the calculation of admittance factors. The average area of the walls of a hollow cylinder may be calculated[9] by the formula:

$$A(av) = \frac{A_o - A_i}{\ln\left(\frac{A_o}{A_i}\right)} \tag{12}$$

or

$$A(av) = 2\pi h \cdot \frac{r_o - r_i}{\ln\left(\frac{r_o}{r_i}\right)} \tag{13}$$

where: A_o = Outside area of sample
A_i = Inside area of sample
r_o = Outside radius of sample
r_i = Inside radius of sample
h = Height of sample.

The length of the sample, L, in the direction of gas flow is:

$$L = r_o - r_i \tag{14}$$

therefore:

$$\frac{L}{A} = \frac{\ln \frac{r_o}{r_i}}{2\pi h} \tag{15}$$

Substituting the relationship in equation (15) for $\frac{L}{A}$ in equation (11) gives the formula

$$F_o = \frac{V_o \ln \frac{r_o}{r_i}}{2\pi h t} \cdot \ln\left(\frac{p_o}{p_t}\right) \tag{16}$$

Equation (16) is equation (1) in Section 2.13.1.

2.14. Mercury Porosimetry

2.14.1. Equipment

Mercury porosimetry can be used to measure the size and distribution of pores in graphite to a minimum pore diameter of approximately 0.02 microns. Figure 19 is an illustration of the mercury porosimeter used to obtain pore size and distribution data presented in Section 3.

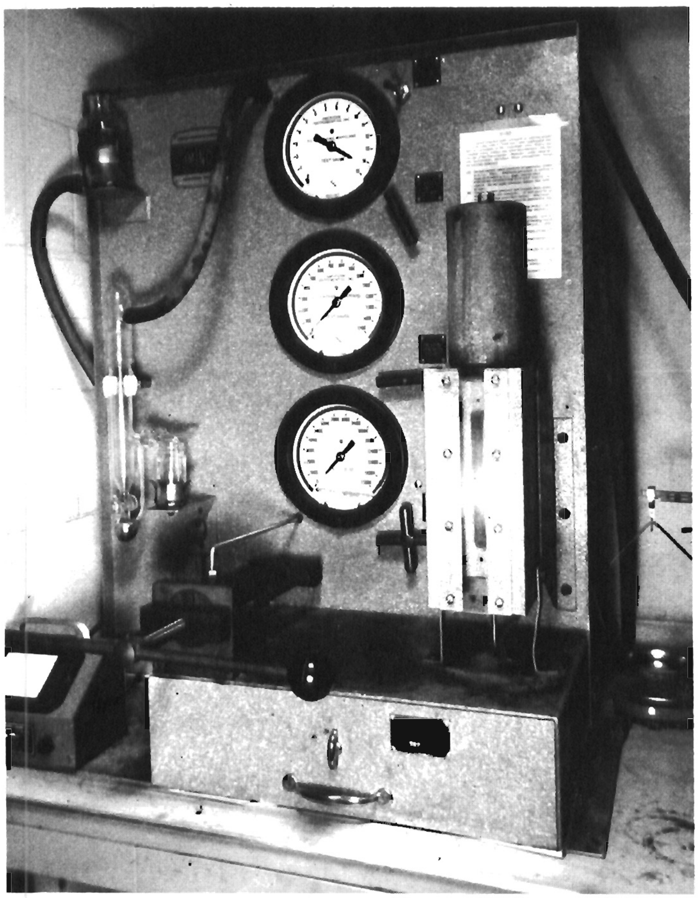


Figure 19. Mercury Porosimetry Equipment

A small graphite sample, approximately 0.5 cubic centimeter in volume, is placed in a penetrometer such as that shown in Figure 20. The penetrometer containing the sample is placed in the glass filling device (left side Figure 19), evacuated and then filled with mercury at a pressure of 100 microns of Hg. After the penetrometer is filled, the excess mercury is drained out of the filling device. Air is introduced into the filling device in predetermined increments of pressure and the mercury level in the graduated penetrometer stem is noted at each pressure. Smaller pores are filled with each increase in pressure. The size of the smallest pore is determined by the formula

$$D = \frac{213}{p} \tag{1}$$

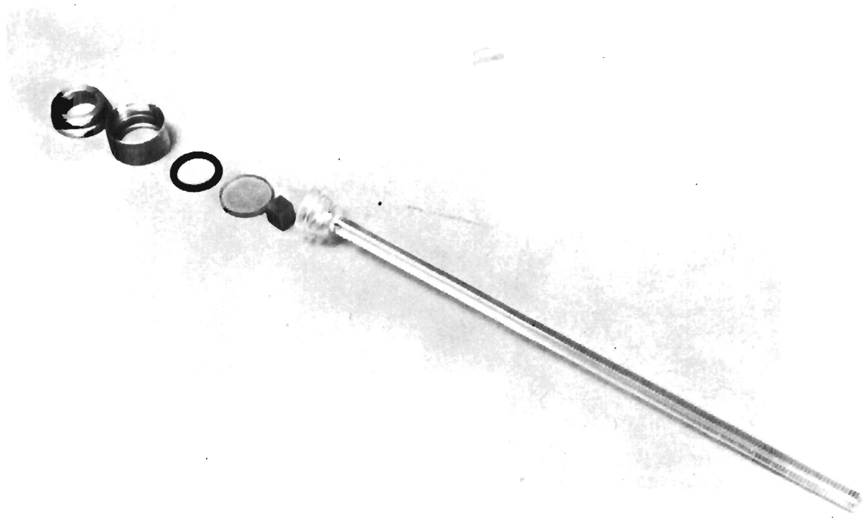


Figure 20. Graphite Sample and Disassembled Penetrometer, Mercury Porosimeter

where: p = Absolute pressure
D = Diameter, in microns, of smallest pore filled at pressure p

Pore volumes are determined from successive readings of the mercury level in the penetrometer stem after each pressure increase. Pore diameters of ten microns and larger are measured with the penetrometer in the filling device. The penetrometer is transferred to the pressure chamber on the right side of the apparatus in Figure 19, for pressures higher than atmospheric. Pressures up to 15,000 pounds per square inch are applied by a hand operated fluid pump.

Since the life of the packing material in the pressure system is significantly shortened by repeated measurements at 15,000 pounds per square inch and since so little useful information is gained in the 5500 to 15,000 pounds per square inch range, measurements were usually limited to a maximum of approximately 5500 pounds per square inch which corresponds to a minimum pore diameter of 0.04 microns.

Pore diameters and distribution are reported in accumulative pore-volume versus pore-diameter curves.

2.14.2. Theory

When mercury under pressure is forced into the pores of a graphite sample, the relationship between the smallest pore filled and the pressure, assuming capillary pores, is expressed [13] by the equation:

$$r = -\frac{2\sigma \cos \theta}{p}$$

or $$D = -\frac{4\sigma \cos \theta}{p} \qquad (2)$$

where:
- p = Pressure on mercury
- r = Radius of smallest pore filled at pressure p
- D = Diameter of smallest pore filled at pressure p
- θ = Contact angle between mercury and graphite (140°)
- σ = Surface tension of mercury (480 dynes/cm), or 27.41×10^{-6} lbs/in^2)

Pores in graphite are irregular in shape; therefore, D is a statistical diameter.

When the above values of σ and θ are substituted into equation (2) and when p is the absolute pressure in pounds per square inch:

$$D = \frac{8400 \times 10^{-6}}{p} \text{ inches}$$

or $$D = \frac{213}{p} \text{ microns} \qquad (3)$$

A source of error in mercury porosimetry is the large pore accessible only through a small opening. In this case, D is the diameter of the opening and the volume is that of the pore. When the opening is less than 0.02 microns (1500 lbs/in^2 pressure), the pore cannot be filled regardless of its size.

2.15. Ash Content

Small samples are taken from several locations in a block of graphite and ground until the particles pass through a 100 mesh screen. After the graphite flour has been thoroughly blended, 10 grams are heated overnight in a muffle furnace at approximately 800°C. Provision must be made for allowing air to enter the furnace so that there is sufficient oxygen for complete combustion of the carbon. Ash content is reported as per cent ash by weight.

3. PHYSICAL PROPERTIES

Physical properties of newly developed graphite grades are more meaningful when compared with the properties of a well established grade. In this report, grade ATJ graphite has been selected as the basis of comparison because it is well established as a high quality fine-grain graphite that has found use in many applications.

3.1. Grade ATJ Graphite

Most of the room temperature physical properties of ATJ graphite are presented in The Industrial Graphite Engineering Handbook, published by National Carbon Company. These properties and their standard deviations are presented in Table 1 of this report to facilitate the comparison of ATJ properties with those of the newly developed grades. Shear strengths are not given in the Handbook; therefore, the apparent shear strength of ATJ has been measured by the clevis method[3] and is included in Table 1. The sample shapes and sizes used for measurement of tensile and compressive strengths as reported herein differ from those used to obtain the Handbook data. Data for both types of samples are given in Table 1.

The high temperature properties of ATJ graphite are presented in Table 2 and in Figures 21 through 24 and 31, 32, 39 and 40. The same procedure will be followed in reporting high-temperature data for other graphite grades.

Figures 25 to 30, inclusive, are with- and across-grain stress-strain curves in tension at temperatures ranging from room temperature to 2700°C. The curves are serrated at temperatures of 2000°C and above, and, in general, the serrations become farther apart as the temperature increases. Stress-strain curves of similar shape were observed under certain test conditions at Jet Propulsion Laboratory, California Institute of Technology during the early phases of their work in the tensile testing of graphite at high temperatures. JPL found that this serrated shape was eliminated when the backlash in the testing machine was reduced and when the strain rate was increased.[14] Serrated stress-strain curves have also been observed for some aluminums at room temperature and for mild steel beyond the yield point at elevated temperatures.[15]

Discontinuities in the apparent shear stress-strain curves, (Figures 41 to 46, inclusive) are caused by bending breaks. The with-grain curves, Figures 41, 42 and 43, show that single bending breaks occurred at room temperature and 2000°C, two at 1000° and 2700°C, three at 1500°C and five at 2500°C, before the samples sheared at the ends of the gauge length. The across-grain curves, Figures 44, 45 and 46, are interpreted in the same manner. As explained in Section 2.8, the purpose of presenting these curves is to show what has happened to the sample during the test and they should not be used as design data.

Stress levels at fracture in the stress-strain curves may not correspond to ultimate strengths in the tables. This can occur whenever the ultimate strength and stress-strain curves were not obtained from the same sample.

It is extremely difficult to adjust a strength tester to start recording stress and strain simultaneously; consequently some of the stress-strain curves (Figure 26, for example) show an increase in stress near the origin of the curve, with little or no increase in strain. This "preloading" must be ignored.

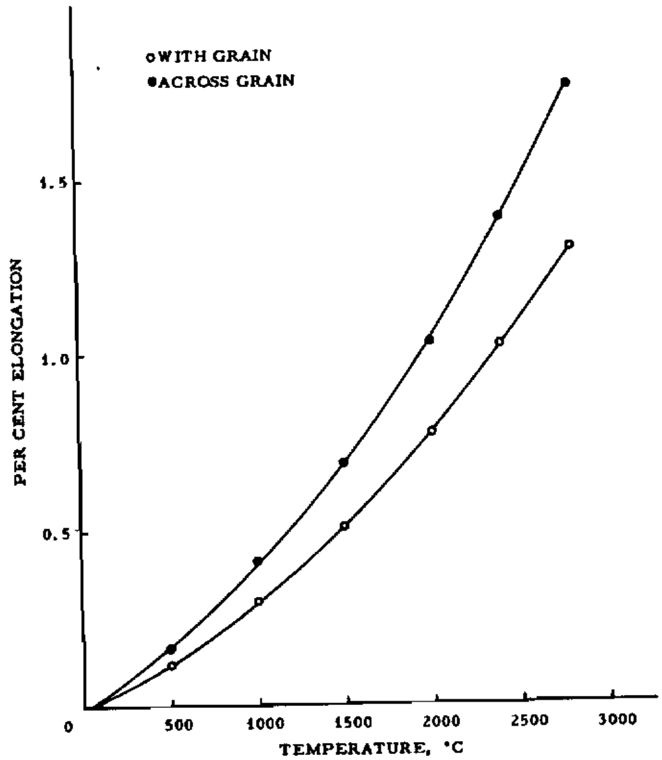
Table 1. Room-Temperature Properties, ATJ Graphite

Properties	With Grain				Across Grain			
	Average	σ	n	No. of Blocks	Average	σ	n	No. of Blocks
Bulk Density, g/cc	1.73*	0.036*	--		---	---	--	--
Specific Resistance, 10^{-4} ohm-cm	11.00*	1.68*	--	--	14.50*	1.45	--	--
Young's Modulus, 10^6 lbs/in^2	1.45*	0.166*	--	--	1.15*	0.095	--	--
Flexural Strength, lbs/in^2	4010*	773*	--	--	3580*	484*	--	--
Compressive Strength, 1-by 1-by 1 in. Sample, lbs/in^2	8270*	1028*	--	--	8540*	1144*	--	--
Compressive Strength ½-inch diameter by ½-inch Sample, lbs/in^2	6700	306	10	1	5670	724	10	1
Tensile Strength, briquette sample, lbs/in^2	1790*	225*	--	--	1420*	226*	--	--
Tensile Strength(1), lbs/in^2	3355	379	11	1	2935	117	10	1
Apparent Shear Strength, lbs/in^2	1505	389	10	1	1820	250	10	1
CTE, 20°-100°C, 10^{-6}/°C	2.19*	0.216*	--	--	3.42*	0.223*	--	--
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ {}^\circ\text{K}}$	0.281*	---	--	--	0.214*	---	--	--
Permeability, Darcy's	0.018*	0.015*	--	--	0.015*	0.019*	--	--
Per Cent, Ash	0.158*	0.038*	--	--	---	---	--	--

* Industrial Graphite Engineering Handbook, National Carbon Co., Div. of Union Carbide Corp.

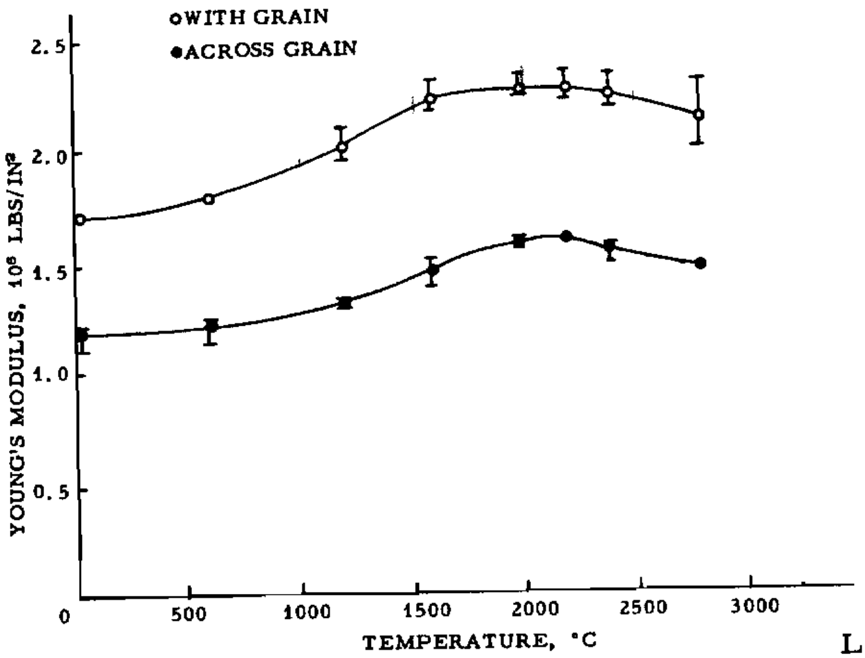
Table 2. High-Temperature Properties, ATJ Graphite, 9 by 20 by 24 Inches

		With Grain					Across Grain				
Properties	Temp. °C	Max.	Min.	Ave.	n	No. of Blocks	Max.	Min.	Ave.	n	No. of Blocks
Thermal Expansion	500	0.119	0.116	0.117	3	1	0.176	0.160	0.168	3	1
Per Cent Elongation	1000	0.296	0.290	0.292	3	1	0.415	0.408	0.411	3	1
$\frac{\Delta L}{L}$ x 100	1500	0.515	0.495	0.507	3	1	0.689	0.681	0.684	3	1
	2000	0.781	0.758	0.772	3	1	1.043	1.020	1.029	3	1
	2400	1.030	1.006	1.020	3	1	1.393	1.364	1.379	3	1
	2800	1.302	1.272	1.291	3	1	1.757	1.749	1.754	3	1
Young's Modulus 10^6 lbs/in²	RT	1.70	1.70	1.70	3	1	1.22	1.11	1.18	3	1
	600	1.80	1.77	1.79	3	1	1.25	1.14	1.21	3	1
	1200	2.10	1.95	2.01	3	1	1.33	1.28	1.31	3	1
	1600	2.31	2.17	2.22	3	1	1.51	1.38	1.46	3	1
	2000	2.33	2.24	2.27	3	1	1.61	1.54	1.58	3	1
	2200	2.35	2.22	2.27	3	1	1.60	1.57	1.59	3	1
	2400	2.34	2.18	2.24	3	1	1.58	1.49	1.55	3	1
	2800	2.30	2.00	2.13	3	1	1.49	1.45	1.47	3	1
Tensile Strength lbs/in²	1000	---	---	3760	1	1	---	---	2745	1	1
	1500	---	---	3740	1	1	---	---	3770	1	1
	2000	6190	5065	5630	2	1	---	---	4070	1	1
	2150	---	---	---	-	-	---	---	4375	1	1
	2250	---	---	6370	1	1	---	---	4720	1	1
	2500	7990	5090	6575	3	1	5920	4180	5100	3	1
	2700	---	---	2935	1	1	5515	2765	4490	3	1
Compressive Strength ½-diameter by ½-inch, lbs/in²	1000	10815	10695	10755	2	1	---	---	6465	1	1
	1500	---	---	11205	1	1	9965	8045	9005	2	1
	2000	9880	9870	9875	2	1	10045	6315	8180	2	1
	2300	---	---	11430	1	1	---	---	11715	1	1
	2400	---	---	18845	1	1	---	---	---	-	-
	2500	21925	18845	20385	2	1	19915	17620	18770	2	1
	2700	Did not break at 33200			1	1	---	---	25975	1	1
Apparent Shear Strength lbs/in²	1000	4095	1375	2735	2	1	---	---	3105	1	1
	1500	4250	2785	3515	2	1	---	---	2690	1	1
	2000	---	---	5050	1	1	---	---	4035	1	1
	2500	---	---	7620	1	1	---	---	5925	1	1
	2700	---	---	8560	1	1	---	---	6725	1	1



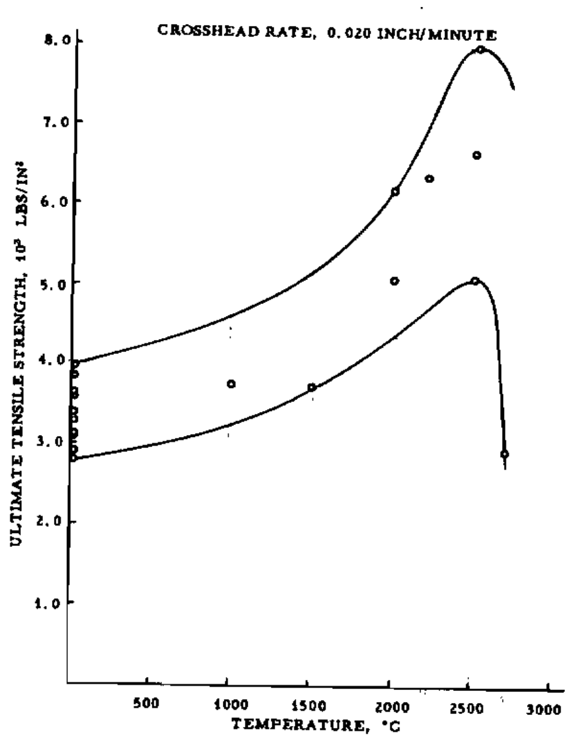
L-445

Figure 21. Thermal Expansion vs. Temperature, ATJ Graphite, 9 by 20 by 24 Inches



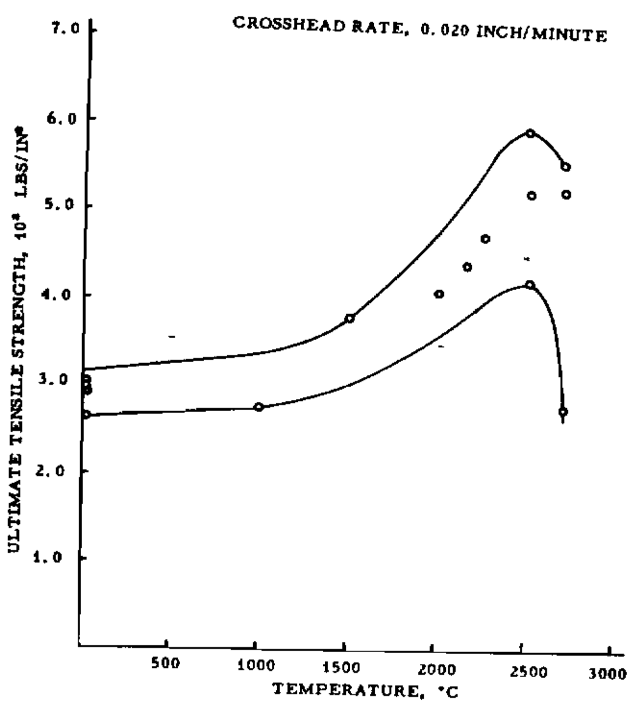
L-446

Figure 22. Young's Modulus vs. Temperature, ATJ Graphite, 9 by 20 by 24 Inches



L-447

Figure 23. With-Grain Ultimate Tensile Strength Vs. Temperature, ATJ Graphite, 9 by 20 by 24 Inches



L-448

Figure 24. Across-Grain Ultimate Tensile Strength Vs. Temperature, ATJ Graphite, 9 by 20 by 24 Inches

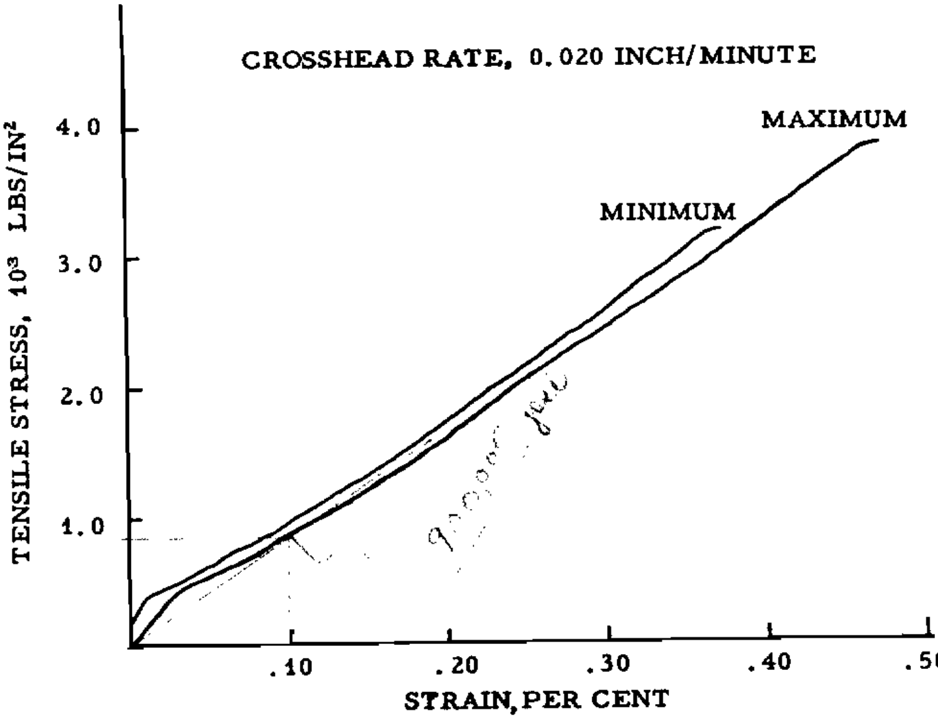


Figure 25. With-Grain Tensile Stress-Strain Curves, ATJ Graphite, 9 by 20 by 24 Inches, Room Temperature

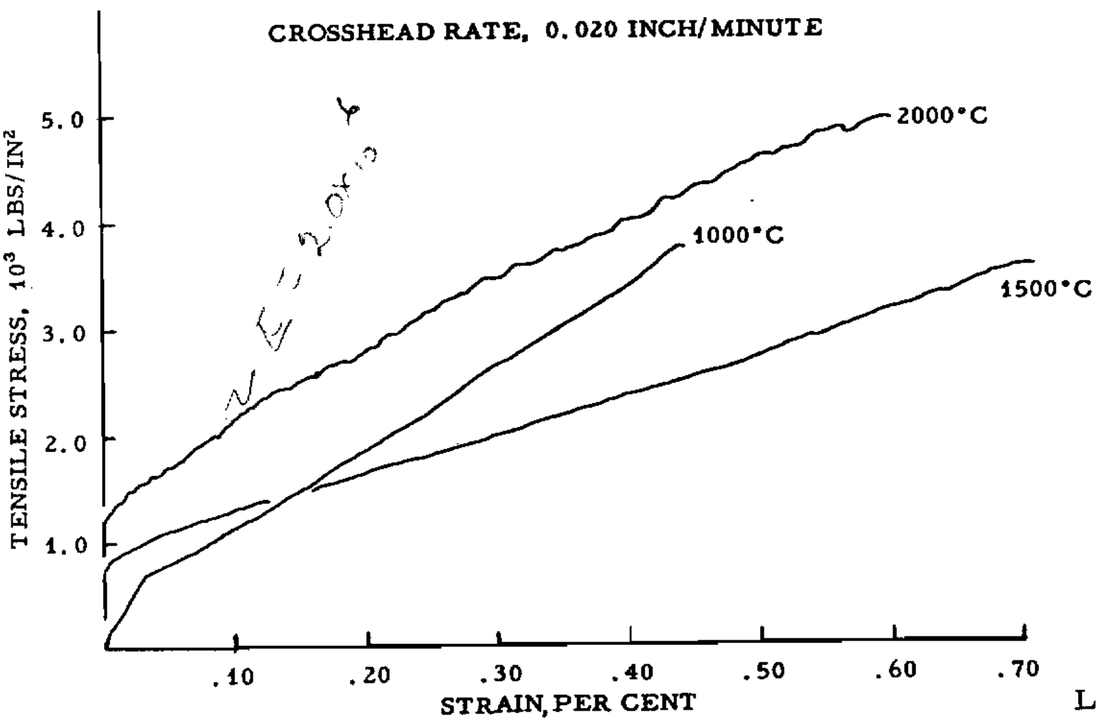
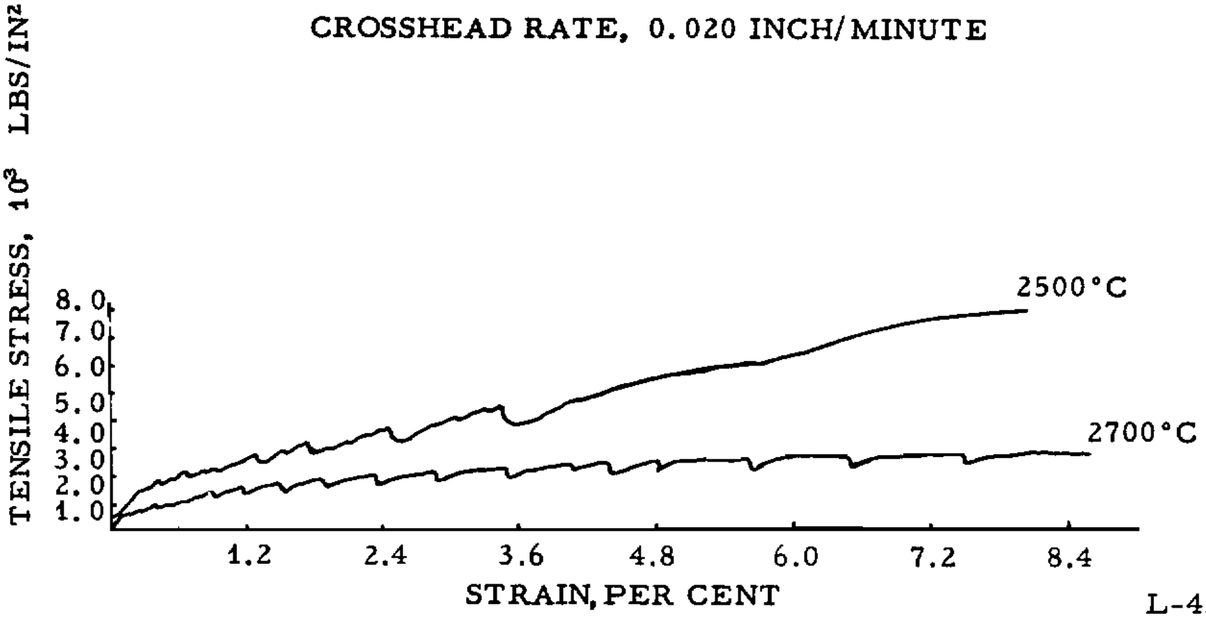
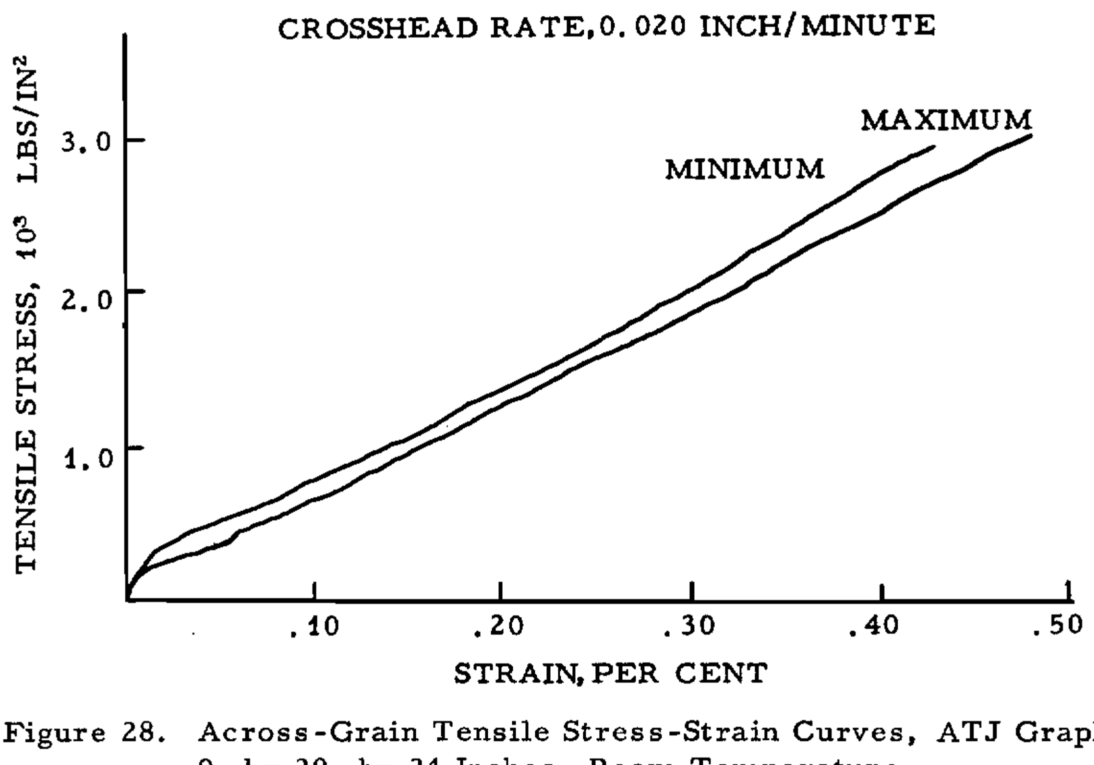


Figure 26. With-Grain Tensile Stress-Strain Curves, ATJ Graphite, 9 by 20 by 24 Inches, 1000°C, 1500°C, 2000°C



L-451

Figure 27. With-Grain Tensile Stress-Strain Curves, ATJ Graphite, 9 by 20 by 24 Inches, 2500°C, 2700°C



L-452

Figure 28. Across-Grain Tensile Stress-Strain Curves, ATJ Graphite, 9 by 20 by 24 Inches, Room Temperature

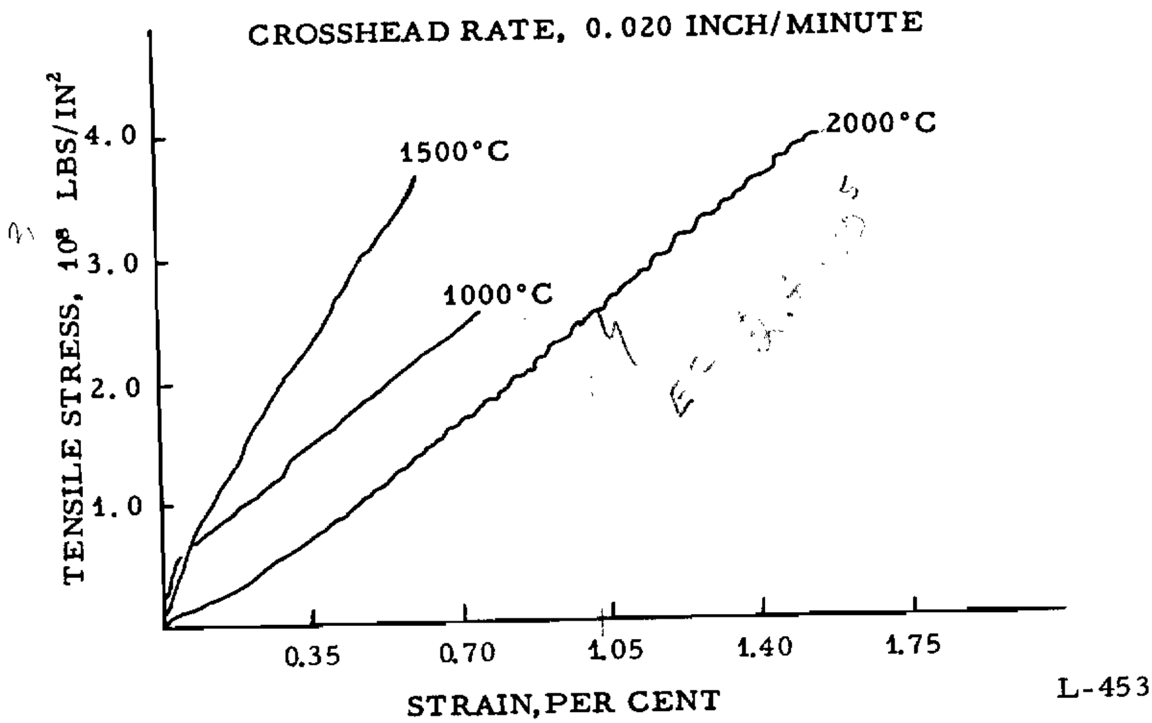


Figure 29. Across-Grain Tensile Stress-Strain Curves, ATJ Graphite, 9 by 20 by 24 Inches, 1000°C, 1500°C, 2000°C

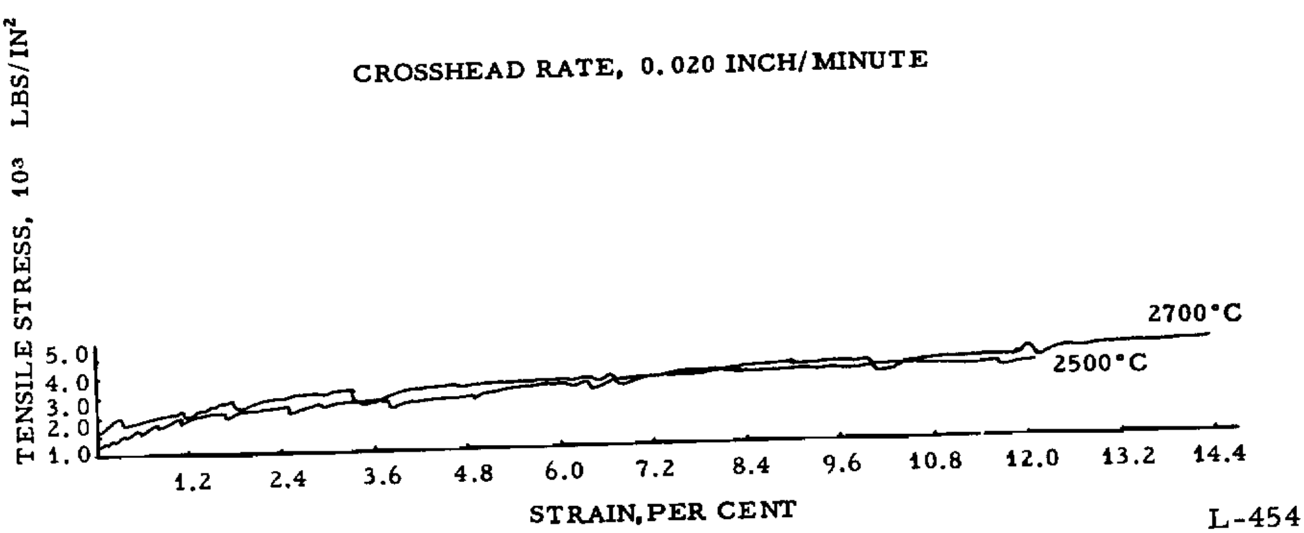


Figure 30. Across-Grain Tensile Stress-Strain Curves, ATJ Graphite, 9 by 20 by 24 Inches, 2500°C, 2700°C

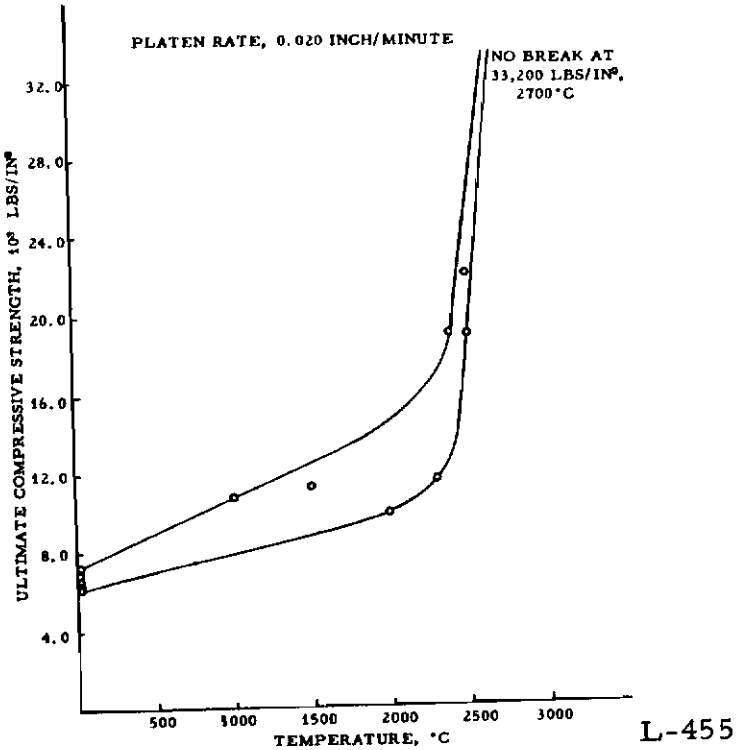


Figure 31. With-Grain Ultimate Compressive Strength vs. Temperature, ATJ Graphite, 9 by 20 by 24 Inches

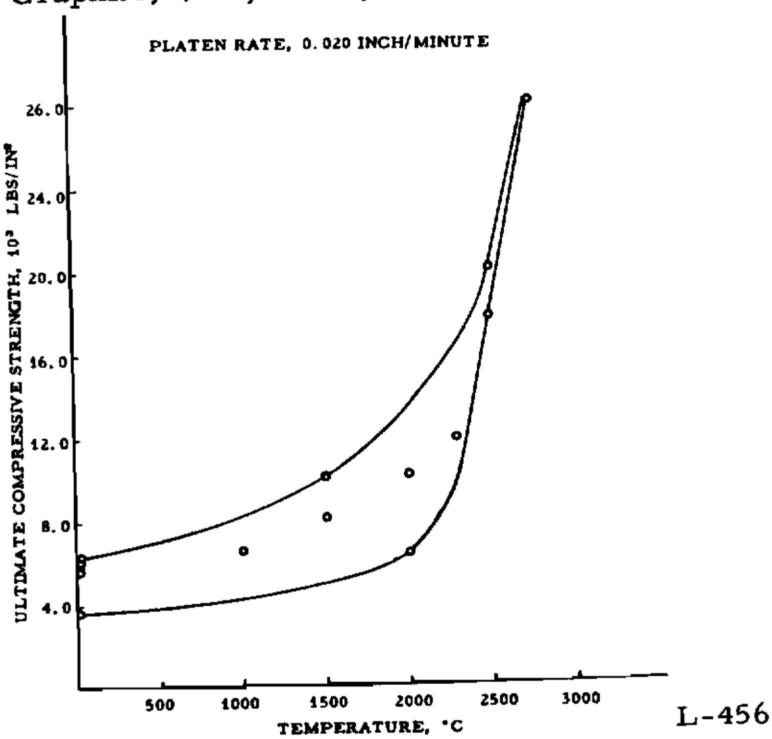


Figure 32. Across-Grain Ultimate Compressive Strength vs. Temperature, ATJ Graphite, 9 by 20 by 24 Inches

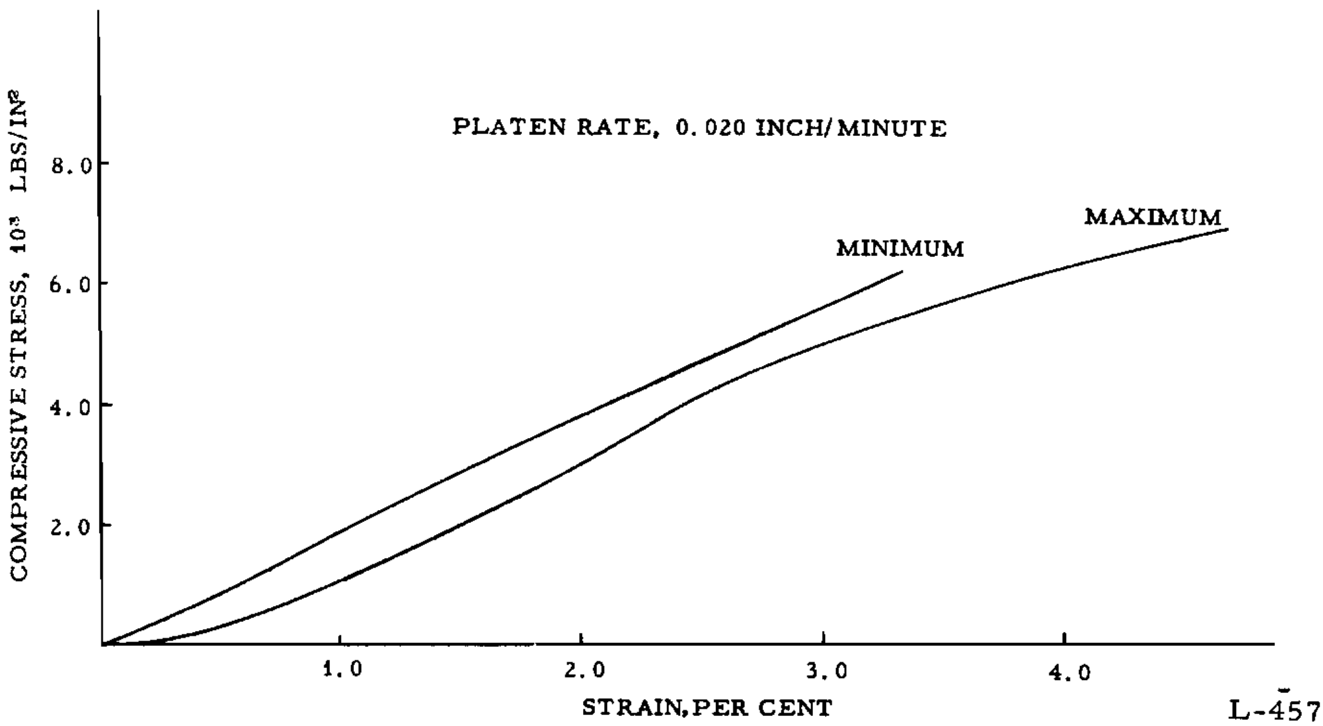


Figure 33. With-Grain Compressive Stress-Strain Curves, ATJ Graphite, Room Temperature, 9 by 20 by 24 Inches

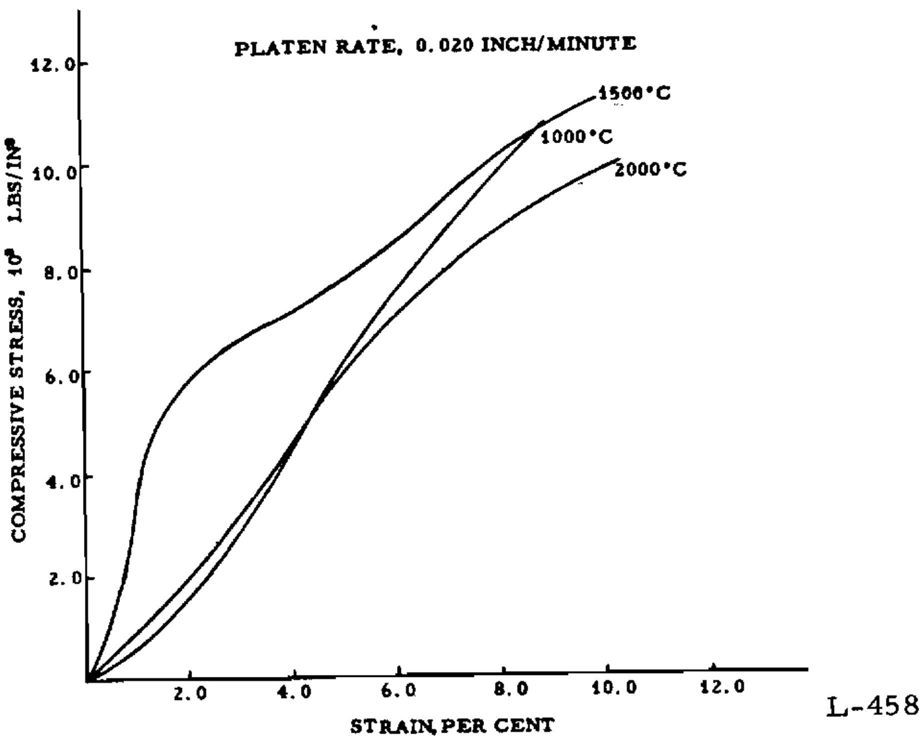
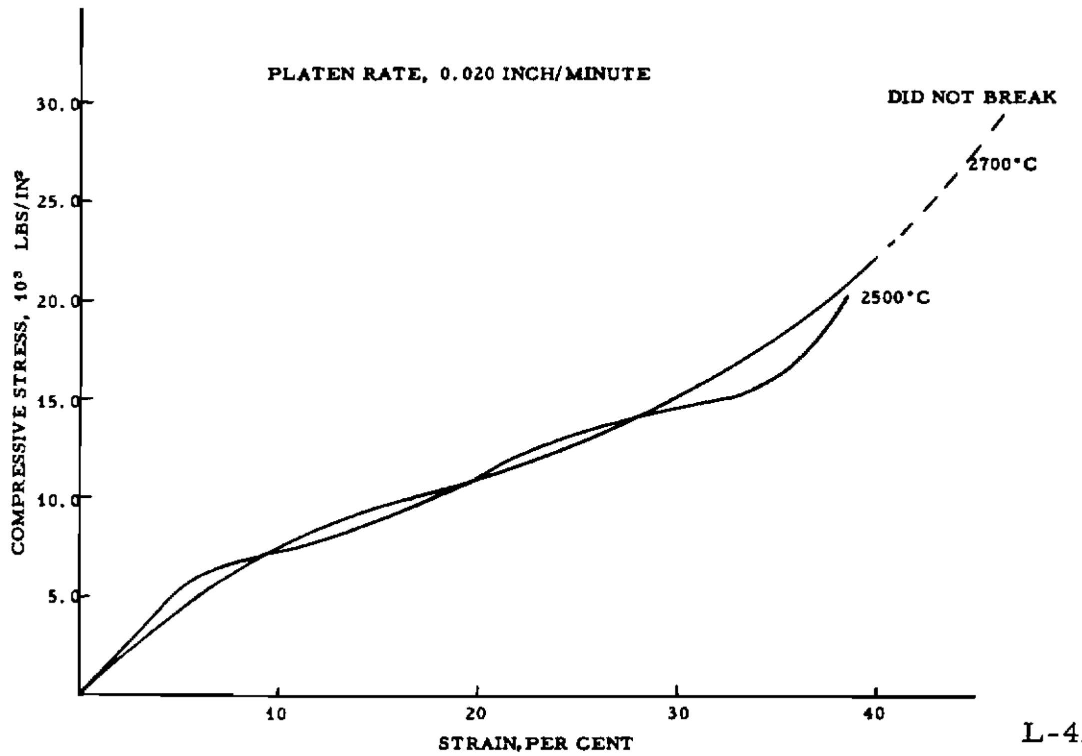
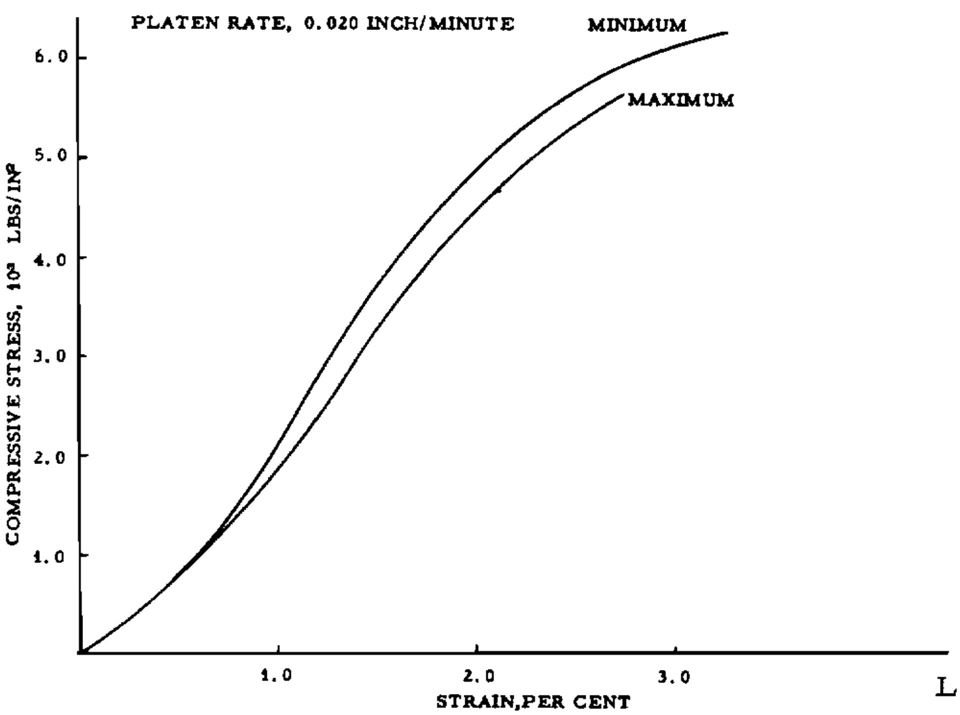


Figure 34. With-Grain Compressive Stress-Strain Curves, ATJ Graphite, 9 by 20 by 24 Inches, 1000°C, 1500°C, 2000°C



L-459

Figure 35. With-Grain Compressive Stress-Strain Curves, ATJ Graphite, 9 by 20 by 24 Inches, 2500°C, 2700°C



L-460

Figure 36. Across-Grain Compressive Stress-Strain Curves, ATJ Graphite, Room Temperature, 9 by 20 by 24 Inches

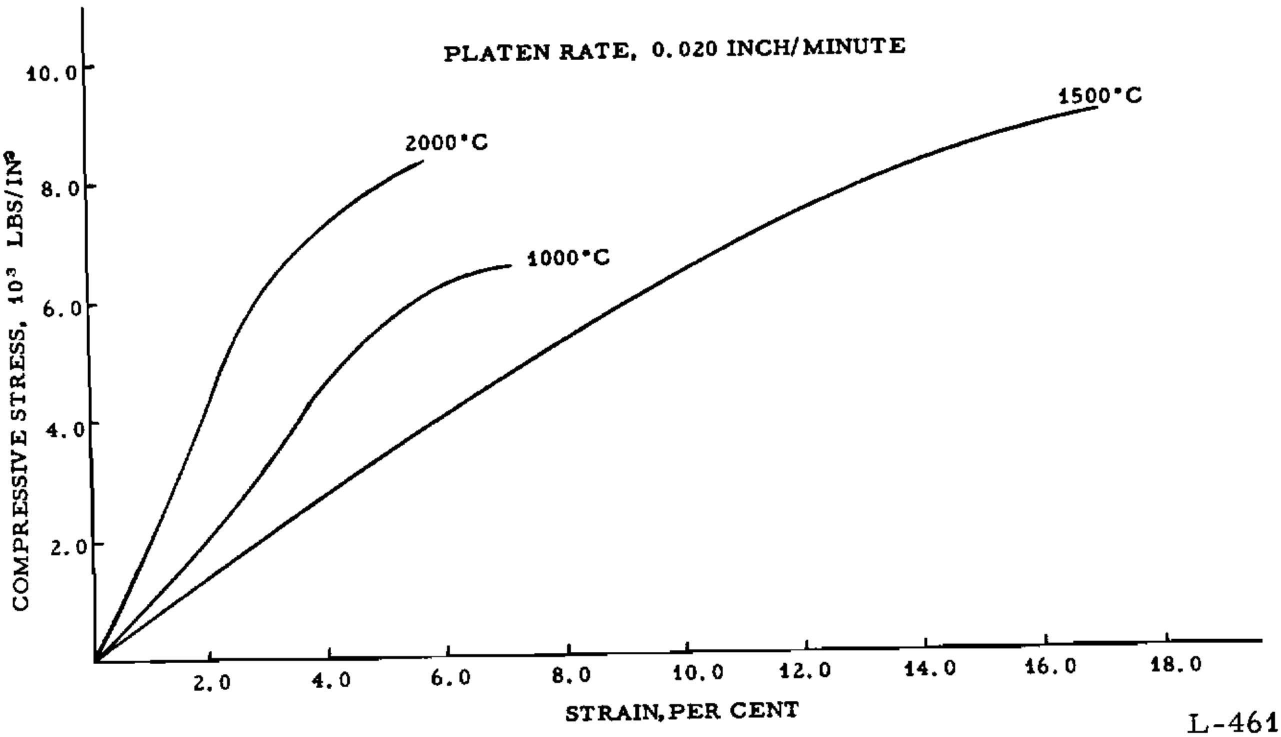


Figure 37. Across-Grain Compressive Stress-Strain Curves, ATJ Graphite, 9 by 20 by 24 Inches, 1000°C, 1500°C, 2000°C

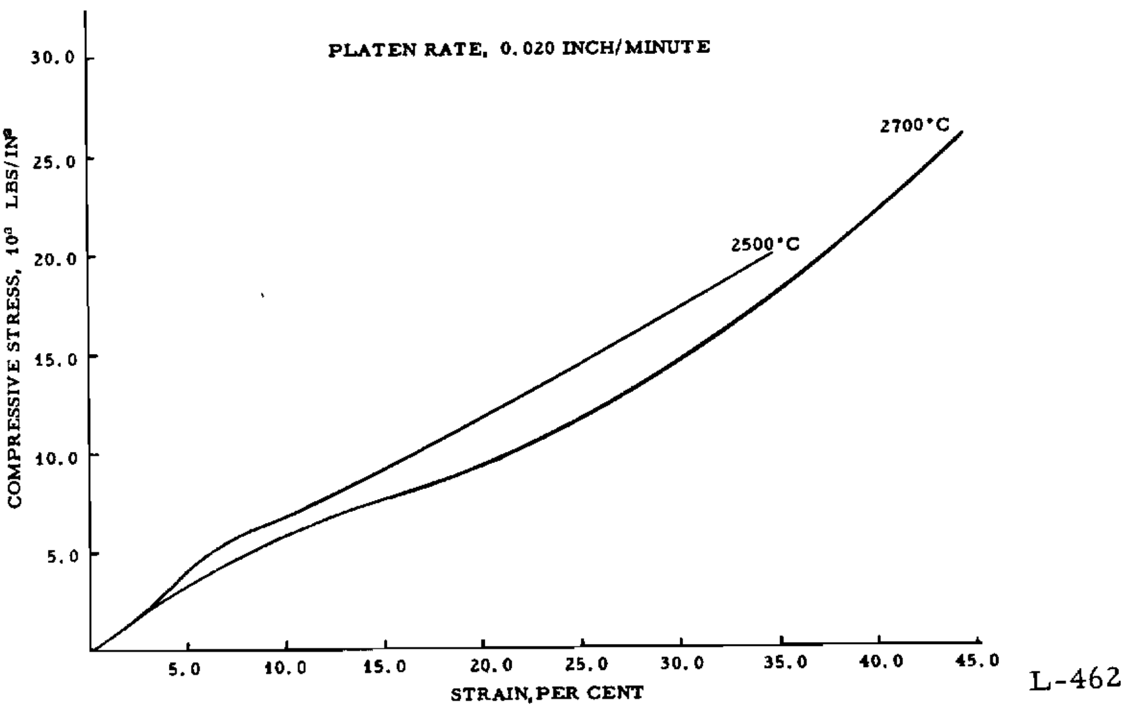
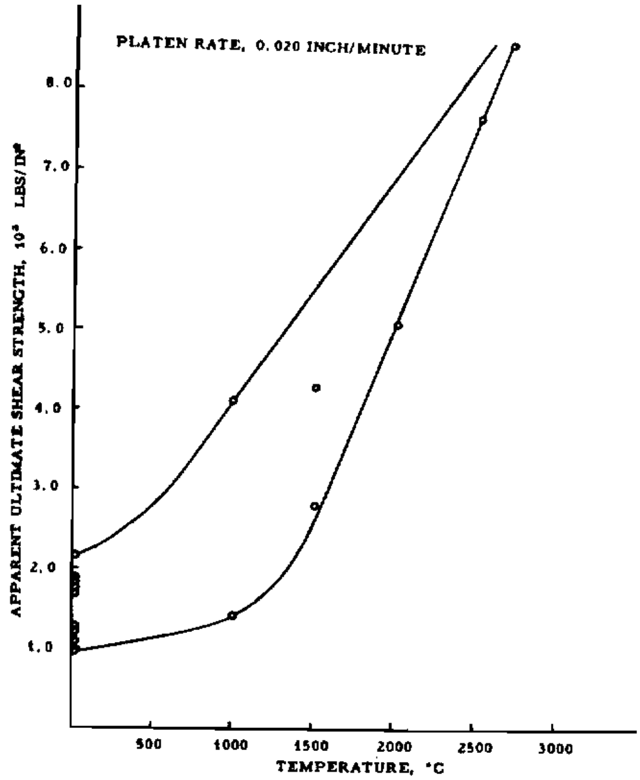
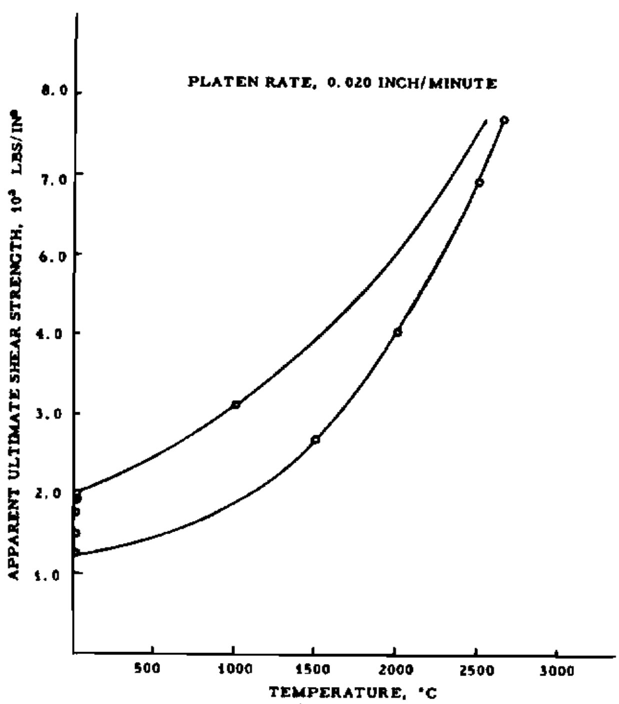


Figure 38. Across-Grain Compressive Stress-Strain Curves, ATJ Graphite, 9 by 20 by 24 Inches, 2500°C, 2700°C



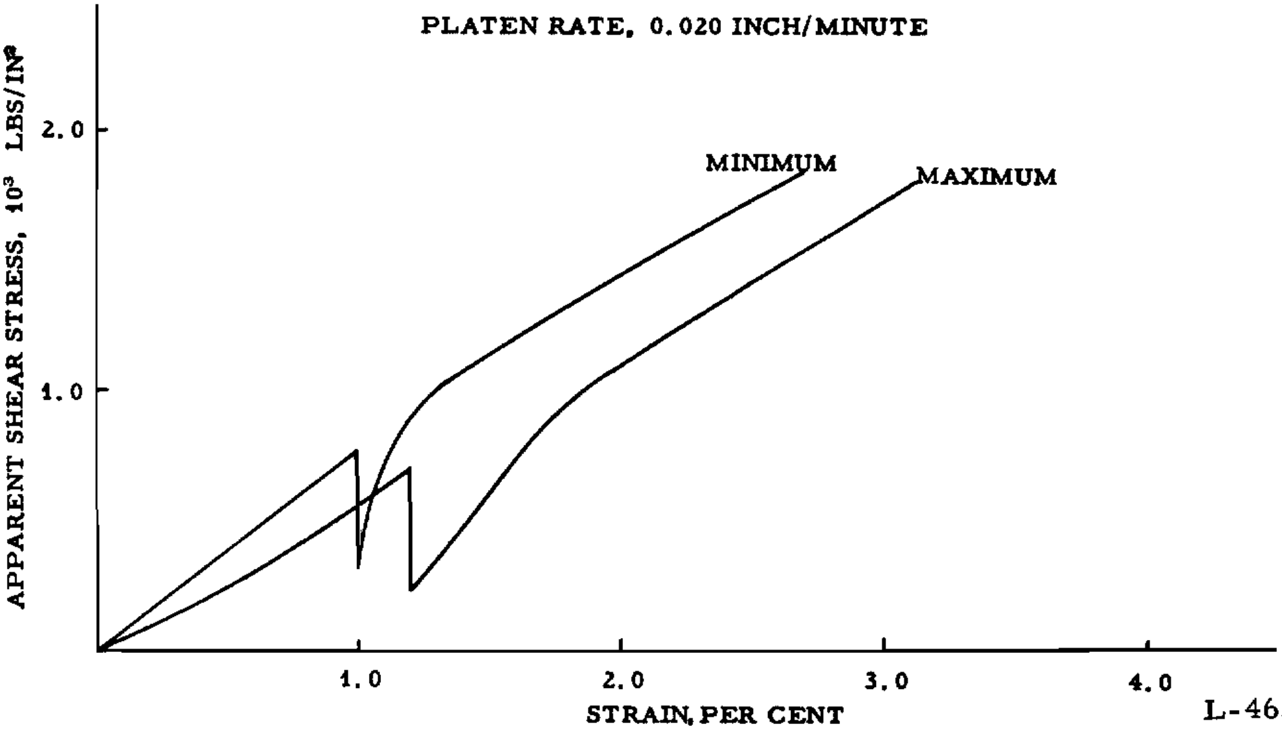
L-463

Figure 39. With-Grain Apparent Ultimate Shear Strength vs. Temperature, ATJ Graphite, 9 by 20 by 24 Inches



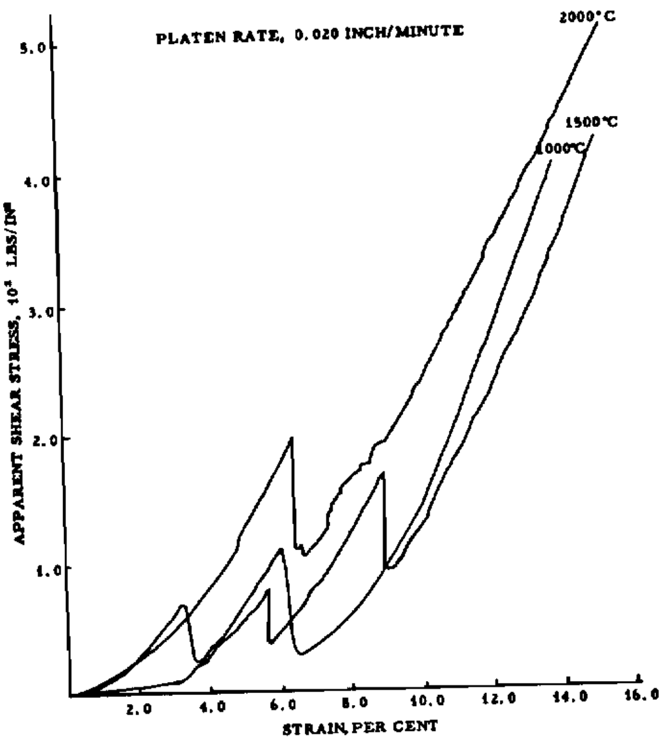
L-464

Figure 40. Across-Grain Apparent Ultimate Shear Strength vs. Temperature, ATJ Graphite, 9 by 20 by 24 Inches



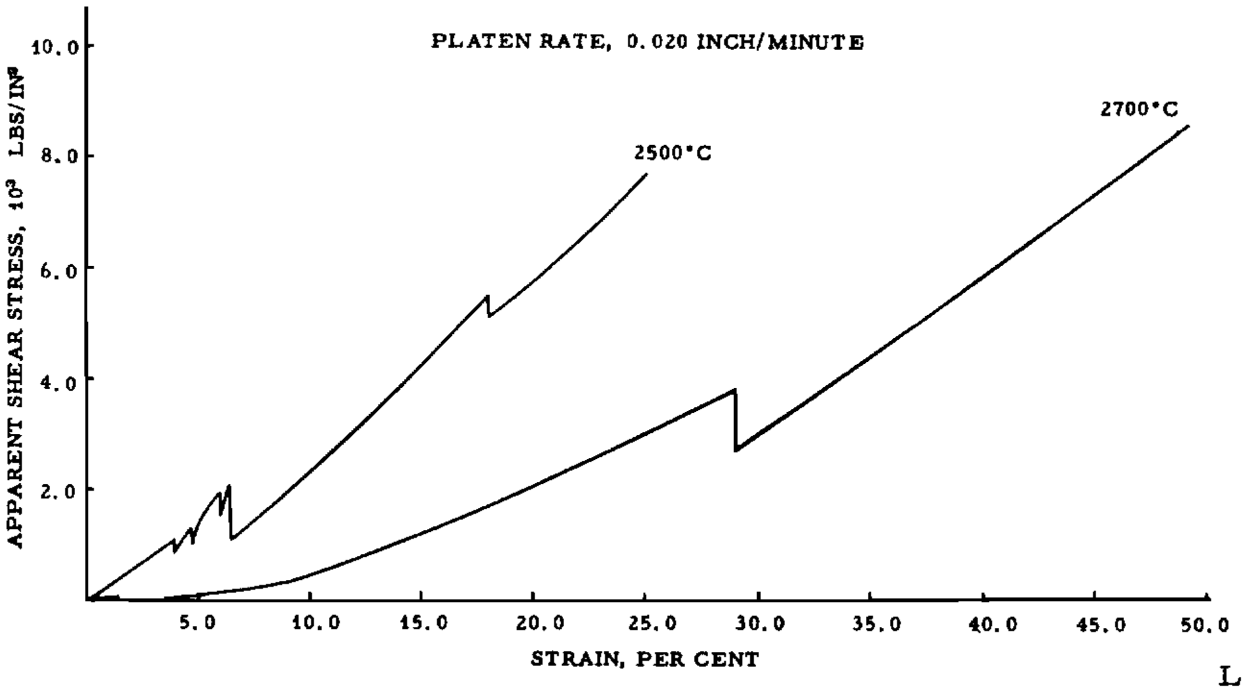
L-465

Figure 41. With-Grain Apparent Shear Stress-Strain Curves, ATJ Graphite, 9 by 20 by 24 Inches, Room Temperature



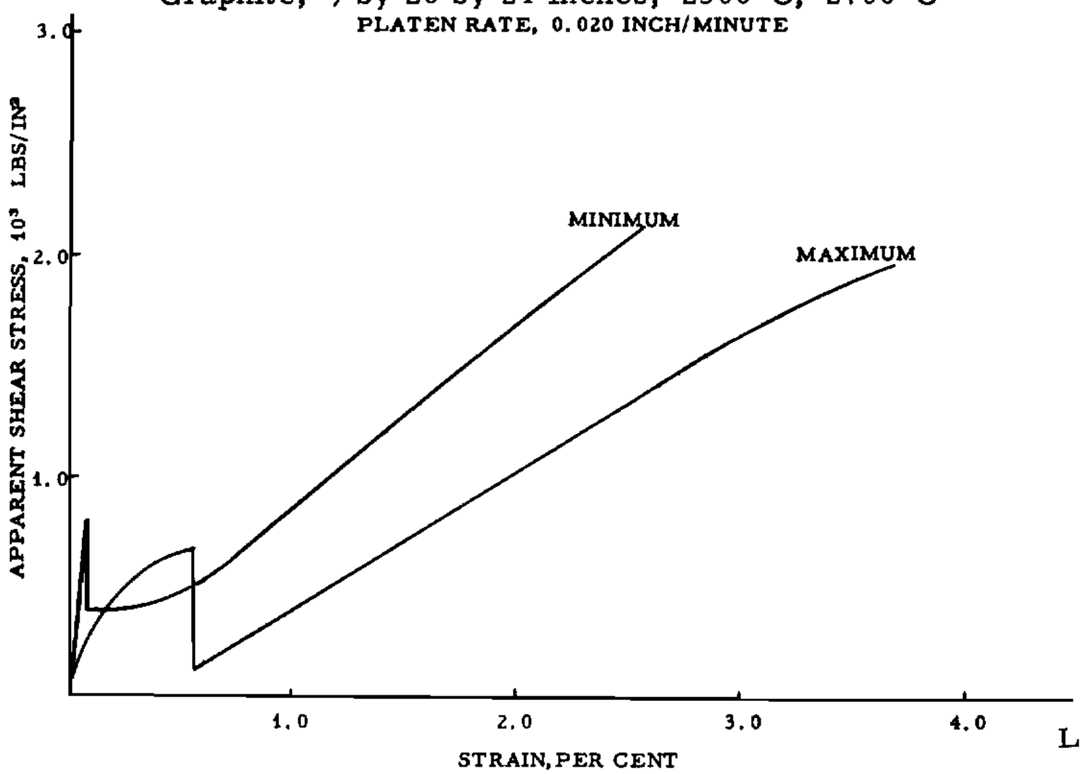
L-466

Figure 42. With-Grain Apparent Shear Stress-Strain Curves, ATJ Graphite, 9 by 20 by 24 Inches, 1000°C, 1500°C, 2000°C



L-467

Figure 43. With-Grain Apparent Shear Stress-Strain Curves, ATJ Graphite, 9 by 20 by 24 Inches, 2500°C, 2700°C



L-468

Figure 44. Across-Grain Apparent Shear Stress-Strain Curves, ATJ Graphite, 9 by 20 by 24 Inches, Room Temperature

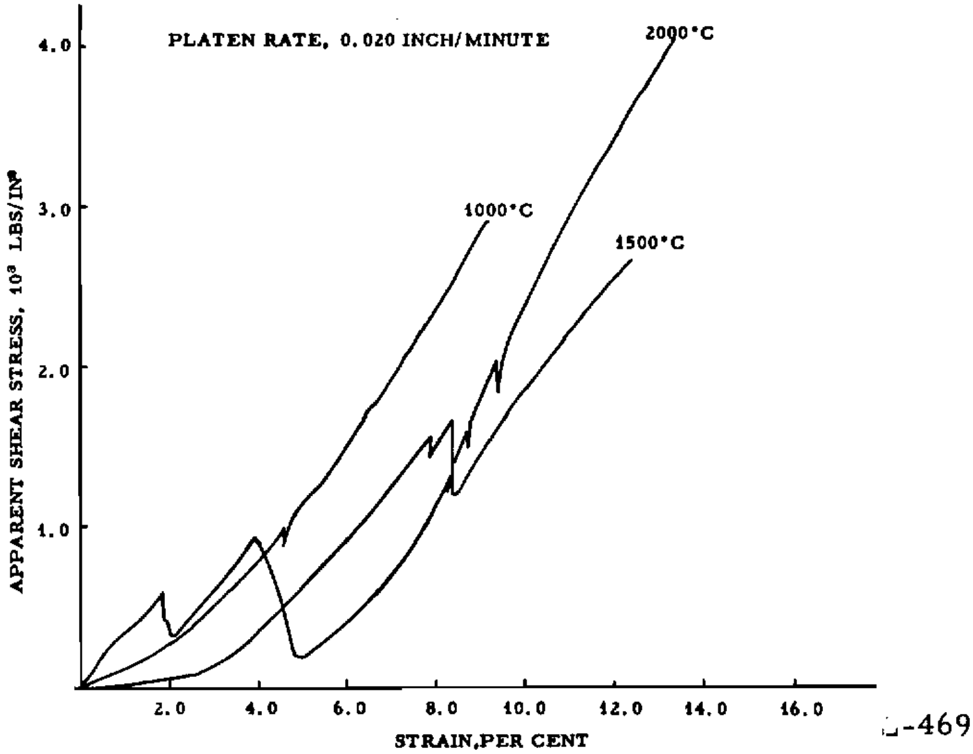


Figure 45. Across-Grain Apparent Shear Stress-Strain Curves, ATJ Graphite, 9 by 20 by 24 Inches, 1000°C, 1500°C, 2000°C

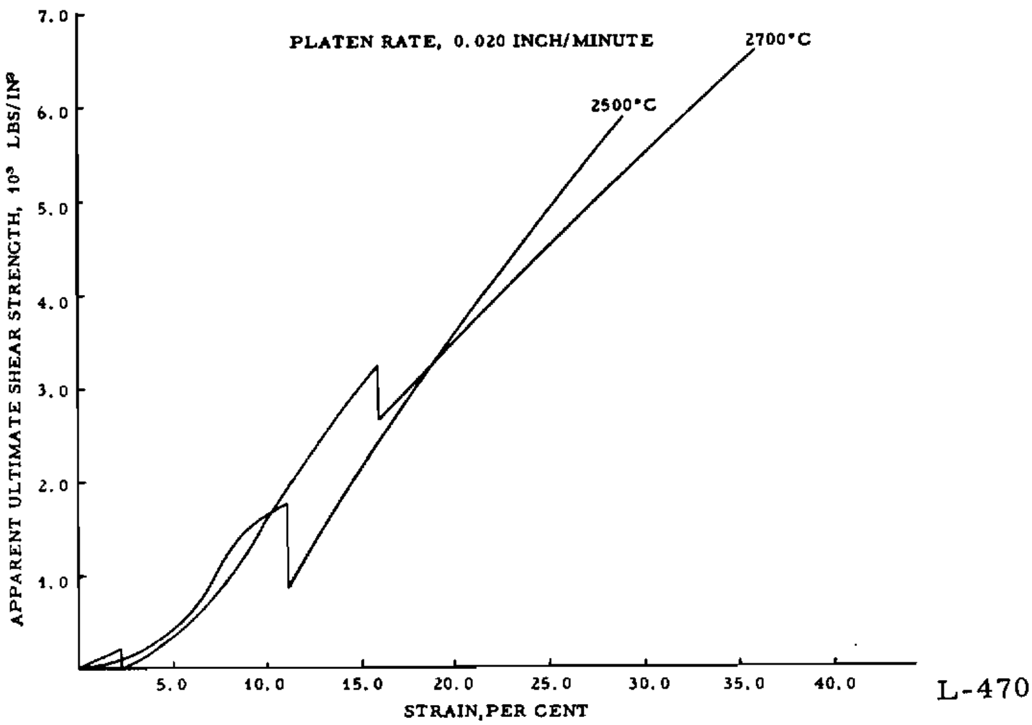
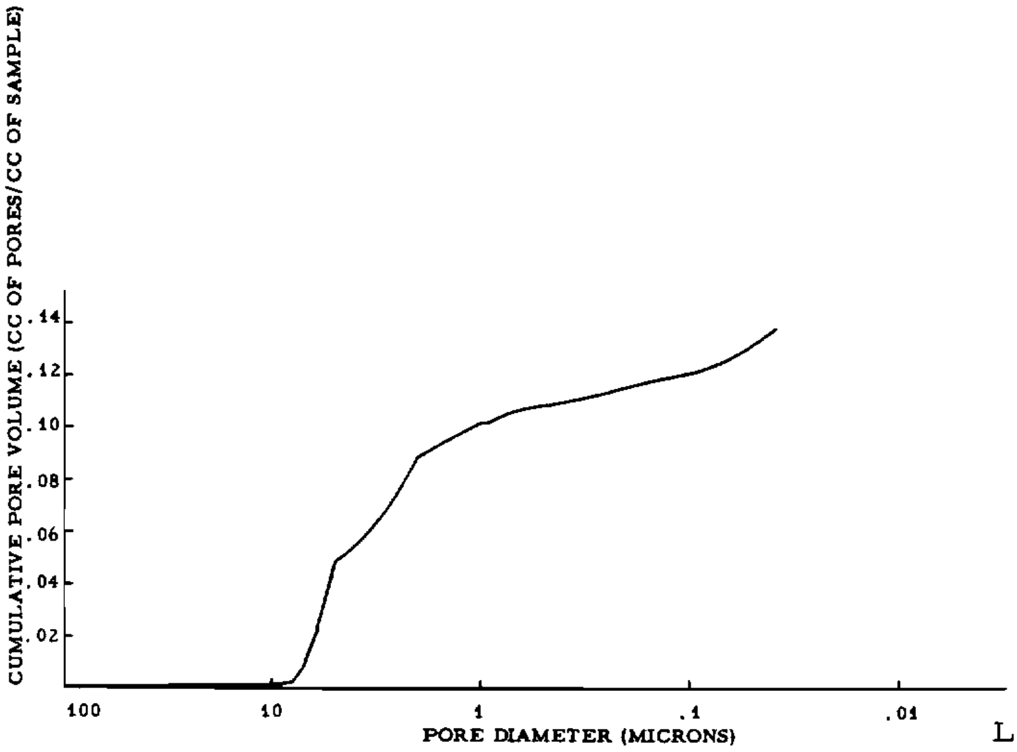


Figure 46. Across-Grain Apparent Shear Stress-Strain Curves, ATJ Graphite, 9 by 20 by 24 Inches, 2500°C, 2700°C



L-471

Figure 47. Pore Size Distribution, Mercury Porosimetry, ATJ Graphite, 9 by 20 by 24 Inches

3.2. Grade ZTA Graphite[16,17]

3.2.1. Grade ZTA, 14-Inch Diameter by 10-Inch Length

Five blocks of ZTA graphite (taken from factory production) were selected for property measurements. A summary of the properties of these five 14-inch diameter by 10-inch length ZTA blocks is presented in Tables 3 and 4, and the properties of the individual blocks are given in Tables 5 to 14, inclusive. Because the blocks were not large enough for complete individual characterization as outlined in the Introduction (Section 1) room-and high-temperature shear strengths and high-temperature compressive strengths have been omitted.

Figures 53 and 54, respectively, are plots of the thermal expansion and Young's modulus data in Table 4. All strength measurements are made at cross head or platen rates of 0.020 inch per minute. The interpretation of stress-strain curves was discussed in Section 3.1.

Table 3. Summary of Room-Temperature Properties, ZTA Graphite, 14-inch Diameter by 10-inch Length

	With Grain				Across Grain			
Properties	Average	σ	n	No. of Blocks	Average	σ	n	No. of Blocks
Bulk Density, g/cc	1.940	0.025	301	5	---	---	---	--
Specific Resistance, 10^{-4} ohm-cm	6.97	0.50	146	5	21.87	1.60	155	5
Young's Modulus, 10^6 lbs/in²	2.80	0.25	146	5	0.75	0.04	155	5
Flexural Strength, lbs/in²	5605	770	146	5	2335	326	155	5
Compressive Strength, 1- by 1- by 1-inch sample, lbs/in²	7150	1338	236	5	12,630	1603	208	5
Compressive Strength, ½-in. dia. by ½-in. sample, lbs/in²	---	---	---	--	---	---	---	--
Tensile Strength, lbs/in²	4435	667	49	5	1530	302	61	5
Apparent Shear Strength, lbs/in²	---	---	---	--	---	---	---	--
CTE, 20°-100°C, 10^{-6}/°C	0.62	0.22	30	5	9.00	0.40	20	5
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec. cm}^2\ °\text{K}}$	0.517	0.063	11	5	0.208	0.025	7	7

	With Grain					Across Grain				
	Max.	Min.	Ave.	n	No. of Blocks	Max.	Min.	Ave.	n	No. of Blocks
Admittance, cm²/sec.	9×10^{-4}	4×10^{-4}	6×10^{-4}	2	2	2×10^{-4}	0.6×10^{-4}	1×10^{-4}	2	2
Per Cent Ash	0.146	0.090	0.114	4	4	---	---	---	-	-

Table 4. Summary of High-Temperature Properties, ZTA Graphite, 14-Inch Diameter by 10-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	With Grain No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n	Across Grain No. of Blocks
Thermal Expansion	500	0.114	0.037	0.068	15	5	0.529	0.44	0.463	15	5
Per Cent Elongation	1000	0.250	0.134	0.182	15	5	1.110	0.915	0.987	15	5
$\frac{\Delta L}{L}$ x 100	1500	0.397	0.249	0.324	15	5	1.731	1.466	1.581	15	5
	2000	0.580	0.380	0.486	15	5	2.497	2.144	2.279	15	5
	2400	0.762	0.500	0.654	15	5	3.280	2.797	2.999	15	5
Young's Modulus -	RT	3.41	2.69	2.99	11	4	0.79	0.68	0.74	10	4
10^6 lb/in²	600	3.49	2.79	3.12	11	4	0.80	0.71	0.75	10	4
	1000	3.63	2.93	3.25	11	4	0.97	0.72	0.77	10	4
	1400	3.84	3.06	3.47	11	4	1.00	0.77	0.84	10	4
	2000	4.40	3.16	3.86	11	4	1.20	0.88	1.02	10	4
	2400	4.42	3.29	4.03	11	4	1.38	1.00	1.16	10	4
	2800	4.27	3.11	3.76	11	4	1.31	0.90	1.12	10	4
Tensile Strength,	1000	5735	3845	5090	10	5	1920	1505	1750	5	5
lbs/in²	1500	7560	5440	6270	7	5	2275	1685	1925	5	5
	1800	---	---	---	--	-	---	---	1950	1	1
	2000	10485	7300	8540	10	5	2715	1575	2150	5	5
	2150	9825	8620	9415	4	1	---	---	---	--	-
	2250	10075	7490	8780	9	5	3435	1910	2355	5	5
	2350	---	---	9355	1	1	---	---	---	--	-
	2500	12030	9100	10075	12	5	3640	1585	2445	6	5
	2700	9505	7205	7660	6	5	2610	2165	2390	4	4
	2800	---	---	---	--	-	---	---	2080	1	1
	3000	---	---	---	--	-	---	---	1765	1	1

Table 5. Room-Temperature Properties, ZTA Graphite, Block No. 20, 14-Inch Diameter by 10-Inch Length

Properties	With Grain Average	With Grain σ	With Grain n	Across Grain Average	Across Grain σ	Across Grain n
Bulk Density, g/cc	1.924	0.029	74	---	---	--
Specific Resistance, 10^{-4} ohm-cm	7.24	0.50	37	21.90	1.13	37
Young's Modulus, 10^{6} lbs/in^2	2.71	0.24	37	0.73	0.04	37
Flexural Strength, lbs/in^2	4740	502	37	2200	230	37
Compressive Strength, 1- by 1- by 1-inch sample, lbs/in^2	7040	994	51	12610	1283	52
Compressive Strength, $\frac{1}{2}$-in. dia. by $\frac{1}{2}$-in. sample, lbs/in^2	---	---	--	---	---	--
Tensile Strength, lbs/in^2	4030	272	12	1200	176	11

Properties	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
CTE, 20°-100°C, 10^{-6}/°C	1.06	0.41	0.58	6	8.66	8.60	8.64	5
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec. cm}^2\ {}^\circ\text{K}}$	0.485	0.407	0.446	2	---	---	0.199	1
Admittance, cm^2/sec	---	---	4×10^{-4}	1	---	---	2×10^{-4}	1
Per Cent Ash	---	---	0.116	1	---	---	---	-

Table 6. High-Temperature Properties, ZTA Graphite, Block No. 20, 14-Inch Diameter by 10-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
Thermal Expansion Per Cent Elongation $\frac{\Delta L}{L} \times 100$	500	0.096	0.067	0.079	3	0.451	0.444	0.447	3
	1000	0.232	0.186	0.206	3	0.948	0.915	0.936	3
	1500	0.396	0.337	0.363	3	1.521	1.446	1.493	3
	2000	0.580	0.487	0.539	3	2.192	2.144	2.170	3
	2400	0.762	0.645	0.700	3	2.901	2.797	2.837	3
Young's Modulus, 10^6 lbs/in^2	RT	2.93	2.85	2.89	2	0.74	0.68	0.71	3
	600	2.98	2.96	2.97	2	0.76	0.71	0.73	3
	1000	3.11	3.10	3.10	2	0.76	0.74	0.75	3
	1400	3.38	3.38	3.38	2	0.92	0.80	0.84	3
	2000	3.68	3.58	3.63	2	1.05	0.88	0.98	3
	2400	3.69	3.58	3.64	2	1.22	1.00	1.11	3
	2800	3.68	3.42	3.55	2	1.13	0.90	1.03	3
Tensile Strength, lbs/in^2	1000	---	---	5115	1	---	---	1910	1
	1500	---	---	5980	1	---	---	1990	1
	2000	---	---	8340	1	---	---	2050	1
	2250	---	---	7610	1	---	---	1950	1
	2500	---	---	9100	1	---	---	2575	1
	2700	---	---	7510	1	---	---	2165	1

Table 7. Room-Temperature Properties, ZTA Graphite, Block No. 23, 14-Inch Diameter by 10-Inch Length

Properties	With Grain			Across Grain		
	Average	σ	n	Average	σ	n
Bulk Density, g/cc	1.953	0.016	72	---	---	--
Specific Resistance, 10^{-4} ohm-cm	6.91	0.30	35	23.18	0.81	37
Young's Modulus, 10^{6} lbs/in^2	2.89	0.20	35	0.73	0.02	37
Flexural Strength, lbs/in^2	5940	541	35	2270	177	37
Compressive Strength, 1-by 1-by 1-inch sample, lbs/in^2	7230	1174	53	12220	1418	27
Compressive Strength, $\frac{1}{2}$-in. dia. by $\frac{1}{2}$-in. sample, lbs/in^2	---	---	--	---	---	--
Tensile Strength, lbs/in^2	4360	406	7	1570	175	8

Properties	With Grain				Across Grain			
	Max.	Min.	Ave.	n	Max.	Min.	Ave.	n
CTE, 20°-100°C, 10^{-6}/°	0.82	0.29	0.56	6	9.73	9.43	9.57	4
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ °\text{K}}$	0.539	0.509	0.524	2	---	---	0.184	1
Admittance, cm^2/sec	---	---	---	-	---	---	---	-
Per Cent Ash	---	---	0.090	1	---	---	---	-

Table 8. High-Temperature Properties, ZTA Graphite, Block No. 23, 14-Inch Diameter by 10-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	n
Thermal Expansion	500	0.067	0.046	0.058	3	0.529	0.456	0.486	3
Per Cent Elongation	1000	0.183	0.134	0.159	3	1.110	1.004	1.043	3
$\frac{\Delta L}{L} \times 100$	1500	0.320	0.249	0.286	3	1.731	1.600	1.646	3
	2000	0.477	0.382	0.430	3	2.497	2.271	2.372	3
	2400	0.638	0.502	0.566	3	3.280	3.006	3.139	3
Young's Modulus,	RT	2.90	2.69	2.78	4	0.76	0.71	0.74	3
10^6 lbs/in^2	600	2.91	2.78	2.83	4	0.80	0.74	0.77	3
	1000	3.08	2.92	2.99	4	0.97	0.78	0.87	3
	1400	3.38	3.06	3.18	4	1.00	0.81	0.91	3
	2000	3.88	3.16	3.53	4	1.20	0.91	1.06	3
	2400	3.78	3.29	3.60	4	1.34	1.00	1.17	3
	2800	3.60	3.10	3.40	4	1.21	1.00	1.12	3
Tensile Strength,	1000	5735	4840	5345	3	---	---	1665	1
lbs/in^2	1500	6980	5535	6310	3	---	---	1785	1
	2000	9750	7510	8355	3	---	---	2165	1
	2250	9345	7710	8560	3	---	---	2245	1
	2500	10200	9345	9765	5	---	---	2390	1
	2700	7205	6655	6930	2	---	---	2355	1

Table 9. Room-Temperature Properties, ZTA Graphite, Block No. 111, 14-Inch Diameter by 10-Inch Length

Properties	With Grain			Across Grain		
	Average	σ	n	Average	σ	n
Bulk Density, g/cc	1.942	0.014	55	---	---	--
Specific Resistance, 10^{-4} ohm-cm	6.70	0.44	28	18.95	0.19	27
Young's Modulus, 10^{6} lbs/in	2.918	0.213	28	0.815	0.025	27
Flexural Strength, lbs/in^2	6070	405	28	2750	248	27
Compressive Strength, 1- by 1- by 1-inch sample, lbs/in^2	7440	1788	45	13180	1247	45
Compressive Strength, $\frac{1}{2}$-in. dia. by $\frac{1}{2}$-in. sample, lbs/in^2	---	---	--	---	---	--
Tensile Strength, lbs/in^2	5055	463	11	1865	202	21

Properties	With Grain				Across Grain			
	Max.	Min.	Ave.	n	Max.	Min.	Ave.	n
CTE, 20°-100°C, 10^{-6}/°C	1.00	0.41	0.64	5	8.54	8.21	8.40	4
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ ^\circ\text{K}}$	0.548	0.528	0.538	2	0.256	0.216	0.236	2
Admittance, cm^2/sec	---	---	---	-	---	---	---	-
Per Cent Ash	---	---	0.146	1	---	---	---	-

Table 10. High-Temperature Properties, ZTA Graphite, Block No. 111, 14-Inch Diameter by 10-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
Thermal Expansion	500	0.114	0.061	0.084	3	0.478	0.468	0.473	3
Per Cent Elongation	1000	0.250	0.155	0.199	3	1.026	0.943	0.994	3
$\frac{\Delta L}{L}$ x 100	1500	0.397	0.293	0.343	3	1.546	1.526	1.570	3
	2000	0.554	0.440	0.497	3	2.277	2.214	2.257	3
	2400	0.700	0.557	0.633	3	2.992	2.977	2.982	3
Young's Modulus,	RT	---	---	3.41	1	0.72	0.69	0.70	2
10^6 lbs/in^2	600	---	---	3.46	1	0.74	0.71	0.72	2
	1000	---	---	3.59	1	0.75	0.73	0.74	2
	1400	--	---	3.77	1	0.81	0.80	0.80	2
	2000	---	---	4.19	1	1.01	0.96	0.98	2
	2400	---	---	4.13	1	1.14	1.10	1.12	2
	2800	---	---	4.16	1	1.18	1.09	1.13	2
Tensile Strength,	1000	5455	3845	4650	2	---	---	1920	1
lbs/in^2	1500	---	---	5960	1	---	---	2275	1
	2000	8895	7920	8550	4	---	---	2715	1
	2150	9825	8620	9415	4	---	---	---	-
	2250	10015	8770	9395	3	---	---	3455	1
	2350	---	---	9355	1	---	---	---	-
	2500	10790	10160	10390	4	---	---	3640	1
	2700	---	---	9505	1	---	---	2610	1

Table 11. Room-Temperature Properties, ZTA Graphite, Block No. 153, 14-Inch Diameter by 10-Inch Length

Properties	With Grain Average	With Grain σ	With Grain n	Across Grain Average	Across Grain σ	Across Grain n
Bulk Density, g/cc	1.955	0.018	54	---	---	--
Specific Resistance, 10^{-4} ohm-cm	6.87	0.49	24	22.04	0.29	28
Young's Modulus, 10^{6} lbs/in^2	2.844	0.265	26	0.760	0.027	28
Flexural Strength, lbs/in^2	6085	736	26	2545	168	28
Compressive Strength, 1- by 1- by 1-inch sample, lbs/in^2	7444	1344	47	13530	1456	44
Compressive Strength, $\frac{1}{2}$-in. dia. by $\frac{1}{2}$-in. sample, lbs/in^2	---	---	--	---	---	--
Tensile Strength, lbs/in^2	4870	539	10	1465	43	10

Properties	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
CTE, 20°-100°C, 10^{-6}/°C	1.21	0.38	0.74	8	9.46	9.34	9.43	4
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ {}^\circ\text{K}}$	0.657	0.449	0.549	3	---	---	0.203	1
Admittance, cm^2/sec	---	---	9×10^{-4}	1	---	---	0.6×10^{-4}	1
Per Cent Ash	---	---	0.104	1	---	---	---	-

Table 12. High-Temperature Properties, ZTA Graphite, Block No. 153, 14-Inch Diameter by 10-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
Thermal Expansion	500	0.060	0.037	0.052	3	0.498	0.489	0.493	3
Per Cent Elongation	1000	0.190	0.148	0.172	3	1.077	1.043	1.062	3
$\frac{\Delta L}{L}$ x 100	1500	0.350	0.288	0.325	3	1.705	1.641	1.674	3
	2000	0.545	0.459	0.507	3	2.398	2.380	2.392	3
	2400	0.714	0.607	0.666	3	3.154	3.111	3.139	3
Young's Modulus, 10^6 lbs/in^2	RT	3.41	3.35	3.38	4	0.76	0.72	0.74	2
	600	3.50	3.42	3.46	4	0.75	0.73	0.74	2
	1000	3.64	3.43	3.55	4	0.78	0.76	0.77	2
	1400	3.83	3.53	3.75	4	0.81	0.80	0.80	2
	2000	4.40	4.17	4.26	4	1.07	0.95	1.01	2
	2400	4.42	4.38	4.40	4	1.37	1.14	1.26	2
	2800	4.27	4.00	4.12	4	1.30	1.12	1.21	2
Tensile Strength, 10^6 lbs/in^2	1000	5625	4905	5315	3	---	---	1745	1
	1500	---	---	7560	1	---	---	1890	1
	1800	---	---	---	-	---	---	1950	1
	2000	---	---	10485	1	---	---	2235	1
	2250	---	---	10075	1	---	---	2745	1
	2500	---	---	12030	1	---	---	2420	1
	2700	---	---	7345	1	---	---	2420	1

Table 13. Room-Temperature Properties, ZTA Graphite, Block 159, 14-Inch Diameter by 10-Inch Length

Properties	With Grain Average	With Grain σ	With Grain n	Across Grain Average	Across Grain σ	Across Grain n
Bulk Density, g/cc	1.923	0.018	46	---	---	--
Specific Resistance, 10^{-4} ohm-cm	7.07	0.61	22	22.67	0.57	26
Young's Modulus, 10^6 lbs/in^2	2.562	0.203	20	0.731	0.022	26
Flexural Strength, lbs/in^2	5365	476	20	1975	192	26
Compressive Strength, 1- by 1- by 1-inch sample, lbs/in^2	6550	1020	40	11330	1713	40
Compressive Strength, $\frac{1}{2}$-in. dia. by $\frac{1}{2}$-in. sample, lbs/in^2	---	---	--	---	---	--
Tensile Strength, lbs/in^2	3615	878	9	1280	273	11

Properties	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
CTE, 20°-100°C, 10^{-6}/°C	1.00	0.47	0.65	5	9.40	9.05	9.28	4
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ {}^\circ\text{K}}$	0.515	0.513	0.514	2	0.216	0.180	0.198	2
Per Cent Ash	---	---	---	-	---	---	---	-

Table 14. High-Temperature Properties, ZTA Graphite, Block No. 159, 14-Inch Diameter by 10-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
Thermal Expansion Per Cent Elongation $\frac{\Delta L}{L} \times 100$	500	0.082	0.052	0.068	3	0.475	0.446	0.458	3
	1000	0.201	0.144	0.173	3	0.959	0.946	0.957	3
	1500	0.350	0.253	0.303	3	1.536	1.512	1.524	3
	2000	0.525	0.380	0.455	3	2.220	2.190	2.204	3
	2400	0.700	0.500	0.605	3	2.942	2.854	2.896	3
Tensile Strength, lbs/in^2	1000	---	---	4485	1	---	---	1505	1
	1500	---	---	5440	1	---	---	1685	1
	2000	---	---	7300	1	---	---	1575	1
	2250	---	---	7490	1	---	---	1910	1
	2500	---	---	9405	1	1745	1585	1665	2
	2700	---	---	7735	1	---	---	---	-
	2800	---	---	---	-	---	---	2080	1
	3000	---	---	---	-	---	---	1765	1

1.93	1.92	1.91	1.90	1.89	1.88	1.87	1.87	1.86	1.87	1.88	1.92
1.93	1.93	1.92	1.92	1.91	1.90	1.89	1.88	1.87	1.88	1.89	1.93
1.94	1.94	1.94	1.94	1.93	1.93	1.91	1.90	1.89	1.89	1.91	1.93
1.95	1.95	1.95	1.96	1.95	1.95	1.94	1.93	1.92	1.92	1.92	1.94
1.96	1.96	1.97	1.97	1.97	1.97	1.96	1.95	1.92	1.94	1.94	1.94
1.96	1.97	1.97	1.97	1.97	1.96	1.97	1.96	1.95	1.94	1.94	1.94
1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.96	1.95	1.94	1.94
1.97	1.96	1.96	1.96	1.96	1.94	1.95	1.97	1.97	1.95	1.93	1.93

L-472

Figure 48. Density Profile, ZTA Graphite Block No. 20, 14-Inch Diameter by 10-Inch Length

1.95		1.95			1.92		1.96		1.98		1.96
1.94		1.95		1.96	1.96		1.98		1.98		1.96
1.95		1.95		1.97	1.99		2.00		1.99		1.96
1.94		1.96		1.98	1.99		2.00		2.00		1.97
1.94		1.97		1.97	1.98		2.00		2.00		1.97
1.95		1.97		1.95	1.97		1.99		1.99		1.98
1.95		1.98		1.94	1.95		1.97		1.98		1.99
1.96		1.95			1.93		1.96		1.97		1.98

L-473

Figure 49. Density Profile, ZTA Graphite Block No. 23, 14-Inch Diameter by 10-Inch Length

1.95	1.94	1.92	1.91	1.91	1.91	1.91	1.91	1.91	1.92	1.93	1.96
1.94	1.95	1.94	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.94	1.95
1.94	1.96	1.96	1.96	1.95	1.95	1.96	1.95	1.95	1.95	1.95	1.95
1.95	1.97	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.97	1.95
1.95	1.98	1.99	2.00	2.00	1.99	1.99	1.99	1.99	1.99	1.98	1.96
1.95	1.97	1.98	1.99	2.00	2.00	1.99	1.99	1.99	1.99	1.98	2.00
1.95	1.96	1.96	1.97	1.98	1.98	1.98	1.98	1.98	1.97	1.98	2.00
1.95	1.93	1.93	1.94	1.96	1.95	1.96	1.95	1.96	1.95	1.95	1.97

L-474

Figure 50. Density Profile, ZTA Graphite Block No. 111, 14-Inch Diameter by 10-Inch Length

1.98	1.96	1.96	1.96	1.95	1.95	1.94	1.95	1.95	1.95	1.94	1.96
1.97	1.97	1.97	1.98	1.97	1.97	1.97	1.97	1.97	1.96	1.96	1.96
1.98	1.98	1.99	2.00	2.00	1.99	1.99	1.99	1.99	1.98	1.97	1.96
1.96	1.98	2.00	2.01	2.01	2.01	2.01	2.01	2.01	1.99	1.98	1.95
1.96	1.99	2.00	2.01	2.01	2.01	2.01	2.01	2.00	1.99	1.98	1.95
1.96	1.98	1.99	1.99	2.00	2.00	2.00	1.99	1.99	1.98	1.97	1.96
1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.95	1.95	1.95	1.95	1.95
1.94	1.92	1.92	1.91	1.91	1.91	1.91	1.91	1.91	1.91	1.92	1.94

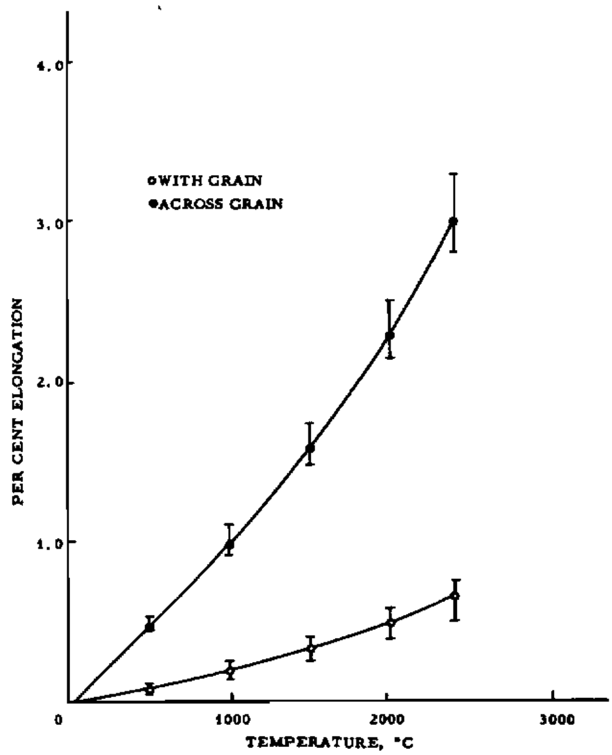
L-475

Figure 51. Density Profile, ZTA Graphite Block No. 153, 14-Inch Diameter by 10-Inch Length

1.92	1.91	1.91	1.90	1.89	1.89	1.88	1.89	1.88	1.89	1.88	1.91
1.93	1.94	1.95	1.95	1.95	1.94	1.94	1.93	1.92	1.92	1.91	1.92
1.92	1.95	1.97	1.98	1.98	1.98	1.97	1.97	1.96	1.95	1.93	1.91
1.92	1.96	1.98	2.01	2.00	2.00	1.99	1.98	1.97	1.96	1.94	1.91
1.93	1.97	1.98	1.99	1.99	1.99	1.99	1.98	1.97	1.96	1.95	1.92
1.94	1.97	1.97	1.98	1.98	1.98	1.97	1.96	1.95	1.95	1.95	1.94
1.96	1.95	1.95	1.95	1.95	1.94	1.94	1.93	1.92	1.92	1.93	1.94

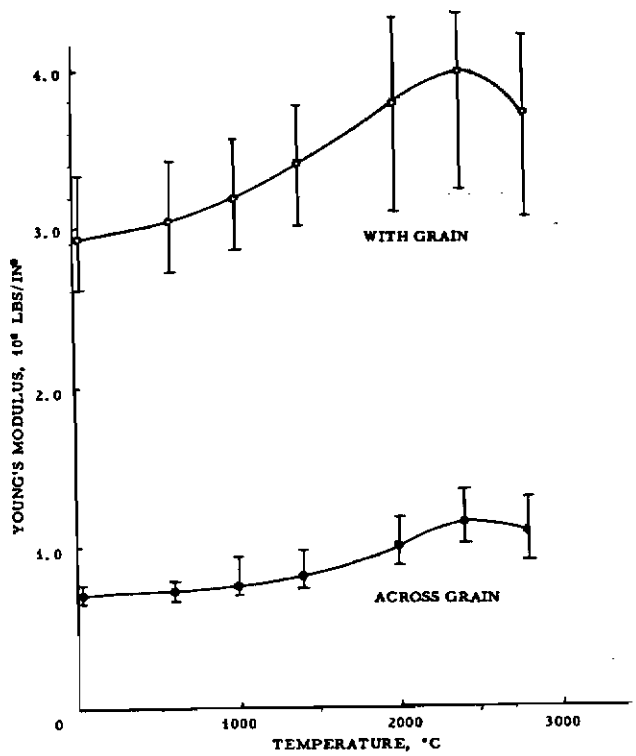
L-476

Figure 52. Density Profile, ZTA Graphite Block No. 159, 14-Inch Diameter by 10-Inch Length



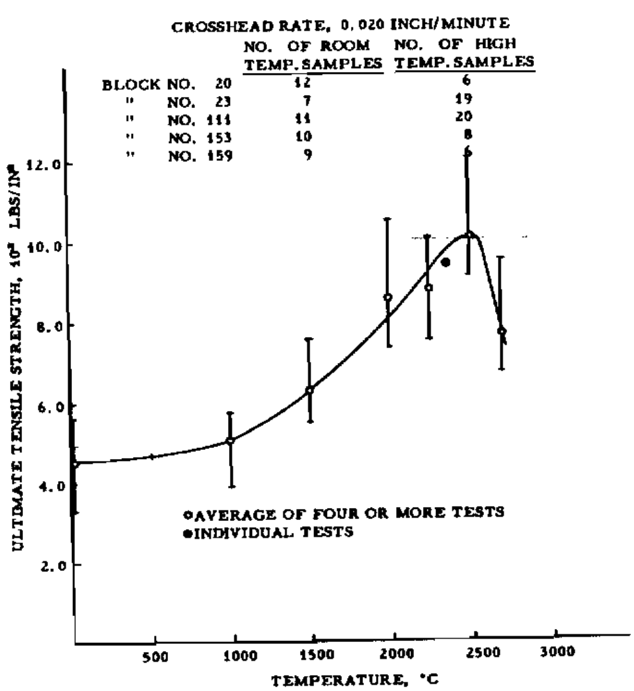
L-477

Figure 53. Thermal Expansion vs. Temperature, ZTA Graphite, 14-Inch Diameter by 10-Inch Length



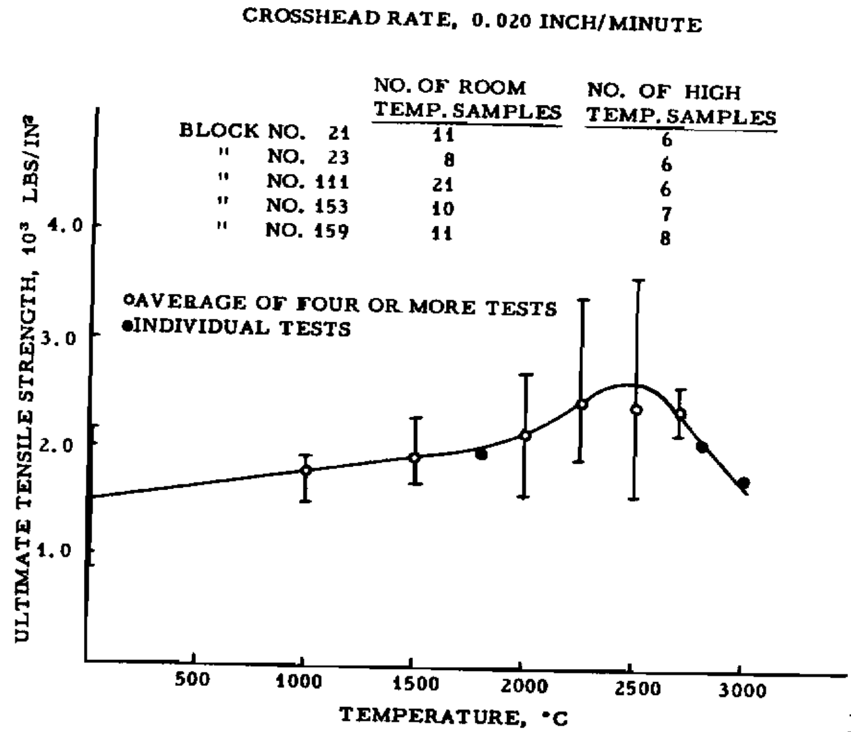
L-478

Figure 54. Young's Modulus vs. Temperature, ZTA Graphite, 14-Inch Diameter by 10-Inch Length



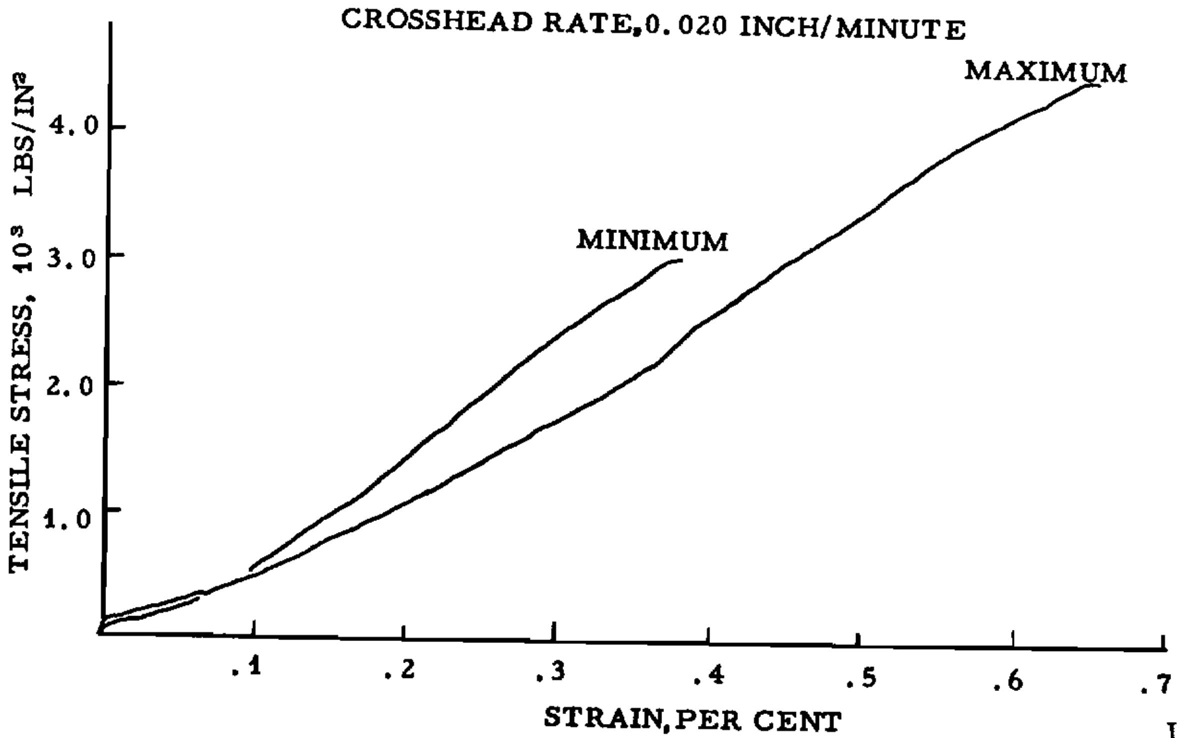
L-479

Figure 55. With-Grain Ultimate Tensile Strength vs. Temperature, ZTA Graphite, 14-Inch Diameter by 10-Inch Length



L-480

Figure 56. Across-Grain Ultimate Tensile Strength vs. Temperature, ZTA Graphite, 14-Inch Diameter by 10-Inch Length



L-481

Figure 57. With-Grain Tensile Stress-Strain Curves, ZTA Graphite, 14-Inch Diameter by 10-Inch Length, Block No. 111, Room Temperature

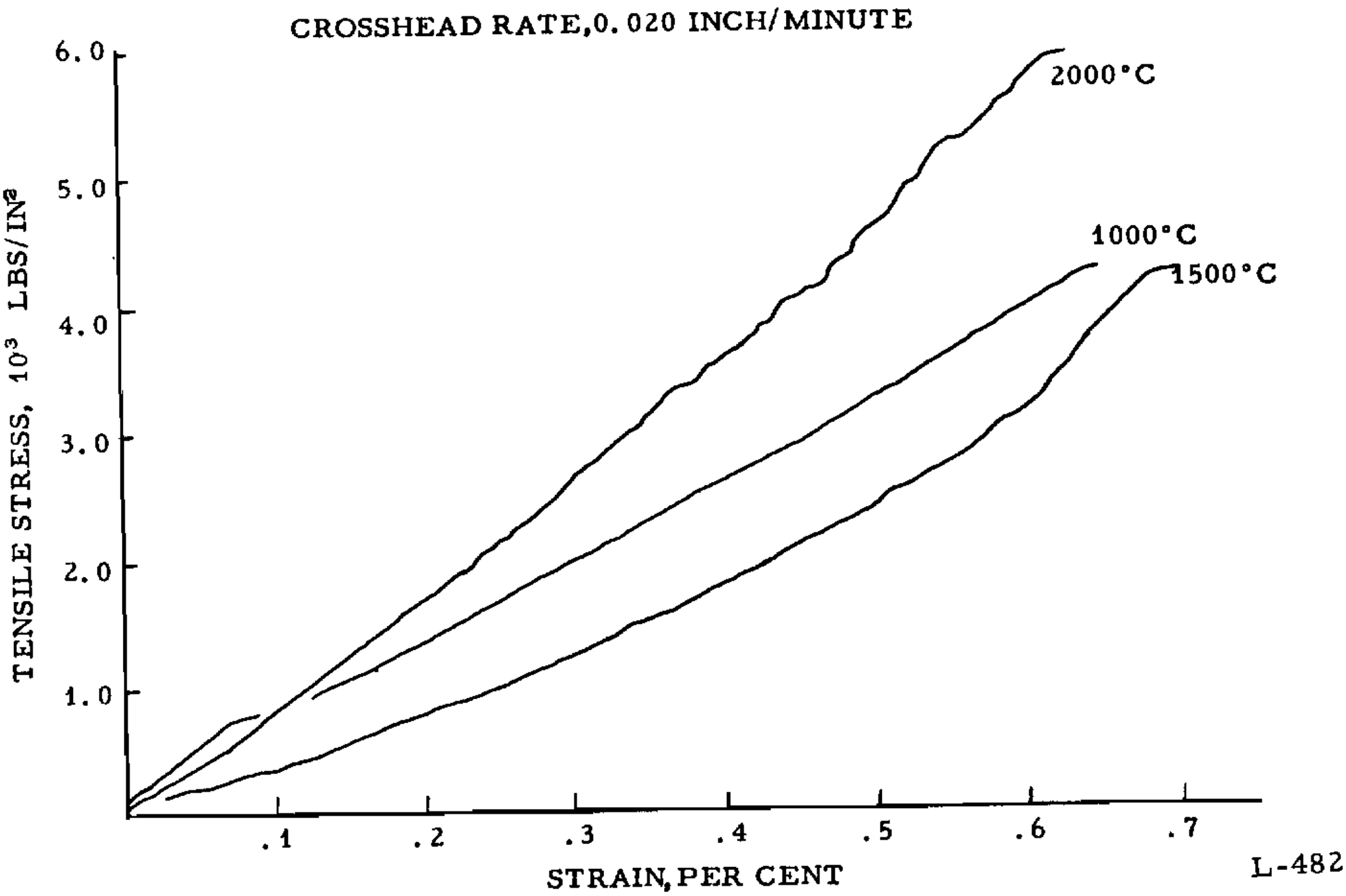


Figure 58. With-Grain Tensile Stress-Strain Curves, ZTA Graphite, 14-Inch Diameter by 10-Inch Length, Block No. 111, 1000°C, 1500°C, 2000°C

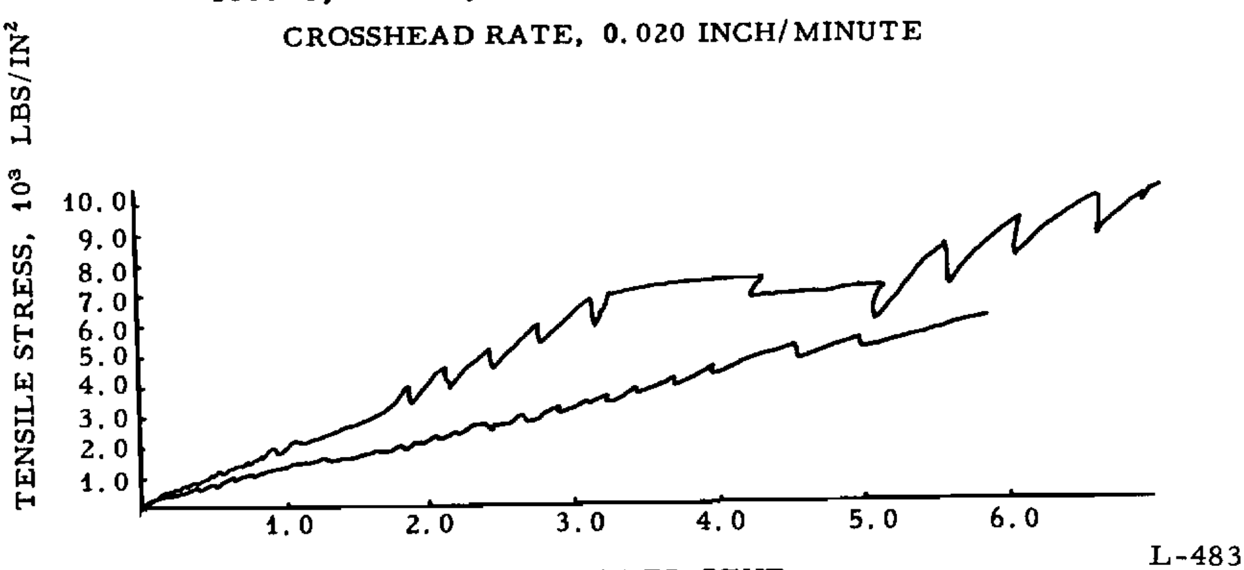
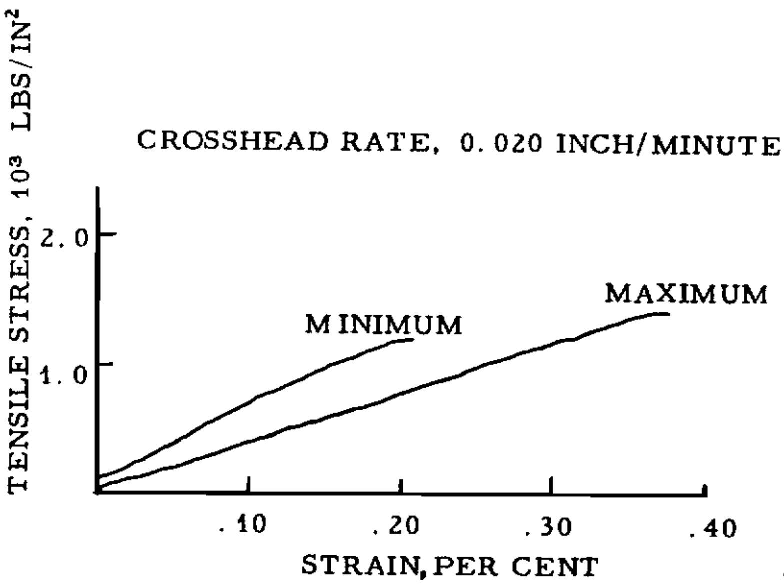
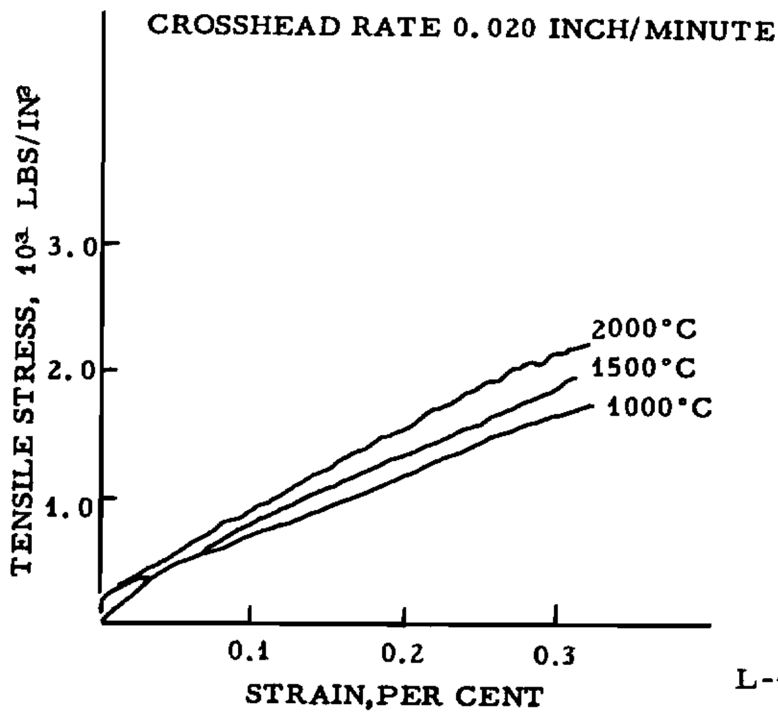


Figure 59. With-Grain Tensile Stress-Strain Curves, ZTA Graphite, 14-Inch Diameter by 10-Inch Length, Block No. 111, 2500°C, 2700°C



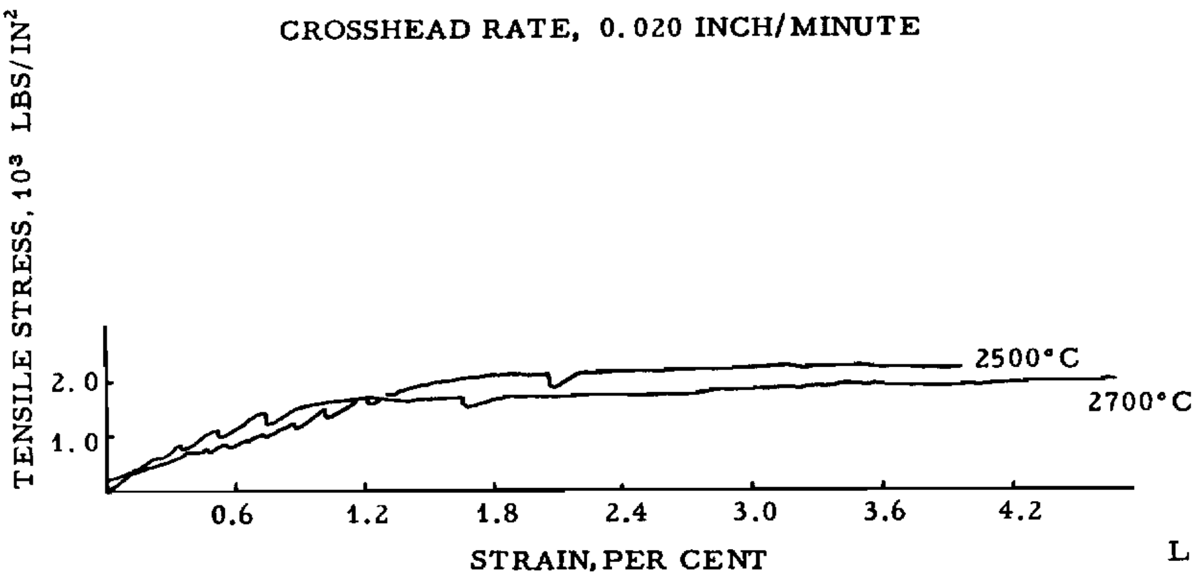
L-484

Figure 60. Across-Grain Tensile Stress-Strain Curves, ZTA Graphite 14-Inch Diameter by 10-Inch Length, Block No. 111, Room Temperature



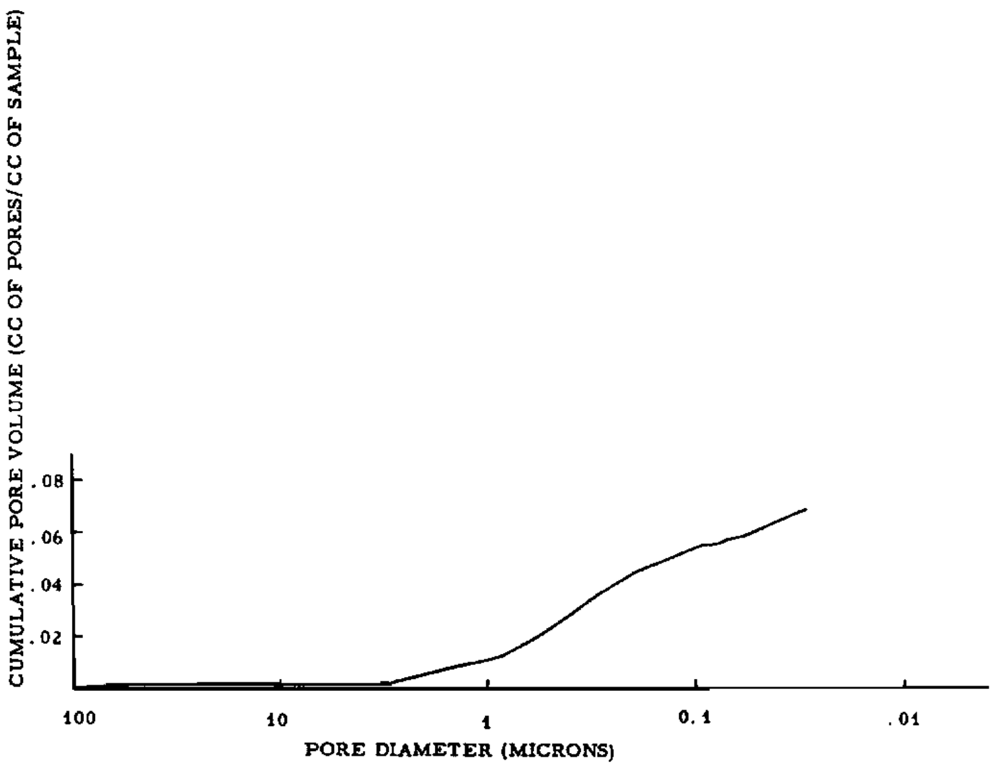
L-485

Figure 61. Across-Grain Tensile Stress-Strain Curves, ZTA Graphite, 14-Inch Diameter by 10-Inch Length, Block No. 111, 1000°C, 1500°C, 2000°C



L-486

Figure 62. Across-Grain Tensile Stress-Strain Curves, ZTA Graphite, 14-Inch Diameter by 10-Inch Length, Block No. 111, 2500°C, 2700°C



L-487

Figure 63. Pore Size Distribution, Mercury Porosimetry, ZTA Graphite, Typical of Both 14- and 8½-Inch Diameter Blocks

3.2.2. Grade ZTA, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Four blocks were selected for the characterization of $8\frac{1}{2}$-inch diameter ZTA graphite. Tables 15 and 16 summarize the properties of these four blocks and Tables 17 to 24, inclusive, give the properties of the individual blocks. Not all properties could be extensively measured on each block because of its small size, so high-temperature strength measurements have been limited to with-grain tensile strength on two blocks.

Figures 66 and 67, respectively, are plots of the thermal expansion and Young's modulus data presented in Table 16.

The dots in Figure 68 represent individual tests, and the curves are suggested maximum and minimum limits. All strength measurements were made at crosshead or platen rates of 0.020 inch per minute.

Table 15. Summary of Room-Temperature Properties, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	With Grain Average	With Grain σ	With Grain n	With Grain No. of Blocks	Across Grain Average	Across Grain σ	Across Grain n	Across Grain No. of Blocks
Bulk Density, g/cc	1.932	.028	145	4	---	---	---	--
Specific Resistance, 10^{-4} ohm-cm	7.43	1.07	74	4	16.09	1.64	71	4
Young's Modulus, 10^{6} lbs/in^2	2.525	0.416	74	4	0.934	0.053	71	4
Flexural Strength, lbs/in^2	5250	581	74	4	2540	342	71	4
Compressive Strength, 1- by 1-by 1-in. lbs/in^2	7570	1856	123	4	11,080	1944	128	4
Tensile Strength, lbs/in^2	4350	485	37	4	1625	196	40	4
CTE, 20-100°C, 10^{-6}/°C	0.90	0.44	18	4	6.87	0.55	15	4
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ °\text{K}}$	0.464	0.060	10	4	0.248	0.040	9	4

	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	With Grain No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n	Across Grain No. of Blocks
Per Cent Ash	0.081	0.062	0.073	4	4	---	---	---	--	--

Table 16. Summary of High-Temperature Properties, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	With Grain No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n	Across Grain No. of Blocks
Thermal Expansion	500	0.135	0.050	0.092	12	4	0.427	0.300	0.366	12	4
Per Cent Elongation	1000	0.299	0.155	0.232	12	4	0.897	0.726	0.797	12	4
$\frac{\Delta L}{L} \times 100$	1500	0.493	0.287	0.400	12	4	1.410	1.154	1.276	12	4
	2000	0.728	0.437	0.587	12	4	1.996	1.627	1.827	12	4
	2400	0.932	0.564	0.758	12	4	2.648	1.997	2.396	12	4
Sonic Modulus,	RT	3.10	1.49	2.09	6	4	0.98	0.79	0.87	5	3
10^6 lbs/in^2	600	3.12	1.55	2.13	6	4	0.96	0.85	0.90	5	3
	1000	3.26	1.61	2.23	6	4	1.00	0.87	0.93	5	3
	1400	3.42	1.76	2.39	6	4	1.11	0.92	1.00	5	3
	2000	3.80	2.03	2.75	6	4	1.35	1.08	1.16	5	3
	2400	3.94	2.27	2.94	6	4	1.41	1.17	1.24	5	3
	2800	3.81	2.15	2.78	6	4	1.35	0.97	1.10	5	3
Tensile Strength,	1000	---	---	---	--	-	---	---	---	--	-
lbs/in^2	1500	---	---	4385	1	1	---	---	---	--	-
	2000	---	---	---	--	-	---	---	---	--	-
	2250	8995	7735	8180	3	2	---	---	---	--	-
	2500	10180	8995	9555	3	2	---	---	---	--	-
	2700	8630	7520	8075	2	2	---	---	---	--	-

Table 17. Room-Temperature Properties, ZTA Graphite, Block No. H-363
$8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	With Grain				Across Grain			
	Average	σ		n	Average	σ		n
Bulk Density, g/cc	1.92	0.03		35	---	---		--
Specific Resistance, 10^{-4} ohm-cm	7.76	1.33		18	16.45	0.69		17
Young's Modulus, 10^6 lbs/in^2	2.410	0.433		18	0.934	0.019		17
Flexural Strength, lbs/in^2	5105	752		18	2430	280		17
Compressive Strength, 1- by 1- by 1-inch, lbs/in^2	6815	2600		31	10455	2155		32
Tensile Strength, lbs/in^2	4580	183		9	1545	63		10
	With Grain							
	Max.	Min.	Ave.	n	Max.	Min.	Ave.	n
CTE, 20°-100°C, 10^{-6}/°C	1.54	0.61	0.92	4	6.96	6.31	6.54	4
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ {}^\circ\text{K}}$	0.560	0.440	0.481	3	---	---	0.234	1
Admittance, cm^2/sec.	---	---	---	-	---	---	---	-
Per Cent Ash	---	---	0.072	1	---	---	---	-

Table 18. High-Temperature Properties, ZTA Graphite, Block No. H-363, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
Thermal Expansion Per Cent Elongation $\frac{\Delta L}{L}$ x 100	500	0.132	0.060	0.106	3	0.373	0.353	0.364	3
	1000	0.292	0.177	0.258	3	0.794	0.759	0.776	3
	1500	0.493	0.320	0.431	3	1.275	1.221	1.256	3
	2000	0.728	0.500	0.639	3	1.823	1.687	1.766	3
	2400	0.932	0.668	0.825	3	2.349	2.215	2.304	3
Young's Modulus, 10^6 lbs/in^2	RT	1.60	1.48	1.54	2	---	---	---	-
	600	1.63	1.54	1.58	2	---	---	---	-
	1000	1.72	1.61	1.66	2	---	---	---	-
	1400	1.90	1.75	1.82	2	---	---	---	-
	2000	2.15	2.02	2.08	2	---	---	---	-
	2400	2.38	2.26	2.32	2	---	---	---	-
	2800	2.25	2.18	2.22	2	---	---	---	-

Table 19. Room-Temperature Properties, ZTA Graphite, Block No. K-366, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	With Grain				Across Grain			
	Average	σ	n		Average	σ	n	
Bulk Density, g/cc	1.93	0.02	37		---	---	--	
Specific Resistance, 10^{-4} ohm-cm	7.54	0.95	19		15.84	0.92	18	
Young's Modulus, 10^{6} lbs/in	2.456	0.384	19		0.935	0.018	18	
Flexural Strength, lbs/in^2	5065	527	19		2440	245	18	
Compressive Strength, 1- by 1- by 1-inch, lbs/in^2	7515	1425	31		10150	1967	32	
Tensile Strength, lbs/in^2	4650	324	9		1720	103	10	
	With Grain				Across Grain			
	Max.	Min.	Ave.	n	Max.	Min.	Ave.	n
CTE, 20-100°C, 10^{-6}/°C	1.60	0.55	0.98	6	7.26	6.13	6.65	3
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2 \text{ °K}}$	0.552	0.420	0.499	3	0.360	0.275	0.317	2
Admittance, cm^2/sec	---	---	---	-	---	---	---	-
Per Cent Ash	---	---	0.075	1	---	---	---	-

Table 20. High-Temperature Properties, ZTA Graphite, Block No. K-366, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
Thermal Expansion	500	0.119	0.053	0.085	3	0.380	0.329	0.346	3
Per Cent Elongation	1000	0.285	0.157	0.222	3	0.809	0.726	0.754	3
$\frac{\Delta L}{L} \times 100$	1500	0.479	0.298	0.388	3	1.277	1.154	1.204	3
	2000	0.693	0.437	0.566	3	1.875	1.627	1.744	3
	2400	0.887	0.573	0.730	3	2.465	2.049	2.246	3
Young's Modulus,	RT	---	---	2.30	1	0.98	0.88	0.93	2
10^6 lbs/in^2	600	---	---	2.41	1	0.96	0.96	0.96	2
	1000	---	---	2.45	1	1.00	0.99	1.00	2
	1400	---	---	2.66	1	1.11	1.05	1.08	2
	2000	---	---	3.00	1	1.35	1.18	1.26	2
	2400	---	---	3.22	1	1.40	1.21	1.30	2
	2800	---	---	3.06	1	1.35	1.05	1.20	2
Tensile Strength,	1000	---	---	---	-	---	---	---	-
lbs/in^2	1500	---	---	4385	1	---	---	---	-
	2000	---	---	---	-	---	---	---	-
	2250	---	---	8995	1	---	---	---	-
	2500	---	---	9485	1	---	---	---	-
	2700	---	---	7520	1	---	---	---	-

Table 21. Room-Temperature Properties, ZTA Graphite, Block No. N-367, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	With Grain Average	With Grain σ	With Grain n	Across Grain Average	Across Grain σ	Across Grain n
Bulk Density, g/cc	1.95	0.02	37	---	---	--
Specific Resistance, 10^{-4} ohm-cm	6.66	0.63	19	15.82	1.19	18
Young's Modulus, 10^{6} lbs/in^2	2.638	0.288	19	0.902	0.082	18
Flexural Strength, lbs/in^2	5355	420	19	2670	305	18
Compressive Strength, 1- by 1- by 1-inch, lbs/in^2	7585	1465	31	11480	935	32
Tensile Strength, lbs/in^2	4120	458	10	1415	141	10

Properties	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
CTE, 20-100°C, 10^{-6}/°C	1.33	0.38	0.70	4	7.86	6.25	7.14	4
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2 \text{ °K}}$	0.453	0.398	0.426	2	0.234	0.219	0.226	3
Admittance, cm^2/sec	---	---	---	-	---	---	---	-
Per Cent Ash	---	---	0.081	1	---		---	-

Table 22. High-Temperature Properties, ZTA Graphite, Block No. N-367, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
Thermal Expansion	500	0.096	0.050	0.079	3	0.417	0.300	0.349	3
Per Cent Elongation	1000	0.238	0.155	0.208	3	0.872	0.728	0.794	3
$\frac{\Delta L}{L} \times 100$	1500	0.418	0.287	0.370	3	1.384	1.191	1.283	3
	2000	0.609	0.437	0.546	3	1.986	1.756	1.865	3
	2400	0.787	0.564	0.704	3	2.596	1.997	2.410	3
Young's Modulus, 10^6 lbs/in^2	RT	2.15	1.80	1.98	2	---	---	0.78	1
	600	2.22	1.85	2.04	2	---	---	0.85	1
	1000	2.26	2.00	2.13	2	---	---	0.88	1
	1400	2.36	2.20	2.28	2	---	---	0.92	1
	2000	3.04	2.33	2.68	2	---	---	1.07	1
	2400	3.46	2.36	2.91	2	---	---	1.22	1
	2800	3.20	2.11	2.66	2	---	---	1.04	1
Tensile Strength, lbs/in^2	1000	---	---	---	-	---	---	---	-
	2000	---	---	---	-	---	---	---	-
	2250	7815	7735	7775	2	---	---	---	-
	2500	10180	8995	9590	2	---	---	---	-
	2700	---	---	8630	1	---	---	---	-

Table 23. Room-Temperature Properties, ZTA Graphite, Block No. M-373, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	With Grain			Across Grain		
	Average	σ	n	Average	σ	n
Bulk Density, g/cc	1.94	0.03	36	---	---	--
Specific Resistance, 10^{-4} ohm-cm	7.42	1.02	18	16.18	1.13	17
Young's Modulus, 10^6 lbs/in^2	2.651	0.475	18	0.965	0.048	17
Flexural Strength, lbs/in^2	5480	493	18	2600	458	17
Compressive Strength, 1- by 1- by 1-inch, lbs/in^2	8320	1346	30	12250	1798	32
Tensile Strength, lbs/in^2	4075	593	9	1815	162	10

	With Grain				Across Grain			
	Max.	Min.	Ave.	n	Max.	Min.	Ave.	n
CTE, 20-100°C, 10^{-6}/°C	1.63	0.64	0.98	4	7.56	6.48	7.08	4
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ \text{°K}}$	0.453	0.398	0.426	2	0.235	0.219	0.227	3
Admittance, cm^2/sec	---	---	---	-	---	---	---	-
Per Cent Ash	---	---	---	-	---	---	---	-

Table 24. High-Temperature Properties, ZTA Graphite, Block No. M-373, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	Temp. °C	With Grain				Across Grain			
		Max.	Min.	Ave.	n	Max.	Min.	Ave.	n
Thermal Expansion Per Cent Elongation $\frac{\Delta L}{L}$ x 100	500	0.135	0.066	0.098	3	0.427	0.394	0.409	3
	1000	0.299	0.185	0.241	3	0.897	0.844	0.864	3
	1500	0.493	0.380	0.411	3	1.410	1.315	1.361	3
	2000	0.697	0.500	0.597	3	1.996	1.843	1.932	3
	2400	0.897	0.640	0.771	3	2.648	2.349	2.51	3
Young's Modulus, 10^6 lbs/in^2	RT	---	---	3.09	1	0.84	0.82	0.83	2
	600	---	---	3.10	1	0.86	0.84	0.85	2
	1000	---	---	3.20	1	0.88	0.86	0.87	2
	1400	---	---	3.40	1	0.96	0.91	0.94	2
	2000	---	---	3.80	1	1.08	1.07	1.08	2
	2400	---	---	3.84	1	1.17	1.16	1.16	2
	2800	---	---	3.82	1	1.10	0.96	1.03	2

1.90	1.90	1.90	1.86	1.90	1.90	1.93
1.92	1.92	1.91	1.91	1.92	1.94	1.96
1.93	1.93	1.92	1.90	1.94	1.96	1.98
1.93	1.93	1.92	1.92	1.95	1.98	2.00
1.94	1.93	1.92	1.93	1.96	1.99	2.00
1.95	1.94	1.94	1.94	1.97	2.00	2.01
1.94	1.95	1.94	1.95	1.97	1.99	2.00
1.91	1.92	1.91	1.92	1.95	1.96	1.98
1.90	1.90	1.84	1.84	1.86	1.91	1.96

Block No. H-363

1.92	1.90	1.88	1.88	1.89	1.91	1.95
1.94	1.95	1.94	1.94	1.95	1.96	1.97
1.97	1.97	1.97	1.97	1.98	1.99	1.99
1.97	1.97	1.95	1.95	1.97	1.99	2.00
1.96	1.95	1.93	1.93	1.95	1.98	1.98
1.95	1.95	1.93	1.92	1.94	1.96	1.97
1.95	1.95	1.94	1.93	1.95	1.96	1.96
1.94	1.94	1.93	1.93	1.94	1.95	1.95
1.91	1.91	1.90	1.91	1.92	1.93	1.93

Block No. K-366

L-516

Figure 64. Density Profile, ZTA Graphite, Blocks No. H-363 and K-366, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

1.93	1.91	1.90	1.90	1.91	1.93	1.95
1.96	1.97	1.97	1.98	1.97	1.98	1.96
1.98	1.99	1.99	1.98	2.00	2.00	1.99
1.98	1.98	1.98	1.97	1.99	2.00	2.00
1.96	1.97	1.96	1.95	1.97	1.98	1.99
1.96	1.96	1.95	1.95	1.97	1.97	1.99
1.95	1.96	1.96	1.96	1.97	1.97	1.97
1.94	1.95	1.95	1.95	1.95	1.96	1.96
1.91	1.90	1.88	1.89	1.90	1.91	1.94

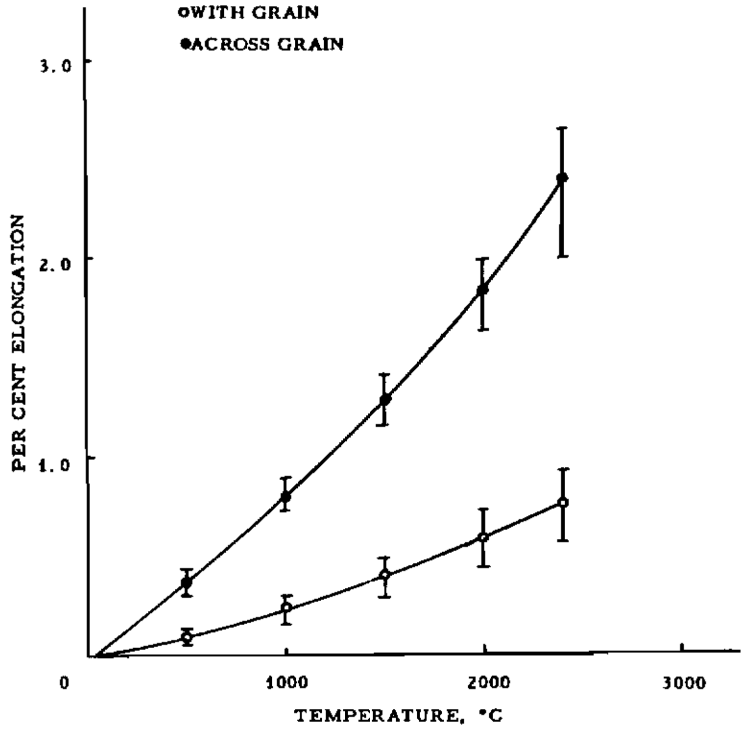
Block No. N-367

1.88	1.87	1.86	1.86	1.87	1.89	1.93
1.91	1.92	1.91	1.91	1.93	1.94	1.95
1.93	1.94	1.94	1.93	1.95	1.96	1.97
1.94	1.94	1.93	1.93	1.95	1.97	1.98
1.95	1.95	1.94	1.93	1.96	1.98	1.99
1.96	1.97	1.96	1.96	1.96	1.99	2.00
1.97	1.98	1.98	1.98	1.99	1.99	2.00
1.96	1.97	1.96	1.96	1.96	1.97	1.96
1.92	1.91	1.90	1.89	1.90	1.92	1.95

L-517

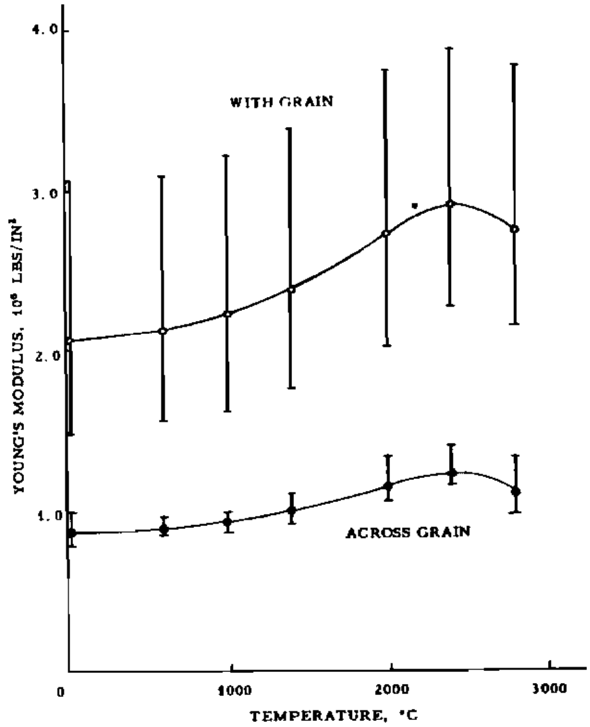
Block No. M-373

Figure 65. Density Profile, ZTA Graphite, Blocks No. N-367 and M-373, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length



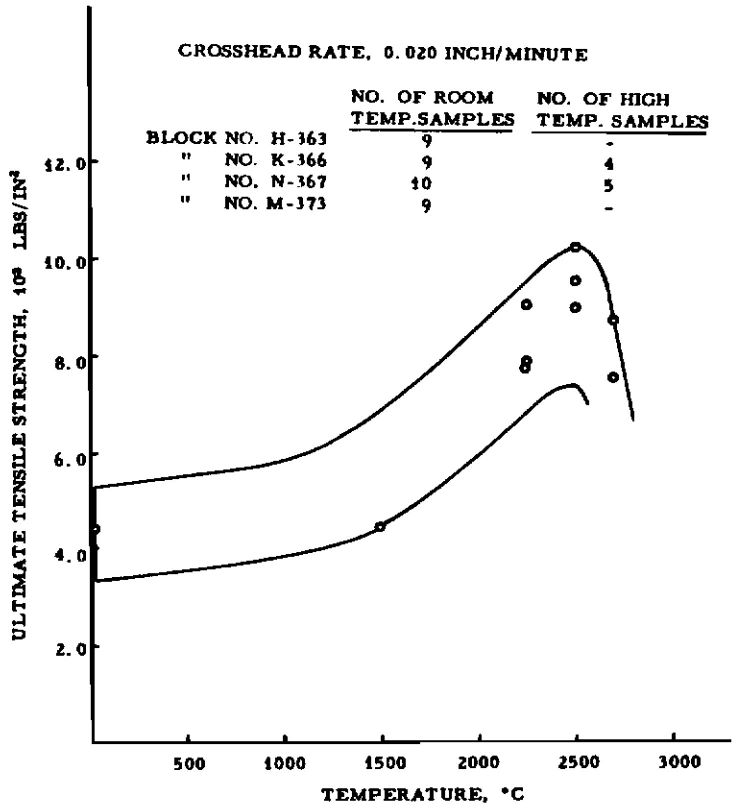
L-518

Figure 66. Thermal Expansion vs. Temperature, ZTA Graphite, 8½-Inch Diameter by 11-Inch Length



L-519

Figure 67. Young's Modulus vs. Temperature, ZTA Graphite, 8½-Inch Diameter by 11-Inch Length



L-520

Figure 68. With-Grain Ultimate Tensile Strength vs. Temperature, ZTA Graphite, 8½-Inch Diameter by 11-Inch Length

3.3. Grade ZTB Graphite[16, 17]

ZTB graphite is one of the nine grades on which tensile and shear strength measurements at room and elevated temperatures and compressive strength at elevated temperatures have been omitted.

Physical properties were obtained from two blocks, $8\frac{1}{2}$ inches in diameter by 11 inches in length. The combined data are presented in Tables 25 and 26, and the properties for the individual blocks are given in Tables 27 to 30, inclusive. Figures 70 and 71, respectively, are plots of the thermal expansion and Young's modulus data presented in Table 26. All strength measurements were made at cross-head of platen rates of 0.020 inch per minute.

Table 25. Summary of Room-Temperature Properties, ZTB Graphite, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	With Grain				Across Grain			
	Average	σ	n	No. of Blocks	Average	σ	n	No. of Blocks
Bulk Density, g/cc	1.98	0.029	44	2	---	---	--	-
Specific Resistance, 10^{-4} ohm-cm	6.68	1.11	22	2	19.74	2.68	22	2
Young's Modulus, 10^{6} lbs/in^2	3.43	0.88	22	2	0.781	0.061	22	2
Flexural Strength, lbs/in^2	6225	1152	11	2	2515	322	11	2
Compressive Strength, 1-by 1-by 1-inch sample, lbs/in^2	9110	1180	10	2	13,080	1750	10	2

Properties	With Grain					Across Grain				
	Max.	Min.	Ave.	n	No. of Blocks	Max.	Min.	Ave.	n	No. of Blocks
CTE, 20-100°C, 10^{-6}/°C	1.25	0.02	0.63	6	2	10.27	7.59	8.67	6	2
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ °\text{K}}$	0.525	0.435	0.469	6	2	0.181	0.172	0.176	6	2
Admittance, cm^2/sec.	3×10^{-4}	3×10^{-4}	3×10^{-4}	3	1	3×10^{-4}	2×10^{-4}	2×10^{-4}	2	1
Per Cent Ash	0.129	0.079	0.104	2	2	---	---	---	-	-

Table 26. Summary of High-Temperature Properties, ZTB Graphite, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	With Grain No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n	Across Grain No. of Blocks
Thermal Expansion Per Cent Elongation $\frac{\Delta L}{L} \times 100$	500	0.081	0.039	0.051	4	2	0.485	0.382	0.423	4	2
	1000	0.202	0.120	0.144	4	2	1.035	0.827	0.904	4	2
	1500	0.364	0.226	0.272	4	2	1.651	1.321	1.456	4	2
	2000	0.516	0.340	0.411	4	2	2.356	1.902	2.090	4	2
	2400	0.719	0.499	0.558	4	2	3.037	2.453	2.693	4	2
	2800	0.620	0.608	0.614	2	1	3.828	3.104	3.409	4	2
Young's Modulus 10^6 lbs/in^2	RT	3.26	2.28	2.70	3	1	0.93	0.70	0.80	3	1
	600	3.33	2.36	2.78	3	1	0.96	0.71	0.82	3	1
	1200	3.67	2.57	3.02	3	1	0.96	0.76	0.85	3	1
	1600	3.88	2.90	3.34	3	1	1.01	0.86	0.92	3	1
	2000	4.23	3.09	3.60	3	1	1.13	0.92	1.04	3	1
	2400	4.37	3.16	3.71	3	1	1.21	1.08	1.14	3	1
	2800	4.13	2.93	3.44	3	1	1.13	1.04	1.09	3	1

Table 27. Room-Temperature Properties, ZTB Graphite, Block No. 1, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	With Grain			Across Grain		
	Average	σ	n	Average	σ	n
Bulk Density, g/cc	1.97	0.031	20	---	---	--
Specific Resistance, 10^{-4} ohm-cm	6.96	0.74	10	17.81	0.70	10
Young's Modulus, 10^6 lbs/in^2	3.19	0.51	10	0.842	0.017	10
Flexural Strength, lbs/in^2	5810	1423	5	2780	288	5
Compressive Strength, 1- by 1- by 1-inch, lbs/in^2	9620	840	5	12170	2020	5

Properties	With Grain				Across Grain			
	Max.	Min.	Ave.	n	Max.	Min.	Ave.	n
CTE, 20°-100°C, 10^{-6}/°C	0.79	0.49	0.68	3	8.00	7.59	7.81	3
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\,°\text{K}}$	0.501	0.435	0.465	3	0.181	0.174	0.177	3
Admittance, cm^2/sec	---	---	---	-	---	---	---	-
Per Cent Ash	---	---	0.129	1	---	---	---	-

Table 28. High-Temperature Properties, ZTB Graphite, Block No. 1, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
Thermal Expansion Per Cent Elongation $\frac{\Delta L}{L} \times 100$	500	0.081	0.041	0.061	2	0.382	0.382	.382	2
	1000	0.202	0.120	0.161	2	0.837	0.827	.832	2
	1500	0.364	0.226	0.295	2	1.345	1.321	1.333	2
	2000	0.516	0.340	0.428	2	1.946	1.902	1.924	2
	2400	0.719	0.501	0.610	2	2.512	2.453	2.482	2
	2800	---	---	---	-	3.181	3.104	3.142	2
Young's Modulus, 10^6 lbs/in^2	RT	3.26	2.28	2.70	3	0.93	0.70	0.80	3
	600	3.33	2.36	2.78	3	0.96	0.71	0.82	3
	1200	3.67	2.57	3.02	3	0.96	0.76	0.85	3
	1600	3.88	2.90	3.34	3	1.01	0.86	0.92	3
	2000	4.23	3.09	3.60	3	1.13	0.92	1.04	3
	2400	4.37	3.16	3.71	3	1.21	1.08	1.14	3
	2800	4.13	2.93	3.44	3	1.13	1.04	1.09	3

Table 29. Room-Temperature Properties, ZTB Graphite, Block No. 2, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	With Grain			Across Grain		
	Average	σ	n	Average	σ	n
Bulk Density, g/cc	1.99	0.029	24	---	---	--
Specific Resistance, 10^{-4} ohm-cm	6.43	1.28	12	21.13	2.36	12
Young's Modulus, 10^{6} lbs/in^{2}	3.70	0.89	12	0.731	0.003	12
Flexural Strength, lbs/in^{2}	6580	1390	6	2295	250	6
Compressive Strength, 1- by 1- by 1-inch, lbs/in^{2}	8600	1340	5	13990	860	5

Properties	With Grain				Across Grain			
	Max.	Min.	Ave.	n	Max.	Min.	Ave.	n
CTE, 20°-100°C, 10^{-6}/°C	1.25	0.02	0.57	3	10.27	8.84	9.52	3
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ °K}$	0.525	0.445	0.473	3	0.179	0.172	0.175	3
Admittance, cm^{2}/sec	3×10^{-4}	3×10^{-4}	3×10^{-4}	3	3×10^{-4}	2×10^{-4}	2×10^{-4}	2
Per Cent Ash	---	---	0.079	1	---	---	---	-

Table 30. High-Temperature Properties, ZTB Graphite, Block No. 2, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	Temp. °C	With Grain				Across Grain			
		Max.	Min.	Ave.	n	Max.	Min.	Ave.	n
Thermal Expansion Per Cent Elongation $\frac{\Delta L}{L} \times 100$	500	0.043	0.039	0.041	2	0.485	0.444	0.464	2
	1000	0.135	0.120	0.128	2	1.035	0.938	0.986	2
	1500	0.255	0.244	0.250	2	1.651	1.505	1.578	2
	2000	0.402	0.386	0.394	2	2.356	2.156	2.256	2
	2400	0.513	0.499	0.506	2	3.037	2.772	2.904	2
	2800	0.620	0.608	0.614	2	3.828	3.521	3.674	2

		1.91			
		1.96			
		1.98			
		1.99	1.99		
		2.00	2.00		
		1.99			
		1.96			
		1.94			

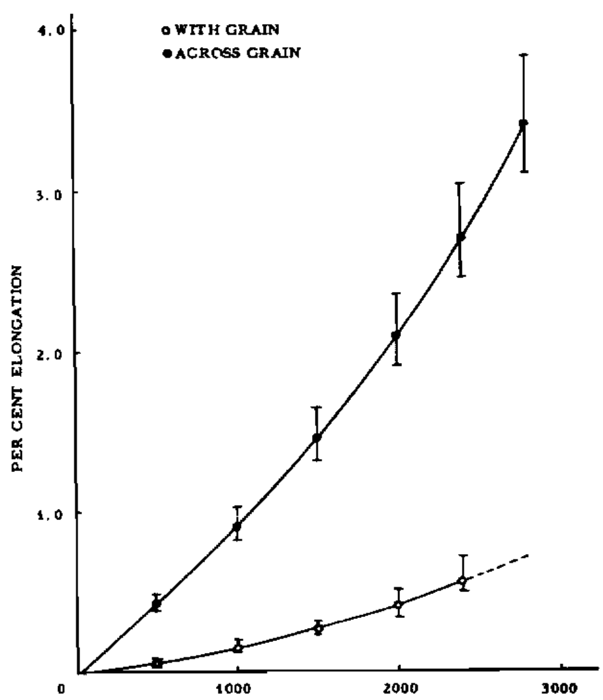
Block No. 1

			1.92		
			1.99		
			2.02		
		2.04	2.05		
		2.05	2.05		
			2.03		
			2.00		
			1.96		

Block No. 2

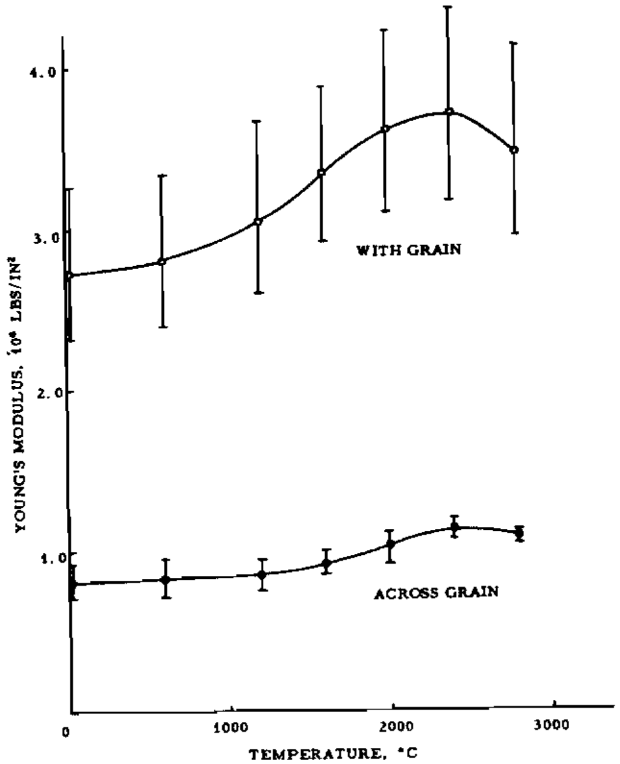
L-521

Figure 69. Density Profile, ZTB Graphite, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length, Blocks No. 1 and 2



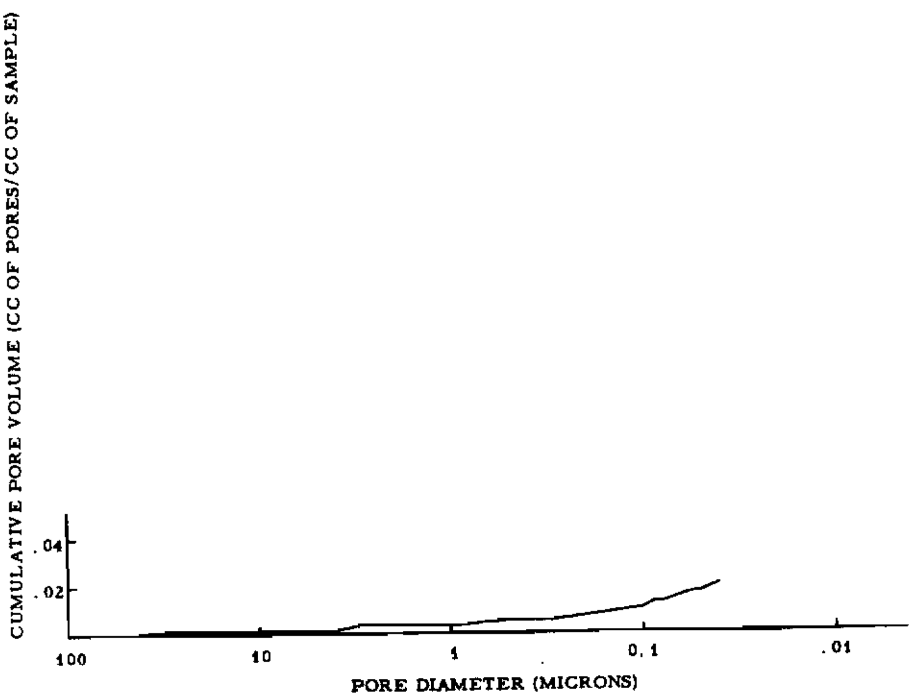
L-522

Figure 70. Thermal Expansion vs. Temperature, ZTB Graphite, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length



L-503

Figure 71. Young's Modulus vs. Temperature, ZTB Graphite, 8½-Inch Diameter by 11-Inch Length



L-523

Figure 72. Pore Size Distribution, Mercury Porosimetry, ZTB Graphite

3.4. Grade ZTC Graphite (16, 17)

Physical properties of ZTC graphite were obtained from two $8\frac{1}{2}$-inch diameter by 11-inch length blocks. Results of the property measurements are summarized in Tables 31 and 32 and the data regarding individual blocks are given in Tables 33 to 36, inclusive. Figure 73 and 74, respectively, are plots of the thermal expansion and Young's modulus data from Table 32. All strength measurements were made at cross-head or platen rates of 0.020 inch per minute.

ZTC graphite is another of the grades for which room-and high-temperature tensile and shear strengths and high-temperature compressive strength were not measured.

Table 31. Summary of Room-Temperature Properties, ZTC Graphite, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	With Grain				Across Grain			
	Average	σ	n	No. of Blocks	Average	σ	n	No. of Blocks
Bulk Density, g/cc	1.93	0.09	97	2	---	---	-	-
Specific Resistance, 10^{-4} ohm-cm	6.97	1.94	42	2	11.97	5.80	56	2
Young's Modulus, 10^{6} lbs/in^2	1.65	0.96	42	2	0.65	0.12	56	2
Flexural Strength, lbs/in^2	1770	495	10	2	1370	160	10	2
Compressive Strength, 1- by 1- by 1-inch lbs/in^2	3925	1680	19	2	5980	990	19	2

Properties	With Grain					Across Grain				
	Max.	Min.	Ave.	n	No. of Blocks	Max.	Min.	Ave.	n	No. of Blocks
CTE, 20-100°C, 10^{-6}/°C	2.69	1.50	2.16	4	2	1080	9.89	10.39	4	2
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2 \text{ °K}}$	0.736	0.374	0.486	6	2	0.237	0.203	0.218	2	2
Admittance, cm^2/sec.	7×10^{-2}	1×10^{-3}	3×10^{-2}	3	2	6×10^{-2}	3×10^{-3}	5×10^{-2}	3	2
Per Cent Ash	1.673	0.949	1.323	2	2	---	---	---	-	-

Table 32. Summary of High-Temperature Properties, ZTC Graphite, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	Temp. °C	With Grain					Across Grain				
		Max.	Min.	Ave.	n	No. of Blocks	Max.	Min.	Ave.	n	No. of Blocks
Thermal Expansion Per Cent Elongation $\frac{\Delta L}{L} \times 100$	500	0.068	0.014	0.040	3	2	0.571	0.510	0.548	4	2
	1000	0.166	0.083	0.119	3	2	1.197	1.064	1.145	4	2
	1500	0.301	0.170	0.226	3	2	1.924	1.670	1.820	4	2
	2000	0.458	0.287	0.361	3	2	2.716	2.357	2.562	4	2
	2400	0.610	0.434	0.501	3	2	3.548	3.214	3.410	4	2
	2800	0.759	0.541	0.626	3	2	4.695	4.332	4.526	4	2
Young's Modulus, 10^6 lbs/in^2	RT	3.24	2.07	2.47	3	2	0.48	0.45	0.46	4	2
	600	3.28	2.10	2.51	3	2	0.55	0.47	0.49	4	2
	1000	3.31	2.22	2.59	3	2	0.57	0.48	0.50	4	2
	1400	3.44	2.35	2.75	3	2	0.60	0.52	0.55	4	2
	2000	3.72	2.88	3.23	3	2	0.76	0.62	0.68	4	2
	2400	4.37	3.24	3.63	3	2	0.93	0.89	0.90	4	2
	2800	4.27	2.90	3.43	3	2	0.94	0.84	0.88	4	2

Table 33. Room-Temperature Properties, ZTC Graphite, Block No. 1, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	With Grain			Across Grain		
	Average	σ	n	Average	σ	n
Bulk Density, g/cc	1.92	0.09	59	---	---	--
Specific Resistance, 10^{-4} ohm-cm	7.15	2.10	27	11.00	5.77	31
Young's Modulus, 10^{6} lbs/in^2	1.72	1.05	27	0.69	0.14	32
Flexural Strength, lbs/in^2	1635	407	5	1380	126	5
Compressive Strength, 1- by 1- by 1-inch, lbs/in^2	3930	717	9	5925	1002	9

	With Grain				Across Grain			
	Max.	Min.	Ave.	n	Max.	Min.	Ave.	n
CTE, 20°-100°C, 10^{6}/°C	1.95	1.50	1.73	2	10.80	10.22	10.51	2
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2 \text{ °K}}$	0.736	0.400	0.534	3	0.237	0.203	0.315	3
Admittance, cm^2/sec	---	---	1×10^{-3}	1	---	---	5×10^{-2}	1
Per Cent Ash	---	---	1.676	1	---	---	---	-

Table 34. High-Temperature Properties, ZTC Graphite, Block No. 1, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
Thermal Expansion Per Cent Elongation $\frac{\Delta L}{L} \times 100$	500	---	---	0.014	1	0.567	0.510	0.538	2
	1000	---	---	0.083	1	0.180	1.064	1.222	2
	1500	---	---	0.170	1	1.887	1.670	1.779	2
	2000	---	---	0.287	1	2.669	2.357	2.513	2
	2400	---	---	0.432	1	3.548	3.214	3.381	2
	2800	---	---	0.577	1	4.695	4.332	4.514	2
Young's Modulus, 10^6 lbs/in^2	RT	---	---	2.09	1	0.46	0.45	0.46	2
	600	---	---	2.15	1	0.47	0.47	0.47	2
	1000	---	---	2.25	1	0.49	0.48	0.49	2
	1400	---	---	2.46	1	0.56	0.53	0.55	2
	2000	---	---	3.10	1	0.70	0.62	0.66	2
	2400	---	---	3.28	1	0.93	0.87	0.90	2
	2800	---	---	3.13	1	0.90	0.84	0.87	2

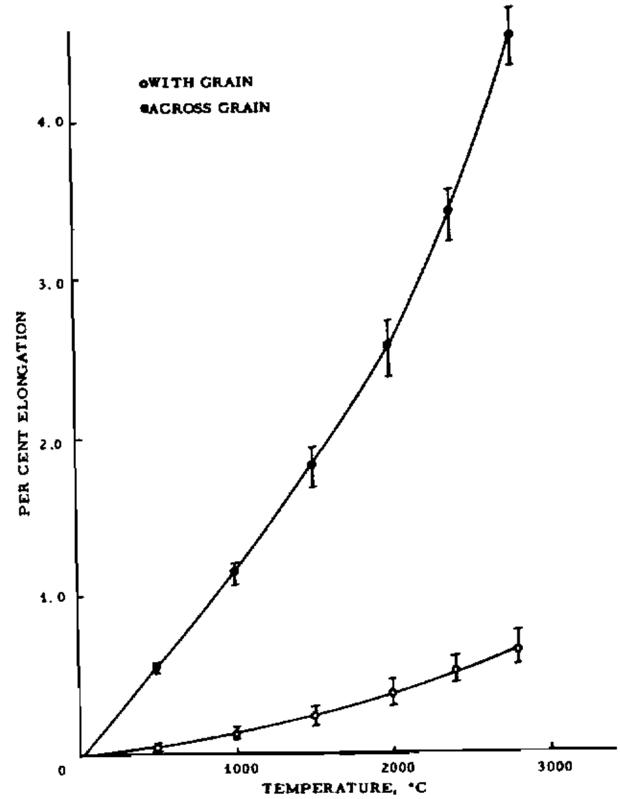
Table 35. Room-Temperature Properties, ZTC Graphite, Block No. 2, $8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	With Grain Average	With Grain σ	With Grain n	Across Grain Average	Across Grain σ	Across Grain n
Bulk Density, g/cc	1.94	0.08	39	---	---	--
Specific Resistance, 10^{-4} ohm-cm	6.90	1.61	15	13.21	5.48	24
Young's Modulus, 10^{6} lbs/in^2	1.53	0.92	15	0.61	0.11	24
Flexural Strength, lbs/in^2	1910	585	5	1365	203	5
Compressive Strength, 1- by 1- by 1-inch, lbs/in^2	3920	1020	10	6030	1024	10

Properties	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
CTE, 20°-100°C, 10^{-6}/°C	2.69	2.48	2.59	2	10.66	9.89	10.28	2
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ °\text{K}}$	0.520	0.374	0.439	3	0.233	0.204	0.222	3
Admittance, cm^2/sec	7×10^{-2}	3×10^{-2}	5×10^{-2}	2	6×10^{-3}	3×10^{-3}	5×10^{-3}	3
Per Cent Ash	---	---	0.949	-	---	---	---	-

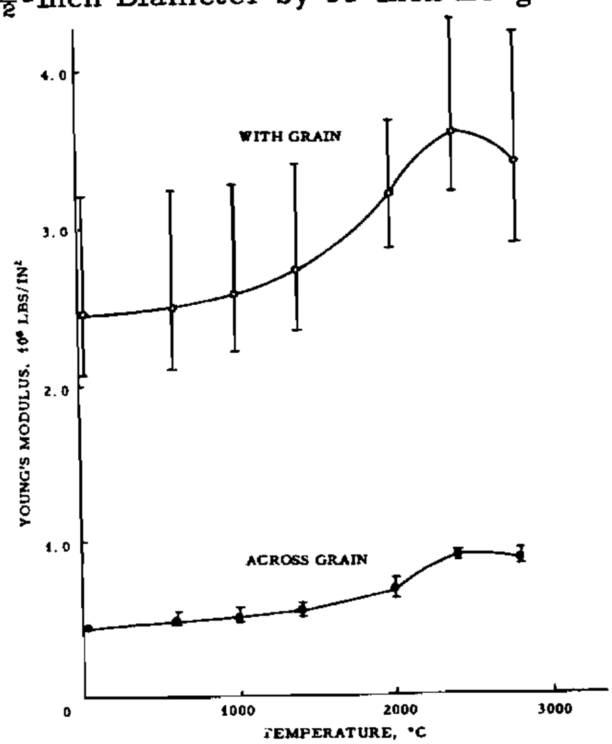
Table 36. High-Temperature Properties, ZTC Graphite, Block No. 2
$8\frac{1}{2}$-Inch Diameter by 11-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
Thermal Expansion Per Cent Elongation $\frac{\Delta L}{L} \times 100$	500	0.068	0.038	0.053	2	0.571	0.544	0.558	2
	1000	0.166	0.108	0.137	2	1.197	1.138	1.168	2
	1500	0.301	0.206	0.454	2	1.924	1.800	1.862	2
	2000	0.458	0.339	0.399	2	2.716	2.507	2.622	2
	2400	0.610	0.460	0.535	2	3.522	3.357	3.440	2
	2800	0.759	0.541	0.650	2	4.598	4.478	4.538	2
Young's Modulus, 10^6 lbs/in^2	RT	3.24	2.07	2.66	2	0.48	0.45	0.47	2
	600	3.28	2.10	2.69	2	0.56	0.47	0.52	2
	1000	3.31	2.22	2.77	2	0.57	0.48	0.53	2
	1400	3.44	2.35	2.90	2	0.60	0.52	0.56	2
	2000	3.92	2.88	3.40	2	0.76	0.66	0.71	2
	2400	4.37	3.24	3.81	2	0.90	0.87	0.89	2
	2800	4.27	2.90	3.59	2	0.94	0.84	0.89	2



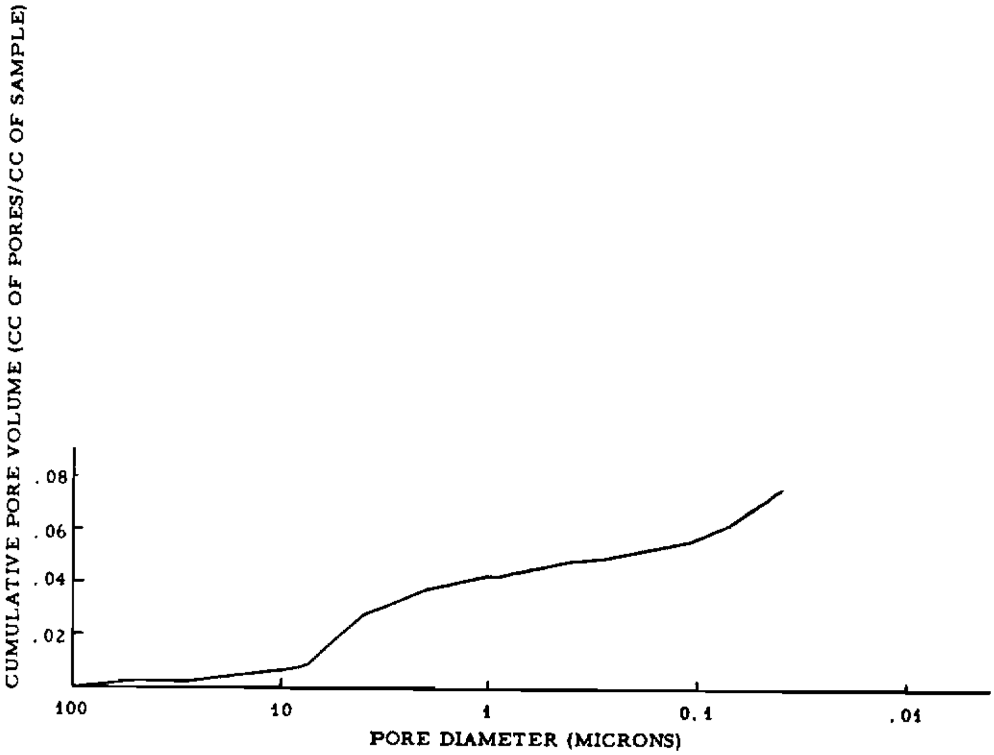
L-524

Figure 73. Thermal Expansion vs. Temperature, ZTC Graphite, 8½-Inch Diameter by 11-Inch Length



L-525

Figure 74. Young's Modulus vs. Temperature, ZTC Graphite, 8½-Inch Diameter by 11-Inch Length .



L-526

Figure 75. Pore Size Distribution, Mercury Porosimetry, ZTC Graphite

3.5. Grade ZTD Graphite[16, 17]

Physical properties were measured on only one block of ZTD graphite 14 inches in diameter by 10 inches in length. This grade was used to evaluate the equipment for measuring ultimate shear strength, and only tensile strength at room and elevated temperatures and compressive strength at elevated temperatures were not included in the characterization.

Apparent shear strength measurements were made at two platen rates, 0.005- and 0.020 inch per minute. All other strength measurements were made only at a cross-head or platen rate of 0.020 inch per minute. The shear strength of graphite in the brittle state appears to be independent of the strain rate (platen rate) as illustrated in Figures 79 and 80; however, it is a function of the strain rate in the transition and plastic states.

Table 37. Room-Temperature Properties, ZTD Graphite, 14-Inch Diameter by 10-Inch Length

Properties	With Grain Average	With Grain σ	With Grain n	With Grain No. of Blocks	Across Grain Average	Across Grain σ	Across Grain n	Across Grain No. of Blocks
Bulk Density, g/cc	2.01	0.019	48	1	---	---	--	-
Specific Resistance, 10^{-4} ohm-cm	5.41	0.18	26	1	7.88	0.43	22	1
Young's Modulus 10^{6} lbs/in²	1.763	0.091	26	1	0.789	0.028	22	1
Flexural Strength, lbs/in²	2655	278	26	1	1315	170	22	1
Compressive Strength, 1- by 1- by 1-inch lbs/in²	5010	547	45	1	6795	957	45	1
Tensile Strength, lbs/in²	1905	398	14	1	670	239	5	1
Apparent Shear Strength, lbs/in² Platen Rate: 0.020 in/min	2160	105	10	1	1620	102	11	1
Apparent Shear Strength, lbs/in² Platen Rate: 0.005 in/min	2085	194	10	1	1320	145	9	1

Properties	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	With Grain No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n	Across Grain No. of Blocks
CTE (20°-100°C), 10^{-6}/°C	1.42	1.15	1.28	4	1	8.21	5.98	6.70	4	1
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ {}^\circ\text{K}}$	0.606	0.554	0.572	3	1	0.449	0.391	0.425	3	1
Admittance, cm²/sec	2×10^{-3}	6×10^{-4}	1×10^{-3}	3	1	1×10^{-3}	7×10^{-4}	9×10^{-4}	3	1
Per Cent Ash	---	---	0.510	1	1	---	---	---	-	-

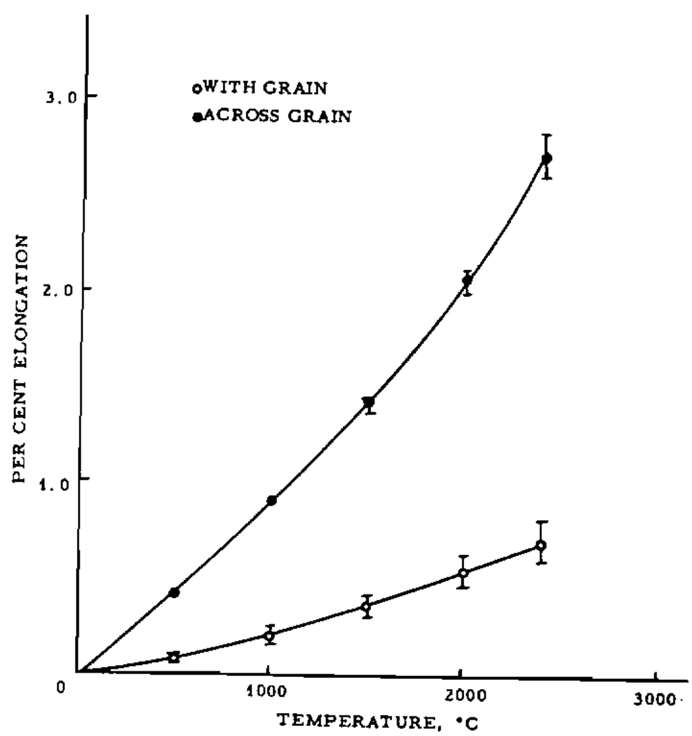
Table 38. High-Temperature Properties, ZTD Graphite, 14-Inch Diameter by 10-Inch Length

Properties	Temp. °C	With Grain Max	With Grain Min.	With Grain Ave.	With Grain n	With Grain No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n	Across Grain No. of Blocks
Thermal Expansion Per Cent Elongation $\frac{\Delta L}{L} \times 100$	500	0.100	0.054	0.073	3	1	0.423	0.394	0.412	3	1
	1000	0.245	0.159	0.196	3	1	0.923	0.877	0.897	3	1
	1500	0.417	0.300	0.353	3	1	1.453	1.372	1.416	3	1
	2000	0.634	0.469	0.536	3	1	2.124	1.988	2.062	3	1
	2400	0.819	0.600	0.695	3	1	2.839	2.611	2.725	3	1
Young's Modulus, 10^6 lbs/in²	RT	2.01	1.90	1.97	3	1	0.80	0.66	0.71	4	1
	500	2.04	1.88	1.98	3	1	0.82	0.68	0.72	4	1
	1000	2.20	1.97	2.10	3	1	0.85	0.72	0.76	4	1
	1500	2.46	2.22	2.34	3	1	0.89	0.80	0.84	4	1
	2000	2.79	2.65	2.73	3	1	1.07	0.99	1.02	4	1
	2400	3.20	2.86	3.06	3	1	1.20	1.17	1.19	4	1
	2500	3.20	2.87	3.05	3	1	---	---	---	-	-
	2600	---	---	---	-	-	1.24	1.16	1.20	4	1
	2800	3.05	2.82	2.98	3	1	1.23	1.07	1.15	4	1
Apparent Shear Strength, lbs/in² Platen Rate = 0.020 in/min	1000	---	---	3200	1	1	---	---	1220	1	1
	1500	---	---	2510	1	1	---	---	1655	1	1
	2000	---	---	3300	1	1	---	---	2590	1	1
	2500	4470	3735	4105	2	1	2620	2295	2455	2	1
	2700	4520	3555	4040	2	1	---	---	3615	1	1
	2800	---	---	4335	1	1	---	---	2125	1	1
Apparent Shear Strength, lbs/in² Platen Rate = 0.005 in/min	1000	---	---	2395	1	1	2015	1750	1885	2	1
	1500	---	---	3115	1	1	3045	2290	2670	2	1
	2000	---	---	3410	1	1	2955	2155	2555	2	1
	2500	6035	4420	5230	2	1	3460	3240	3350	2	1
	2700	7085	5635	6360	2	1	---	---	5235	1	1
	2800	---	---	3386	1	1	4110	3450	3780	2	1

	2.01	2.01	2.02	2.03	2.03	2.04	2.04	2.03	2.01	2.00	1.99
	2.01	2.03	2.04	2.05	2.05	2.05	2.05	2.04	2.03	2.02	2.01
1.99	1.99	2.03	2.05	2.05	2.05	2.06	2.05	2.05	2.04	2.02	2.01
1.99	2.01	2.02	2.04	2.05	2.05	2.06	2.05	2.05	2.03	2.02	2.01
2.00	2.00	2.02	2.04	2.04	2.05	2.05	2.04	2.02	2.03	2.01	2.00
2.00	2.00	2.01	2.03	2.04	2.04	2.05	2.04	2.04	2.02	2.01	2.00
1.99	2.00	2.01	2.03	2.03	2.04	2.05	2.04	2.03	2.02	2.01	2.00
1.99	1.99	2.01	2.03		2.04	2.04	2.04	2.03	2.00	1.98	

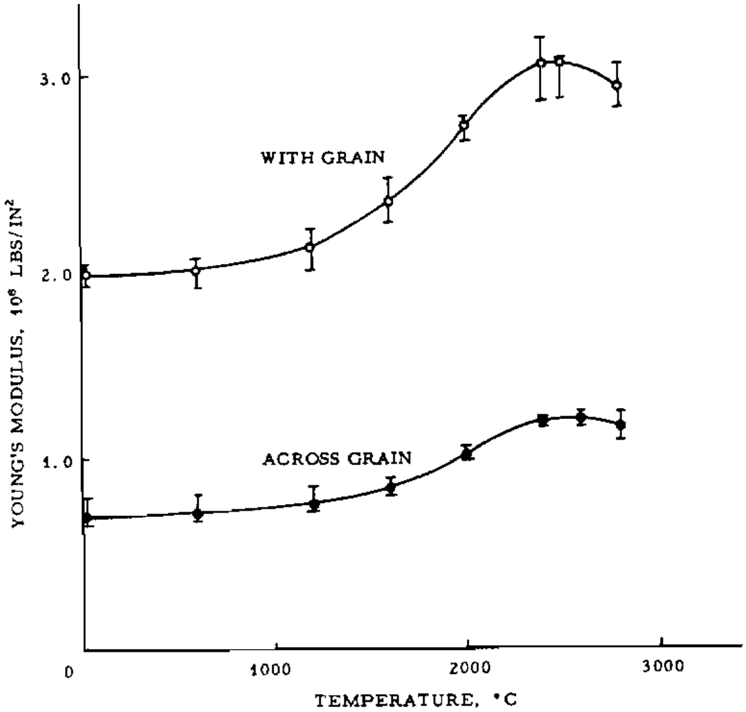
L-527

Figure 76. Density Profile, ZTD Graphite, 14-Inch Diameter by 10-Inch Length



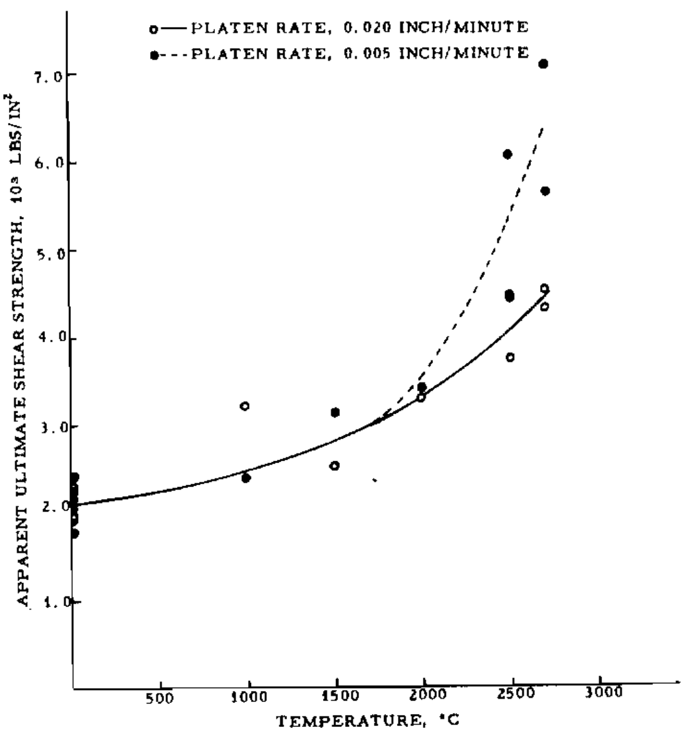
L-528

Figure 77. Thermal Expansion vs. Temperature, ZTD Graphite, 14-Inch Diameter by 10-Inch Length



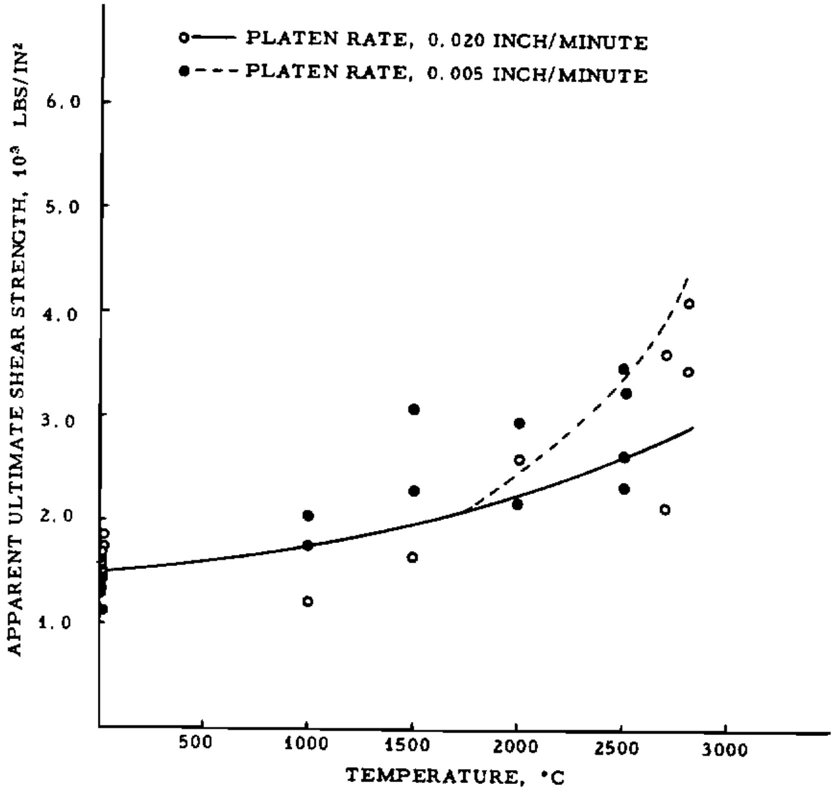
L-529

Figure 78. Young's Modulus vs. Temperature, ZTD Graphite, 14-Inch Diameter by 10-Inch Length



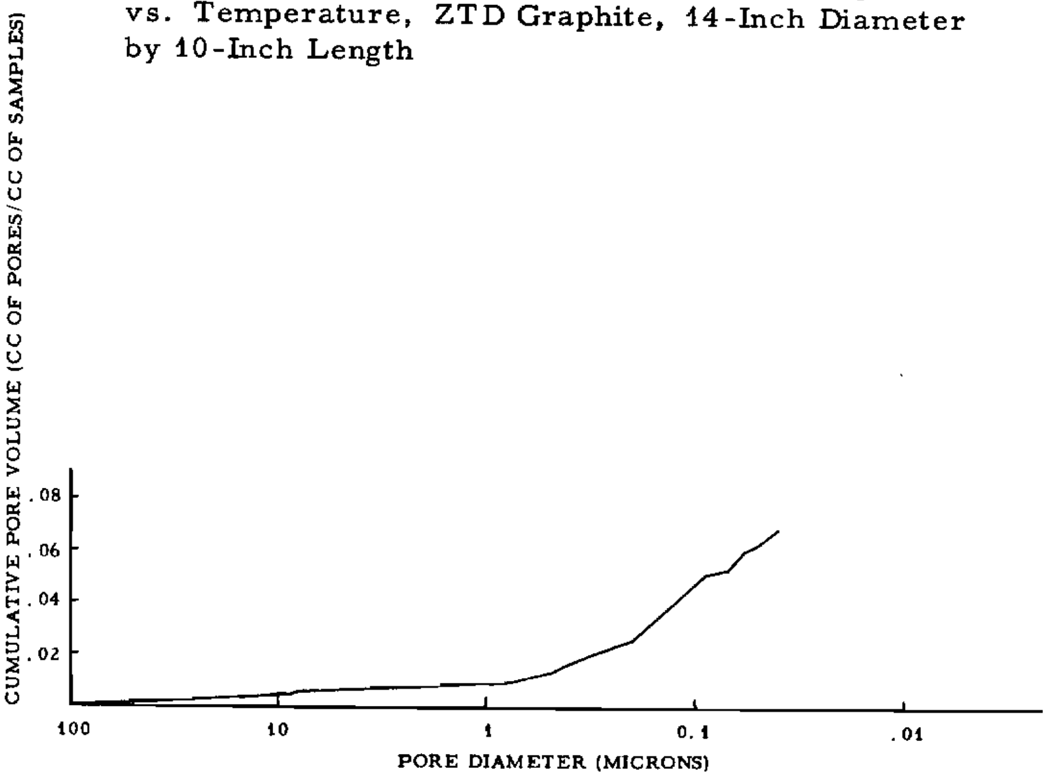
L-530

Figure 79. With-Grain Apparent Ultimate Shear Strength vs. Temperature, ZTD Graphite, 14-Inch Diameter by 10-Inch Length



L-531

Figure 80. Across-Grain Apparent Ultimate Shear Strength vs. Temperature, ZTD Graphite, 14-Inch Diameter by 10-Inch Length



L-532

Figure 81. Pore Size Distribution, Mercury Porosimetry, ZTD Graphite

3.6. Grade ZTE Graphite [16, 17]

Only one 30-inch diameter by $23\frac{1}{2}$-ingh length block was used in the characterization of ZTE graphite, but enough stock was available to allow complete measurement of properties as outlined in Section 1. The interpretation of stress-strain curves was discussed in Section 3.1. All strength measurements were made with cross-head or platen rates of 0.020 inch per minute.

Table 39. Room-Temperature Properties, ZTE Graphite, 30-Inch Diameter by $23\frac{1}{2}$-Inch Length

Properties	With Grain Average	With Grain σ	With Grain n	With Grain No. of Blocks	Across Grain Average	Across Grain σ	Across Grain n	Across Grain No. of Blocks
Bulk Density, g/cc	1.96	0.015	108	1	---	---	--	-
Specific Resistance	8.94	0.59	65	1	20.40	0.250	41	1
Young's Modulus, 10^6 lbs/in^2	2.444	0.205	65	1	0.800	0.280	41	1
Flexural Strength, lbs/in^2	4335	264	64	1	2316	278	41	1
Compressive Strength, 1- by 1- by 1-inch lbs/in^2	5760	363	15	1	6780	385	15	1
Compressive Strength, $\frac{1}{2}$-inch dia. by $\frac{1}{2}$-inch, lbs/in^2	8350	482	10	1	12,035	460	10	1
Tensile Strength, lbs/in^2	3385	264	11	1	1460	108	10	1
Apparent Shear Strength, lbs/in^2	2620	251	10	1	2165	327	10	1

Properties	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	With Grain No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n	Across Grain No. of Blocks
CTE (20°-100°C), 10^{-6}/°C	1.00	0.61	0.80	4	1	8.09	5.44	6.77	4	1
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ {}^\circ\text{K}}$	0.391	0.325	0.352	3	1	0.217	0.173	0.194	3	1
Admittance, 10^3 cm^2/sec	$1\text{x}10^{-2}$	$2\text{x}10^{-3}$	$7\text{x}10^{-3}$	3	1	$3\text{x}10^{-2}$	$2\text{x}10^{-3}$	$1\text{x}10^{-2}$	3	1
Per Cent Ash	---	---	0.398	1	1	---	---	---	-	-

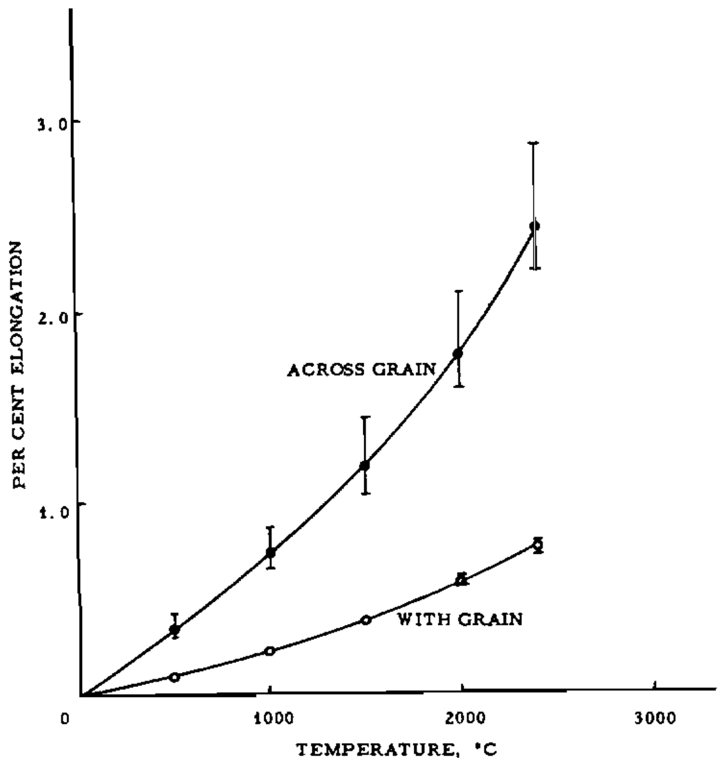
Table 40. High-Temperature Properties, ZTE Graphite, 30-Inch Diameter by $23\frac{1}{2}$-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
Thermal Expansion Per Cent Elongation $\frac{\Delta L}{L} \times 100$	500	0.085	0.074	0.081	3	0.414	0.285	0.329	3
	1000	0.225	0.193	0.213	3	0.874	0.651	0.728	3
	1500	0.394	0.348	0.370	3	1.439	1.033	1.175	3
	2000	0.606	0.548	0.572	3	2.089	1.590	1.762	3
	2400	0.790	0.706	0.756	3	2.859	2.196	2.423	3
Young's Modulus, 10^6 lbs/in²	RT	2.68	2.33	2.52	3	0.73	0.67	0.70	3
	600	2.77	2.37	2.56	3	0.74	0.68	0.72	3
	1200	3.06	2.60	2.79	3	0.79	0.69	0.74	3
	1600	3.28	2.92	3.07	3	0.90	0.77	0.82	3
	2000	3.34	2.98	3.17	3	1.03	0.84	0.91	3
	2400	3.50	3.07	3.33	3	1.18	0.92	1.03	3
	2500	---	---	---	-	1.19	0.95	1.05	3
	2800	3.37	2.98	3.21	3	1.15	0.77	0.97	3
Tensile Strength, lbs/in²	1000	---	---	3865	1	---	---	1775	1
	1500	---	---	4660	1	---	---	2250	1
	2000	---	---	4905	1	---	---	2440	1
	2500	---	---	5855	1	---	---	2665	1
	2600	---	---	---	-	---	---	2640	1
	2700	---	---	5535	1	---	---	1290	1
Compressive Strength, $\frac{1}{2}$-inch diameter by $\frac{1}{2}$-inch lbs/in²	1000	---	---	8200	1	---	---	12475	1
	1500	---	---	9575	1	---	---	14055	1
	2000	---	---	12170	1	14830	11865	13350	2
	2500	---	---	15280	1	15915	14515	15215	2
	2700	---	---	16145	1	15380	12225	13800	2
	2800	---	---	16995	1	---	---	---	-
	2900	No break at		33105	1	---	---	---	-
Apparent Shear Strength, lbs/in²	1000	---	---	2335	1	2750	2065	2410	2
	1500	---	---	4840	1	3515	3455	3485	2
	2000	---	---	5510	1	3515	3310	3415	2
	2500	---	---	7185	1	5175	3770	4475	2
	2700	---	---	5855	1	---	---	3515	1

1.950	1.951	1.947	1.949	1.953
1.947	1.975	1.981	1.982	1.979
1.948	1.949	1.945	1.946	1.948

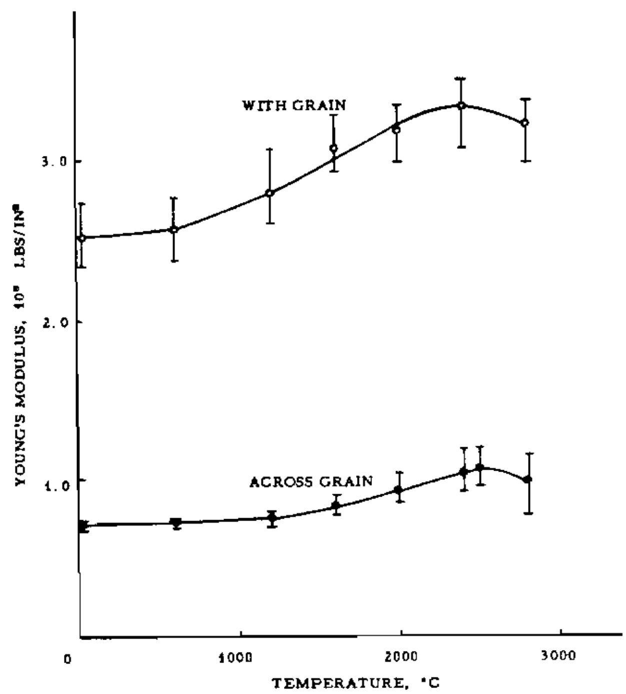
Figure 82. Density Profile, ZTE Graphite, 30-Inch Diameter by $23\frac{1}{2}$-Inch Length

L-533



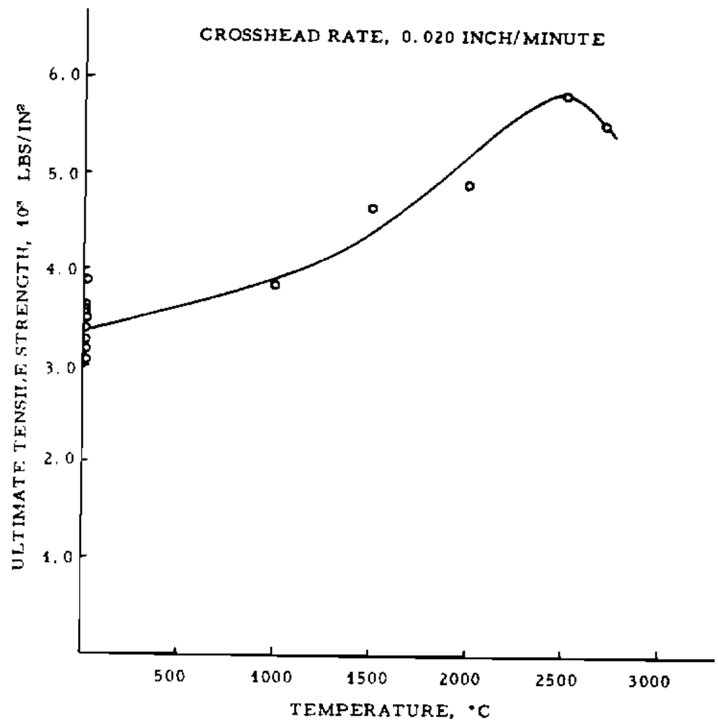
L-534

Figure 83. Thermal Expansion vs. Temperature, ZTE Graphite, 30-Inch Diameter by 23½-Inch Length



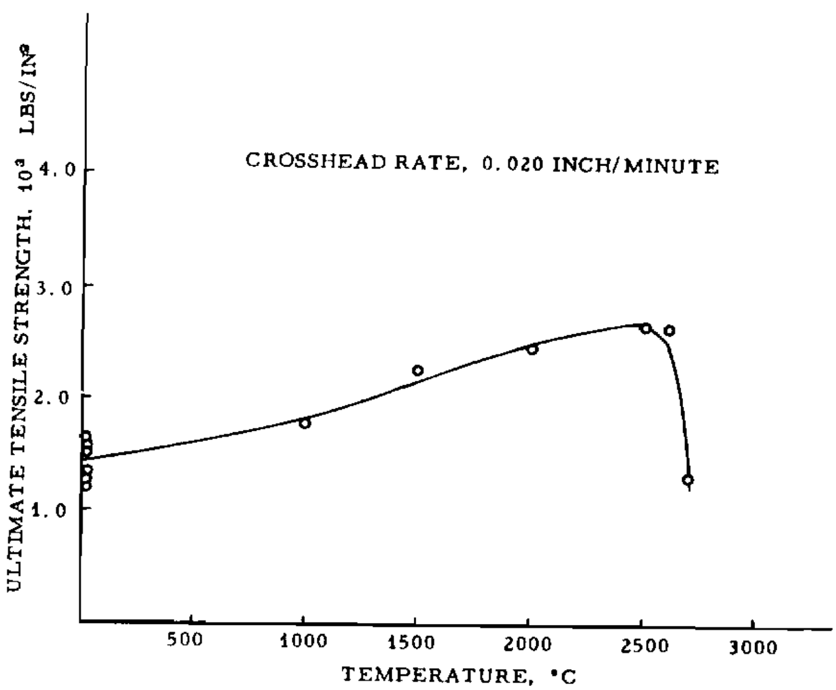
L-535

Figure 84. Young's Modulus vs. Temperature, ZTE Graphite, 30-Inch Diameter by 23½-Inch Length.



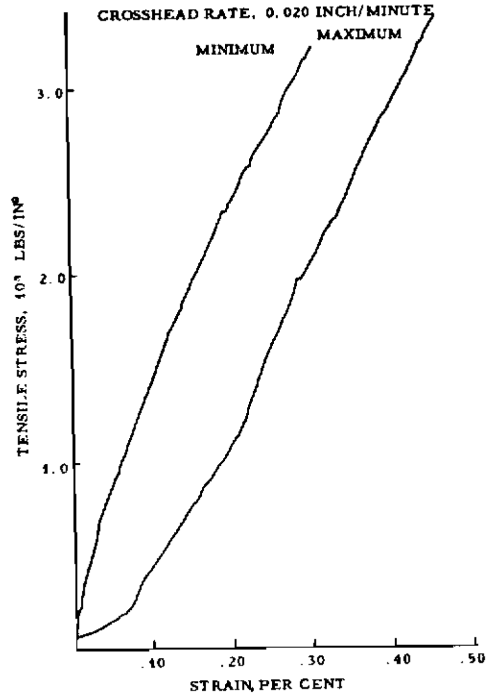
L-536

Figure 85. With-Grain Ultimate Tensile Strength vs. Temperature, ZTE Graphite, 30-Inch Diameter by 23- Inch Length



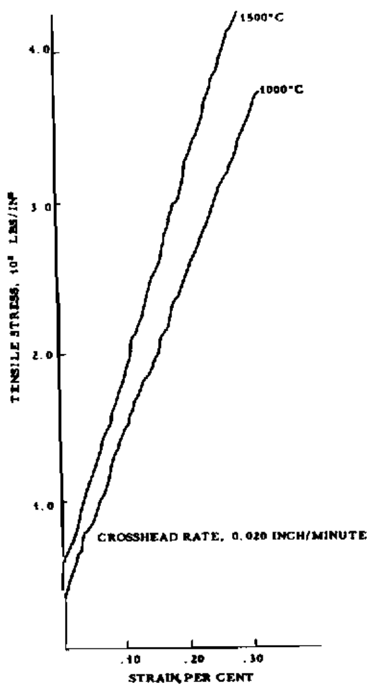
L-537

Figure 86. Across-Grain Ultimate Tensile Strength vs. Temperature, ZTE Graphite, 30-Inch Diameter by 23- Inch Length



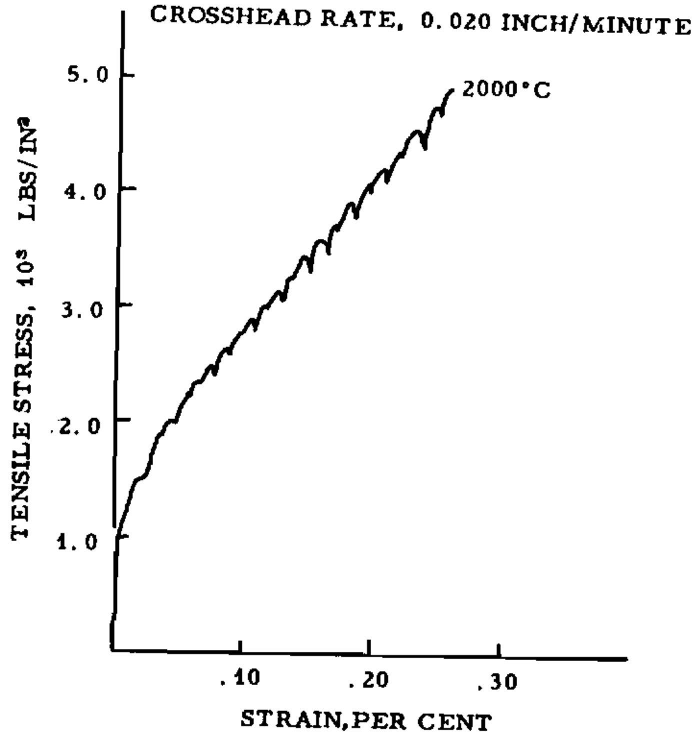
L-538

Figure 87. With-Grain Tensile Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23– Inch Length, Room Temperature



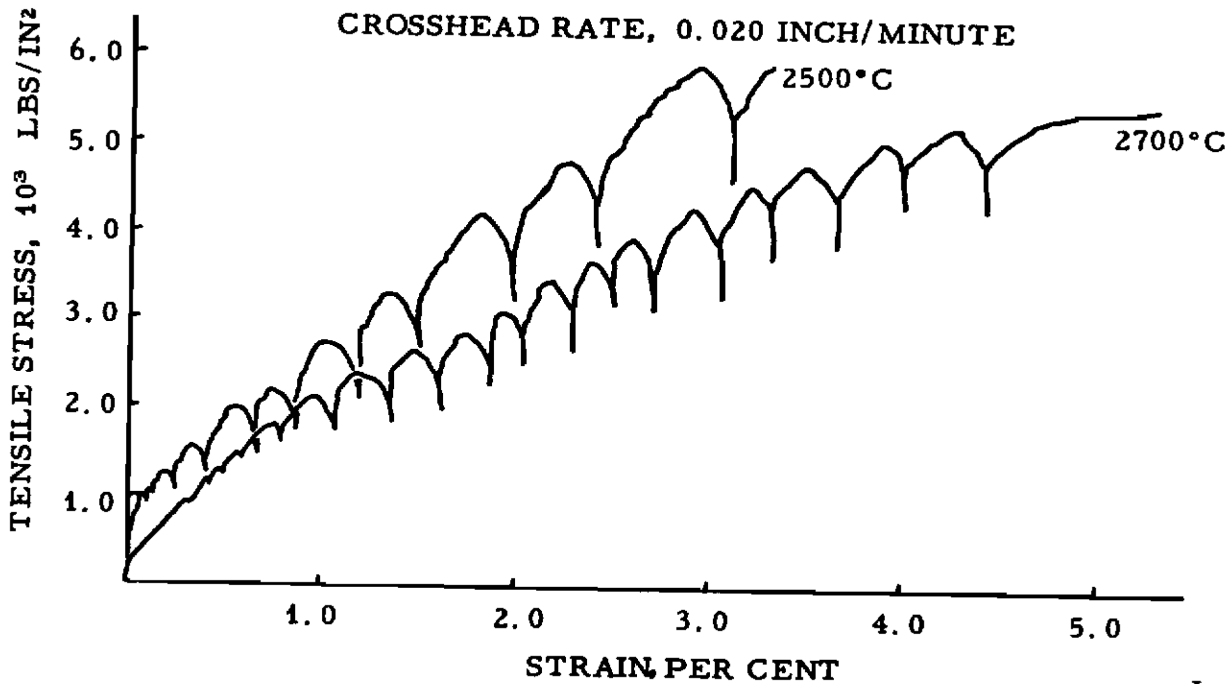
L-539

Figure 88. With-Grain Tensile Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23– Inch Length, 1000°C, 1500°C



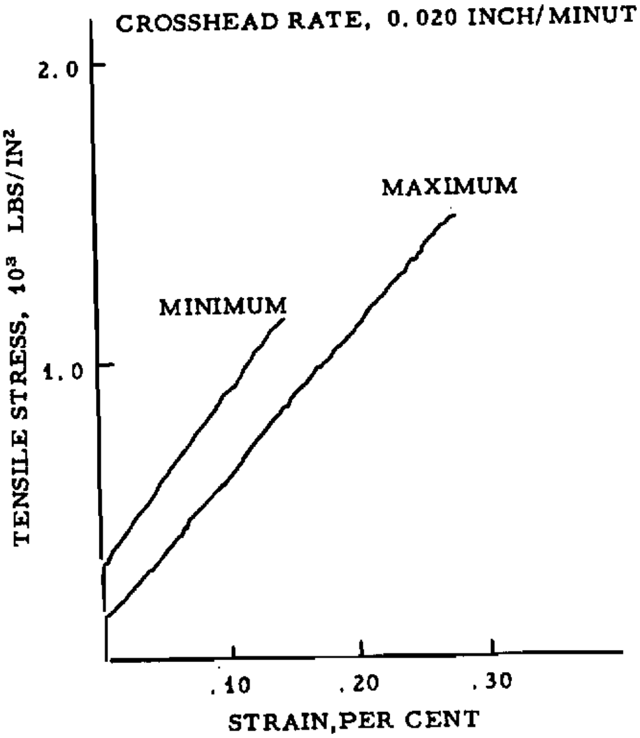
L-540

Figure 89. With-Grain Tensile Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23– Inch Length, 2000°C



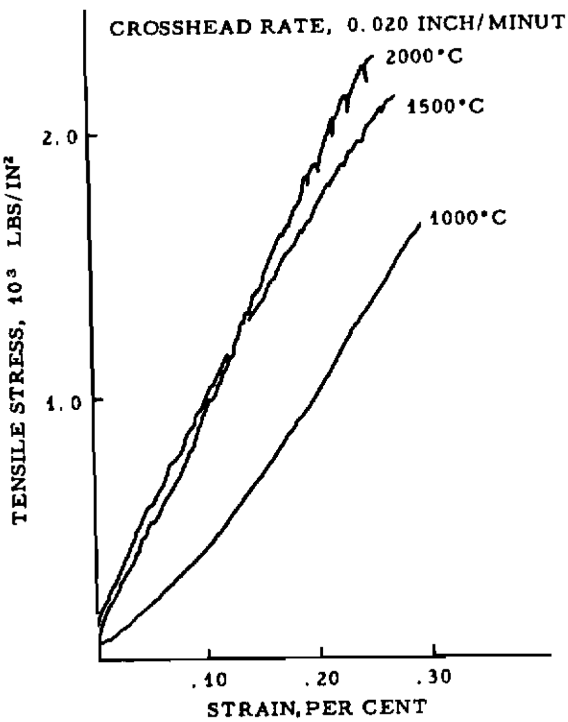
L-541

Figure 90. With-Grain Tensile Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23– Inch Length, 2500°C, 2700°C



L-542

Figure 91. Across-Grain Tensile Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23– Inch Length, Room Temperature



L-543

Figure 92. Across-Grain Tensile Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23 – Inch Length, 1000°C, 1500°C, 2000°C

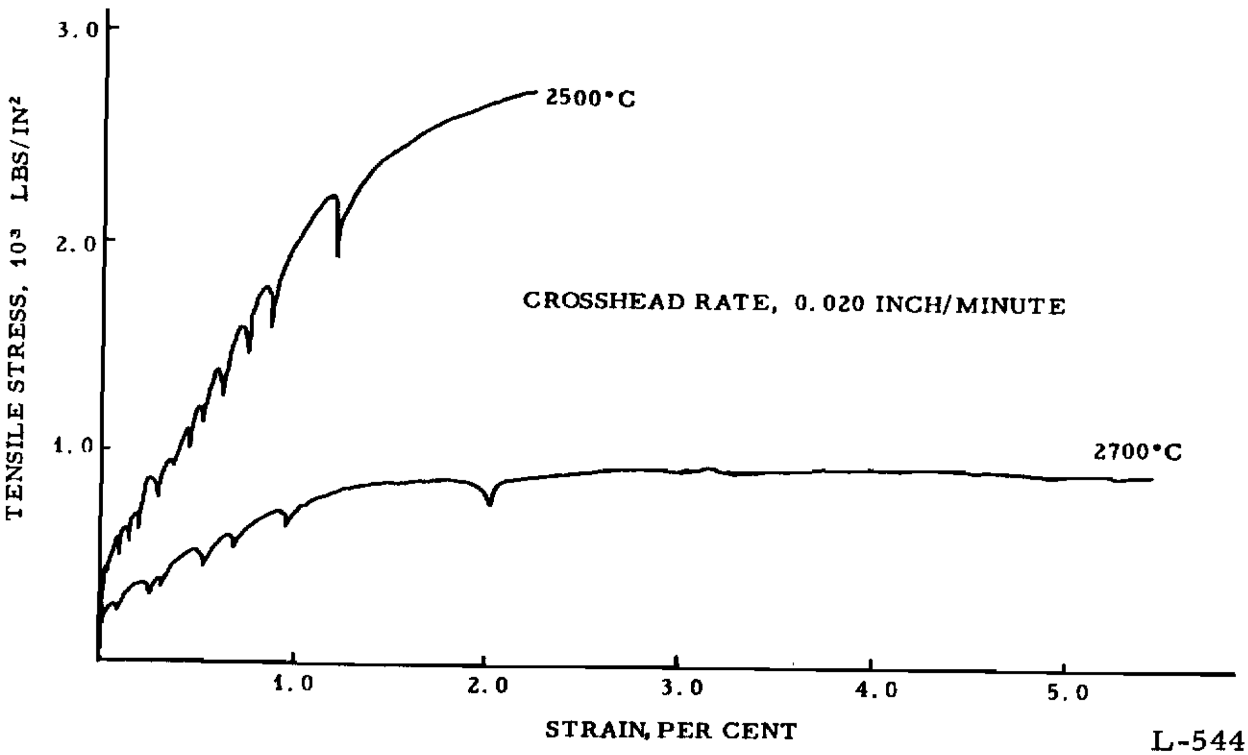
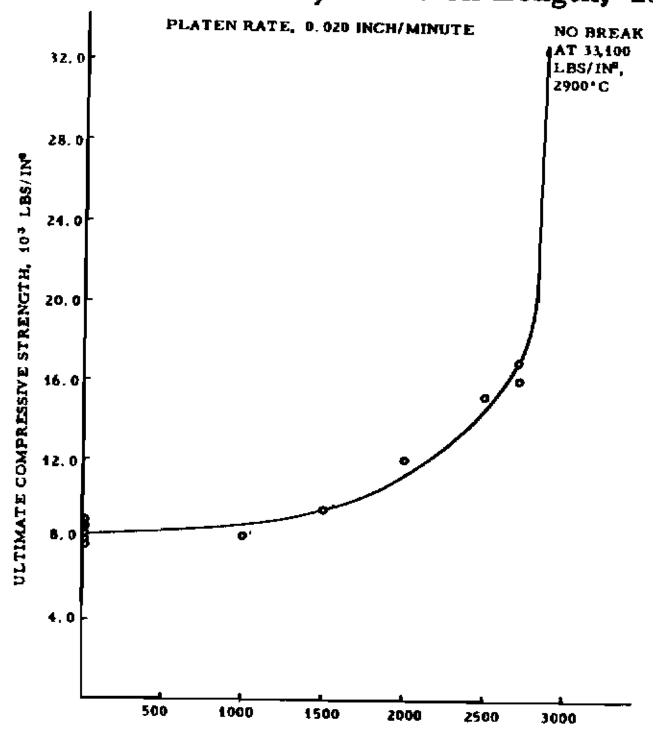
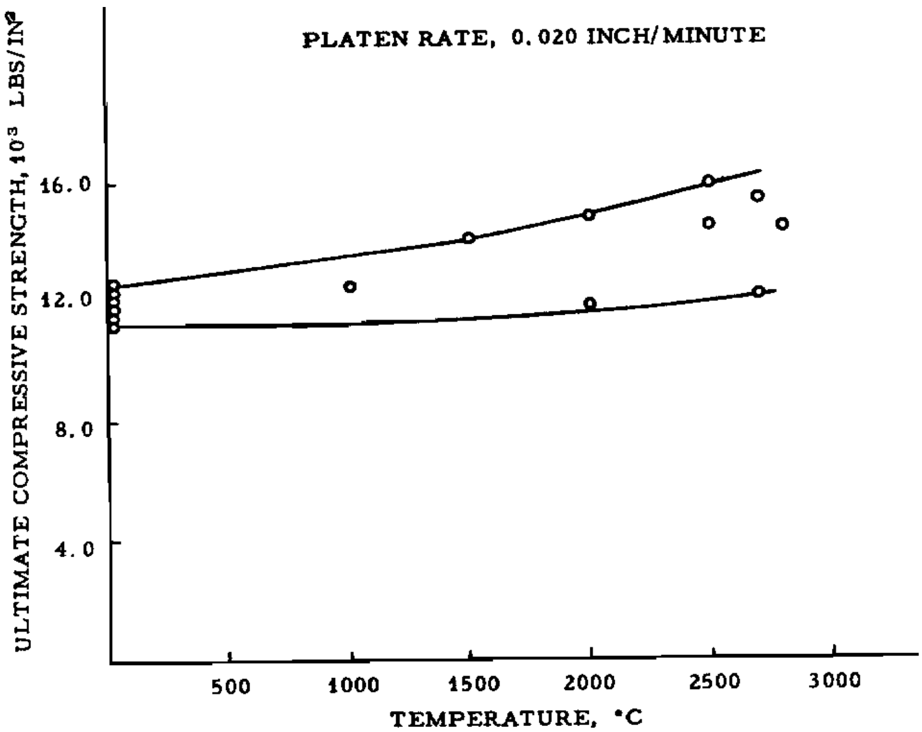


Figure 93. Across-Grain Tensile Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23—Inch Length, 2500°C, 2700°C



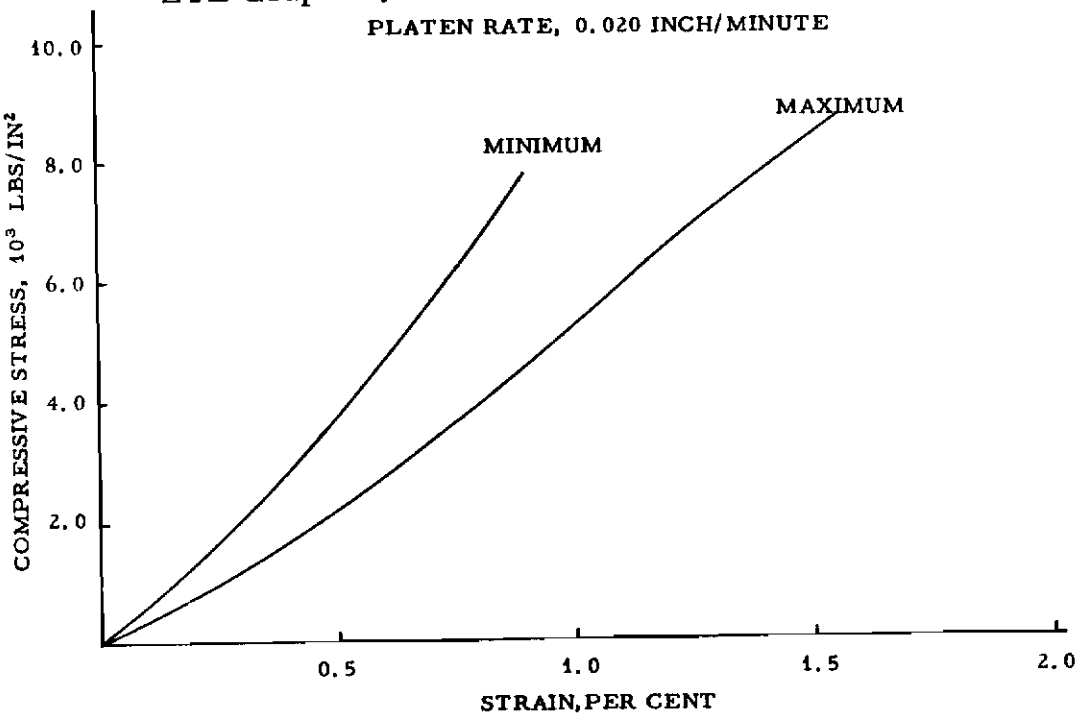
L-545

Figure 94. With-Grain Ultimate Compressive Strength vs. Temperature, ZTE Graphite, 30-Inch Diameter by 23—Inch Length



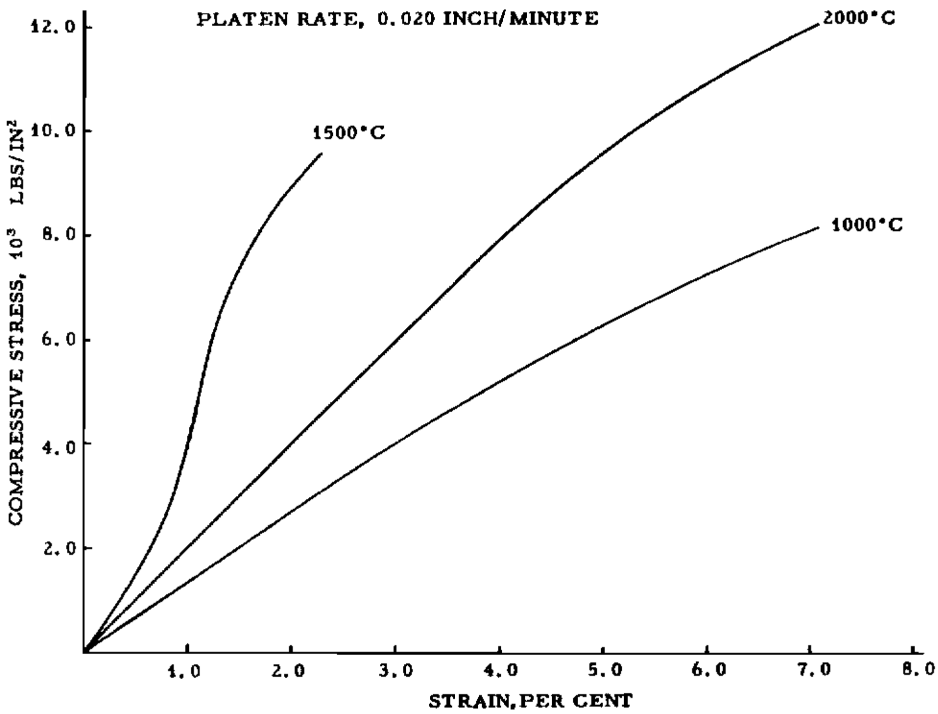
L-546

Figure 95. Across-Grain Ultimate Compressive Strength vs. Temperature, ZTE Graphite, 30-Inch Diameter by 23 - Inch Length



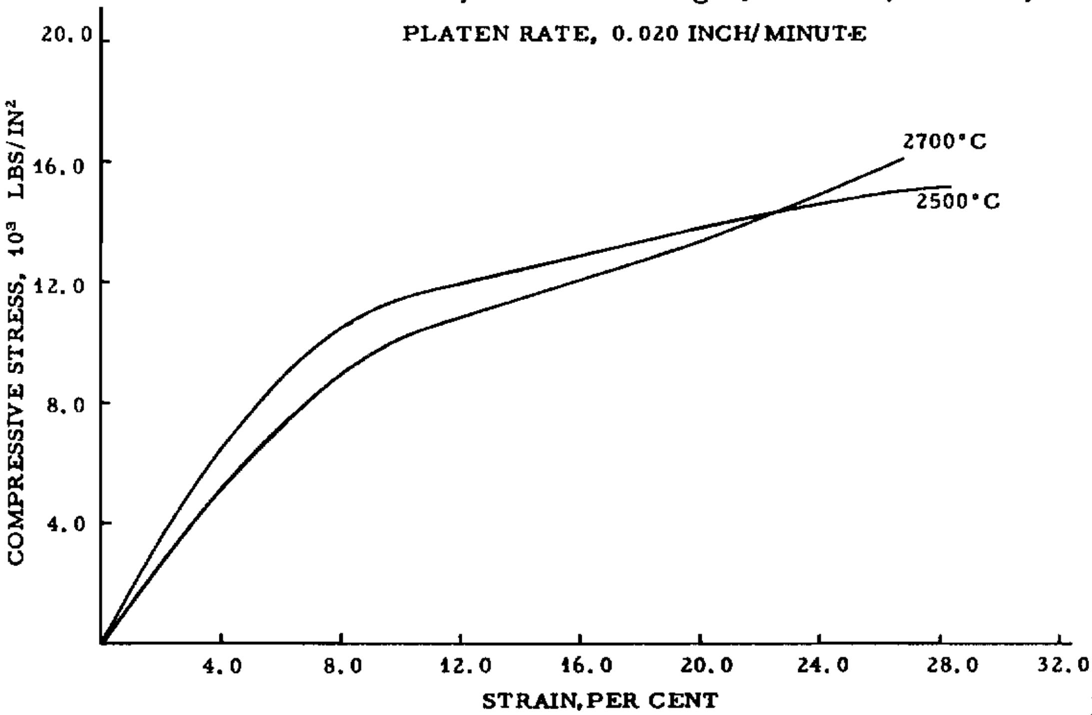
L-547

Figure 96. With-Grain Compressive Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23 – Inch Length, Room Temperature



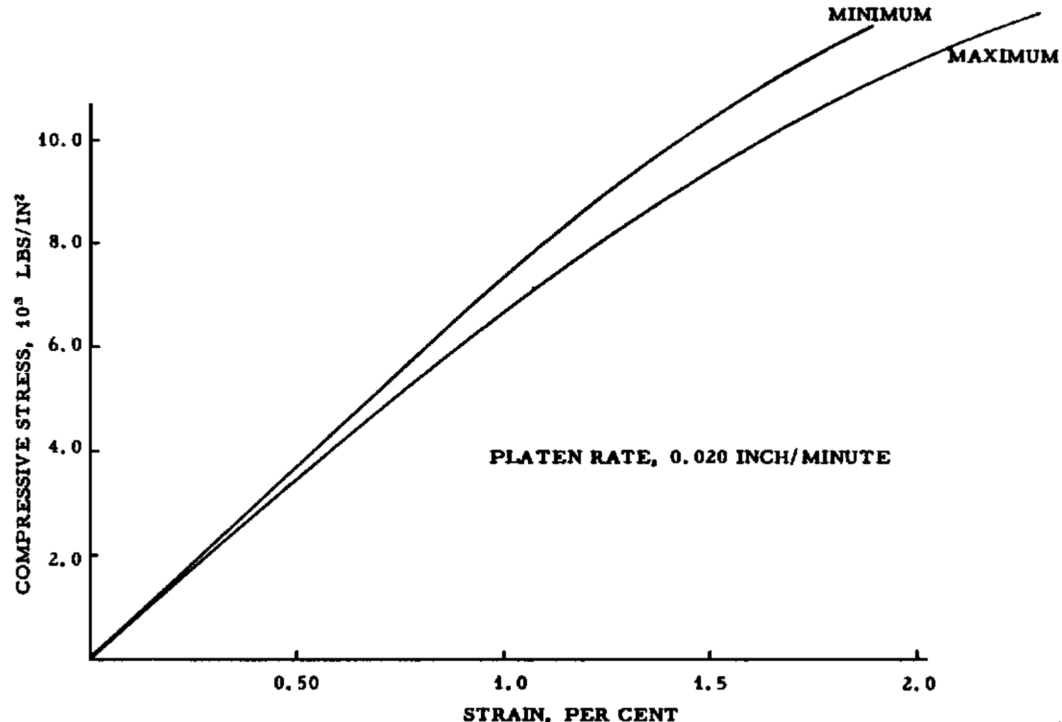
L-548

Figure 97. With-Grain Compressive Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23 – Inch Length, 1000°C, 1500°C, 2000°C



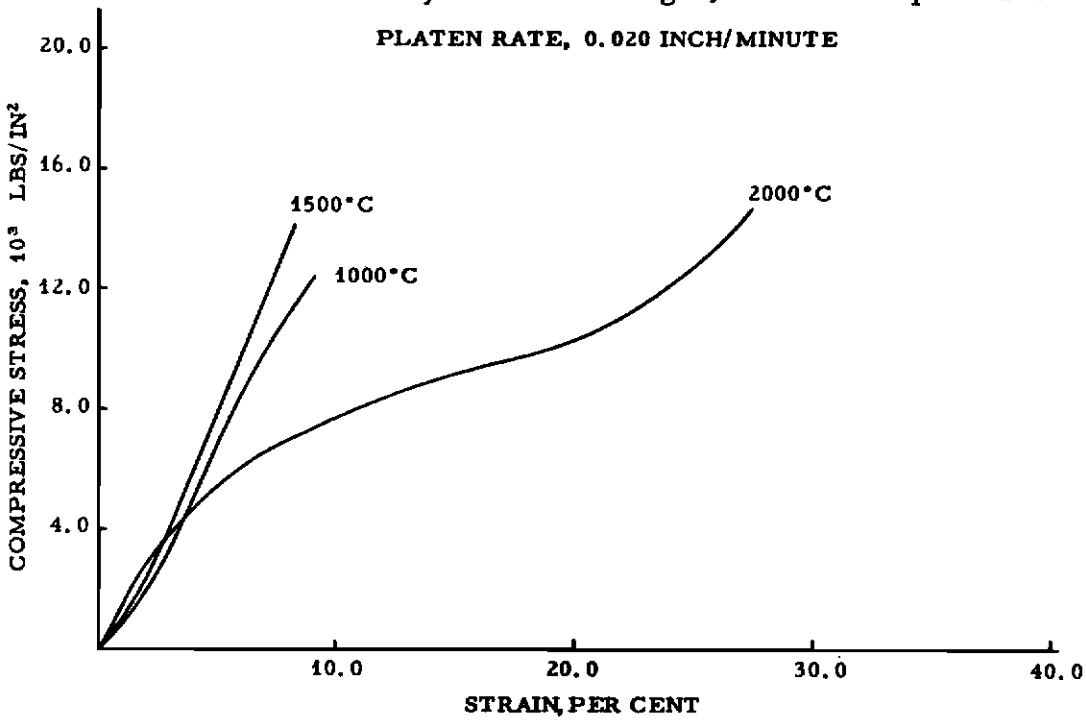
L-549

Figure 98. With-Grain Compressive Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23 – Inch Length, 2500°C, 2700°C



L-550

Figure 99. Across-Grain Compressive Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23 - Inch Length, Room Temperature



L-551

Figure 100. Across-Grain Compressive Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23 – Inch Length, 1000°C, 1500°C, 2000°C

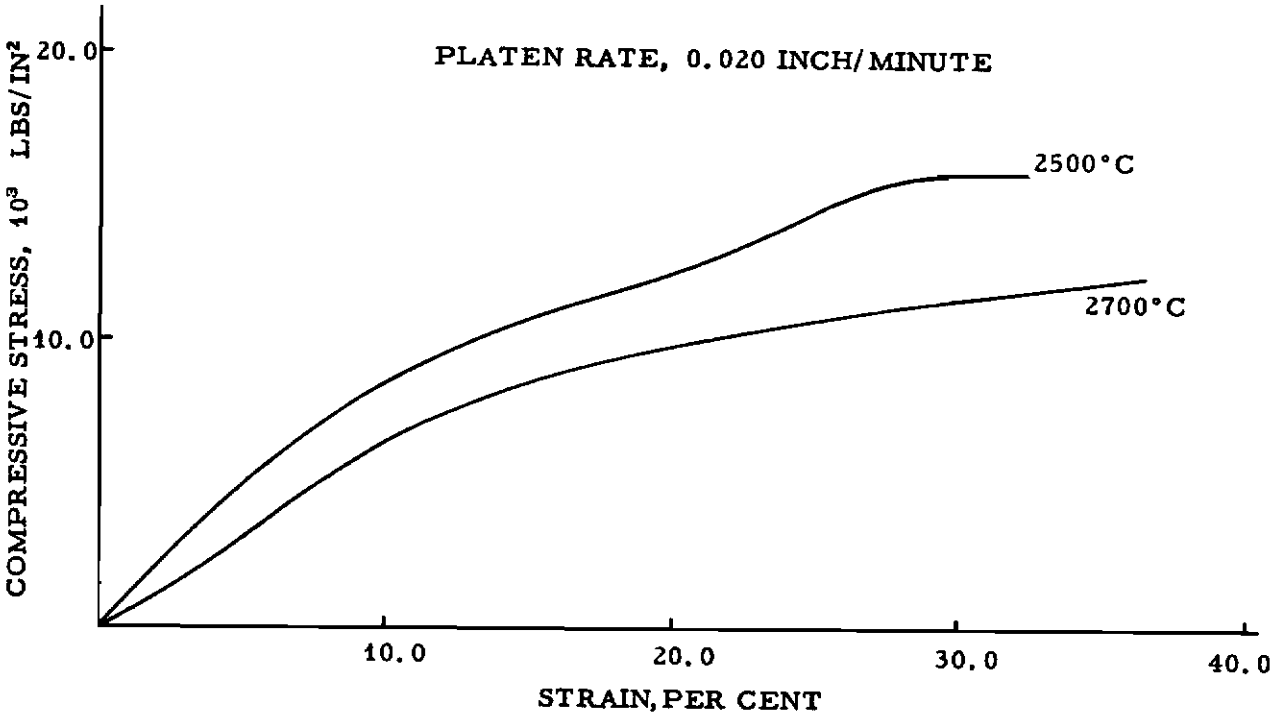
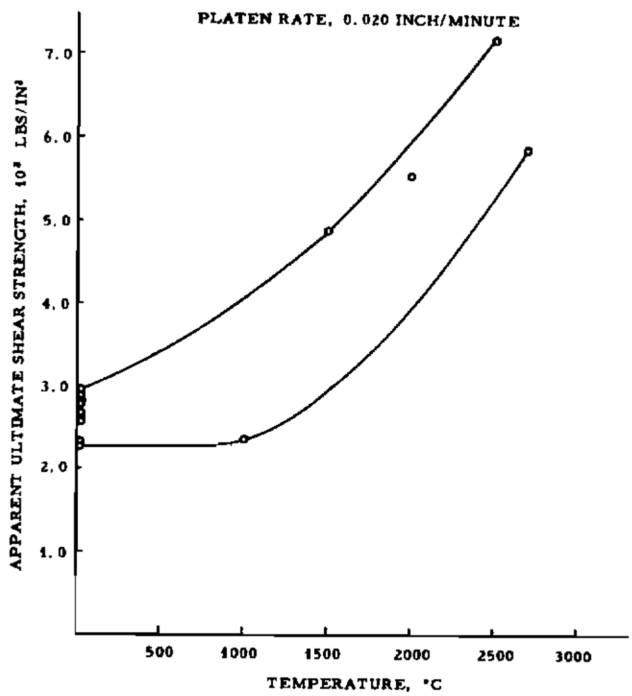


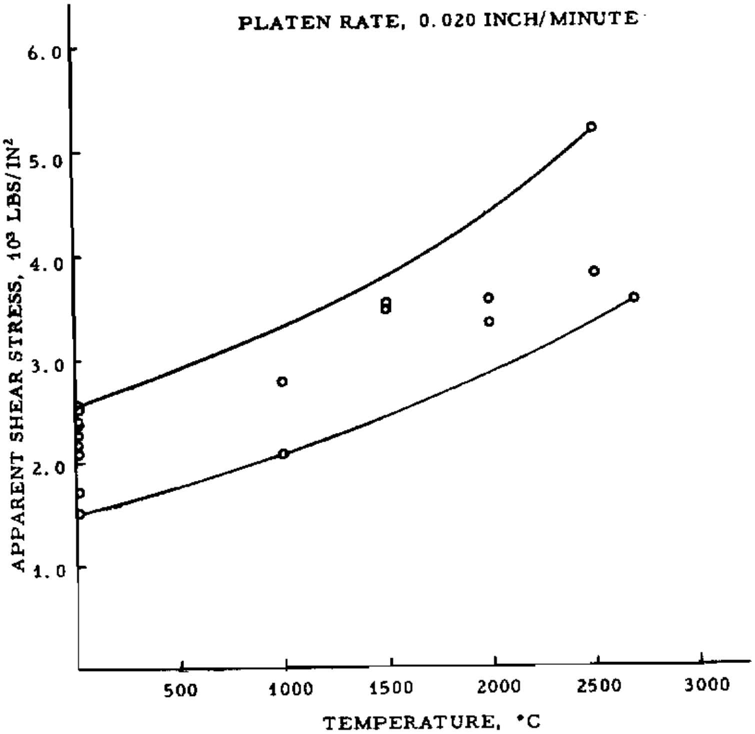
Figure 101. Across-Grain Compressive Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23—Inch Length, 2500°C, 2700°C

L-552



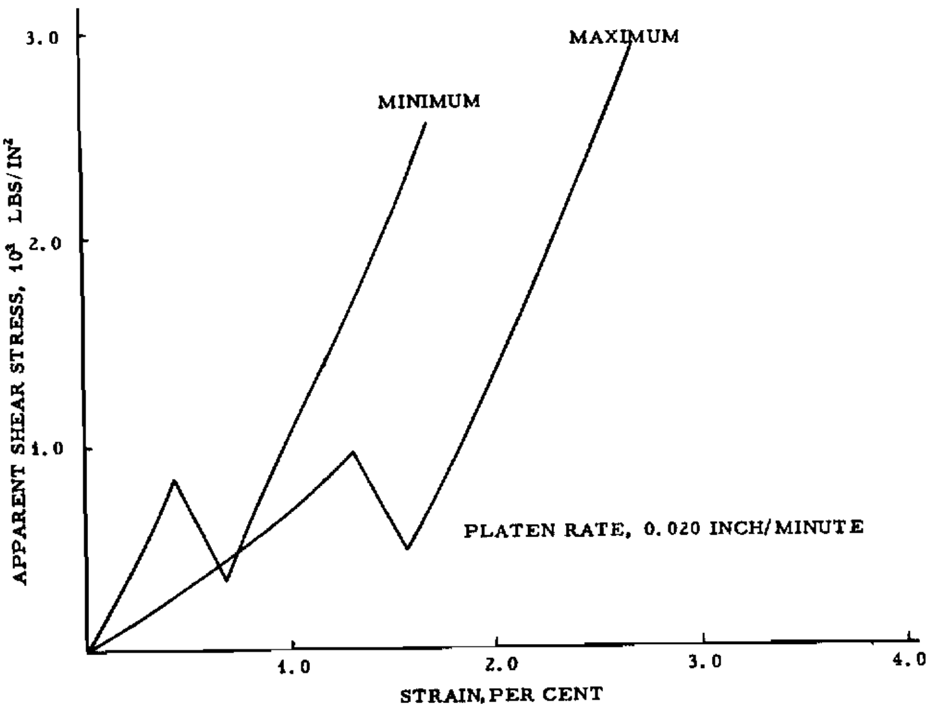
L-553

Figure 102. With-Grain Apparent Ultimate Shear Strength vs. Temperature, ZTE Graphite, 30-Inch Diameter by 23 – Inch Length



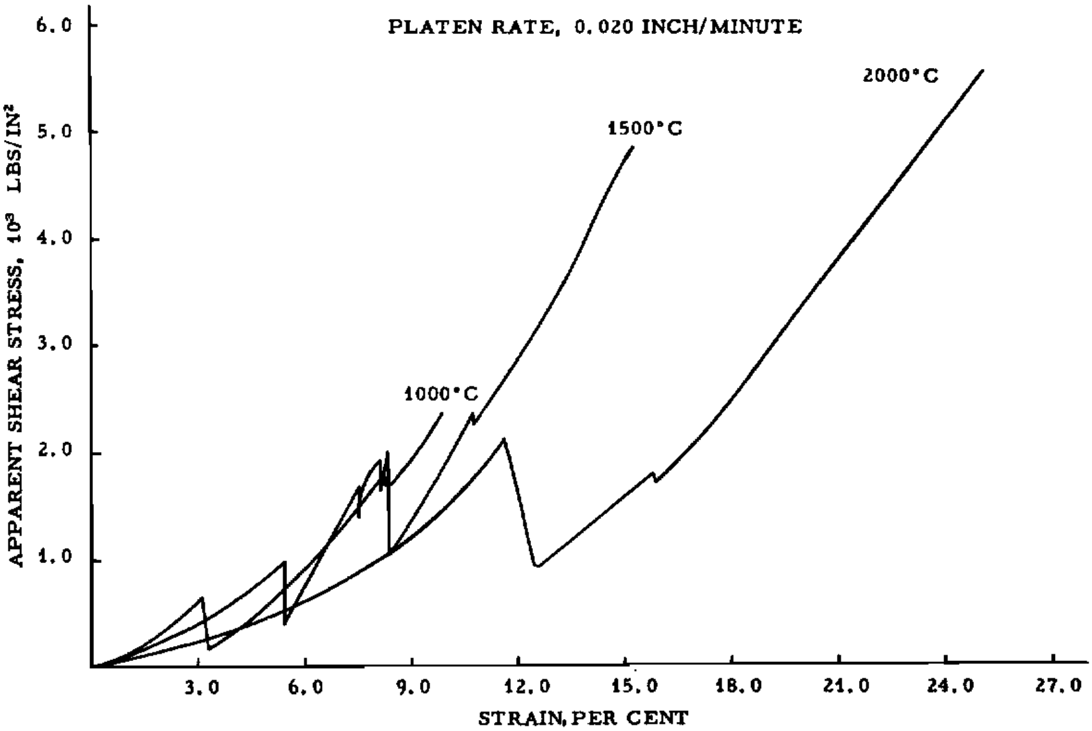
L-554

Figure 103. Across-Grain Apparent Ultimate Shear Strength vs. Temperature, ZTE Graphite, 30-Inch Diameter by 23- Inch Length



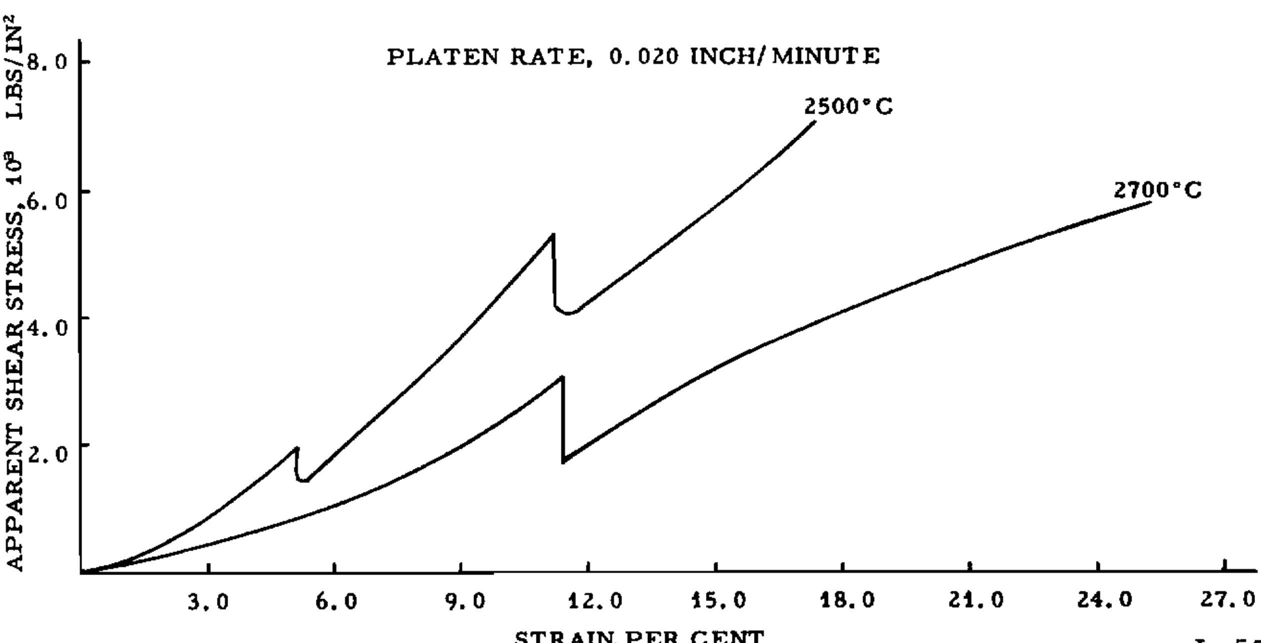
L-555

Figure 104. With-Grain Apparent Shear Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23 – Inch Length, Room Temperature



L-556

Figure 105. With-Grain Apparent Shear Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23-Inch Length, 1000°C, 1500°C, 2000°C



L-557

Figure 106. With-Grain Apparent Shear Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23-Inch Length, 2500°C, 2700°C

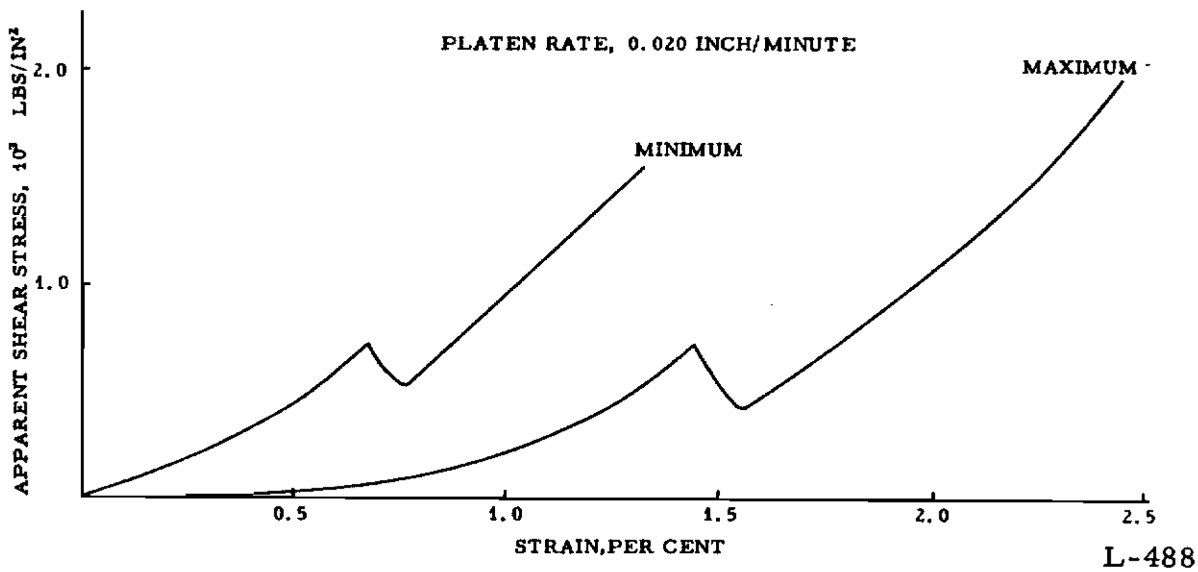


Figure 107. Across-Grain Apparent Shear Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23 – Inch Length, Room Temperature

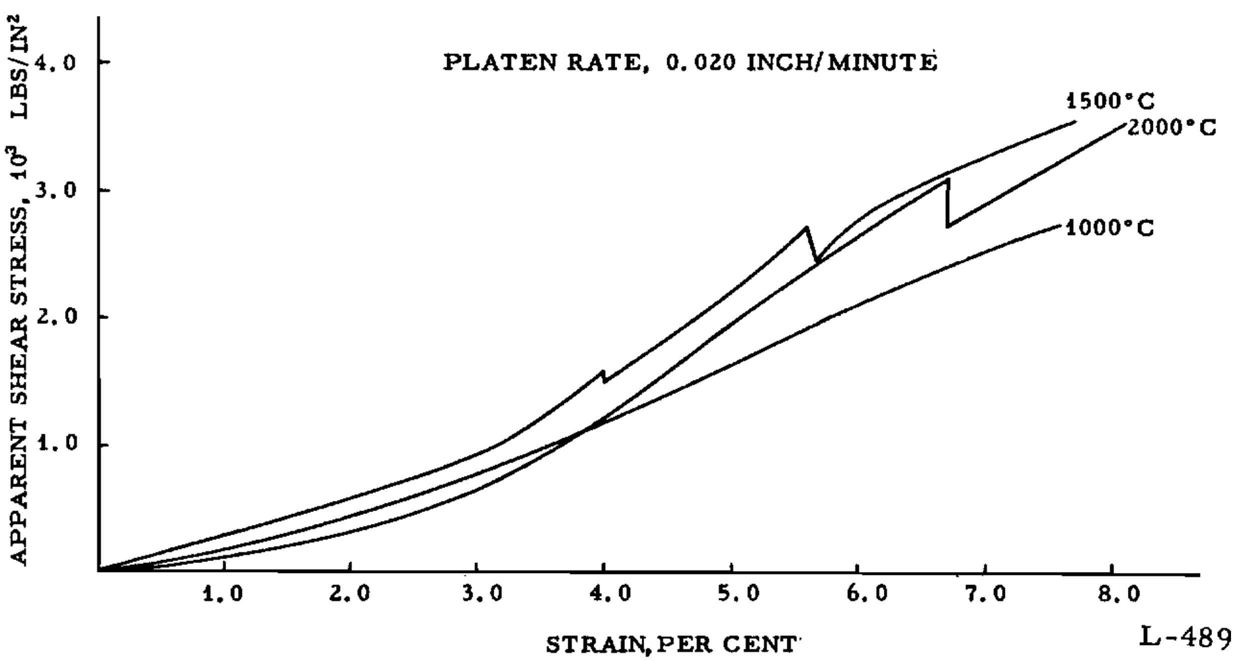
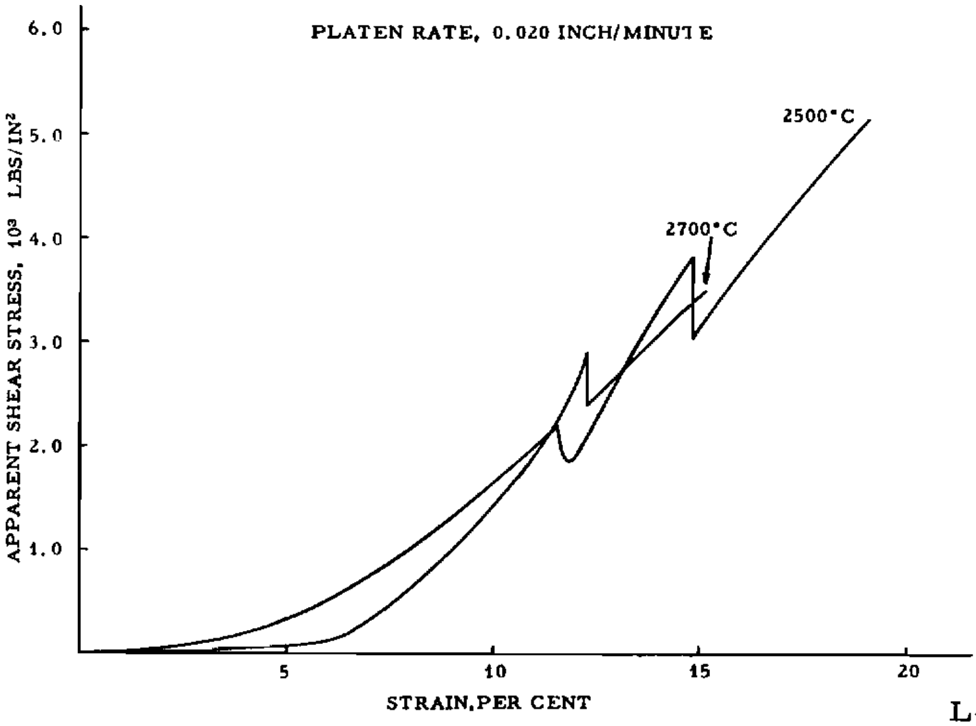
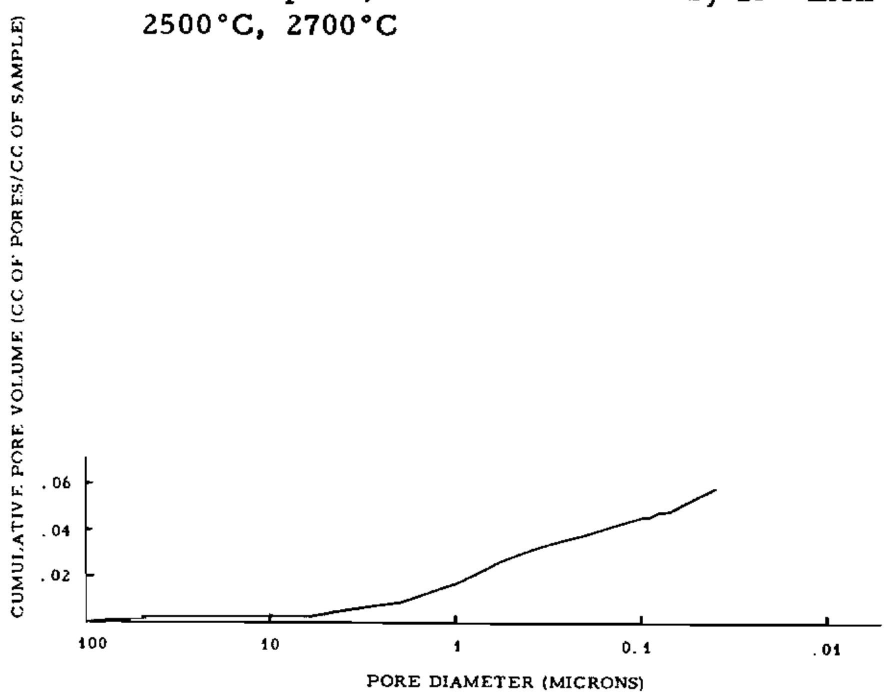


Figure 108. Across-Grain Apparent Shear Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23 – Inch Length, 1000°C, 1500°C, 2000°C



L-490

Figure 109. Across-Grain Apparent Shear Stress-Strain Curves, ZTE Graphite, 30-Inch Diameter by 23—Inch Length, 2500°C, 2700°C



L-491

Figure 110. Pore Size Distribution, Mercury Porosimetry ZTE Graphite

3.7. Grade ZTF Graphite[16, 17]

One complete block of 14-inch diameter by 11-inch length ZTF graphite, Block 137A, and a fraction of another, Block 1, were used for physical property measurements. Block 1 was limited to room-temperature properties; Block 137A included high-temperature thermal expansion and Young's modulus as well as room-temperature properties.

Table 41 summarizes the room-temperature properties measured on both blocks whereas Tables 42 and 43 give the properties of blocks 1 and 137A, respectively. All strength measurements were made at cross-head or platen rates of 0.020 inch per minute.

Table 41. Summary of Room-Temperature Properties, ZTF Graphite, 14-Inch Diameter by 11-Inch Length

Properties	With Grain				Across Grain			
	Average	σ	n	No. of Blocks	Average	σ	n	No. of Blocks
Bulk Density, g/cc	1.99	0.01	91	2	---	---	--	-
Specific Resistance, 10^{-4} ohm-cm	7.31	0.61	48	2	20.50	1.68	43	2
Young's Modulus, 10^6 lbs/in^2	2.76	0.27	48	2	0.76	0.05	43	2
Flexural Strength, lbs/in^2	3875	508	48	2	1505	185	42	2
Compressive Strength, 1- by 1- by 1-inch lbs/in^2	6930	1175	47	1	8940	990	46	1

Properties	With Grain					Across Grain				
	Max.	Min.	Ave.	n	No. of Blocks	Max.	Min.	Ave.	n	No. of Blocks
CTE (20-100°C), 10^{-6}/°C	1.03	0.29	0.60	7	2	8.75	7.44	8.44	8	2
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ °\text{K}}$	0.405	0.335	0.374	3	1	0.085	0.078	0.081	4	1
Admittance, cm^2/sec	1×10^{-3}	4×10^{-4}	6×10^{-4}	4	1	2×10^{-4}	2×10^{-4}	2×10^{-4}	3	1
Per Cent Ash	0.275	0.274	0.275	2	1	---	---	---	--	-

Table 42. Room-Temperature Properties, ZTF Graphite, Block No. 1, 14-Inch Diameter by 11-Inch Length

Properties	With Grain			Across Grain		
	Average	σ	n	Average	σ	n
Bulk Density, g/cc	2.00	0.01	19	---	---	--
Specific Resistance, 10^{-4} ohm-cm	7.55	0.59	8	18.64	0.16	11
Young's Modulus, 10^{6} lbs/in^2	2.49	0.62	8	0.79	0.01	11
Flexural Strength, lbs/in^2	3270	301	8	1650	163	10
Compressive Strength, 1- by 1- by 1-inch, lbs/in^2	---	---	--	---	---	--

Properties	With Grain				Across Grain			
	Max.	Min.	Ave.	n	Max.	Min.	Ave.	n
CTE, $10^{-6}/°C$, 20°-100°C	0.76	0.29	0.56	3	8.75	8.57	8.69	4
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ °K}$	---	---	---	-	---	---	---	-
Admittance, cm^2/sec	---	---	---	-	---	---	---	-
Per Cent Ash	---	---	---	-	---	---	---	-

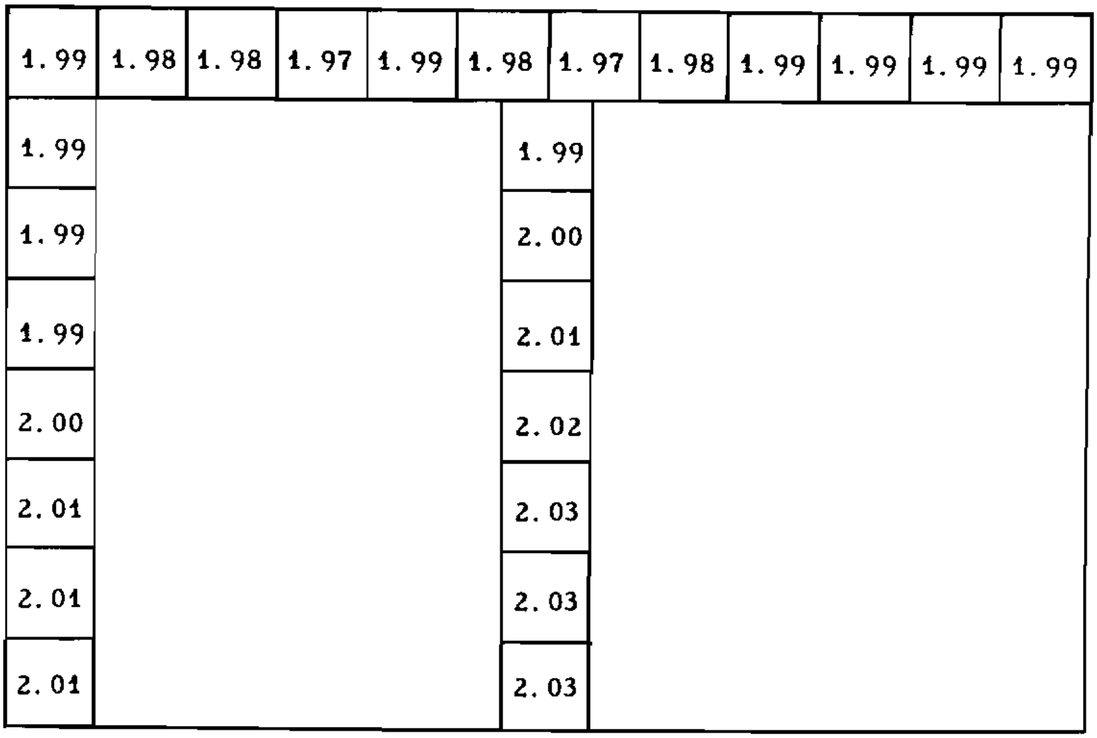
Table 43. Room-Temperature Properties, ZTF Graphite, Block No. 137A, 14-Inch Diameter by 11-Inch Length

Properties	With Grain Average	With Grain σ	With Grain n	Across Grain Average	Across Grain σ	Across Grain n
Bulk Density, g/cc	1.99	0.01	72	---	---	--
Specific Resistance, 10^{-4} ohm-cm	7.24	0.62	40	21.48	1.22	32
Young's Modulus, 10^{6} lbs/in^2	2.83	0.25	40	0.73	0.03	32
Flexural Strength, lbs/in^2	4005	420	40	1435	150	32
Compressive Strength, lbs/in^2	6930	1175	47	8940	990	46

Properties	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
CTE, $10^{-6}/°C$, 20°-100°C	1.03	0.35	0.63	4	8.66	7.44	8.20	4
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ °K}$	0.405	0.335	0.374	3	0.085	0.078	0.081	4
Admittance, cm^2/sec	$1x10^{-3}$	$4x10^{-4}$	$6x10^{-4}$	4	$2x10^{-4}$	$2x10^{-4}$	$2x10^{-4}$	3
Per Cent Ash	0.276	0.274	0.275	2	---	---	---	-

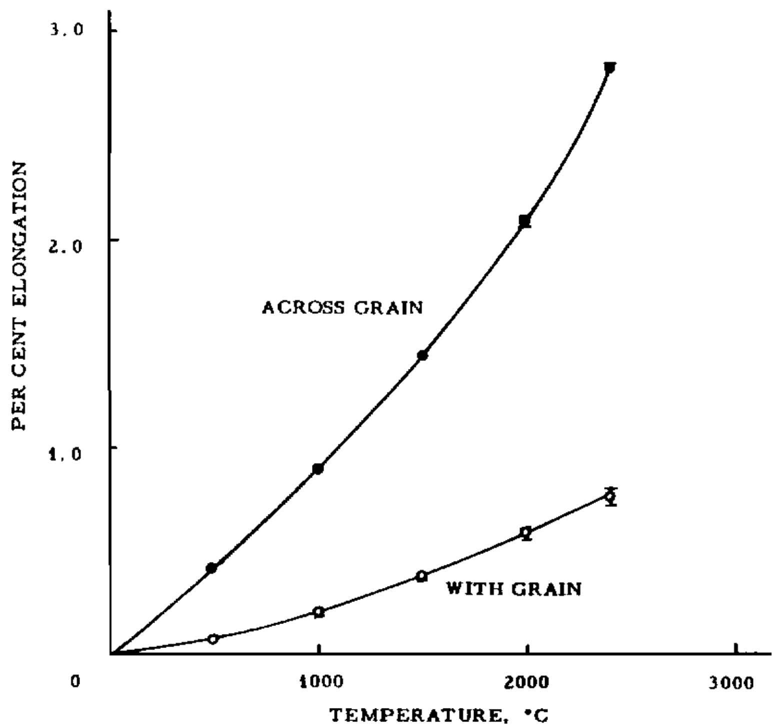
Table 44. High-Temperature Properties, ZTF Graphite, Block No. 137A, 14-Inch Diameter by 11-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	With Grain No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n	Across Grain No. of Blocks
Thermal Expansion Per Cent of Length Ambient Temperature	500	0.072	0.056	0.064	3	1	0.423	0.403	0.412	3	1
	1000	0.209	0.177	0.197	3	1	0.910	0.875	0.890	3	1
	1500	0.394	0.350	0.374	3	1	1.453	1.423	1.437	3	1
	2000	0.602	0.535	0.577	3	1	2.085	2.040	2.066	3	1
	2400	0.792	0.711	0.762	3	1	2.836	2.814	2.822	3	1
Young's Modulus - Sonic, 10^6 lbs/in^2	RT	2.93	2.87	2.90	3	1	0.66	0.63	0.65	4	1
	600	3.01	2.94	2.97	3	1	0.67	0.66	0.665	4	1
	1200	3.27	3.25	3.26	3	1	0.73	0.70	0.715	4	1
	1600	3.55	3.49	3.52	3	1	0.81	0.75	0.78	4	1
	2000	3.94	3.75	3.86	3	1	1.01	0.84	0.91	4	1
	2400	4.22	3.93	4.09	3	1	1.05	0.97	1.00	4	1
	2500	4.24	3.87	4.10	3	1	---	---	---	-	-
	2600	---	---	---	-	-	1.11	0.96	1.00	4	1
	2800	4.18	3.40	3.88	3	1	0.97	0.85	0.93	4	1



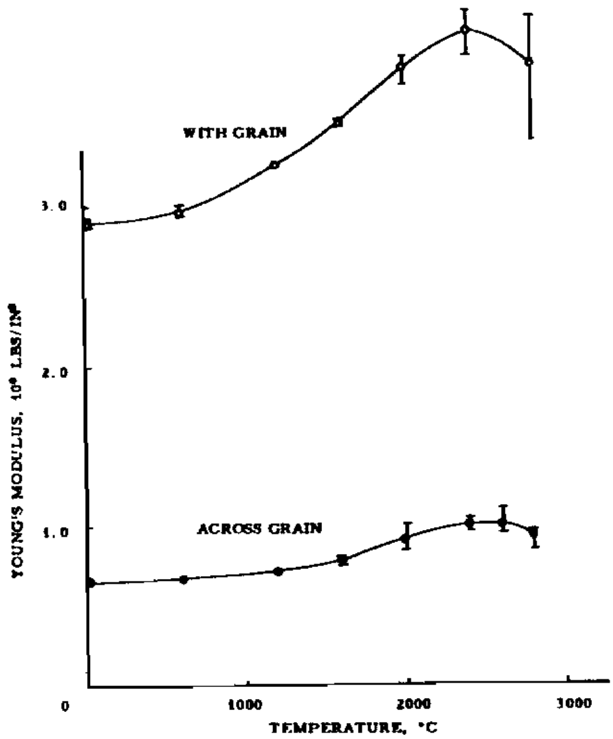
L-492

Figure 111. Density Profile, ZTF Graphite, Block No. 137A, 14-Inch Diameter by 10-Inch Length



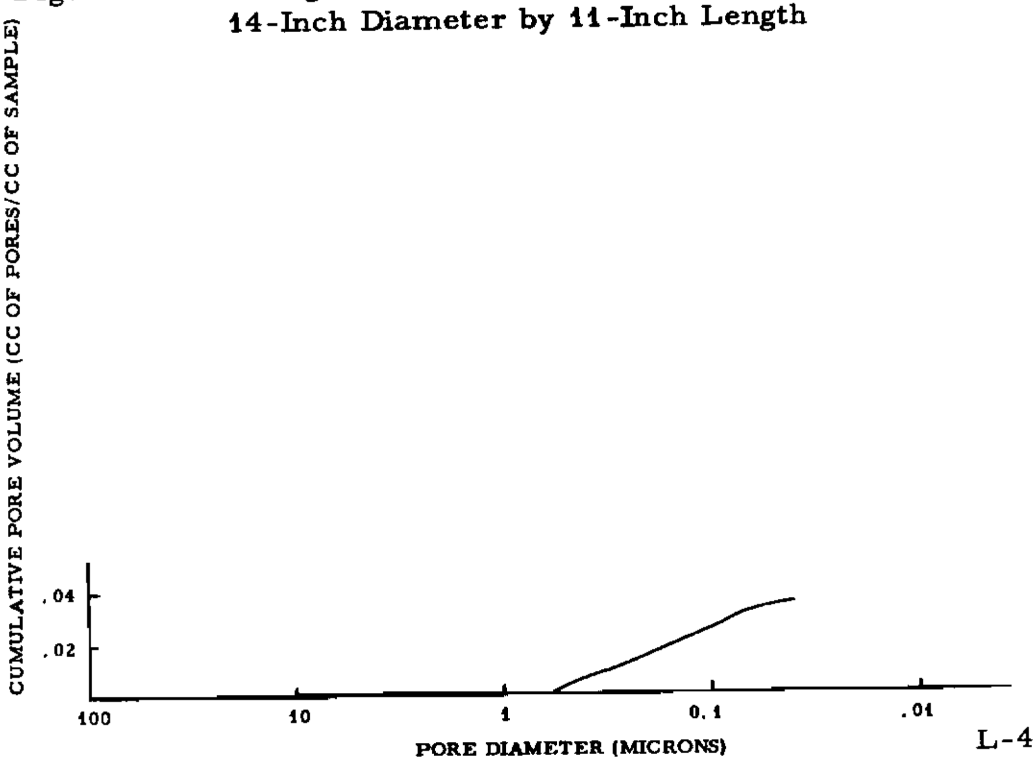
L-493

Figure 112. Thermal Expansion vs. Temperature, ZTF Graphite, 14-Inch Diameter by 11-Inch Length



L-494

Figure 113. Young's Modulus vs. Temperature, ZTF Graphite, 14-Inch Diameter by 11-Inch Length



L-495

Figure 114. Pore Size Distribution, Mercury Porosimetry ZTF Graphite

3.8. Grade RVA Graphite[18, 19]

Physical properties were obtained from three blocks of 33-inch diameter by 42-inch length RVA graphite. The combined data of the three blocks are given in Tables 45 and 46, and the results of the measurements on individual blocks are presented in Tables 47 to 52, inclusive. Figures 118 and 119, respectively, are plots of the thermal expansion and Young's modulus data from Table 46. Again the unusual stress-strain curves in tension (serrated) were in evidence. The interpretation of stress-strain curves was discussed in Section 3.1. All strength measurements are made at cross-head or platen rates of 0.020 inch per minute.

Table 45. Summary of Room-Temperature Properties, RVA Graphite, 33-Inch Diameter by 42-Inch Length

Properties	With Grain: Average	σ	n	No. of Blocks	Across Grain: Average	σ	n	No. of Blocks
Bulk Density, g/cc	1.84	0.019	312	3	---	---	---	-
Specific Resistance, 10^{-4} ohm-cm	12.21	0.37	149	3	15.73	0.96	162	3
Young's Modulus, 10^{6} lbs/in^{2}	1.837	0.069	128	3	1.301	0.110	162	3
Flexural Strength, lbs/in^{2}	3800	312	135	3	2995	286	121	3
Compressive Strength, 1- by 1- by 1-inch, lbs/in^{2}	9960	1308	46	3	9000	2000	46	3
Compressive Strength, ½-inch diameter by ½-inch, lbs/in^{2}	10255	909	30	3	10590	532	30	3
Tensile Strength, lbs/in^{2}	2975	423	30	3	2115	185	29	3
Apparent Shear Strength, lbs/in^{2}	2690	228	32	3	2380	267	34	3
CTE (20°-100°C), 10^{-6}/°C	1.65	.09	12	3	2.77	.07	12	3

Properties	With Grain: Max.	Min.	Ave.	n	No. of Blocks	Across Grain: Max.	Min.	Ave.	n	No. of Blocks
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ {}^\circ\text{K}}$	0.284	0.239	0.262	9	3	0.246	0.202	0.225	9	3
Permeability, Darcy's	0.0025	0.0008	0.0016	9	3	0.0019	0.0004	0.0011	9	3
Admittance, cm^{2}/sec.	1×10^{-1}	1×10^{-2}	8×10^{-2}	9	3	1×10^{-1}	5×10^{-2}	8×10^{-2}	6	3
Per Cent Ash	0.657	0.175	0.382	3	3	---	---	---	-	-

Table 46. Summary of High-Temperature Properties, RVA Graphite, 33-Inch Diameter by 42-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	With Grain No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n	Across Grain No. of Blocks
CTE	500	0.133	0.108	0.116	9	3	0.170	0.147	0.155	9	3
Per Cent Elongation	1000	0.300	0.269	0.288	9	3	0.381	0.326	0.359	9	3
$\frac{\Delta L}{L} \times 100$	1500	0.545	0.469	0.500	9	3	0.683	0.554	0.613	9	3
	2000	0.805	0.720	0.768	9	3	1.024	0.883	0.941	9	3
	2400	1.094	0.967	1.031	9	3	1.370	1.206	1.275	9	3
	2800	1.389	1.247	1.318	9	3	1.738	1.555	1.638	9	3
Young's Modulus,	RT	2.17	1.71	1.94	9	3	1.44	1.20	1.33	10	3
10^6 lbs/in²	600	2.20	1.77	1.98	9	3	1.47	1.22	1.35	10	3
	1200	2.27	1.93	2.13	9	3	1.62	1.37	1.49	10	3
Sonic	1600	2.41	2.14	2.26	9	3	1.81	1.52	1.68	10	3
	2000	2.60	2.25	2.39	9	3	2.02	1.75	1.86	10	3
	2200	2.62	2.28	2.40	9	3	2.03	1.74	1.86	10	3
	2400	2.60	2.27	2.38	9	3	1.96	1.71	1.81	10	3
	2800	2.49	2.18	2.31	9	3	1.75	1.55	1.64	10	3
Tensile Strength,	1000	4380	3140	3855	3	3	3235	2400	2745	3	3
lbs/in²	1500	4645	3885	4280	3	3	3480	3260	3385	3	3
	2000	5250	4130	4685	3	3	4150	3670	3860	3	3
	2500	7220	5280	6180	3	3	4670	4180	4440	3	3
	2700	5005	4240	4540	3	3	4515	3540	4005	3	3
Compressive Strength,	1000	9980	8775	9345	3	3	11665	9820	10490	3	3
½-inch diameter by	1500	13090	9475	11748	3	3	12580	12225	12125	3	3
½ inch, lbs/in²	2000	15535	10235	12935	3	3	14260	13545	13855	3	3
	2500	19455	17200	18205	4	3	21355	18100	19405	3	3
	2700	No break	18945	?	3	3	18285	17670	17995	3	3
	2800	---	---	---	-	-	---	---	25365	1	1
Apparent Shear Strength,	1000	5260	2490	3715	4	3	4450	2545	3495	3	3
lbs/in²	1500	4890	4090	4465	3	3	4450	2905	3915	3	3
	2000	6080	3270	5070	3	3	4535	3760	4200	3	3
	2500	7235	5035	6430	4	3	5175	4725	4960	3	3
	2700	6745	3930	5275	3	3	6845	5860	6355	3	3
	2900	---	---	---	-	-	---	---	7335	1	1

Table 47. Room-Temperature Properties, RVA Graphite, Block No. A-19, 33-Inch Diameter by 42-Inch Length

Properties	With Grain Average	With Grain σ	With Grain n	Across Grain Average	Across Grain σ	Across Grain n
Bulk Density, g/cc	1.825	0.012	81	---	---	--
Specific Resistivity, 10^{-4} ohm-cm	12.25	0.38	45	16.87	0.	35
Young's Modulus, 10^{6} lbs/in^2	1.810	0.066	45	1.185	0.055	35
Flexural Strength, lbs/in^2	3770	280	42	2870	176	35
Compressive Strength, 1- by 1- by 1-inch, lbs/in^2	9425	1160	15	7730	1350	15
Compressive Strength, $\frac{1}{2}$-inch diameter by $\frac{1}{2}$-inch, lbs/in^2	9675	876	10	10255	133	10
Tensile Strength, lbs/in^2	3200	180	10	2190	183	9
Apparent Shear Strength, lbs/in^2	2515	175	10	2190	187	11

Properties	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
CTE, $10^{-6}/°C$, 20°-100°C	1.67	1.62	1.64	4	2.89	2.83	2.85	4
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ °K}$	0.268	0.259	0.262	3	0.246	0.202	0.226	3
Permeability, Darcy's	0.0017	0.0010	0.0014	3	0.0016	0.0009	0.0012	3
Admittance, cm^2/sec	$9x10^{-2}$	$4x10^{-2}$	$7x10^{-2}$	3	$9x10^{-2}$	$5x10^{-2}$	$7x10^{-2}$	2
Per Cent Ash	---	---	0.647	1	---	---	---	-

Table 48. High-Temperature Properties, RVA Graphite, Block A-19, 33-Inch Diameter by 42-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	n
Thermal Expansion	500	0.119	0.114	0.117	3	0.150	0.147	0.148	3
Per Cent Elongation	1000	0.229	0.296	0.297	3	0.375	0.326	0.350	3
$\frac{\Delta L}{L} \times 100$	1500	0.510	0.509	0.510	3	0.626	0.554	0.588	3
	2000	0.785	0.781	0.783	3	0.955	0.883	0.915	3
	2400	1.055	1.027	1.044	3	1.289	1.206	1.247	3
	2800	1.389	1.261	1.345	3	1.616	1.555	1.583	3
Young's Modulus,	RT	1.95	1.89	1.92	3	1.38	1.25	1.32	3
10^6 lbs/in^2	600	1.99	1.91	1.95	3	1.42	1.27	1.35	3
	1200	2.23	2.08	2.14	3	1.51	1.37	1.44	3
	1600	2.41	2.18	2.26	3	1.66	1.54	1.61	3
	2000	2.56	2.25	2.39	3	1.79	1.75	1.77	3
	2400	2.49	2.27	2.36	3	1.73	1.71	1.72	3
	2800	2.31	2.18	2.24	3	1.58	1.55	1.57	3
Tensile Strength,	1000	---	---	4380	1	---	---	3235	1
lbs/in^2	1500	---	---	4645	1	---	---	3480	1
	2000	---	---	5250	1	---	---	4150	1
	2500	---	---	6040	1	---	---	4180	1
	2700	---	---	4380	1	---	---	3965	1
Compressive Strength,	1000	---	---	8775	1	---	---	9820	1
$\frac{1}{2}$-inch diameter by $\frac{1}{2}$-inch	1500	---	---	13090	1	---	---	12225	1
lbs/in^2	2000	---	---	10235	1	---	---	14260	1
	2500	---	---	17200	1	---	---	18100	1
	2700	---	---	22345	1	---	---	18285	1
	2800	---	---	---	-	---	---	25365	1
Apparent Shear Strength,	1000	5260	3505	4380	2	---	---	3485	1
lbs/in^2	1500	---	---	4890	1	---	---	4390	1
	2000	---	---	5860	1	---	---	4300	1
	2500	7065	6390	6728	2	---	---	5175	1
	2700	---	---	6745	1	---	---	6360	1
	2900	---	---	---	-	---	---	---	-

Table 49. Room-Temperature Properties, RVA Graphite, Block No. A-20, 33-Inch Diameter by 42-Inch Length

Properties	With Grain			Across Grain		
	Average	σ	n	Average	σ	n
Bulk Density, g/cc	1.842	0.021	114	---	---	--
Specific Resistance, 10^{-4} ohm-cm	12.34	0.35	49	15.20	0.92	65
Young's Modulus, 10^{6} lbs/in2	1.829	0.053	44	1.317	0.106	65
Flexural Strength, lbs/in^2	3880	336	49	3165	288	44
Compressive Strength, 1- by 1- by 1-inch, lbs/in^2	10250	1235	15	9790	1830	15
Compressive Strength, ½-inch diameter by ½-inch, lbs/in^2	10680	1024	10	11000	349	10
Tensile Strength, lbs/in^2	2605	284	10	2045	135	10
Apparent Shear Strength, lbs/in^2	2755	265	12	2395	197	12

	With Grain				Across Grain			
	Max.	Min.	Ave.	n	Max.	Min.	Ave.	n
CTE, $10^{-6}/°C$, 20°-100°C	1.79	1.73	1.76	4	2.80	2.74	2.77	4
Thermal Conductivity $\frac{\text{cal-cm}}{\text{sec cm}^2 \text{ °K}}$	0.268	0.258	0.265	3	0.239	0.216	0.224	3
Permeability, Darcy's	0.0016	0.0012	0.0013	3	0.0014	0.0009	0.0012	3
Admittance, cm^2/sec	9×10^{-2}	8×10^{-2}	8×10^{-2}	3	1×10^{-1}	6×10^{-2}	8×10^{-2}	2
Per Cent Ash	---	---	0.313	1	---	---	---	-

Table 50. High-Temperature Properties, RVA Graphite, Block No. A-20, 33-Inch Diameter by 42-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	n
Thermal Expansion Per Cent Elongation $\frac{\Delta L}{L} \times 100$	500	0.113	0.108	0.121	3	0.170	0.155	0.161	3
	1000	0.300	0.275	0.287	3	0.381	0.359	0.367	3
	1500	0.545	0.498	0.516	3	0.683	0.608	0.636	3
	2000	0.805	0.783	0.793	3	1.024	0.937	0.969	3
	2400	1.094	1.065	1.080	3	1.370	1.268	1.308	3
	2800	1.354	1.343	1.350	3	1.738	1.605	1.665	3
Youngs's Modulus, 10^6 lbs/in²	RT	2.17	1.71	1.97	3	1.42	1.28	1.35	3
	600	2.20	1.77	2.01	3	1.44	1.31	1.37	3
	1200	2.27	1.93	2.13	3	1.59	1.51	1.55	3
	1600	2.31	2.14	2.24	3	1.81	1.72	1.78	3
	2000	2.38	2.31	2.34	3	2.02	1.89	1.95	3
	2200	2.39	2.32	2.36	3	2.03	1.92	1.97	3
	2400	2.39	2.30	2.33	3	1.96	1.84	1.90	3
	2800	2.37	2.26	2.31	3	1.75	1.60	1.66	3
Tensile Strength, lbs/in²	1000	---	---	4040	1	---	---	2400	1
	1500	---	---	4310	1	---	---	3260	1
	2000	---	---	4680	1	---	---	3670	1
	2500	---	---	7220	1	---	---	4475	1
	2700	---	---	4240	1	---	---	4515	1
Compressive Strength, ½-inch diameter by ½-inch lbs/in²	1000	---	---	9980	1	---	---	9980	1
	1500	---	---	12680	1	---	---	12580	1
	2000	---	---	15535	1	---	---	13545	1
	2500	---	---	19455	1	---	---	18760	1
	2700	Did not break at		31500	1	---	---	18030	1
Apparent Shear Strength, lbs/in²	1000	---	---	2490	1	---	---	2545	1
	1500	---	---	4090	1	---	---	4450	1
	2000	---	---	3270	1	---	---	3760	1
	2500	---	---	5035	1	---	---	4980	1
	2700	---	---	3930	1	---	---	5860	1

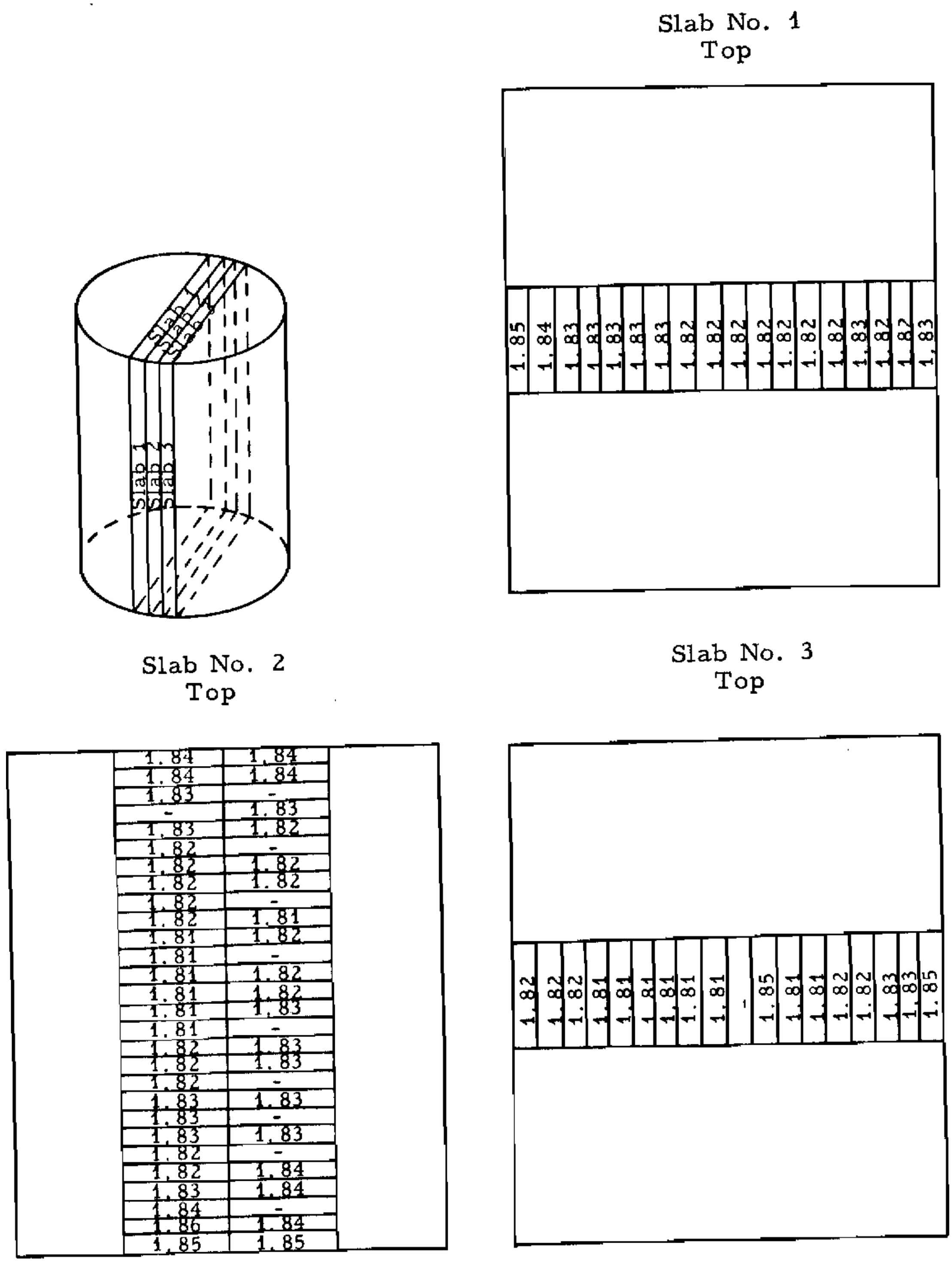
Table 51. Room-Temperature Properties, RVA Graphite, Block No. A-24
33-Inch Diameter by 42-Inch Length

Properties	With Grain Average	With Grain σ	With Grain n	Across Grain Average	Across Grain σ	Across Grain n
Bulk Density, g/cc	1.844	0.016	117	---	---	
Specific Resistance, 10^{-4} ohm-cm	12.06	0.34	55	15.65	0.66	62
Young's Modulus, 10^{6} lbs/in^2	1.878	0.070	39	1.349	0.092	62
Flexural Strength, lbs/in^2	3735	301	44	2925	276	42
Compressive Strength, 1- by 1- by 1-inch, lbs/in^2	10200	1425	16	9450	2175	16
Compressive Strength, ½-inch diameter by ½-inch, lbs/in^2	10420	491	10	10505	680	10
Tensile Strength, lbs/in^2	3120	479	10	2125	219	10
Apparent Shear Strength, lbs/in^2	2780	110	10	2560	170	11

Properties	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
CTE, 10^{-6}/°C, 20°-100°C	1.62	1.50	1.56	4	2.71	2.65	2.70	4
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ ^\circ\text{K}}$	0.284	0.239	0.260	3	0.227	0.220	2.24	3
Permeability, Darcy's	0.0025	0.0008	0.0019	3	0.0019	0.0004	0.0011	3
Admittance, cm^2/sec	1×10^{-1}	6×10^{-2}	7×10^{-2}	3	1×10^{-1}	7×10^{-3}	9×10^{-2}	2
Per Cent Ash	---	---	0.175	1	---	---	---	-

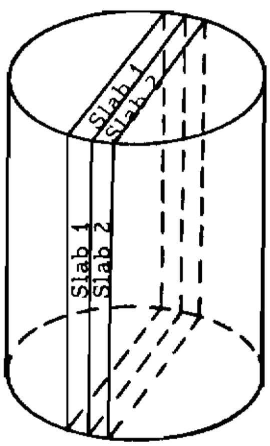
Table 52. High-Temperature Properties, RVA Graphite, Block No. A-24, 33-Inch Diameter by 42-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
Thermal Expansion Per Cent Elongation $\frac{\Delta L}{L} \times 100$	500	0.111	0.110	0.111	3	0.161	0.153	0.156	3
	1000	0.286	0.269	0.279	3	0.366	0.353	0.361	3
	1500	0.475	0.469	0.473	3	0.633	0.590	0.615	3
	2000	0.734	0.720	0.728	3	0.952	0.931	0.940	3
	2400	0.969	0.967	0.968	3	1.288	1.251	1.270	3
	2800	1.269	1.247	1.258	3	1.697	1.634	1.665	3
Young's Modulus, 10^6 lbs/in^2	RT	1.93	1.92	1.93	3	1.44	1.20	1.31	3
	600	2.04	1.97	1.99	3	1.47	1.22	1.34	3
	1200	2.17	2.11	2.13	3	1.62	1.39	1.48	3
	1600	2.37	2.22	2.29	3	1.80	1.52	1.65	3
	2000	2.60	2.31	2.43	3	1.99	1.75	1.85	3
	2400	2.60	2.33	2.44	3	1.90	1.74	1.82	3
	2800	2.49	2.29	2.38	3	1.73	1.63	1.69	3
Tensile Strength, lbs/in^2	1000	---	---	3140	1	---	---	2595	1
	1500	---	---	3885	1	---	---	3410	1
	2000	---	---	4130	1	---	---	3755	1
	2500	---	---	5280	1	---	---	4670	1
	2700	---	---	5005	1	---	---	3540	1
Compressive Strength, ½-inch diameter by ½-inch lbs/in^2	1000	---	---	9285	1	---	---	11665	1
	1500	---	---	9475	1	---	---	12575	1
	2000	---	---	13040	1	---	---	13755	1
	2500	18335	17825	18080	2	---	---	21355	1
	2700	---	---	18945	1	---	---	17670	1
Apparent Shear Strength, lbs/in^2	1000	---	---	3605	1	---	---	4450	1
	1500	---	---	4410	1	---	---	2905	1
	2000	---	---	6080	1	---	---	4535	1
	2500	---	---	7235	1	---	---	4725	1
	2700	---	---	5145	1	---	---	6845	1



L-496

Figure 115. Density Profile, RVA Graphite, Block No. A-19, 33-Inch Diameter by 42-Inch Length



Slab No. 1
Top

1.88	1.88	1.87	1.86	1.86	1.85	1.85	1.85	1.84	1.84	1.84	1.84	1.84	[illegible]	1.85	1.86	1.86	1.87	1.87	1.88	1.88	1.89
1.86	1.84	1.83	1.82	1.82	1.81	1.81	1.81	1.81	1.81	-	1.81	1.81	1.81	1.81	1.81	1.82	1.84	1.83	1.83	1.84	1.85
1.88	1.87	1.87	1.87	1.86	1.85	1.85	1.84	1.84	1.84	1.83	1.83	1.84	1.86	1.85	1.85	1.86	1.87	1.87	1.88	1.88	1.88

Slab No. 2
Top

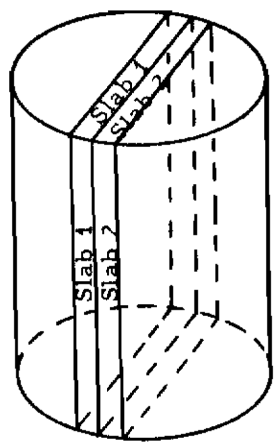
1.85	1.85
1.85	1.86
1.84	1.85
1.84	1.84
1.83	-
1.83	1.84
1.83	1.84
1.82	1.83
1.82	1.83
1.82	1.82
1.82	1.82
1.82	1.82
1.85	-
1.85	1.82
1.85	1.83
1.85	1.84
1.85	1.83
1.84	1.84
1.83	1.84
1.83	-
1.82	1.84
1.82	1.84
1.82	1.85
1.85	1.85
1.85	1.86
1.83	1.88

L-497

Figure 116. Density Profile, RVA Graphite, Block No. A-20, 33-Inch Diameter by 42-Inch Length

Slab No. 1
Top

1.89	1.88	1.87	1.87	1.87	1.86	1.86	1.84	1.84	-	1.83	1.83	1.83	1.84	1.84	1.85	1.85	1.86	1.87	1.87	1.87
1.87	1.85	1.83	1.83	1.83	1.83	1.82	1.83	1.87	1.82	1.82	1.82	1.82	1.82	1.82	1.83	1.83	1.83	1.84	1.83	1.84
1.89	1.87	1.87	1.87	1.87	1.86	1.86	1.85	1.85	1.85	1.87	1.85	1.85	1.85	1.85	1.85	1.86	1.86	1.87	1.87	1.88

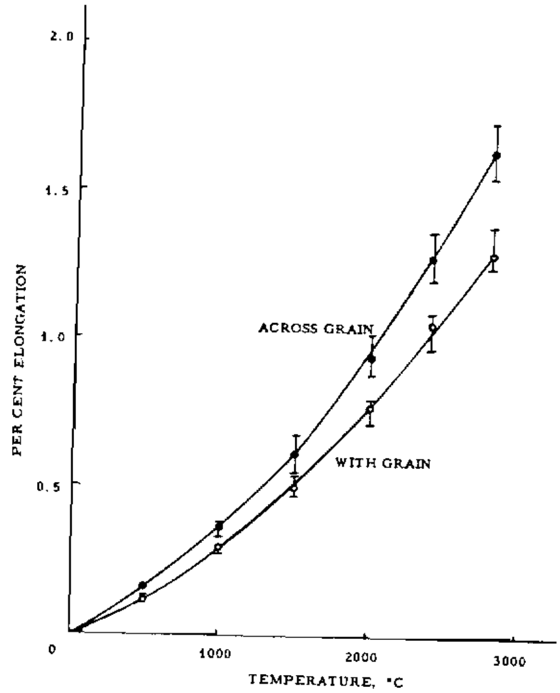


Slab No. 2
Top

1.86	1.86
1.85	1.84
1.85	1.83
1.84	1.83
1.84	1.83
1.84	1.83
1.84	1.84
1.84	1.84
1.84	1.84
1.85	1.84
1.85	1.84
1.84	1.84
1.83	1.83
-	1.82
1.83	1.82
1.82	1.82
1.82	1.82
1.83	1.83
1.84	1.83
1.84	1.83
1.84	1.84
1.85	1.84
1.85	1.84
1.85	1.84
1.85	1.83
1.85	1.86
1.86	1.84
1.85	1.84

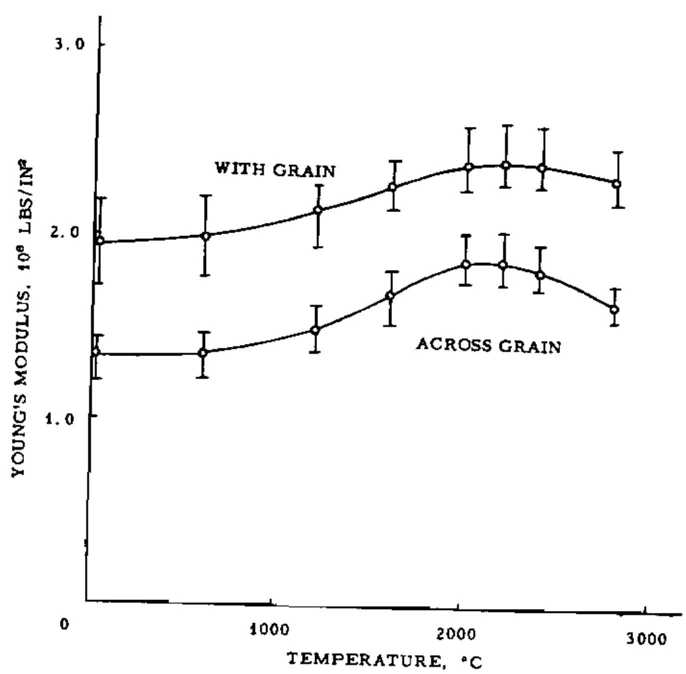
L-498

Figure 117. Density Profile, RVA Graphite, Block No. A-24, 33-Inch Diameter by 42-Inch Length



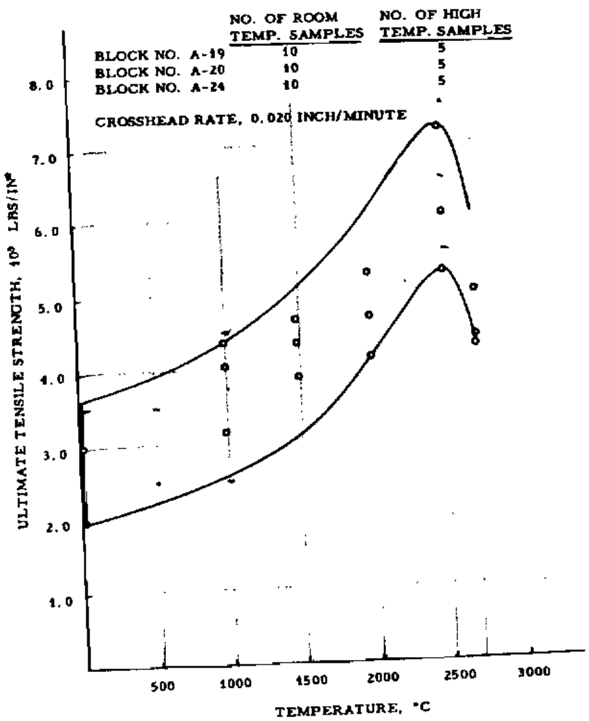
L-499

Figure 118. Thermal Expansion vs. Temperature, RVA Graphite, 33-Inch Diameter by 42-Inch Length



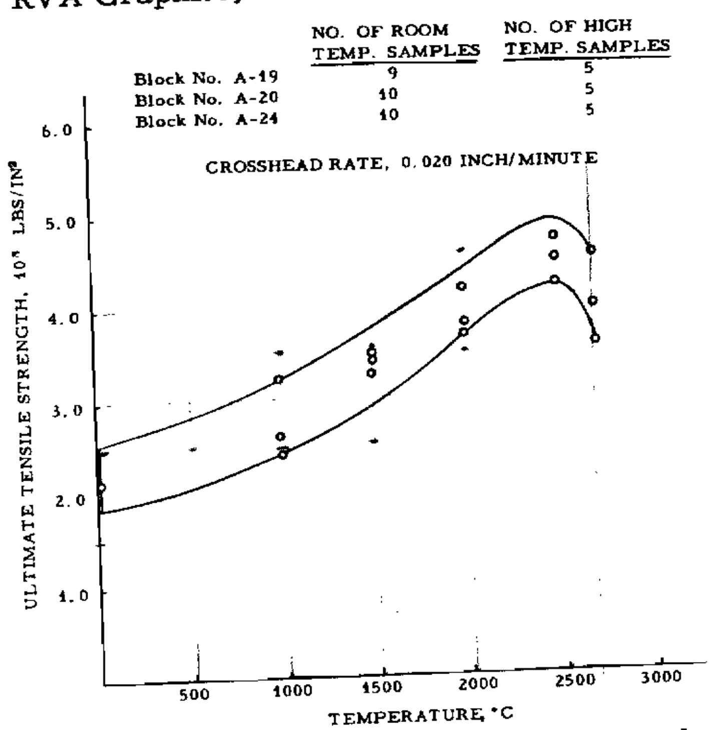
L-500

Figure 119. Young's Modulus vs. Temperature, RVA Graphite, 33-Inch Diameter by 42-Inch Length



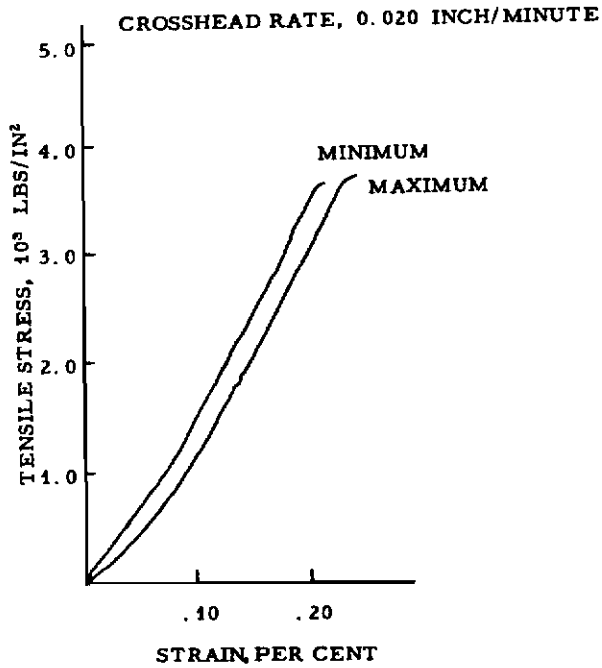
L-501

Figure 120. With-Grain Ultimate Tensile Strength vs. Temperature, RVA Graphite, 33-Inch Diameter by 42-Inch Length



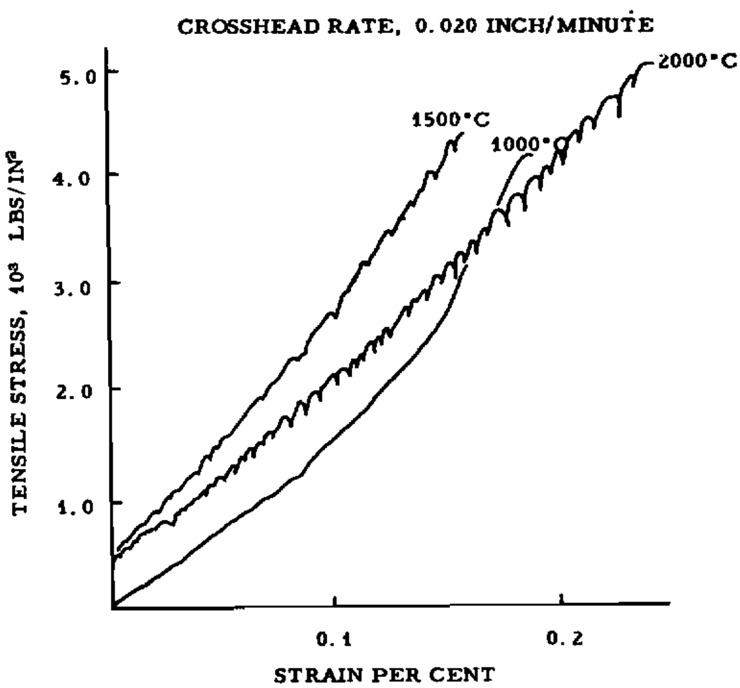
L-502

Figure 121. Across-Grain Ultimate Tensile Strength vs. Temperature, RVA Graphite, 33-Inch Diameter by 42-Inch Length



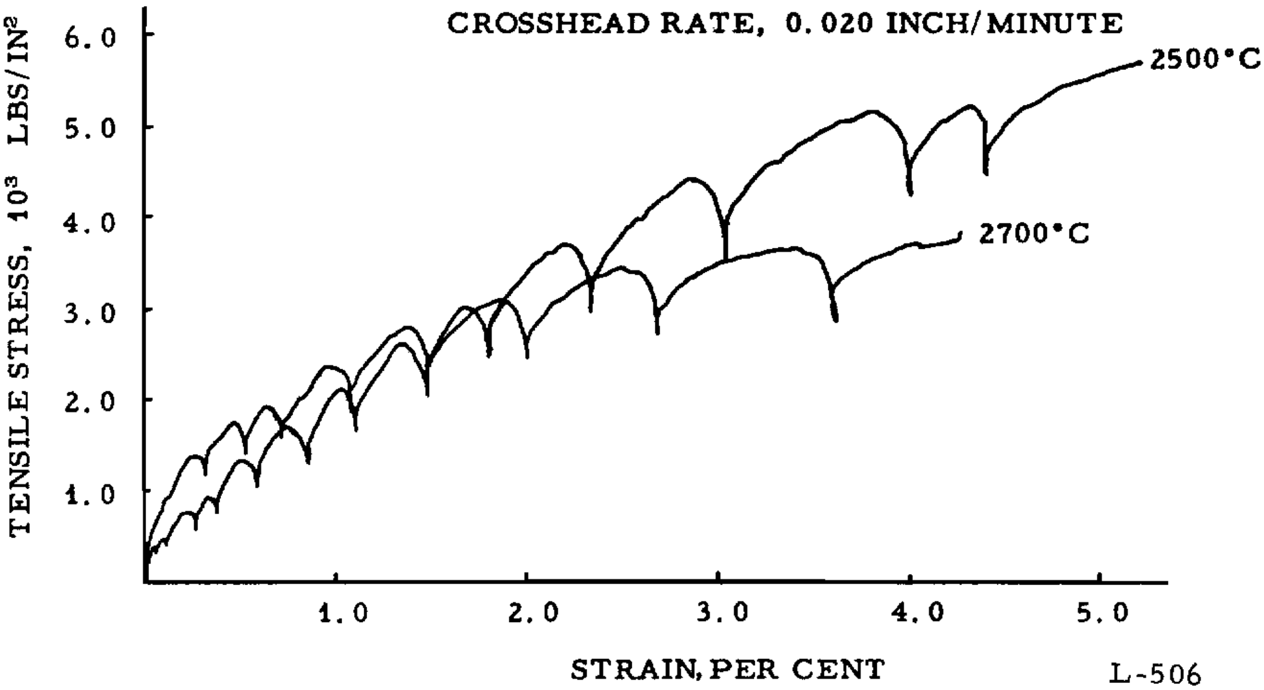
L-504

Figure 122. With-Grain Tensile Stress-Strain Curves, RVA Graphite, 33-Inch Diameter by 42-Inch Length, Block No. A-19, Room Temperature



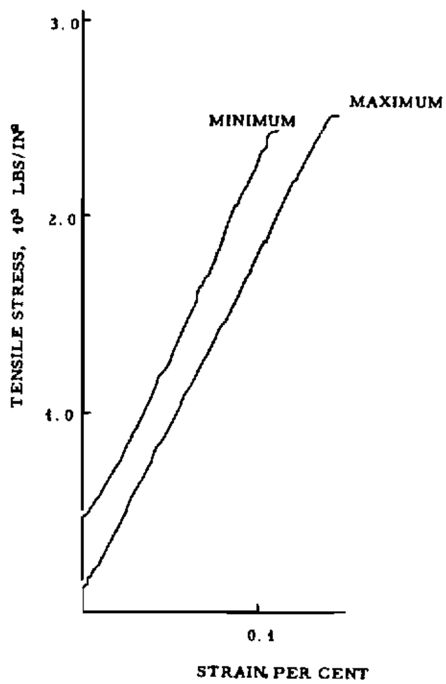
L-505

Figure 123. With-Grain Tensile Stress-Strain Curves, RVA Graphite, 33-Inch Diameter by 42-Inch Length, Block No. A-19, 1000°C, 1500°C, 2000°C



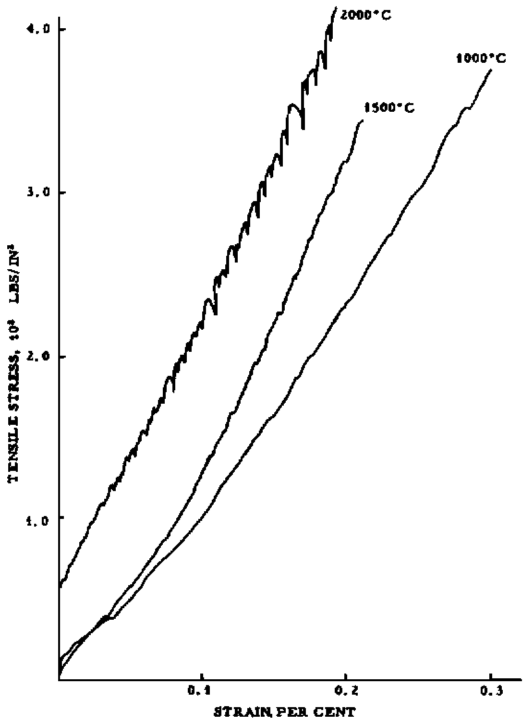
L-506

Figure 124. With-Grain Tensile Stress-Strain Curve, RVA Graphite, 33-Inch Diameter by 42-Inch Length, Block No. A-19, 2500°C, 2700°C



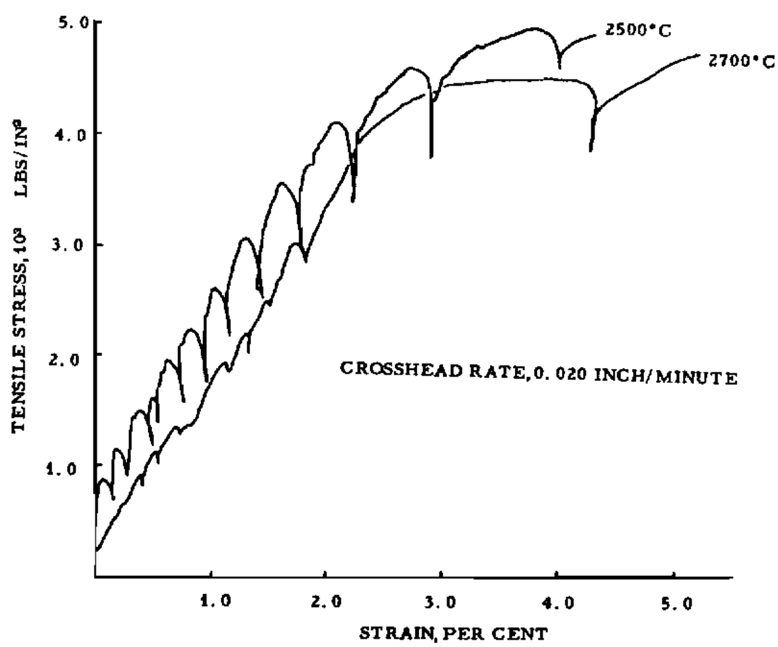
L-507

Figure 125. Across-Grain Tensile Stress-Strain Curves, RVA Graphite, 33-Inch Diameter by 42-Inch Length, Block No. A-19, Room Temperature



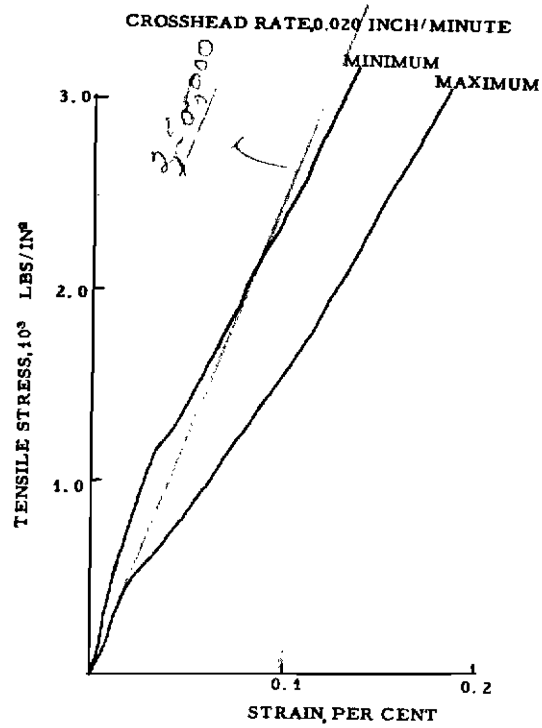
L-508

Figure 126. Across-Grain Tensile Stress-Strain Curves, RVA Graphite, 33-Inch Diameter by 42-Inch Length, Block No. A-19, 1000°C, 1500°C, 2000°C



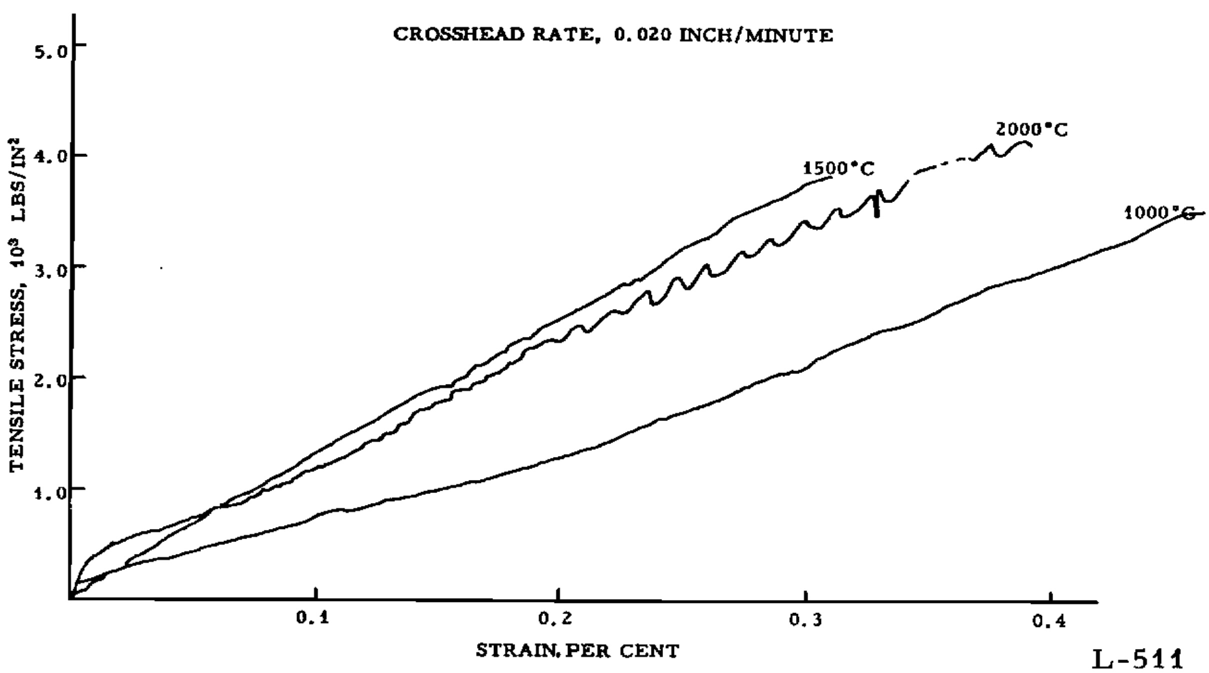
L-509

Figure 127. Across-Grain Tensile Stress-Strain Curves, RVA Graphite 33-Inch Diameter by 42-Inch Length, Block No. A-19, 2500°C, 2700°C



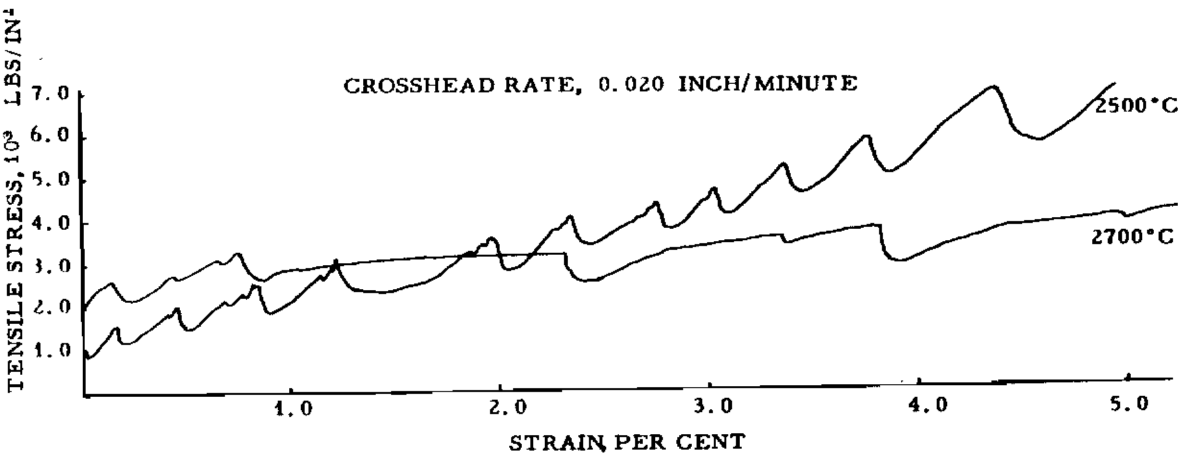
L-510

Figure 128. With-Grain Tensile Stress-Strain Curves, RVA Graphite, 33-Inch Diameter by 42-Inch Length, Block No. A-20, Room Temperature



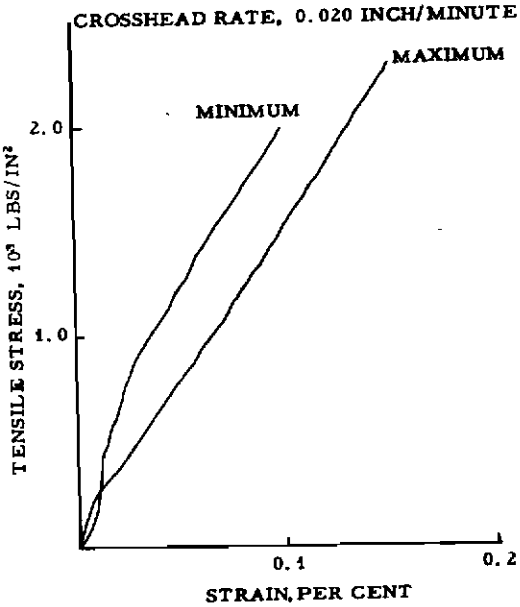
L-511

Figure 129. With-Grain Tensile Stress-Strain Curves, RVA Graphite, 33-Inch Diameter by 42-Inch Length, Block No. A-20, 1000°C, 1500°C, 2000°C



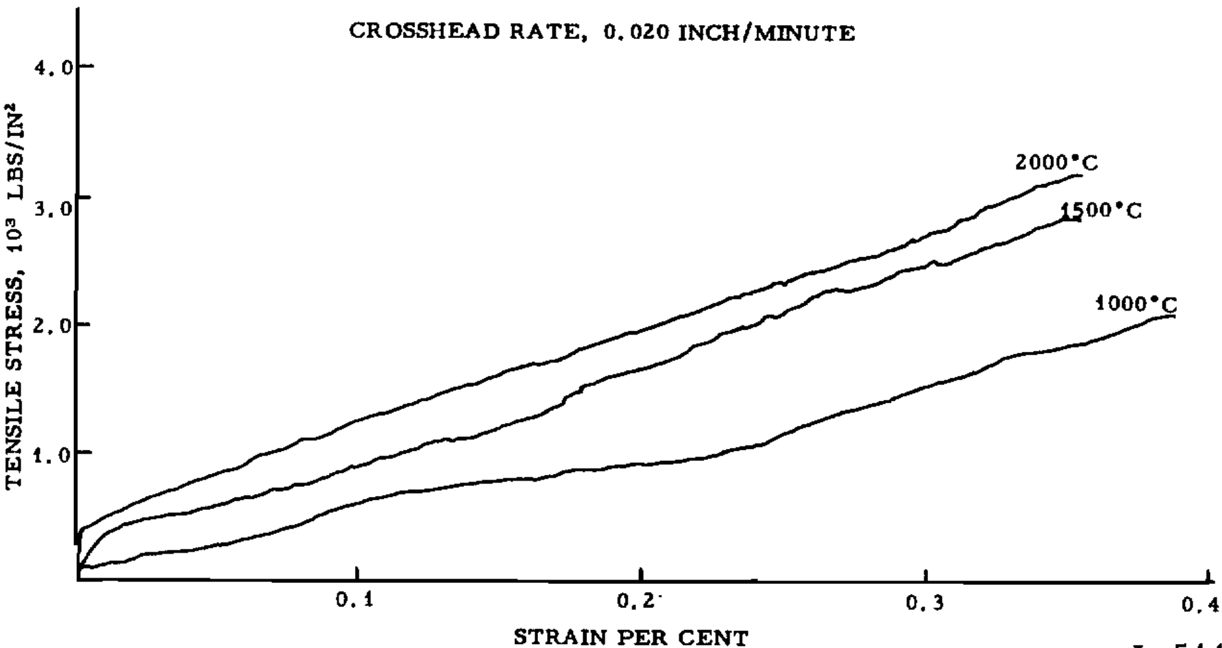
L-512

Figure 130. With-Grain Tensile Stress-Strain Curves, RVA Graphite, 33-Inch Diameter by 42-Inch Length, Block No. A-20, 2500°C, 2700°C



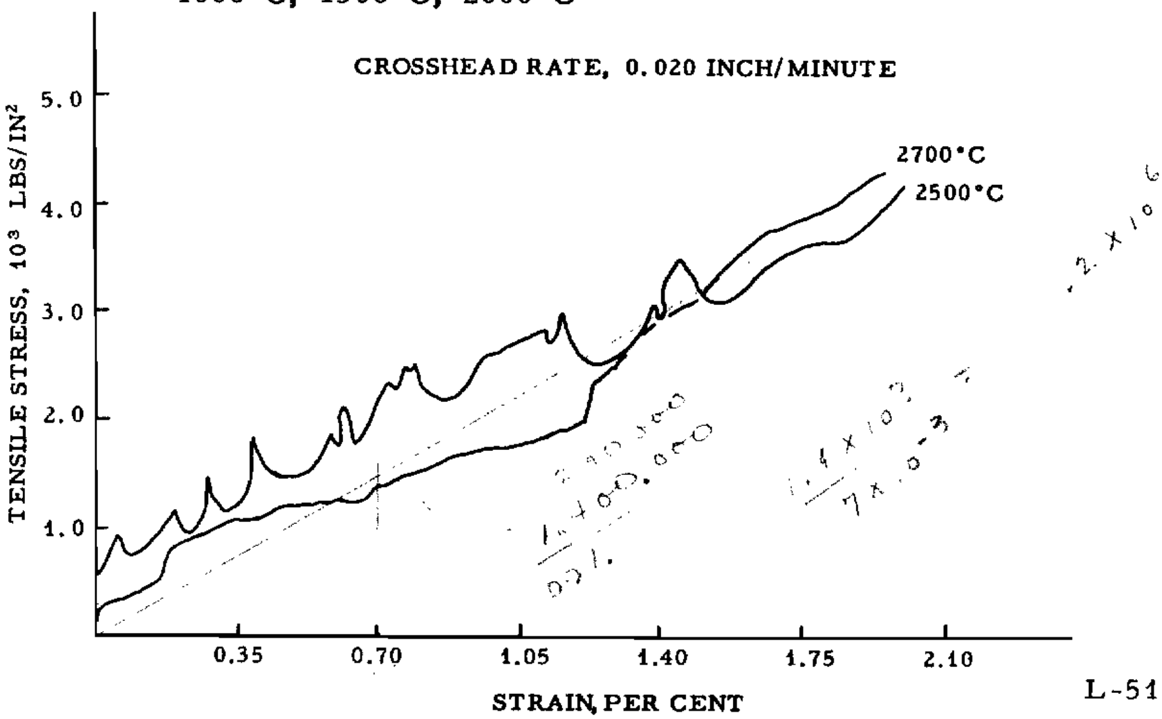
L-513

Figure 131. Across-Grain Tensile Stress-Strain Curves, RVA Graphite, 33-Inch Diameter by 42-Inch Length, Block No. A-20, Room Temperature



L-514

Figure 132. Across-Grain Tensile Stress-Strain Curves, RVA Graphite, 33-Inch Diameter by 42-Inch Length, Block No. A-20, 1000°C, 1500°C, 2000°C



L-515

Figure 133. Across-Grain Tensile Stress-Strain Curves, RVA Graphite, 33-Inch Diameter by 42-Inch Length, Block No. A-20, 2500°C, 2700°C

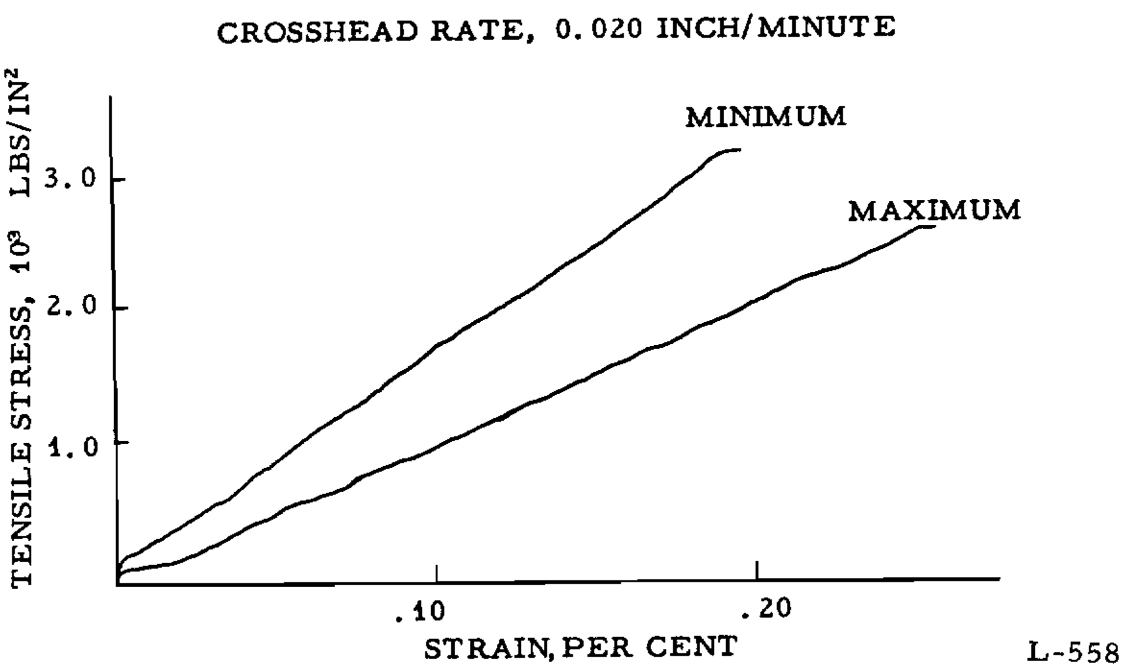


Figure 134. With-Grain Tensile Stress-Strain Curves, RVA Graphite, 33-Inch Diameter by 42-Inch Length, Block No. A-24, Room Temperature

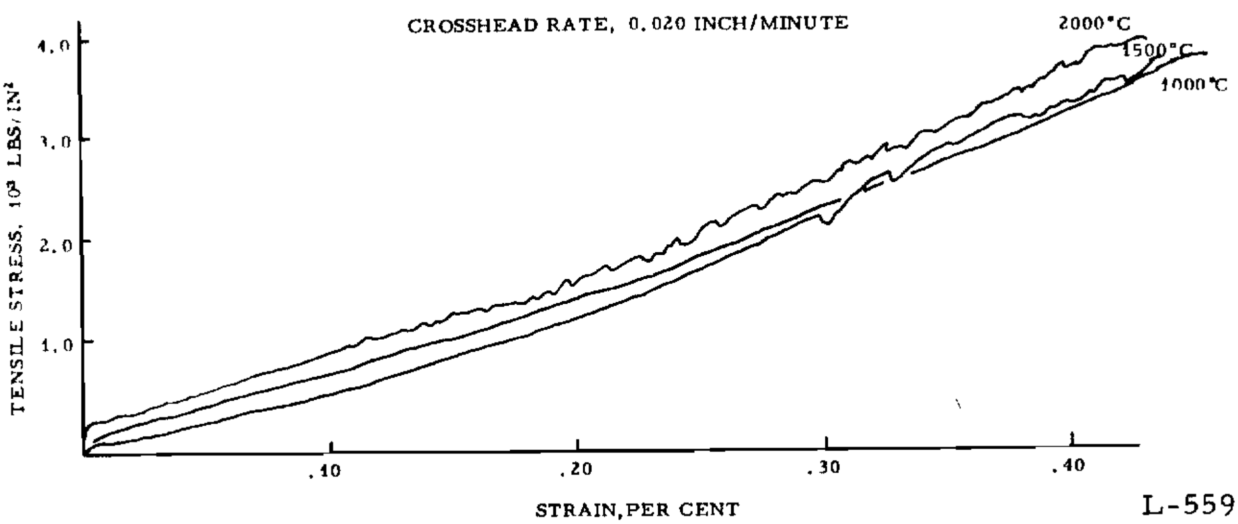


Figure 135. With-Grain Tensile Stress-Strain Curves, RVA Graphite, 33-Inch Diameter by 42-Inch Length, Block No. A-24, 1000°C, 1500°C, 2000°C

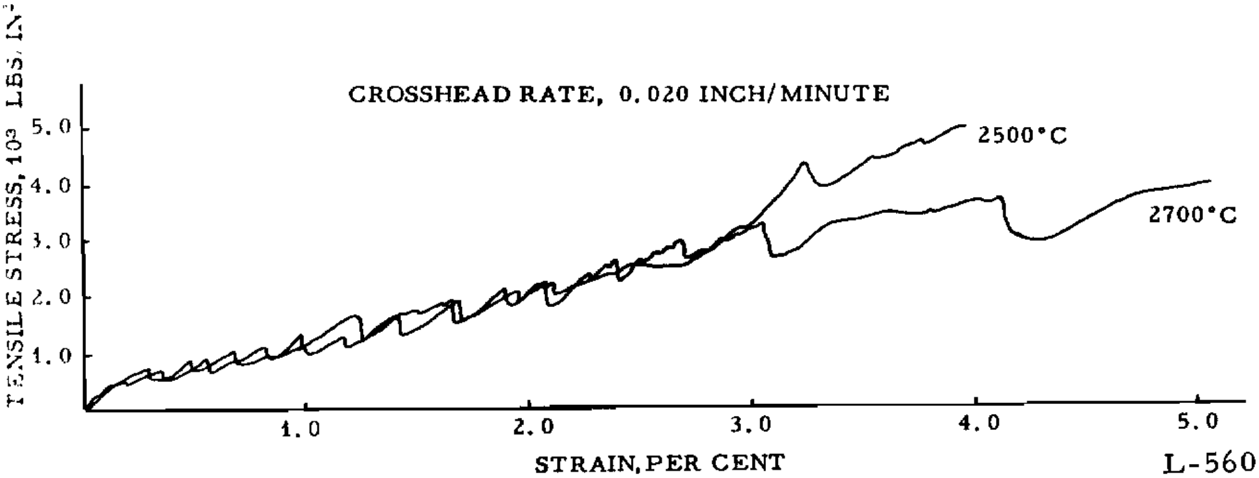


Figure 136. With-Grain Tensile Stress-Strain Curves, RVA Graphite, 33-Inch Diameter by 42-Inch Length, Block No. A-24, 2500°C, 2700°C

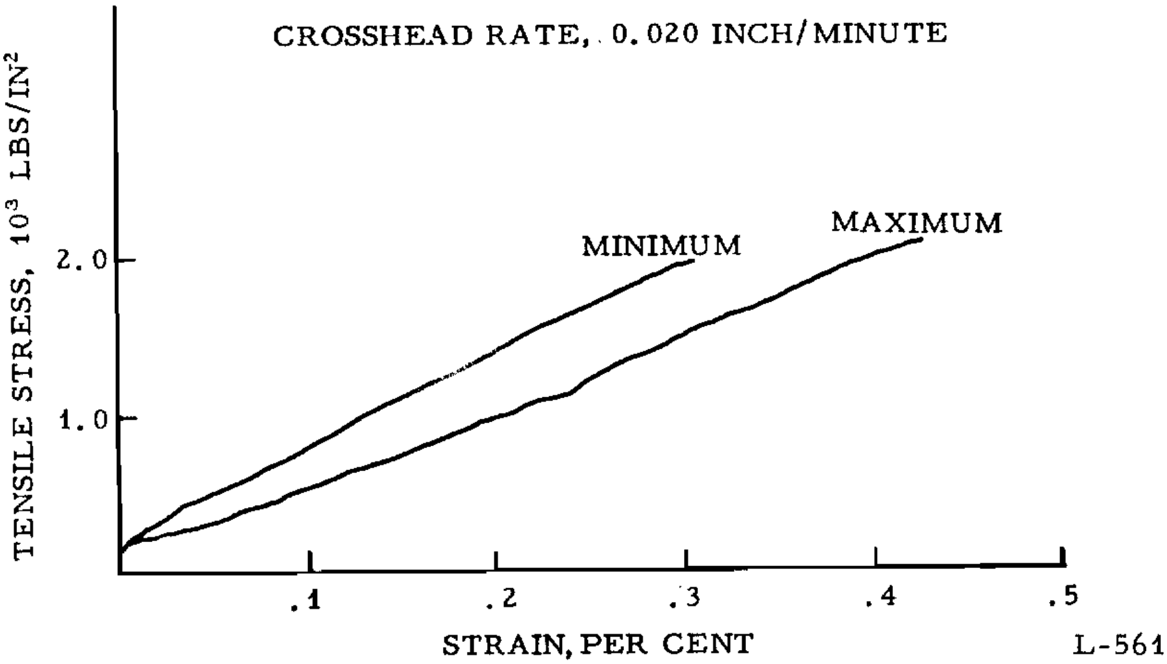
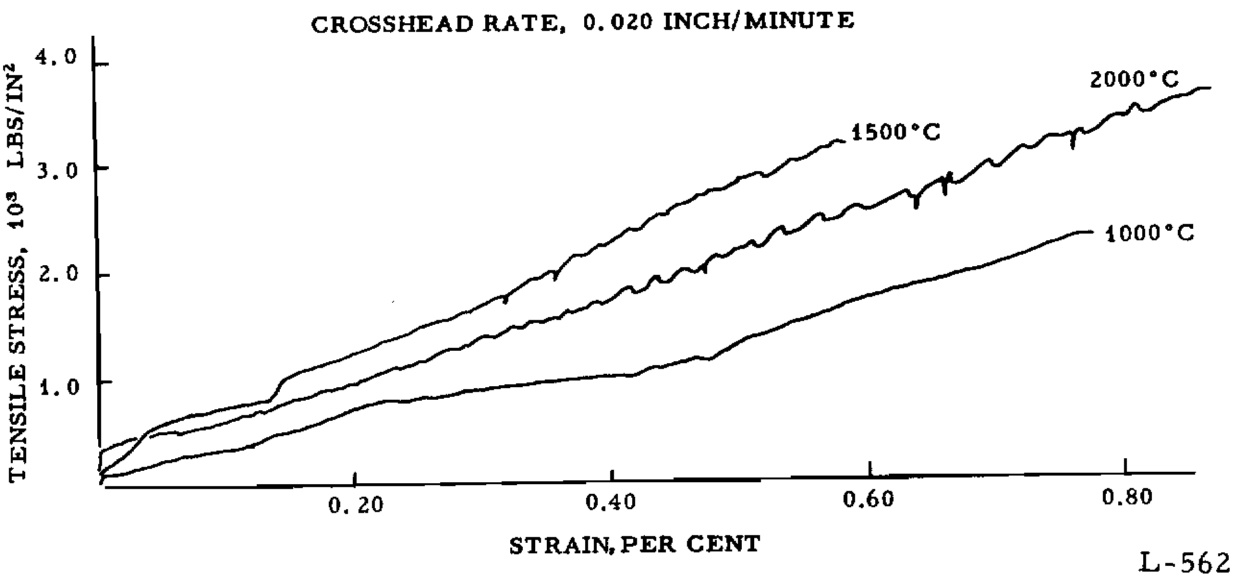
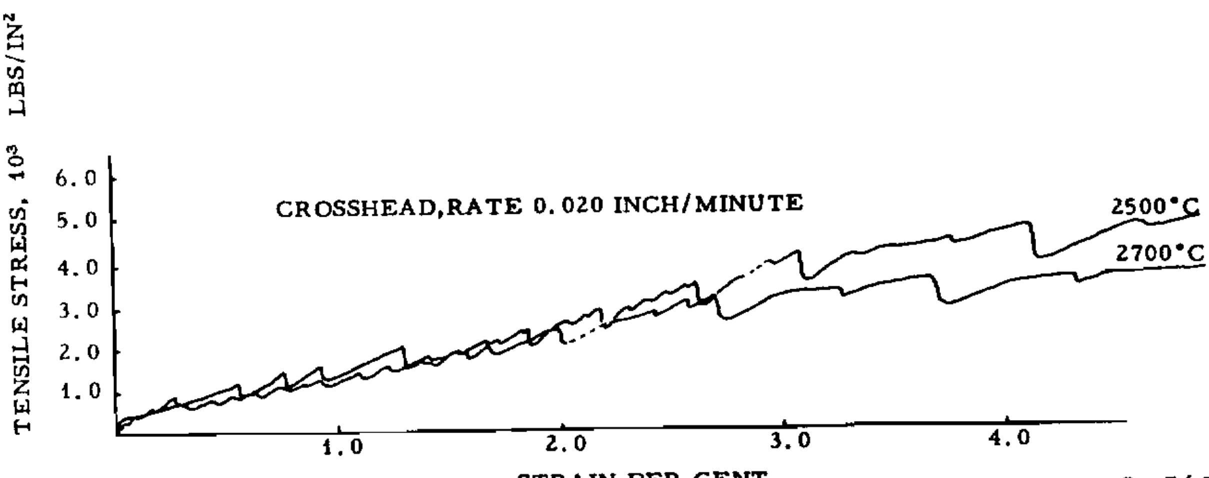


Figure 137. Across-Grain Tensile Stress-Strain Curves, RVA Graphite, 33-Inch Diameter by 42-Inch Length, Block No. A-24, Room Temperature



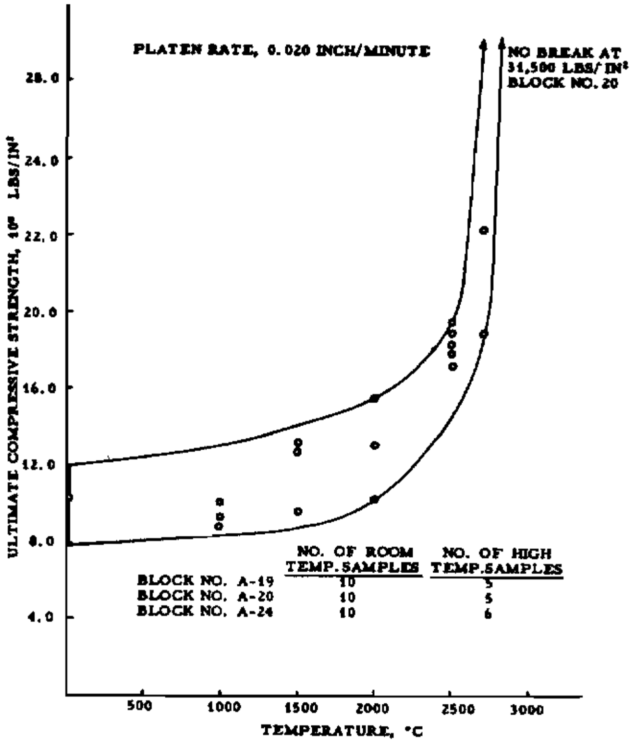
L-562

Figure 138. Across-Grain Tensile Stress-Strain Curves, RVA Graphite, 33-Inch Diameter by 42-Inch Length, Block No. A-24, 1000°C, 1500°C, 2000°C



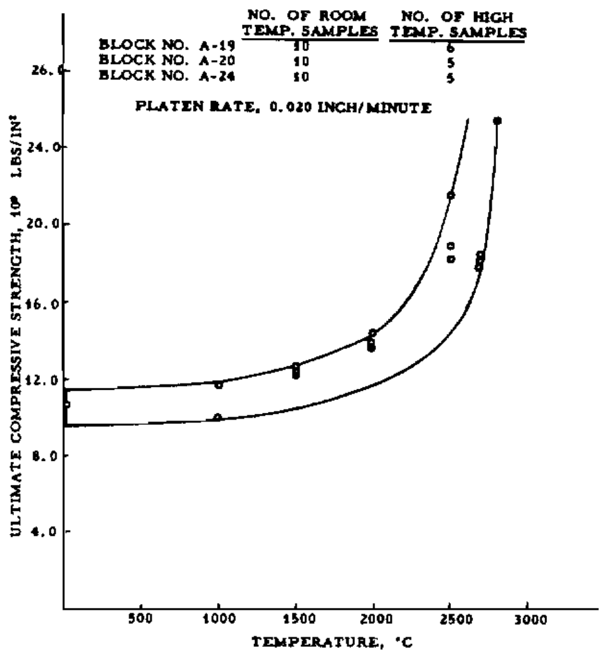
L-563

Figure 139. Across-Grain Tensile Stress-Strain Curves, RVA Graphite, 33-Inch Diameter by 42-Inch Length, Block No. A-24, 2500°C, 2700°C



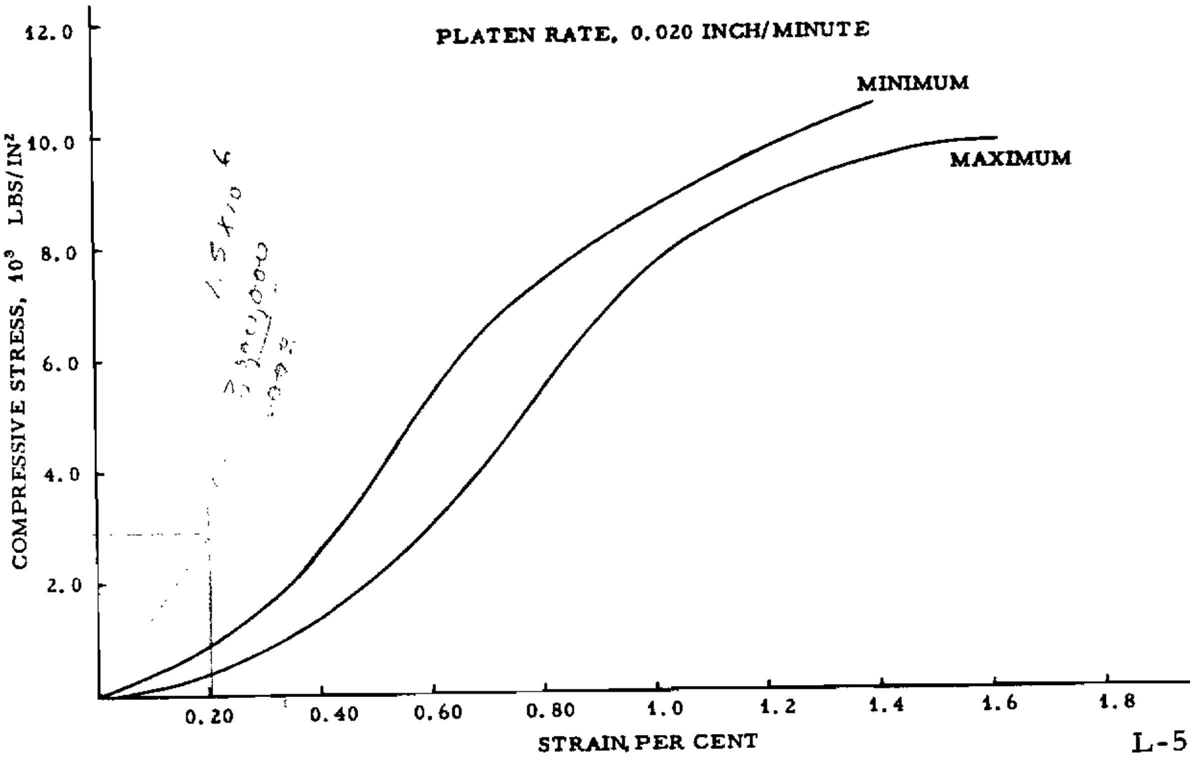
L-564

Figure 140. With-Grain Ultimate Compressive Strength vs. Temperature, RVA Graphite, 33-Inch Diameter by 42-Inch Length



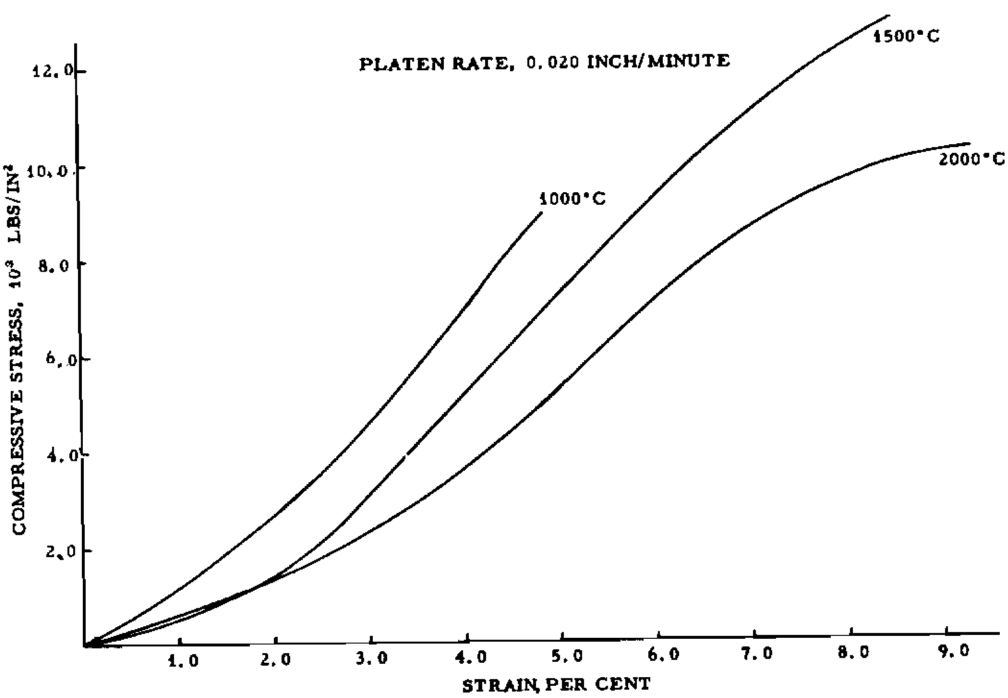
L-565

Figure 141. Across-Grain Ultimate Compressive Strength vs. Temperature, RVA Graphite, 33-Inch Diameter by 42-Inch Length



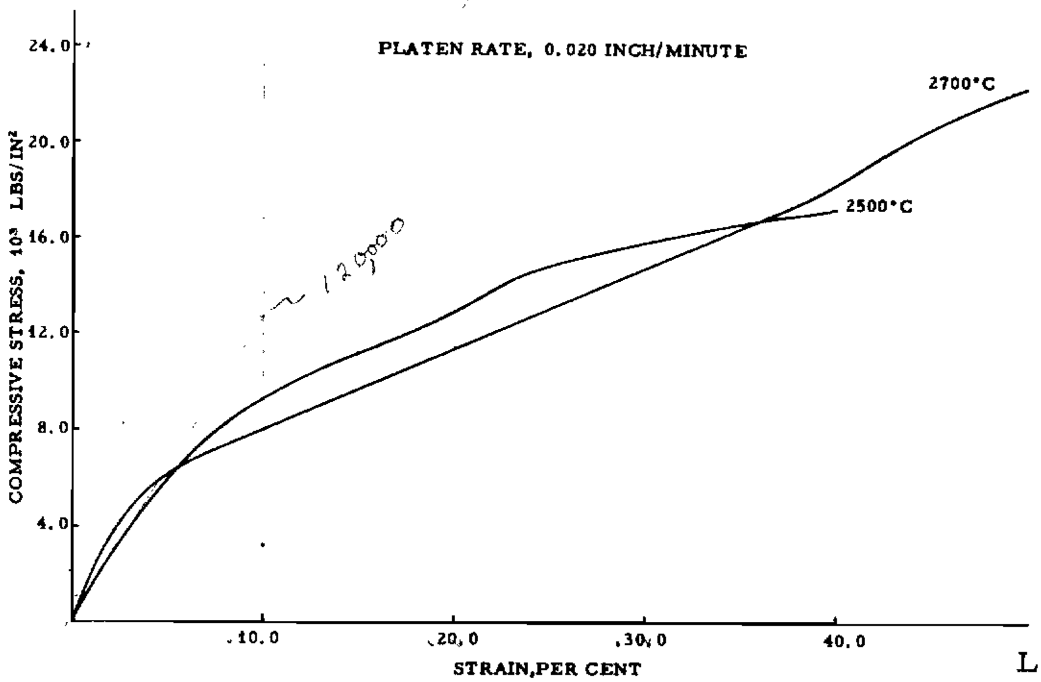
L-566

Figure 142. With-Grain Compressive Stress-Strain Curves, RVA Graphite, Block No. A-19, 33-Inch Diameter by 42-Inch Length, Room Temperature



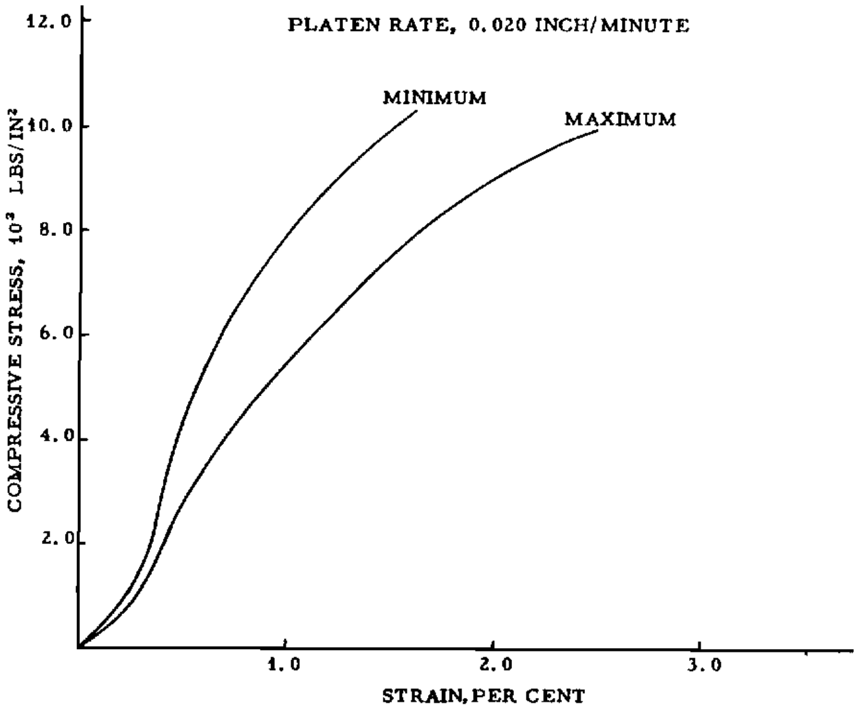
-567

Figure 143. With-Grain Compressive Stress-Strain Curves, RVA Graphite, Block No. A-19, 33-Inch Diameter by 42-Inch Length, 1000°C, 1500°C, 2000°C



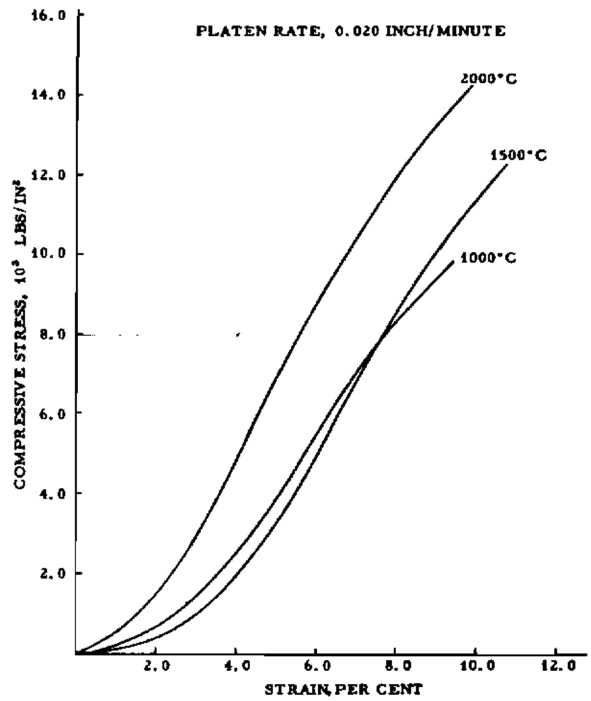
L-568

Figure 144. With-Grain Compressive Stress-Strain Curves, RVA Graphite, Block No. A-19, 33-Inch Diameter by 42-Inch Length, 2500°C, 2700°C



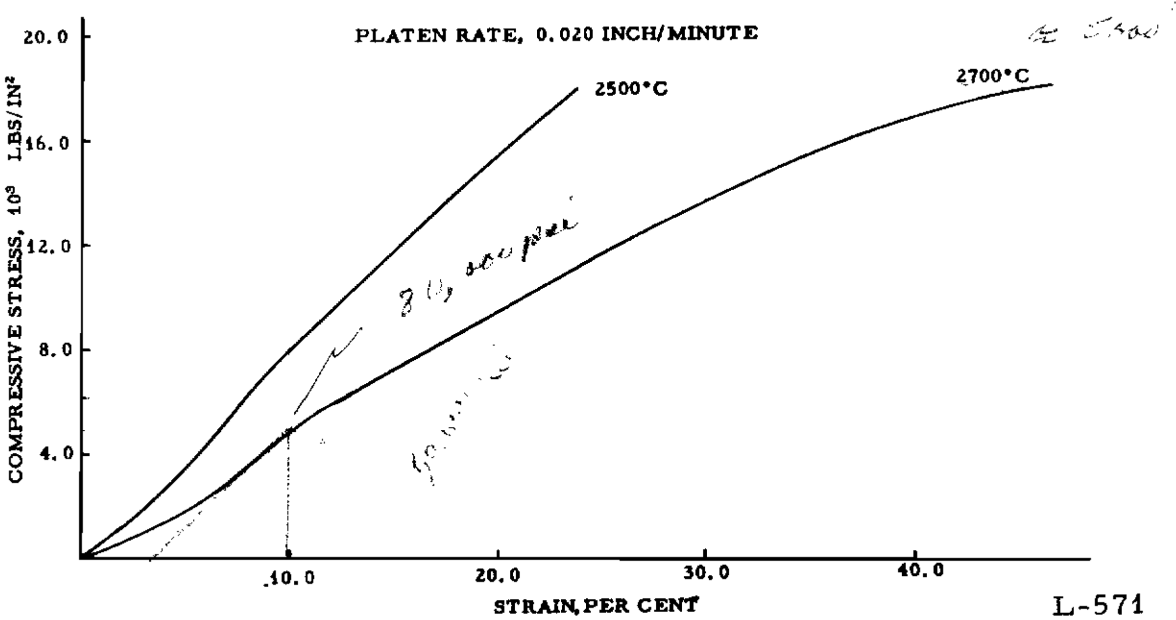
L-569

Figure 145. Across-Grain Compressive Stress-Strain Curves, RVA Graphite, Block No. A-19, 33-Inch Diameter by 42-Inch Length, Room Temperature



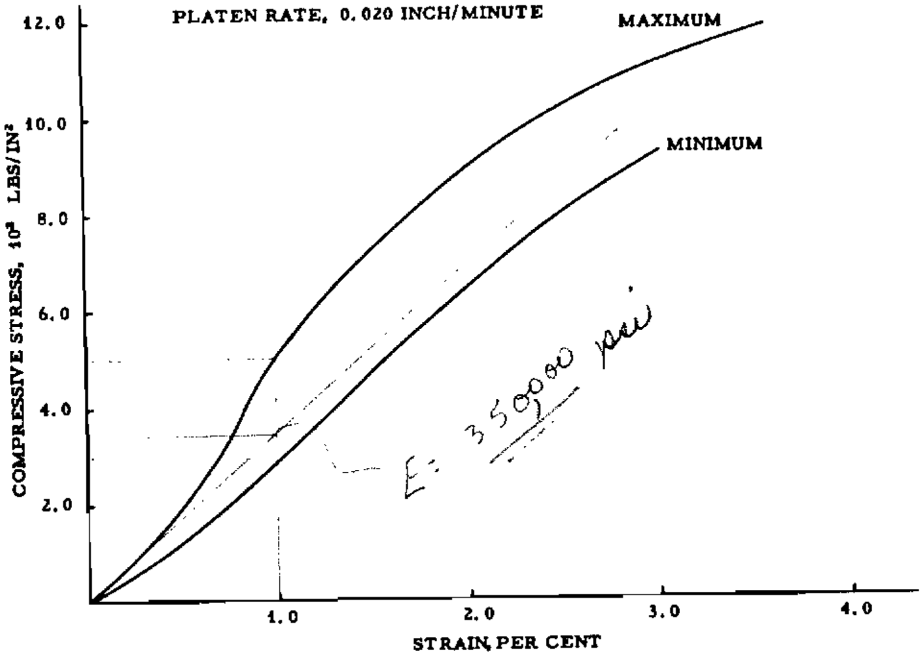
L-570

Figure 146. Across-Grain Compressive Stress-Strain Curves, RVA Graphite, Block No. A-19, 33-Inch Diameter by 42-Inch Length, 1000°C, 1500°C, 2000°C



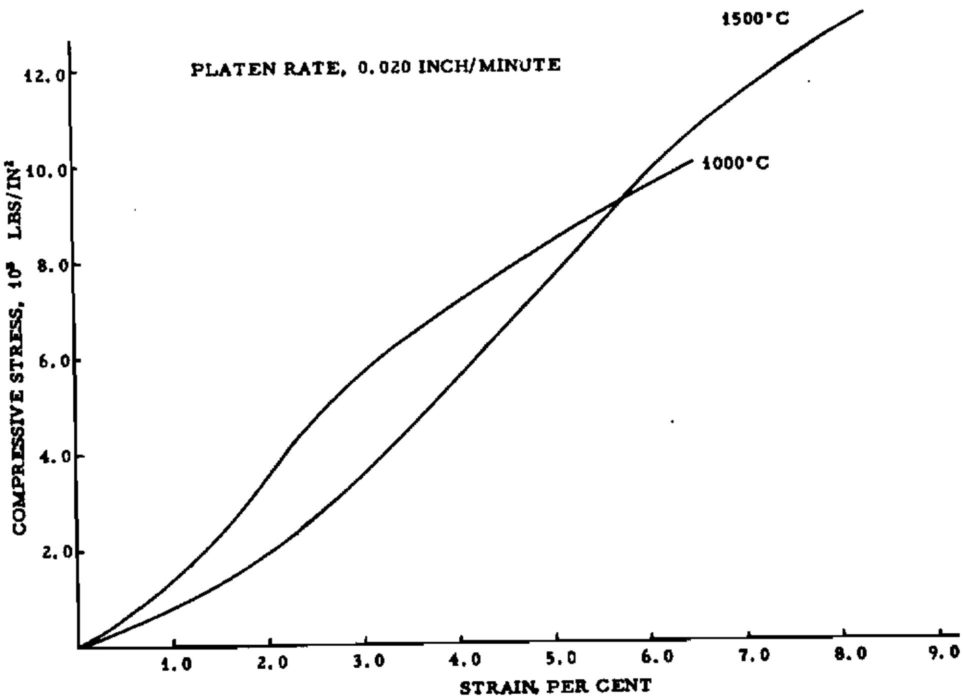
L-571

Figure 147. Across-Grain Compressive Stress-Strain Curves, RVA Graphite, Block No. A-19, 33-Inch Diameter by 42-Inch Length, 2500°C, 2700°C



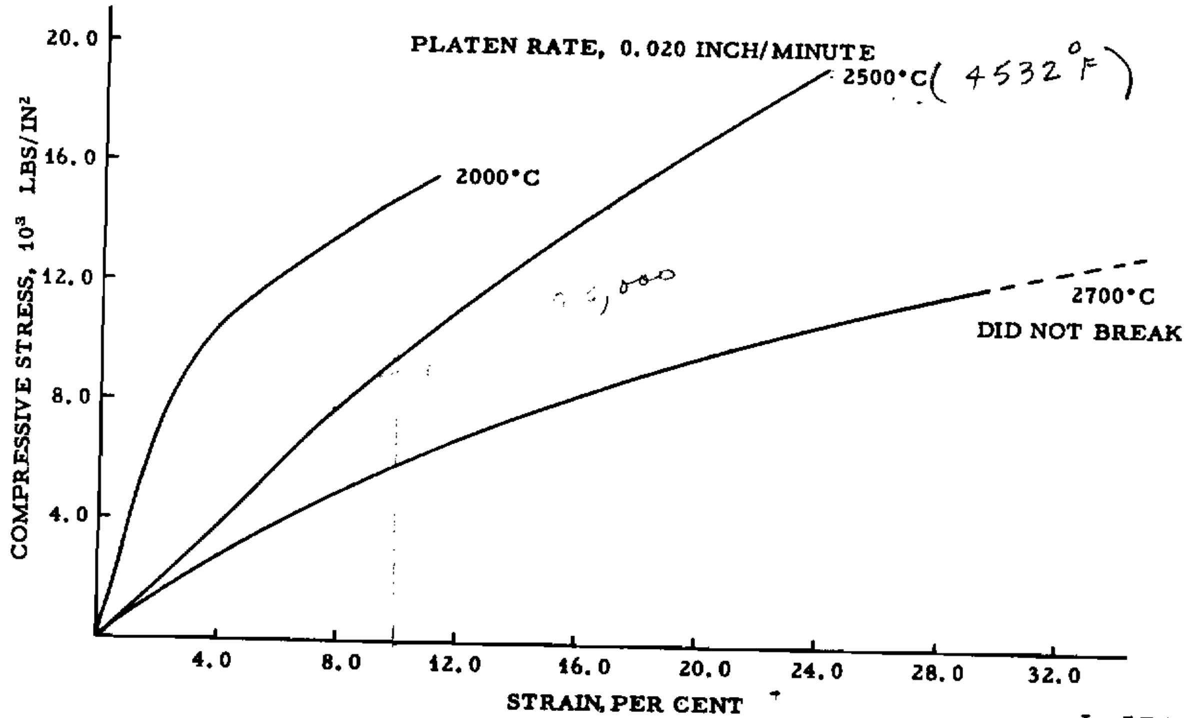
L-572

Figure 148. With-Grain Compressive Stress-Strain Curves, RVA Graphite, Block No. A-20, 33-Inch Diameter by 42-Inch Length, Room Temperature



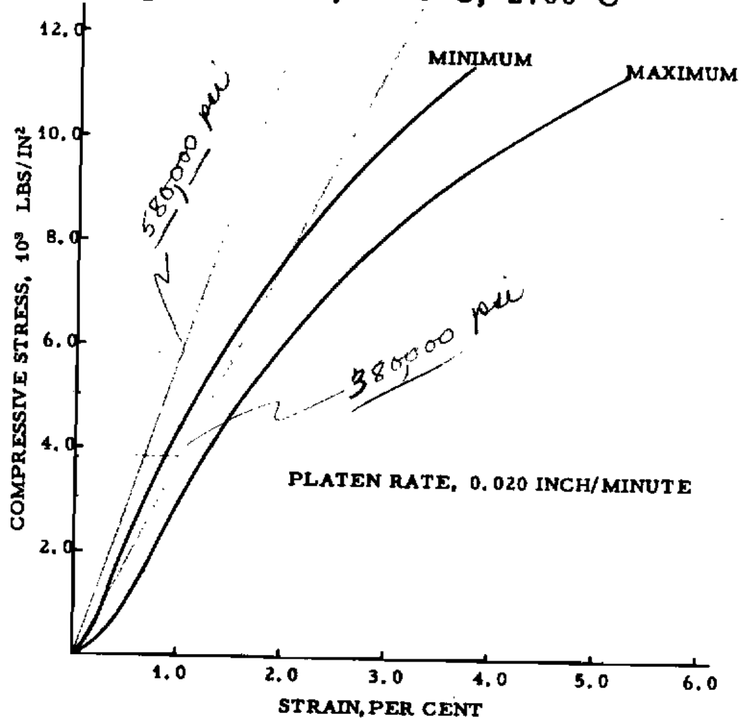
L-573

Figure 149. With-Grain Compressive Stress-Strain Curves, RVA Graphite, Block No. A-20, 33-Inch Diameter by 42-Inch Length, 1000°C, 1500°C



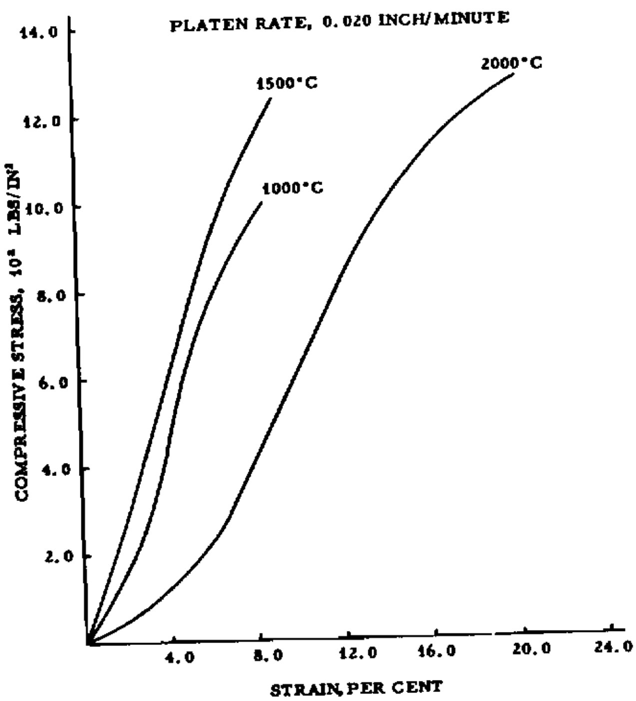
L-574

Figure 150. With-Grain Compressive Stress-Strain Curves, RVA Graphite, Block No. A-20, 33-Inch Diameter by 42-Inch Length, 2000°C, 2500°C, 2700°C



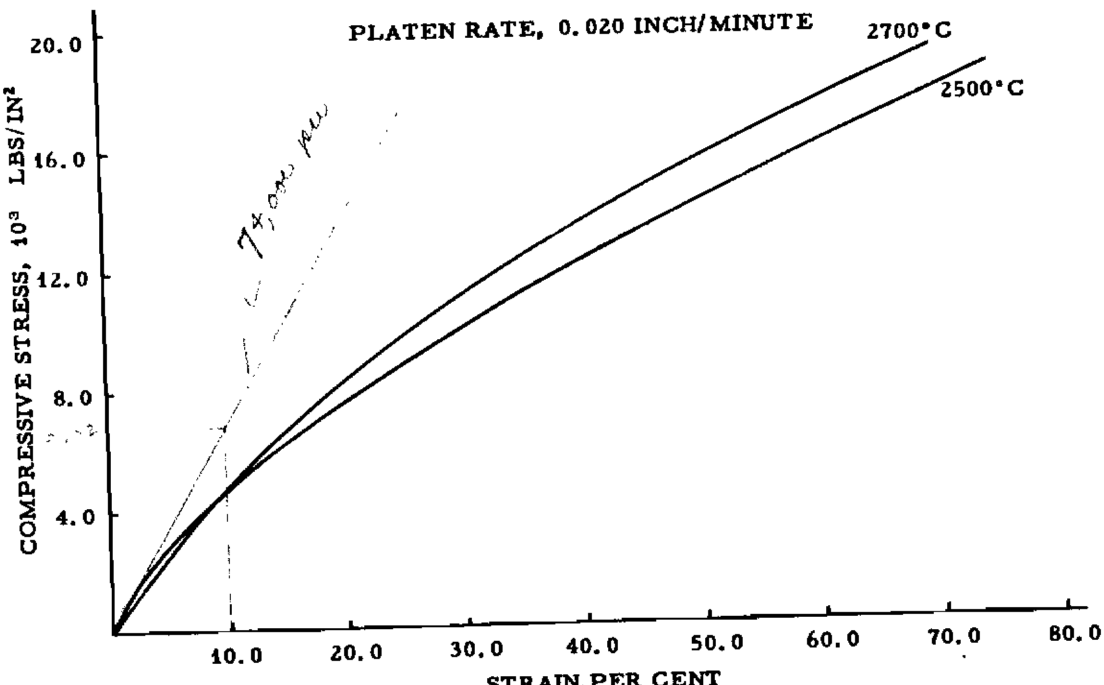
L-575

Figure 151. Across-Grain Compressive Stress-Strain Curves, RVA Graphite, Block No. A-20, 33-Inch Diameter by 42-Inch Length, Room Temperature



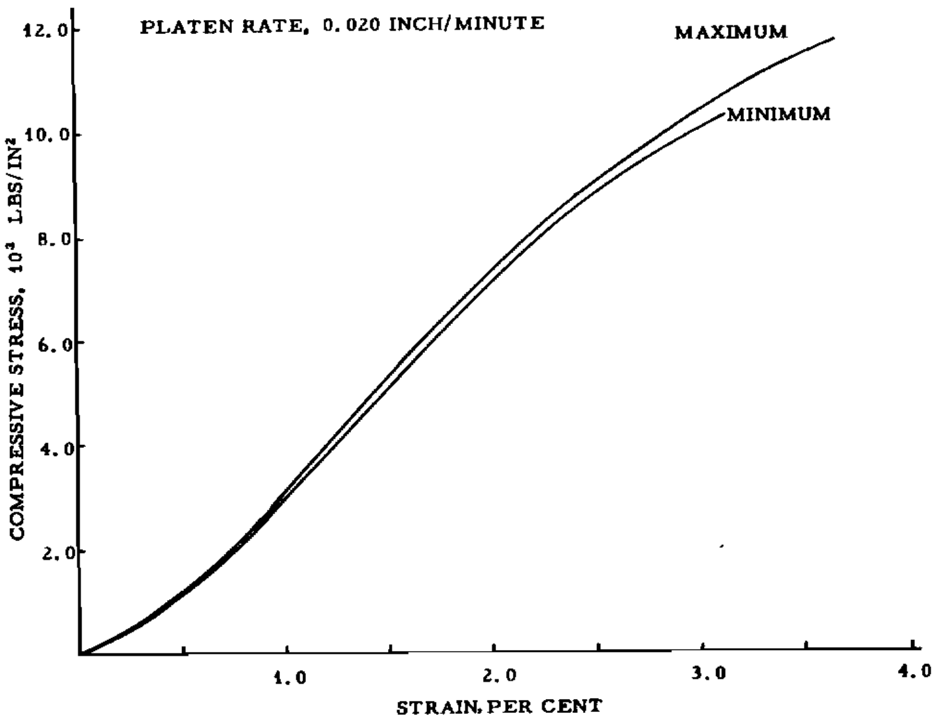
L-576

Figure 152. Across-Grain Compressive Stress-Strain Curves, RVA Graphite, Block No. A-20, 33-Inch Diameter by 42-Inch Length, 1000°C, 1500°C, 2000°C



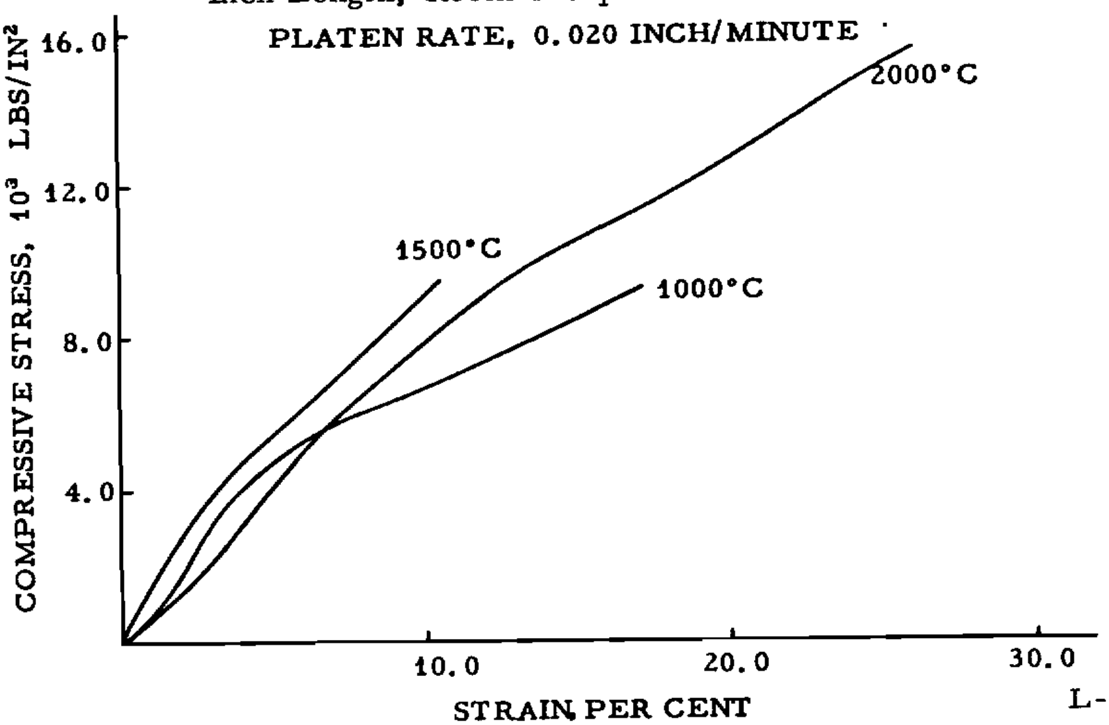
577

Figure 153. Across-Grain Compressive Stress-Strain Curves, RVA Graphite, Block No. A-20, 33-Inch Diameter by 42-Inch Length, 2500°C, 2700°C



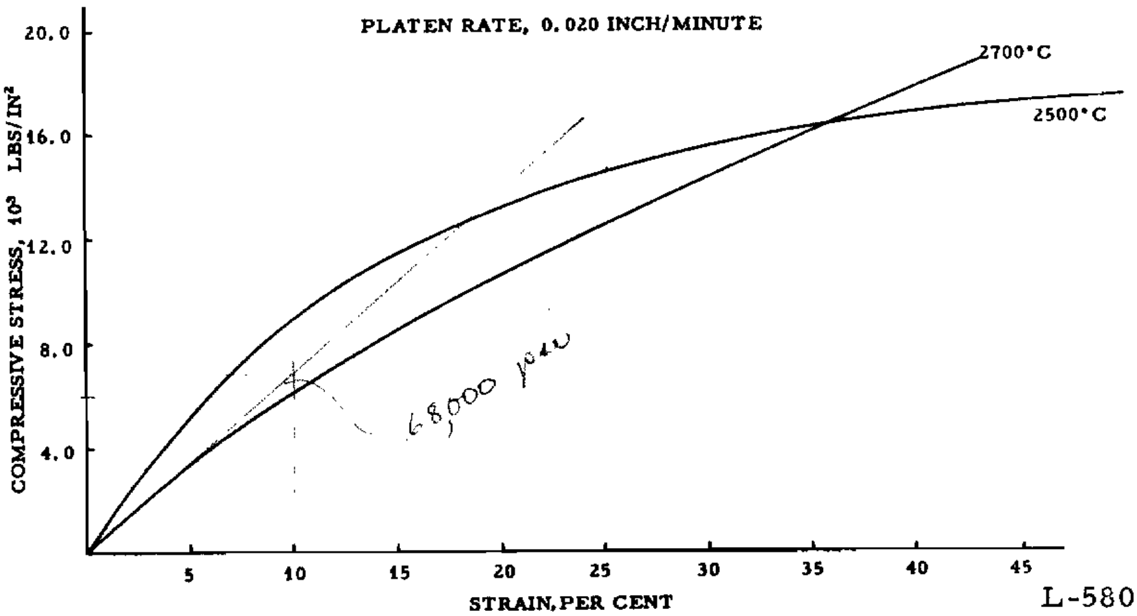
L-578

Figure 154. With-Grain Compressive Stress-Strain Curves, RVA Graphite, Block No. A-24, 33-Inch Diameter by 42-Inch Length, Room Temperature



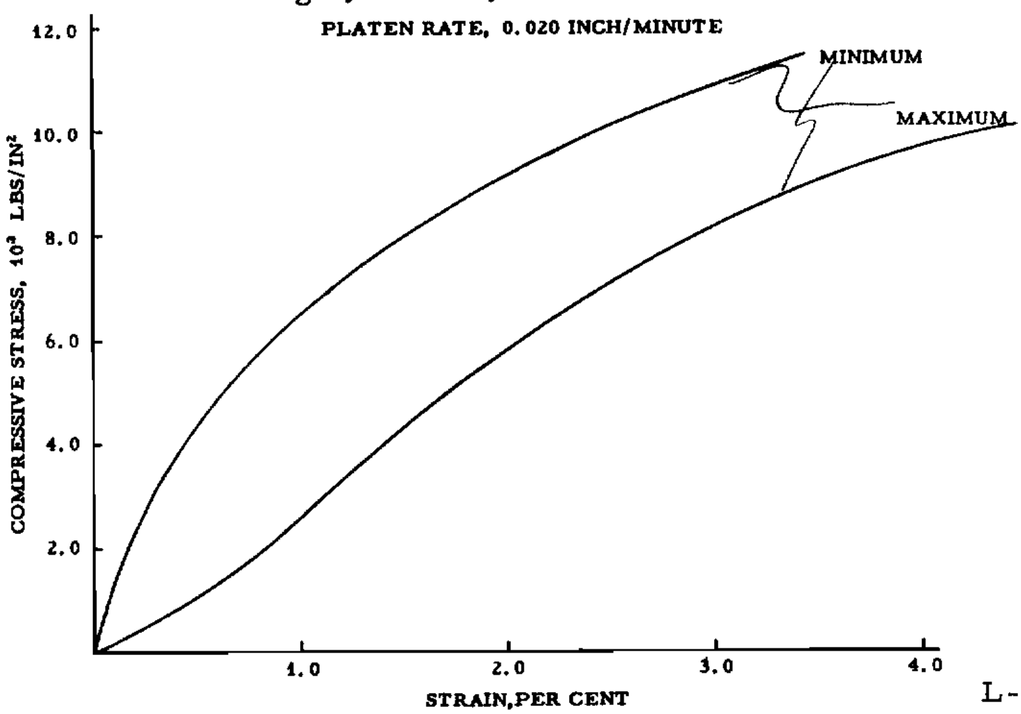
L-579

Figure 155. With-Grain Compressive Stress-Strain Curves, RVA Graphite, Block No. A-24, 33-Inch Diameter by 42-Inch Length, 1000°C, 1500°C, 2000°C



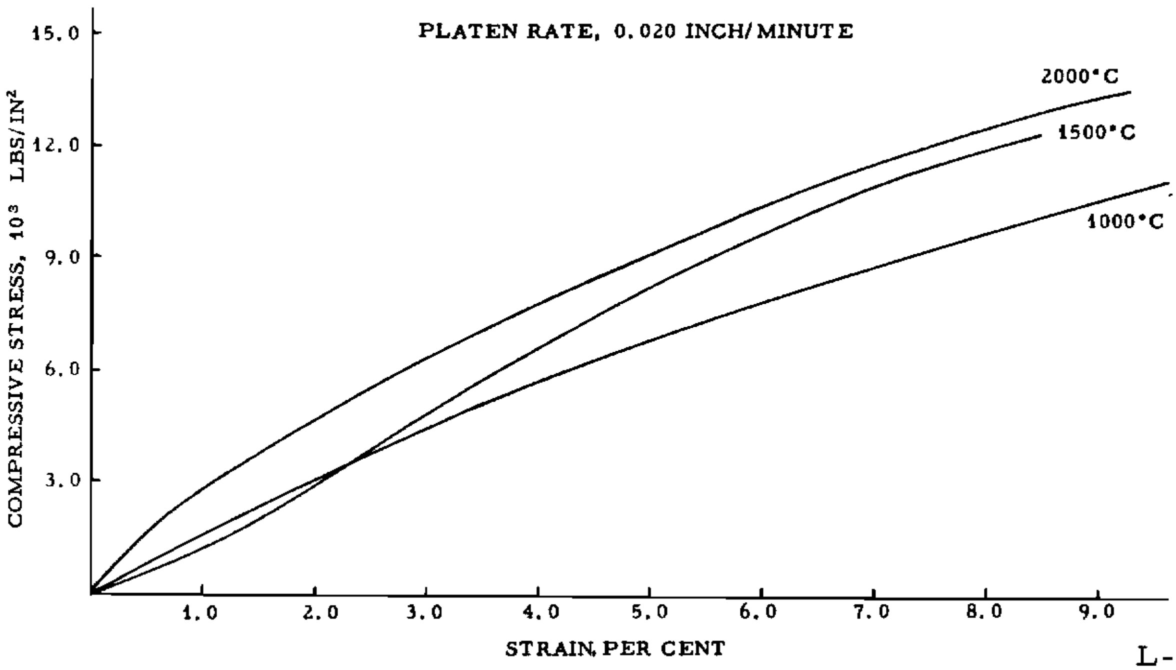
L-580

Figure 156. With-Grain Compressive Stress-Strain Curves, RVA Graphite, Block No. A-24, 33-Inch Diameter by 42-Inch Length, 2500°C, 2700°C



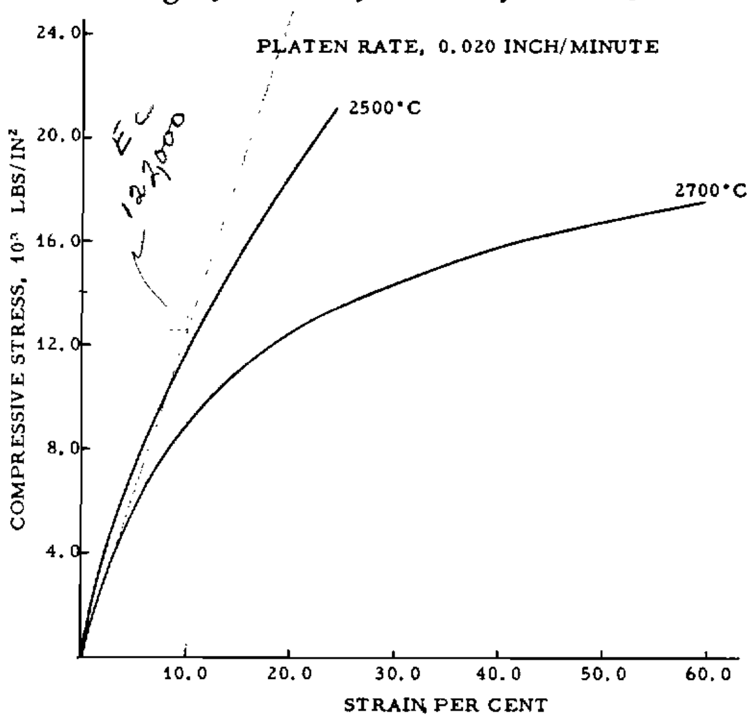
L-581

Figure 157. Across-Grain Compressive Stress-Strain Curves, RVA Graphite, Block No. A-24, 33-Inch Diameter by 42-Inch Length, Room Temperature



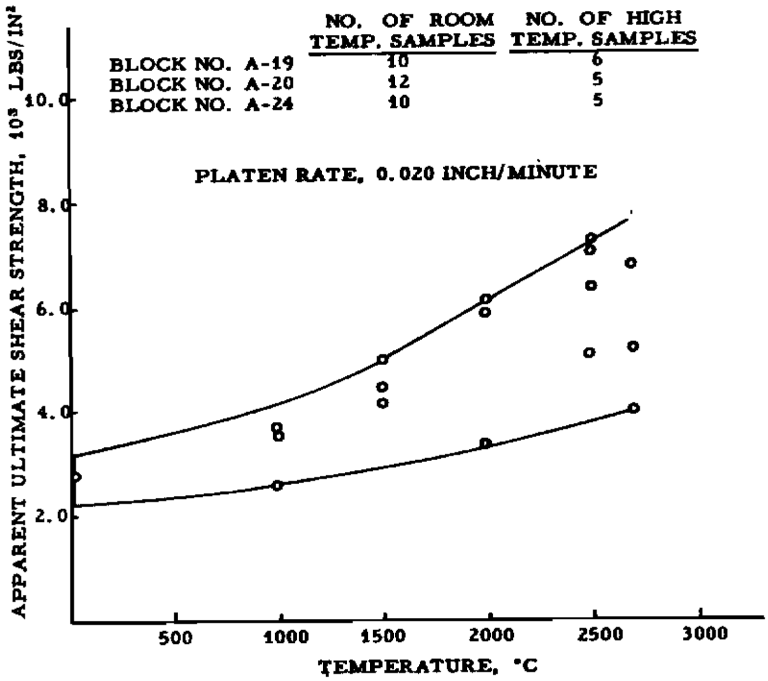
L-582

Figure 158. Across-Grain Compressive Stress-Strain Curves, RVA Graphite, Block No. A-24, 33-Inch Diameter by 42-Inch Length, 1000°C, 1500°C, 2000°C



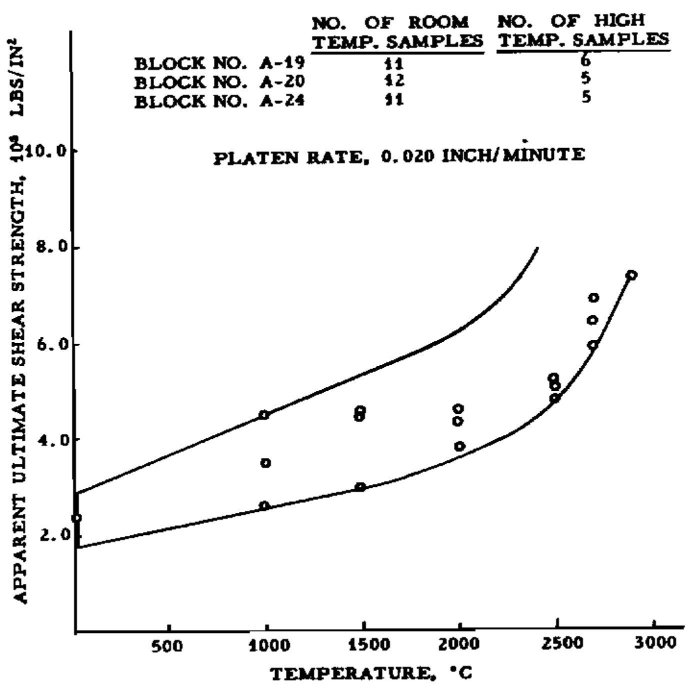
L-583

Figure 159. Across-Grain Compressive Stress-Strain Curves, RVA Graphite, Block No. A-24, 33-Inch Diameter by 42-Inch Length, 2500°C, 2700°C



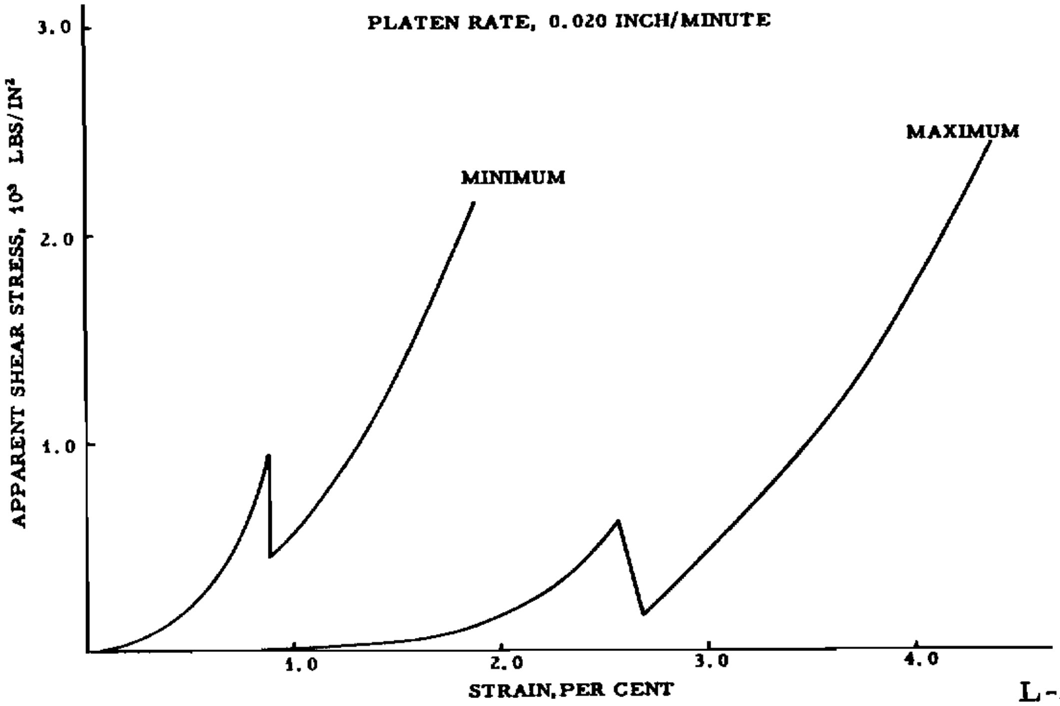
L-584

Figure 160. With-Grain Apparent Ultimate Shear Strength vs. Temperature, RVA Graphite, 33-Inch Diameter by 42-Inch Length



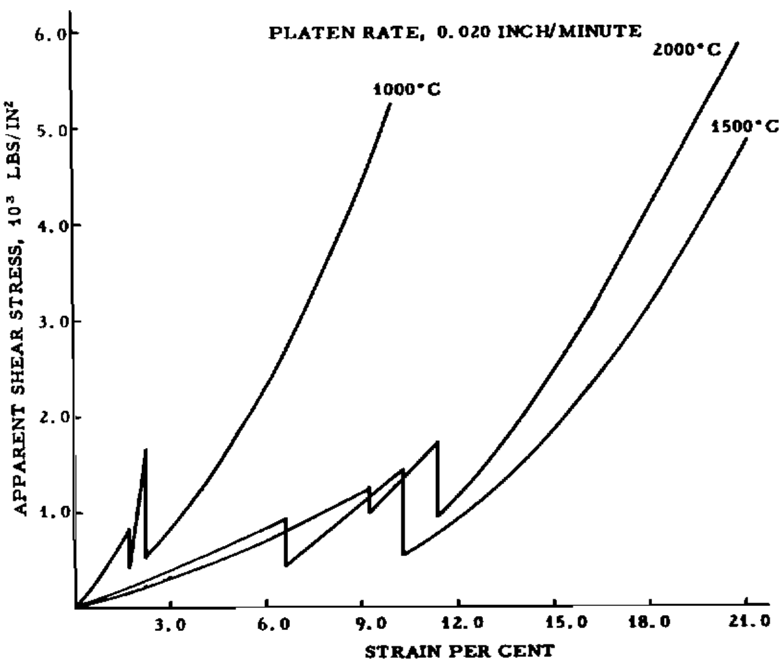
L-585

Figure 161. Across-Grain Apparent Ultimate Shear Strength vs. Temperature, RVA Graphite, 33-Inch Diameter by 42-Inch Length



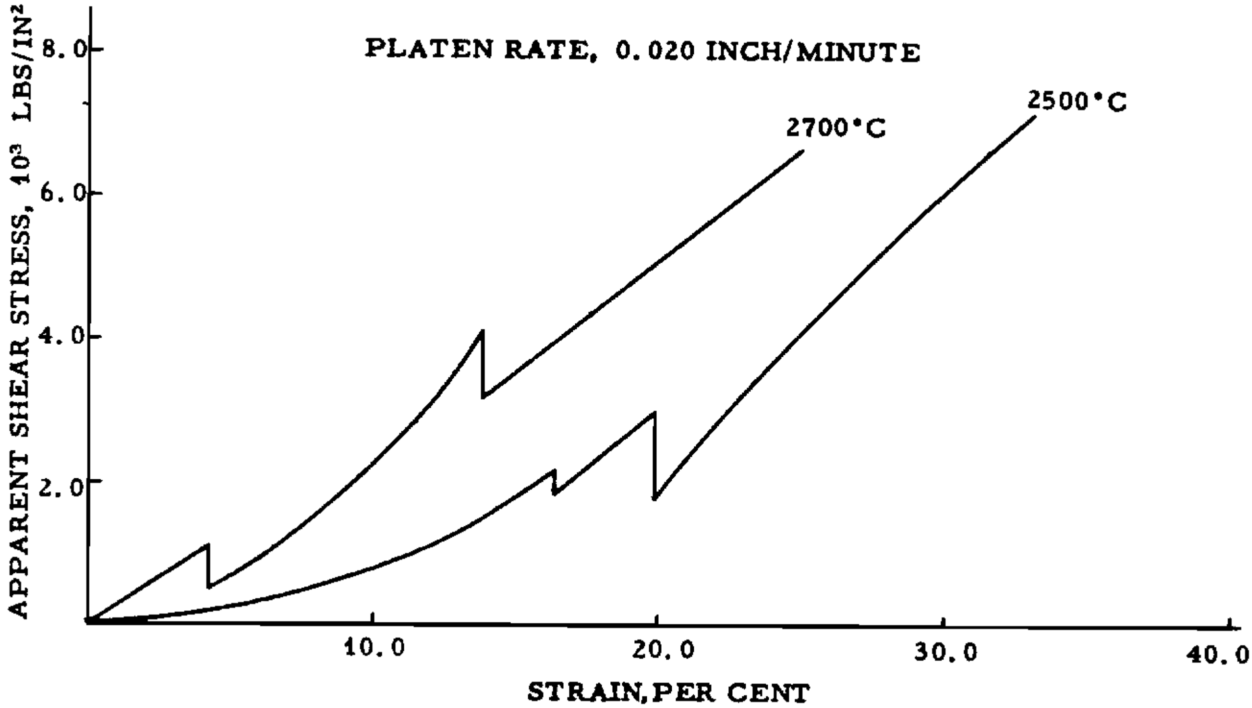
L-586

Figure 162. With-Grain Apparent Shear Stress-Strain Curves, RVA Graphite, Block No. A-19, 33-Inch Diameter by 42-Inch Length, Room Temperature



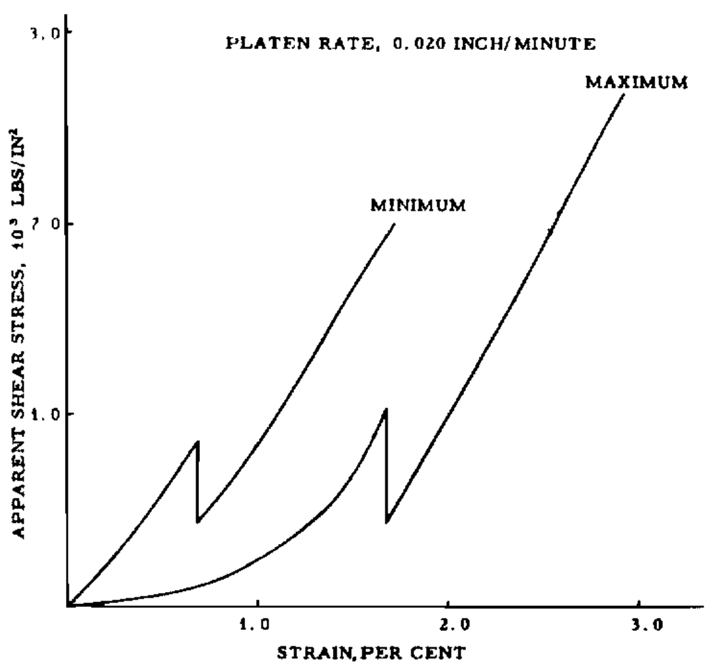
L-587

Figure 163. With-Grain Apparent Shear Stress-Strain Curves, RVA Graphite, Block No. A-19, 33-Inch Diameter by 42-Inch Length, 1000°C, 1500°C, 2000°C



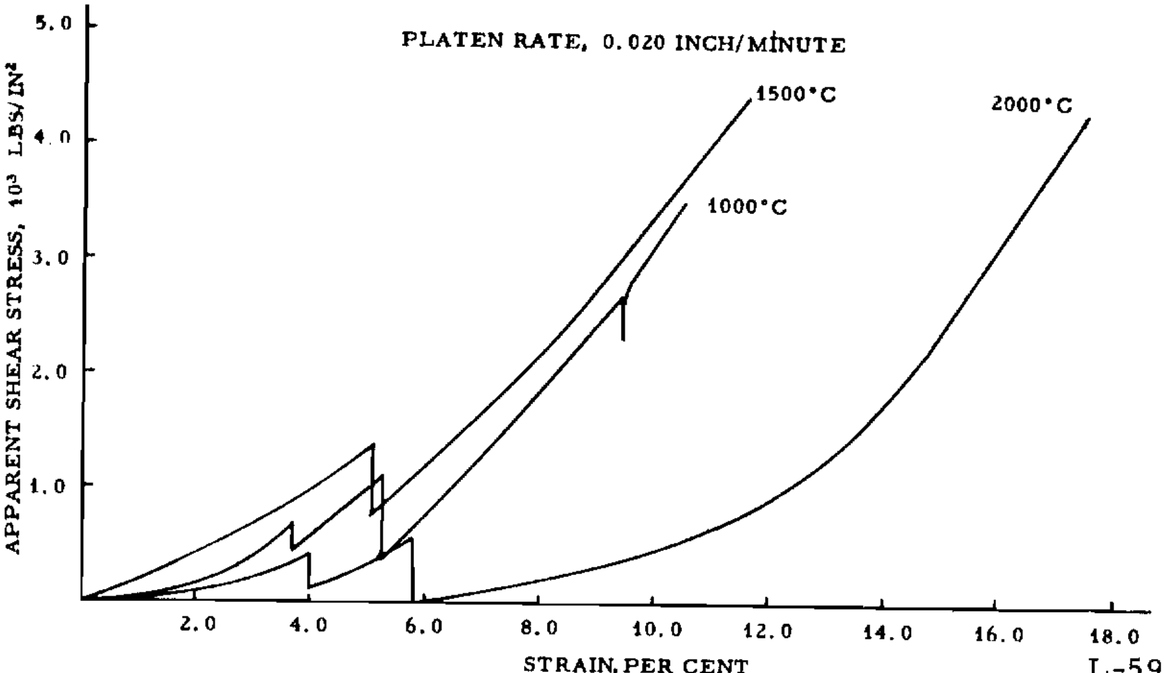
L-588

Figure 164. With-Grain Apparent Shear Stress-Strain Curves, RVA Graphite, Block No. A-19, 33-Inch Diameter by 42-Inch Length, 2500°C, 2700°C



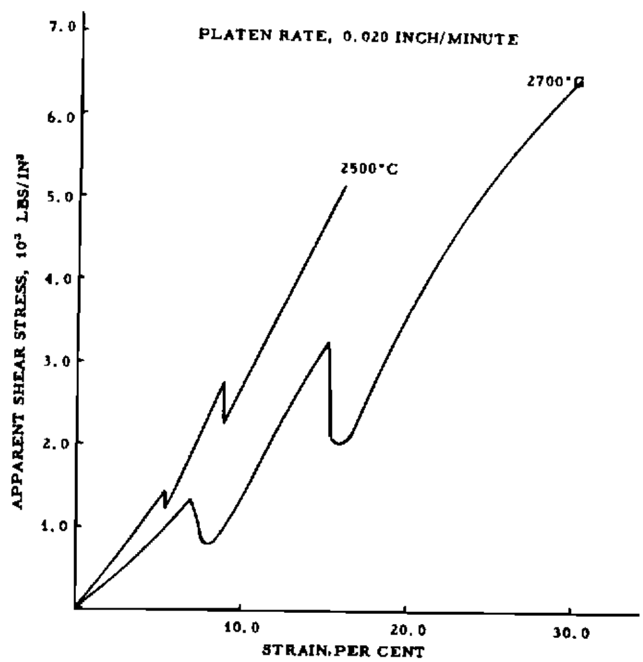
L-589

Figure 165. Across-Grain Apparent Shear Stress-Strain Curves, RVA Graphite, Block No. A-19, 33-Inch Diameter by 42-Inch Length, Room Temperature



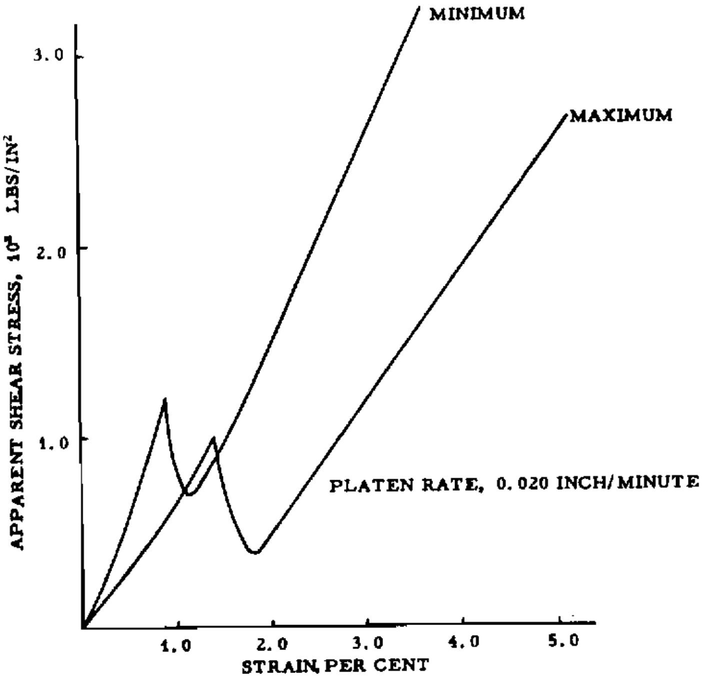
L-590

Figure 166. Across-Grain Apparent Shear Stress-Strain Curves, RVA Graphite, Block No. A-19, 33-Inch Diameter by 42-Inch Length, 1000°C, 1500°C, 2000°C



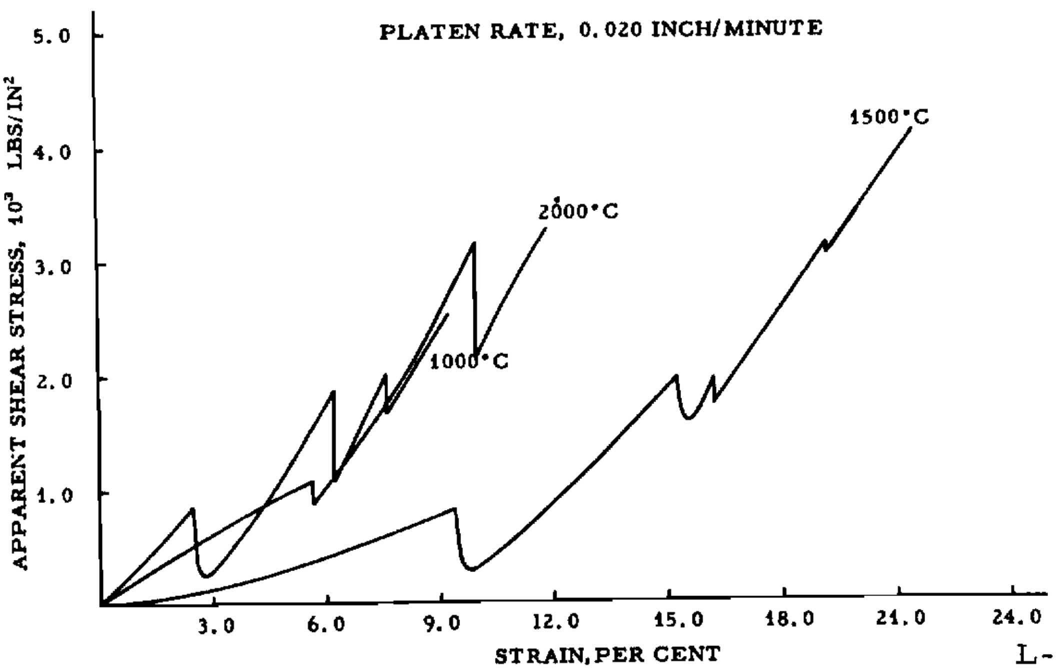
L-591

Figure 167. Across-Grain Apparent Shear Stress-Strain Curves, RVA Graphite, Block No. A-19, 33-Inch Diameter by 42-Inch Length, 2500°C, 2700°C



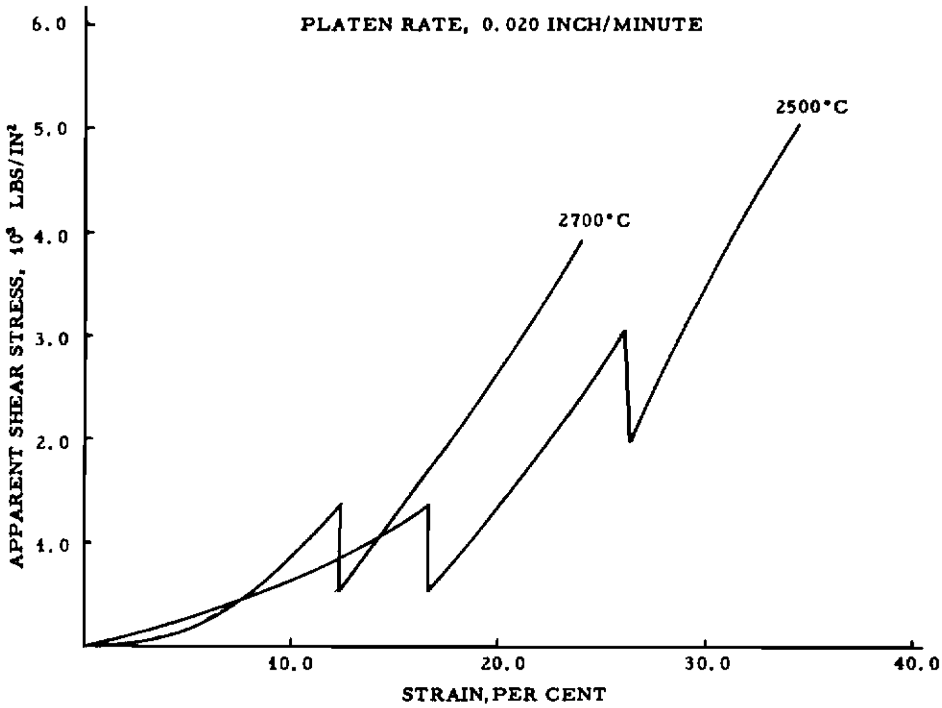
L-592

Figure 168. With-Grain Apparent Shear Stress-Strain Curves, RVA Graphite, Block No. A-20, 33-Inch Diameter by 42-Inch Length, Room Temperature



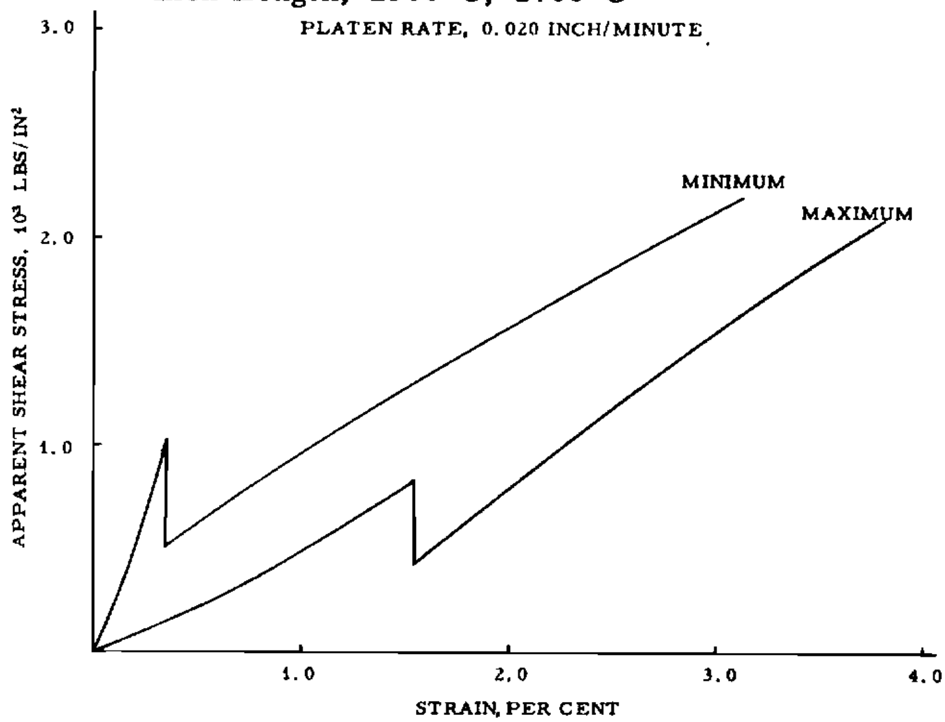
L-593

Figure 169. With-Grain Apparent Shear Stress-Strain Curves, RVA Graphite, Block No. A-20, 33-Inch Diameter by 42-Inch Length, 1000°C, 1500°C, 2000°C



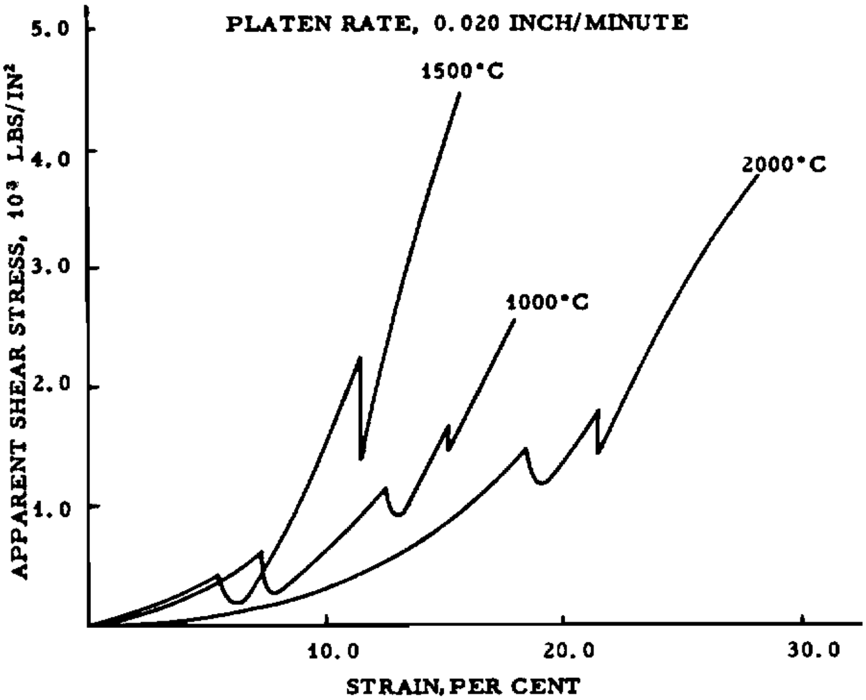
L-594

Figure 170. With-Grain Apparent Shear Stress-Strain Curves, RVA Graphite, Block No. A-20, 33-Inch Diameter by 42-Inch Length, 2500°C, 2700°C



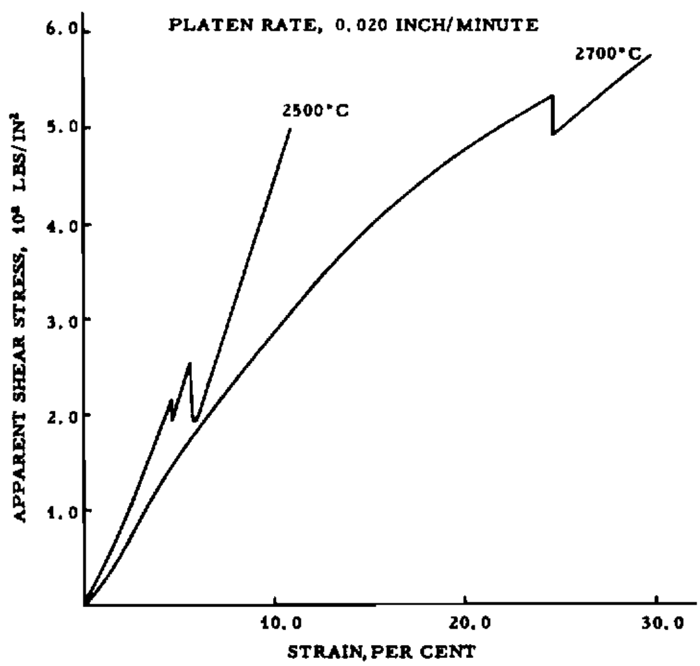
L-595

Figure 171. Across-Grain Apparent Shear Stress-Strain Curves, RVA Graphite, Block No. A-20, 33-Inch Diameter by 42-Inch Length, Room Temperature



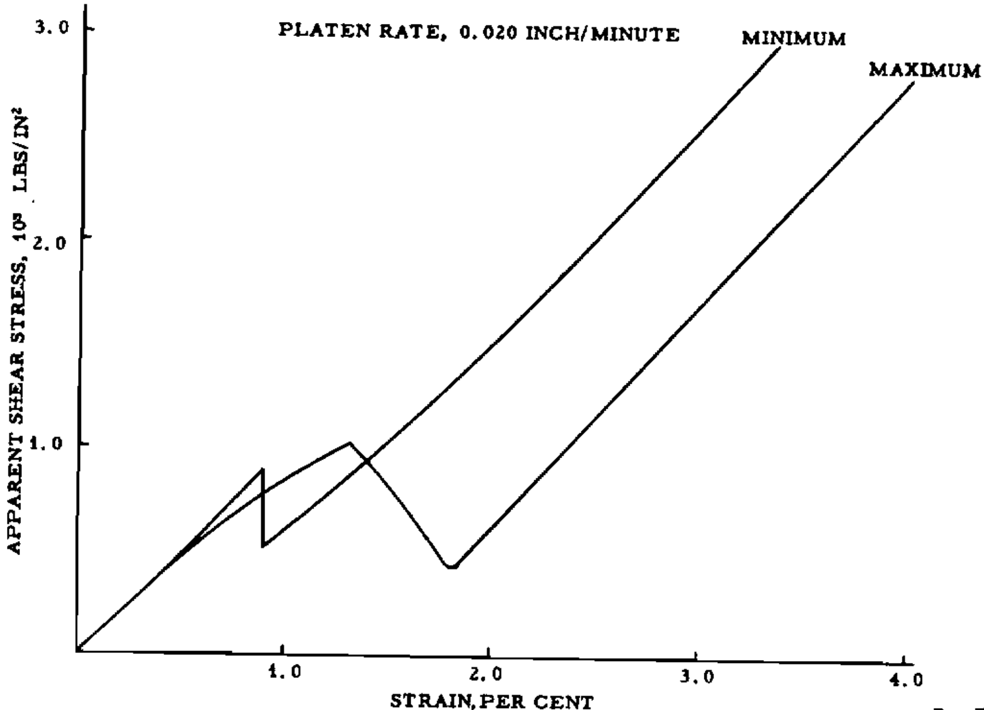
L-596

Figure 172. Across-Grain Apparent Shear Stress-Strain Curves, RVA Graphite, Block No. A-20, 33-Inch Diameter by 42-Inch Length, 1000°C, 1500°C, 2000°C



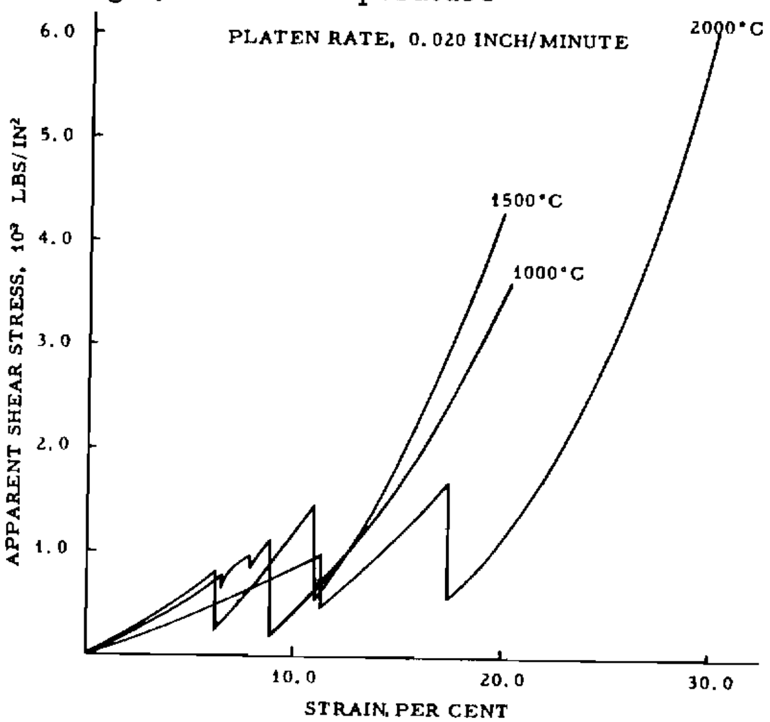
L-597

Figure 173. Across-Grain Apparent Shear Stress-Strain Curves, RVA Graphite, Block No. A-20, 33-Inch Diameter by 42-Inch Length, 2500°C, 2700°C



L-598

Figure 174. With-Grain Apparent Shear Stress-Strain Curves, RVA Graphite, Block No. A-24, 33-Inch Diameter by 42-Inch Length, Room Temperature



L-599

Figure 175. With-Grain Apparent Shear Stress-Strain Curves, RVA Graphite, Block No. A-24, 33-Inch Diameter by 42-Inch Length, 1000°C, 1500°C, 2000°C

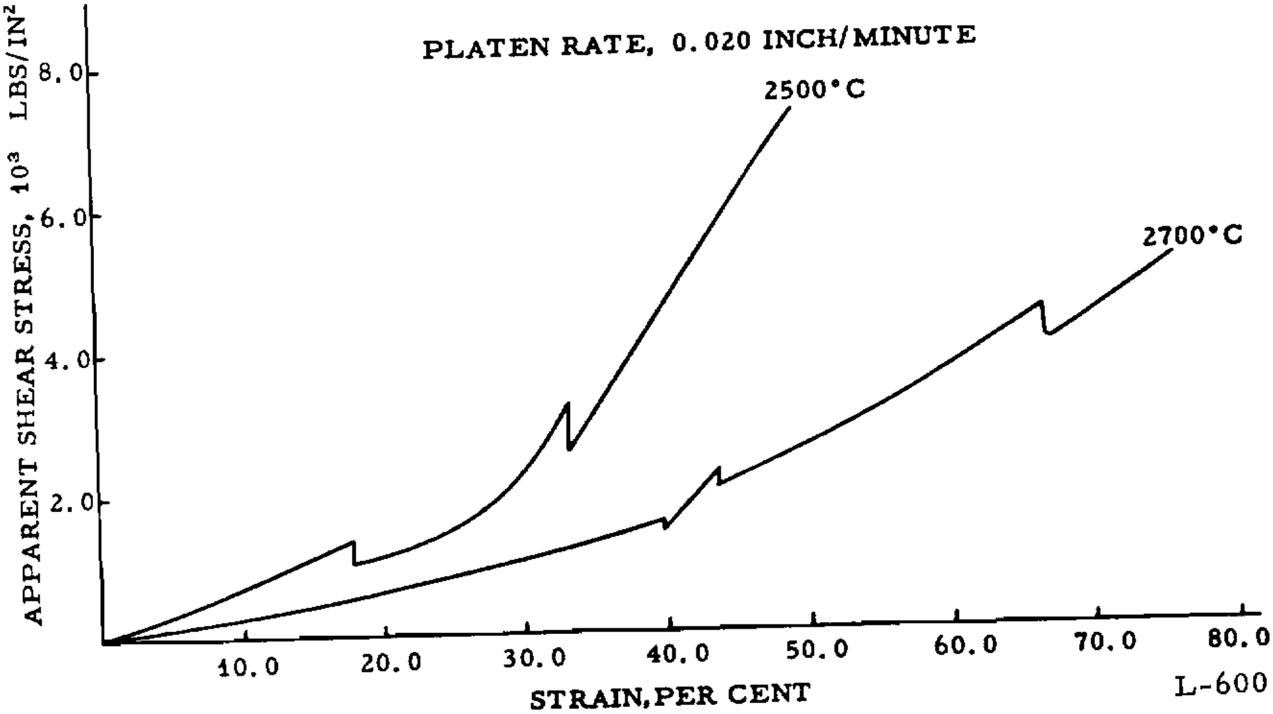


Figure 176. With-Grain Apparent Shear Stress-Strain Curves, RVA Graphite, Block No. A-24, 33-Inch Diameter by 42-Inch Length, 2500°C, 2700°C

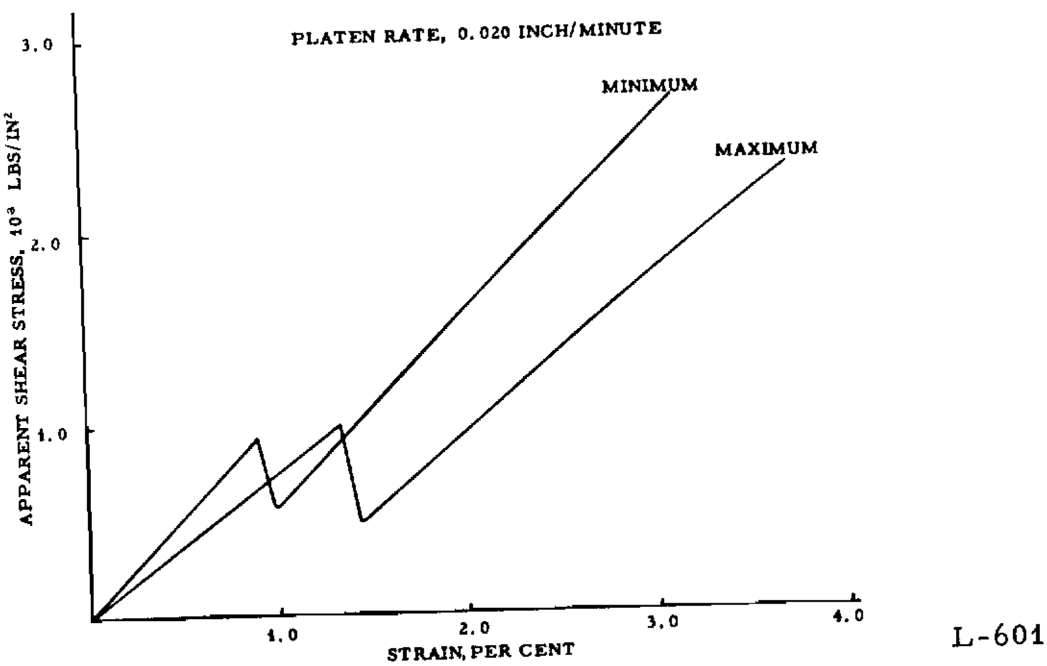
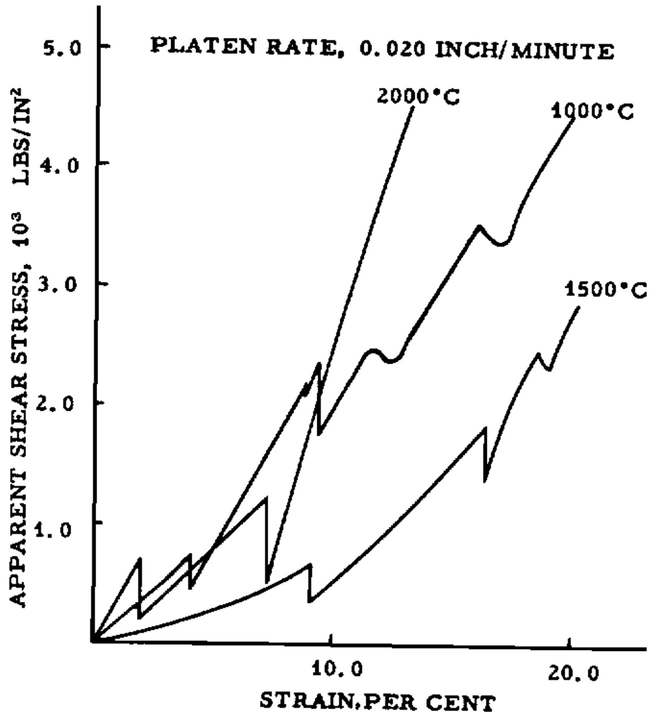
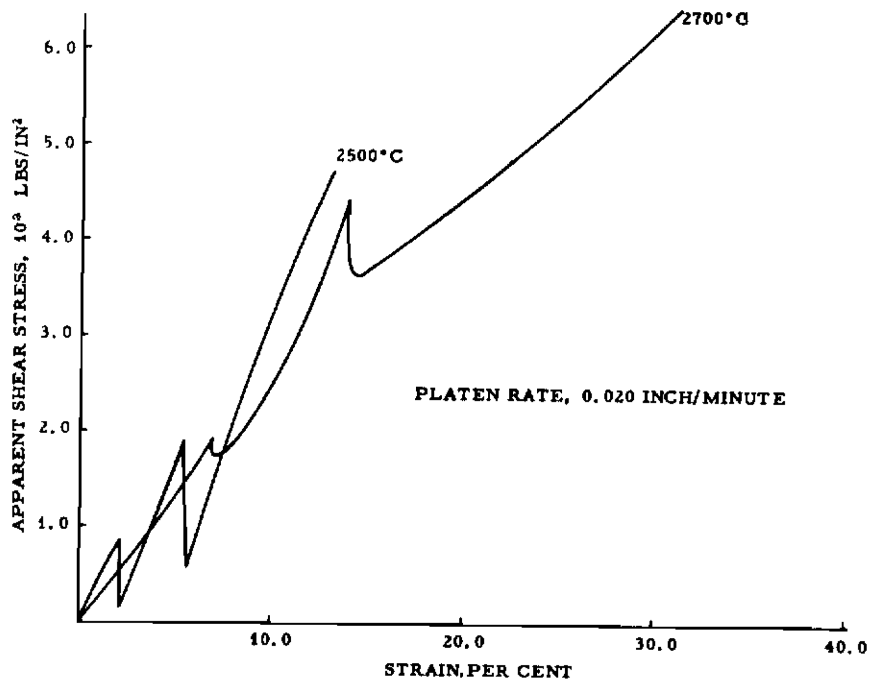


Figure 177. Across-Grain Apparent Shear Stress-Strain Curves, RVA Graphite, Block No. A-24, 33-Inch Diameter by 42-Inch Length, Room Temperature



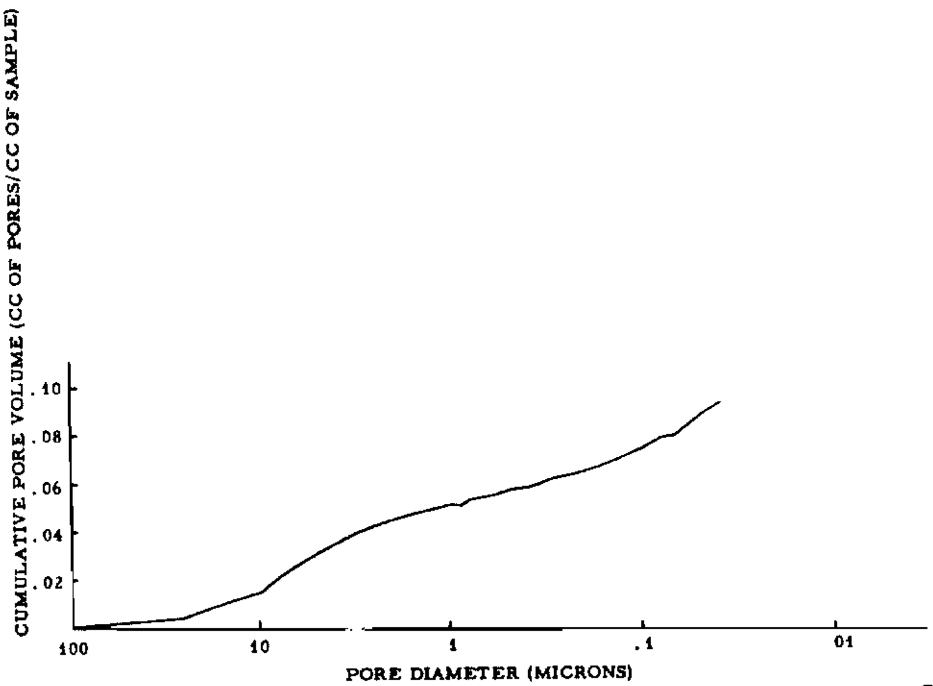
L-602

Figure 178. Across-Grain Apparent Shear Stress-Strain Curves, RVA Graphite, Block No. A-24, 33-Inch Diameter by 42-Inch Length, 1000°C, 1500°C, 2000°C



L-603

Figure 179. Across-Grain Apparent Shear Stress-Strain Curves, RVA Graphite, Block No. A-24, 33-Inch Diameter by 42-Inch Length, 2500°C, 2700°C



L-604

Figure 180. Pore Size Distribution, Mercury Porosimetry, RVA Graphite

3.9. Grade RVC Graphite [20, 21]

Two 18-inch diameter by 17-inch length blocks were used for the characterization of RVC graphite. One, Block No. 163, was completely characterized as outlined in Section 1. The other, Block 175, was limited to room temperature properties, with the exception of high-temperature thermal expansion.

Physical properties of the two blocks are summarized in Tables 53 and 54, and those for individual blocks are reported in Tables 55 through 58, inclusive. Figure 182 is a plot of the thermal expansion data presented in Table 54. The interpretation of stress-strain curves was discussed in Section 3.1. All strength measurements were made at cross-head or platen rates of 0.020 inch per minute.

Table 53. Summary of Room-Temperature Properties, RVC Graphite, 18-Inch Diameter by 17-Inch Length

Properties	With Grain Average	With Grain σ	With Grain n	With Grain No. of Blocks	Across Grain Average	Across Grain σ	Across Grain n	Across Grain No. of Blocks
Bulk Density, g/cc	1.84	0.01	40	3	---	---	--	-
Specific Resistance, 10^{-4} ohm-cm	13.08	0.48	20	2	16.41	0.83	20	2
Young's Modulus, 10^{6} lbs/in^2	1.77	0.06	20	2	1.38	0.08	20	2
Flexural Strength, lbs/in^2	3215	206	10	2	2040	270	10	2
Compressive Strength, 1- by 1- by 1-inch, lbs/in^2	11160	660	20	2	10940	890	20	2
Compressive Strength, $\frac{1}{2}$-inch diameter by $\frac{1}{2}$-inch, lbs/in^2	10920	1143	9	1	11215	779	9	1
Tensile Strength, lbs/in^2	2730	185	11	1	1300	236	10	1
Apparent Shear Strength, lbs/in^2	2455	254	10	1	2125	169	10	1

	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	With Grain No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n	Across Grain No. of Blocks
CTE, 20°-100°C, 10^{-6}/°C	3.75	3.65	3.69	6	2	4.50	4.26	4.45	6	2
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ °\text{K}}$	0.280	0.260	0.268	6	2	0.259	0.225	0.236	6	2
Permeability, 10^{-3} Darcy's	1.27	0.40	0.72	4	1	0.56	0.23	0.36	4	1
Admittance, cm^2/sec	---	---	$6x10^{-3}$	1	1	---	---	$3x10^{-3}$	1	1
Per Cent Ash	0.266	0.226	0.238	4	2	---	---	---	-	-

Table 54. Summary of High-Temperature Properties, RVC Graphite 18-Inch Diameter by 17-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	With Grain No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n	Across Grain No. of Blocks
Thermal Expansion	500	0.208	0.171	0.195	6	2	1.246	1.220	1.234	6	2
Per Cent Elongation,	1000	0.464	0.417	0.450	6	2	0.538	0.508	0.529	6	2
$\frac{\Delta L}{L}$ x 100	1500	0.782	0.743	0.770	6	2	0.893	0.868	0.883	6	2
	2000	1.172	1.097	1.132	6	2	1.328	1.281	1.296	6	2
	2400	1.488	1.412	1.453	6	2	1.680	1.628	1.663	6	2
	2800	1.809	1.720	1.760	6	2	2.047	1.071	2.011	6	2
Young's Modulus, 10^6 lbs/in^2	RT	1.92	1.72	1.85	3	1	1.58	1.49	1.53	3	1
	500	2.02	1.82	1.94	3	1	1.66	1.56	1.59	3	1
	1200	2.25	1.93	2.14	3	1	1.77	1.67	1.71	3	1
	1600	2.43	2.25	2.32	3	1	1.89	1.87	1.88	3	1
	1800	2.43	2.22	2.31	3	1	---	---	---	-	-
	2000	2.44	2.20	2.30	3	1	1.93	1.89	1.91	3	1
	2400	2.29	2.11	2.19	3	1	1.78	1.72	1.75	3	1
	2800	2.12	1.85	1.99	3	1	1.62	1.54	1.58	3	1
Tensile Strength, lbs/in^2	1000	4180	2730	3285	3	1	---	---	1870	1	1
	1500	---	---	3190	1	1	---	---	2420	1	1
	2000	4550	3830	4190	2	1	---	---	2260	1	1
	2500	5610	5190	5375	3	1	4985	3265	4125	2	1
	2700	5170	2600	4285	3	1	3550	2540	3045	2	1
Compressive Strength, ½-inch diameter by ½-in.	1000	---	---	11870	1	1	---	---	11160	1	1
	1500	---	---	12680	1	1	---	---	13590	1	1
	1700	---	---	---	-	-	---	---	13590	1	1
	2000	---	---	17470	1	1	14205	13240	13720	2	1
	2500	---	---	20140	1	1	21490	18970	20230	2	1
	2700	No break at		30680	1	1	23225	16740	19980	2	1
Apparent Shear Strength, lbs/in^2	1000	---	---	2620	1	1	---	---	3745	1	1
	1500	---	---	3840	1	1	---	---	3735	1	1
	2000	---	---	3820	1	1	---	---	4005	1	1
	2500	---	---	5870	1	1	---	---	5120	1	1
	2700	---	---	6520	1	1	---	---	5335	1	1

Table 55. Room-Temperature Properties, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length

Properties	With Grain			Across Grain		
	Average	σ	n	Average	σ	n
Bulk Density, g/cc	1.84	0.01	20	---	---	--
Specific Resistance, 10^{-4} ohm-cm	12.71	0.33	10	16.03	0.79	10
Young's Modulus, 10^6 lbs/in^2	1.71	0.04	10	1.29	0.04	10
Flexural Strength, lbs/in^2	3138	310	5	1875	175	5
Compressive Strength, 1- by 1- by 1-inch, lbs/in^2	10850	750	10	10300	650	10
Compressive Strength, ½-inch diameter by ½-inch, lbs/in^2	10920	1143	9	11215	779	9
Tensile Strength, lbs/in^2	2730	185	11	1300	236	10
Apparent Shear Strength, lbs/in^2	2455	254	10	2125	169	10

Properties	With Grain				Across Grain			
	Max.	Min.	Ave.	n	Max.	Min.	Ave.	n
CTE, $10^{-6}/°C$, 20°-100°C	3.68	3.65	3.66	3	4.50	4.26	4.42	3
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ °K}$	0.280	0.267	0.273	3	0.259	0.226	0.240	3
Permeability-N_2, 10^{-3} Darcy's	---	---	---	-	---	---	---	-
Admittance, cm^2/sec	---	---	---	-	---	---	---	-
Per Cent Ash	0.266	0.233	0.250	2	---	---	---	-

Table 56. High-Temperature Properties, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
Thermal Expansion	500	0.208	0.171	0.195	3	0.246	0.220	0.234	3
Per Cent Elongation	1000	0.464	0.417	0.447	3	0.538	0.508	0.528	3
$\frac{\Delta L}{L} \times 100$	1500	0.782	0.743	0.769	3	0.893	0.868	0.883	3
	2000	1.150	1.097	1.127	3	1.301	1.281	1.290	3
	2400	1.467	1.448	1.460	3	1.676	1.699	1.672	3
	2800	1.787	1.736	1.762	3	2.039	2.003	2.017	3
Young's Modulus	RT	1.92	1.72	1.85	3	1.58	1.49	1.53	3
10^6 lbs/in^2	500	2.02	1.82	1.94	3	1.66	1.56	1.59	3
	1200	2.25	1.93	2.14	3	1.57	1.67	1.71	3
	1600	2.43	2.25	2.32	3	1.89	1.87	1.88	3
	1800	2.43	2.22	2.31	3	---	---	---	-
	2000	2.44	2.20	2.30	3	1.93	1.89	1.91	3
	2400	2.29	2.11	2.19	3	1.78	1.72	1.75	3
	2800	2.12	1.85	1.99	3	1.62	1.54	1.58	3
Tensile Strength	1000	4180	2730	3285	3	---	---	1870	1
lbs/in^2	1500	---	---	3190	1	---	---	2420	1
	2000	4550	3830	4190	2	---	---	2260	1
	2500	5610	5190	5375	3	4985	3265	4125	2
	2700	5170	2600	4285	3	3550	2540	3045	2
Compressive Strength	1000	---	---	11870	1	---	---	11160	1
½-inch diameter by ½-inch	1500	---	---	12680	1	---	---	13590	1
lbs/in^2	1700	---	---	---	-	---	---	13950	1
	2000	---	---	17470	1	14205	13240	13720	2
	2500	---	---	20140	1	21490	18970	20230	2
	2700	No break at		30680	1	23225	16740	19980	2
Apparent Shear Strength	1000	---	---	2620	1	---	---	3745	1
lbs/in^2	1500	---	---	3840	1	---	---	3735	1
	2000	---	---	3820	1	---	---	4005	1
	2500	---	---	5870	1	---	---	5120	1
	2700	---	---	6520	1	---	---	5335	1

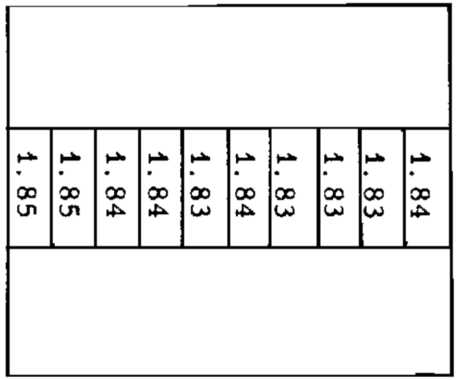
Table 57. Room-Temperature Properties, RVC Graphite, Block No. 175, 18-Inch Diameter by 17-Inch Length

Properties	With Grain Average	With Grain σ	With Grain n	Across Grain Average	Across Grain σ	Across Grain n
Bulk Density, g/cc	1.85	0.01	21	---	---	--
Specific Resistance, 10^{-4} ohm-cm	13.13	0.07	10	16.75	0.73	11
Young's Modulus-Sonic, 10^{6} lbs/in^2	1.81	0.03	10	1.44	0.03	10
Flexural Strength, lbs/in^2	3310	155	5	2200	240	5
Compressive Strength, 1- by 1- by 1-inch, lbs/in^2	11400	300	10	11600	450	10

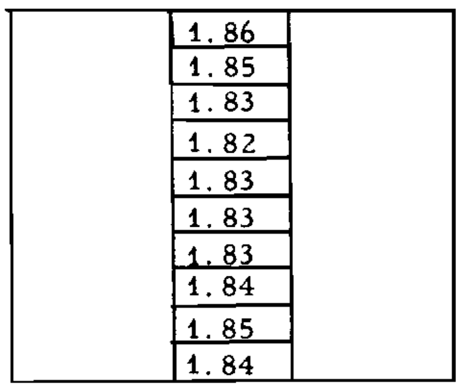
	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
CTE, $10^{-6}/°C$, 20°-100°C	3.75	3.69	3.72	3	4.50	4.44	4.47	3
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ °K}$	0.266	0.260	0.262	3	0.238	0.225	0.231	3
Permeability-N_2, 10^{-3} Darcy's	1.27	0.40	0.72	4	0.56	0.23	0.36	4
Admittance-N_2, cm^2/sec	---	---	6×10^{-2}	1	---	---	3×10^{-2}	1
Per Cent Ash	0.227	0.226	0.227	2	---	---	---	-

Table 58. High-Temperature Properties, RVC Graphite, Block No. 175, 18-Inch Diameter by 17-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
Thermal Expansion Per Cent Elongation $\frac{\Delta L}{L} \times 100$	500	0.201	0.190	0.195	3	0.238	0.226	0.234	3
	1000	0.455	0.448	0.452	3	0.533	0.526	0.530	3
	1500	0.776	0.766	0.770	3	0.885	0.882	0.883	3
	2000	1.172	1.112	1.136	3	1.328	1.283	1.302	3
	2400	1.488	1.412	1.446	3	1.680	1.628	1.653	3
	2800	1.809	1.720	1.758	3	2.047	1.971	2.005	3

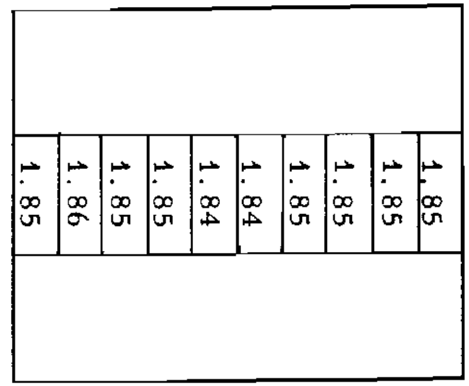


Slab No. 1

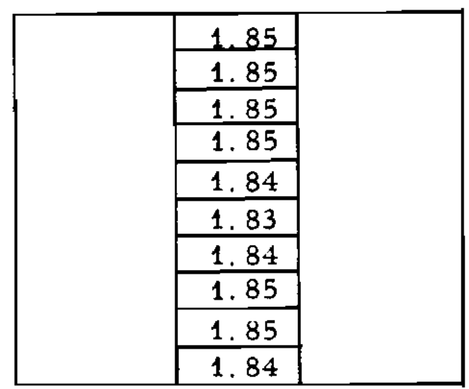


Slab No. 2

Block No. 163



Slab No. 1

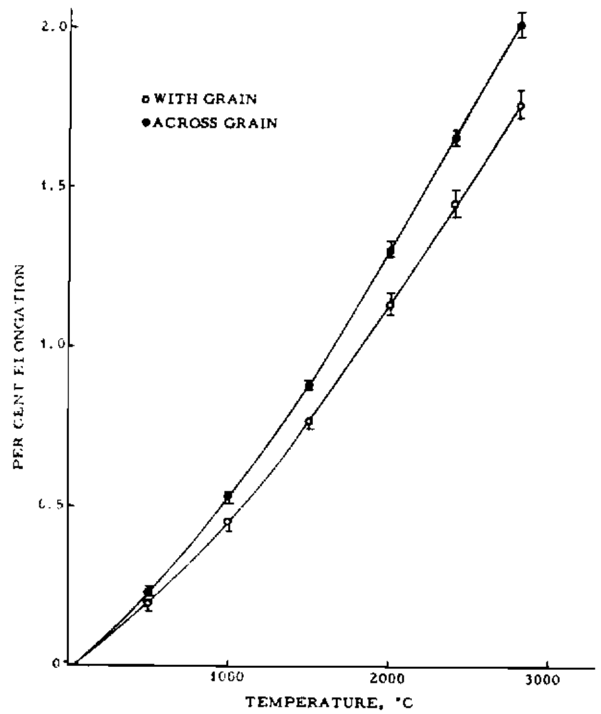


Slab No. 2

Block No. 175

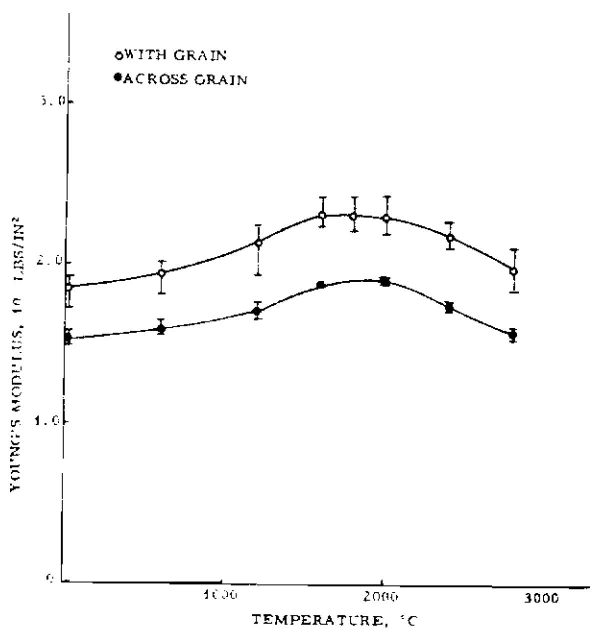
L-605

Figure 181. Density Profile, RVC Graphite, Blocks No. 163 and 175, 18-Inch Diameter by 17-Inch Length



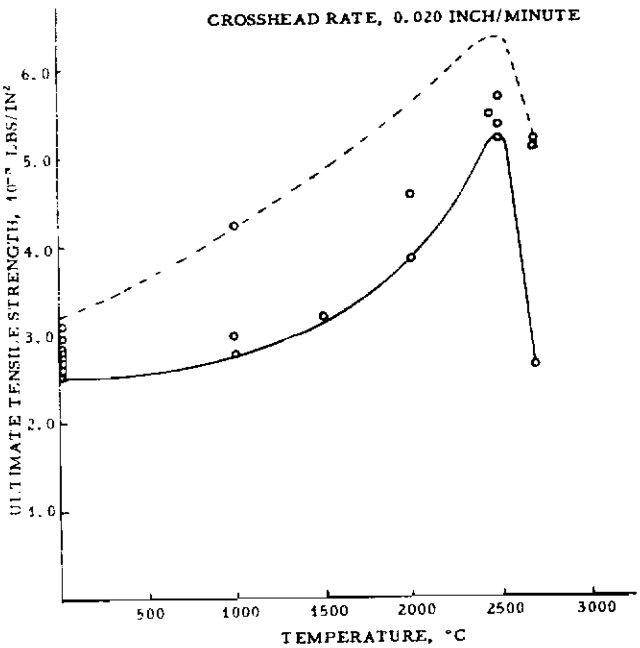
L-606

Figure 182. Thermal Expansion vs. Temperature, RVC Graphite, 18-Inch Diameter by 17-Inch Length



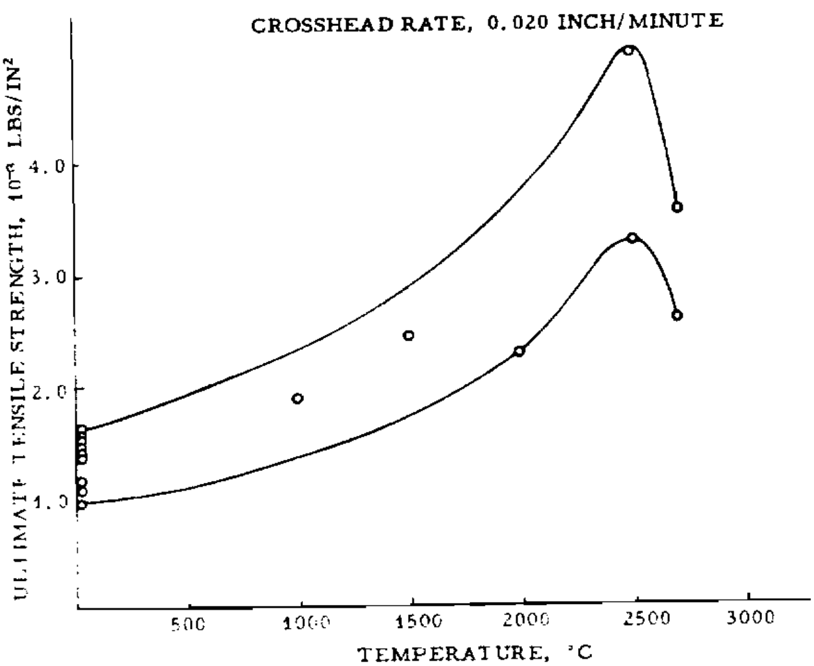
L-607

Figure 183. Young's Modulus vs. Temperature, RVC Graphite, 18-Inch Diameter by 17-Inch Length, Block No. 163



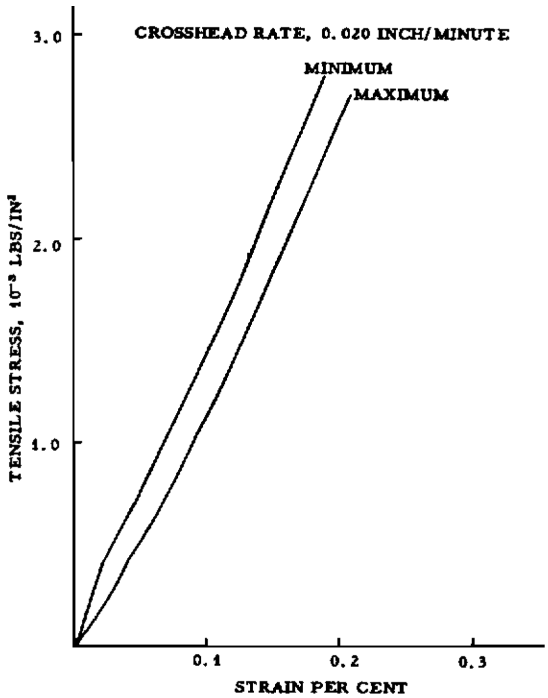
L-608

Figure 184. With-Grain Ultimate Tensile Strength vs. Temperature, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length



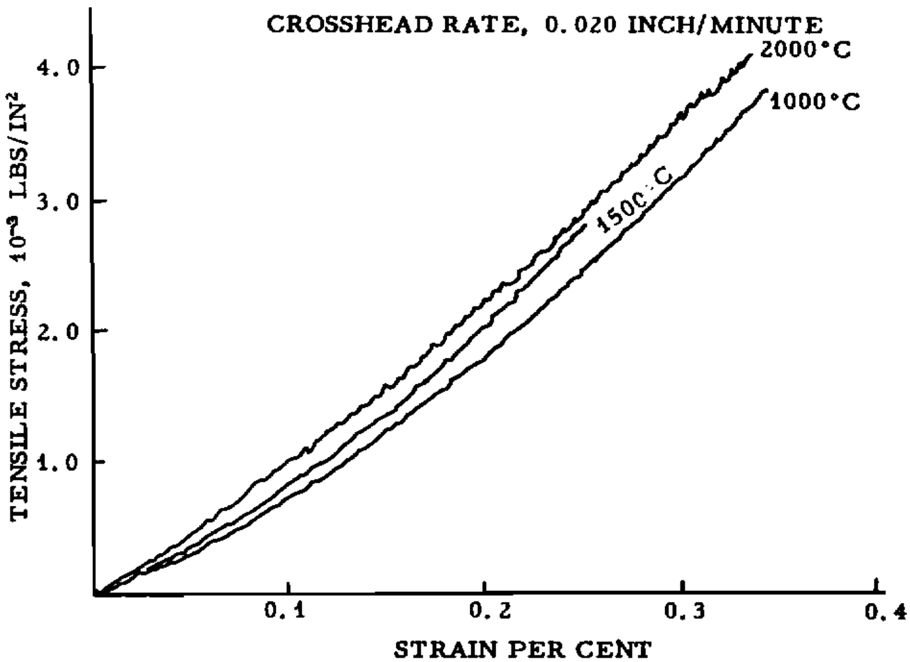
L-609

Figure 185. Across-Grain Ultimate Tensile Strength vs. Temperature, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length



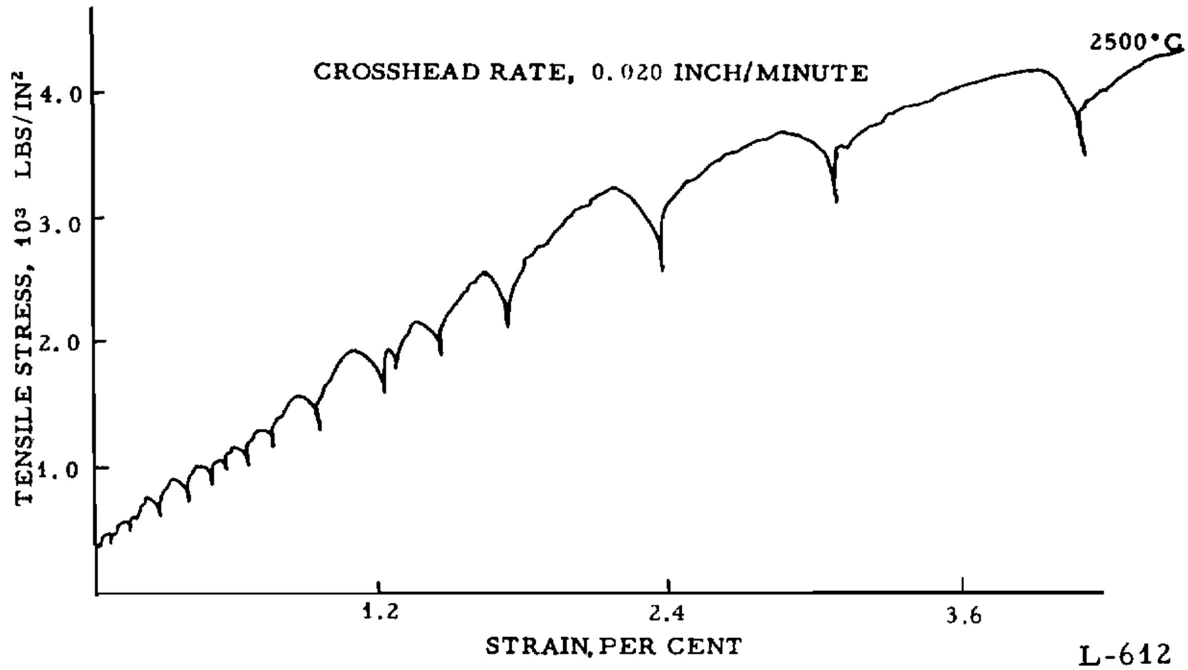
L-610

Figure 186. With-Grain Tensile Stress-Strain Curves, RVC Graphite, 18-Inch Diameter by 17-Inch Length, Block No. 163, Room Temperature



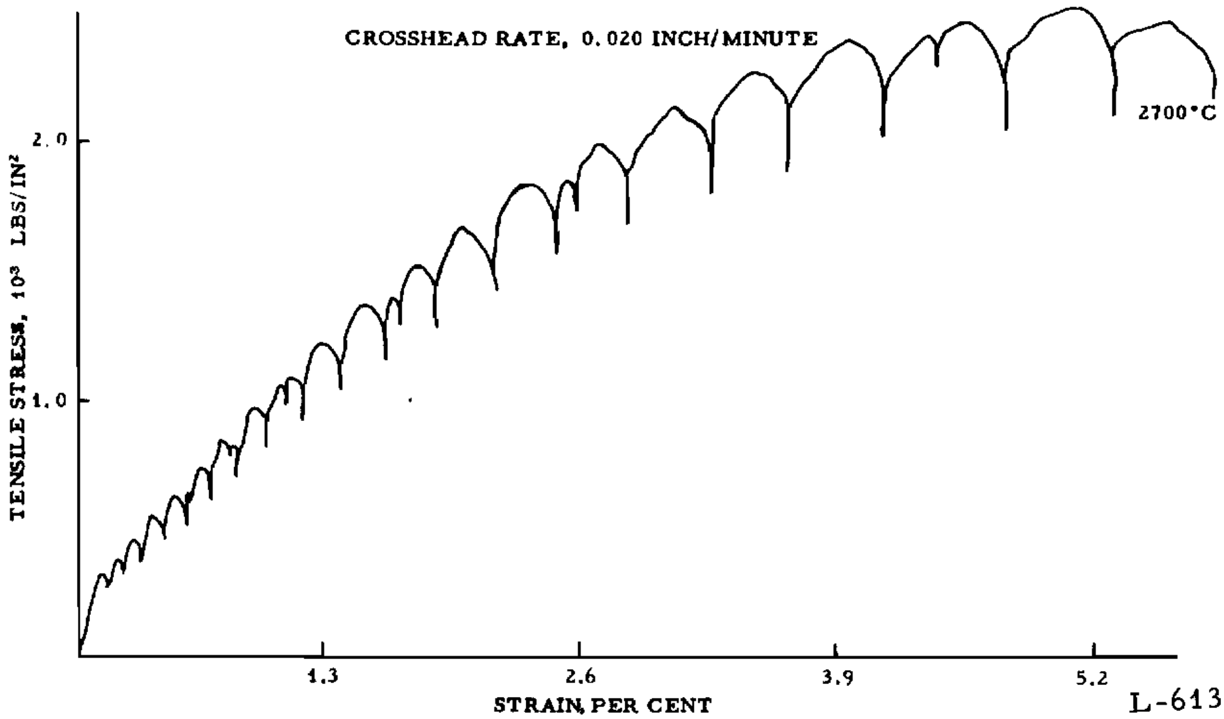
L-611

Figure 187. With-Grain Tensile Stress-Strain Curves, RVC Graphite, 18-Inch Diameter by 17-Inch Length, Block No. 163, 1000°C, 1500°C, 2000°C



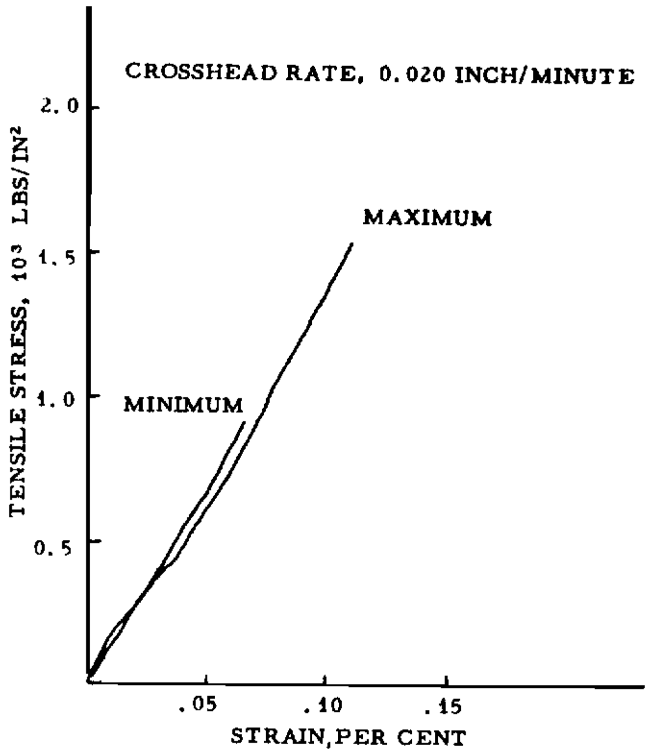
L-612

Figure 188. With-Grain Tensile Stress-Strain Curves, RVC Graphite, 18-Inch Diameter by 17-Inch Length, Block No. 163, 2500°C



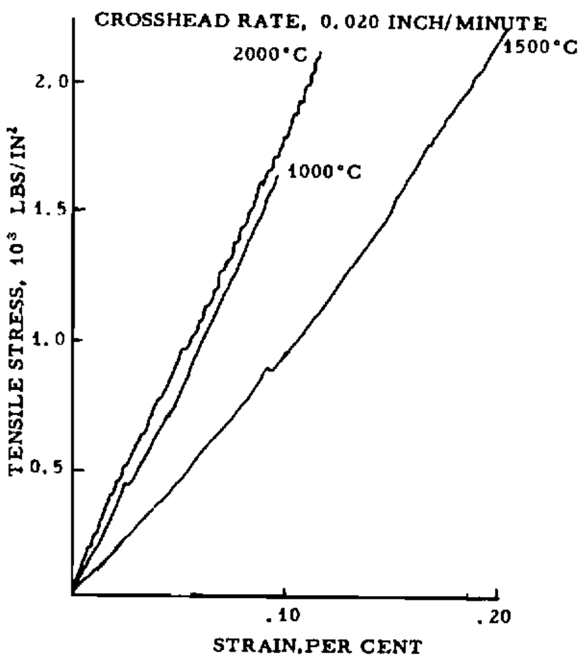
L-613

Figure 189. With-Grain Tensile Stress-Strain Curves, RVC Graphite, 18-Inch Diameter by 17-Inch Length, Block No. 163, 2700°C



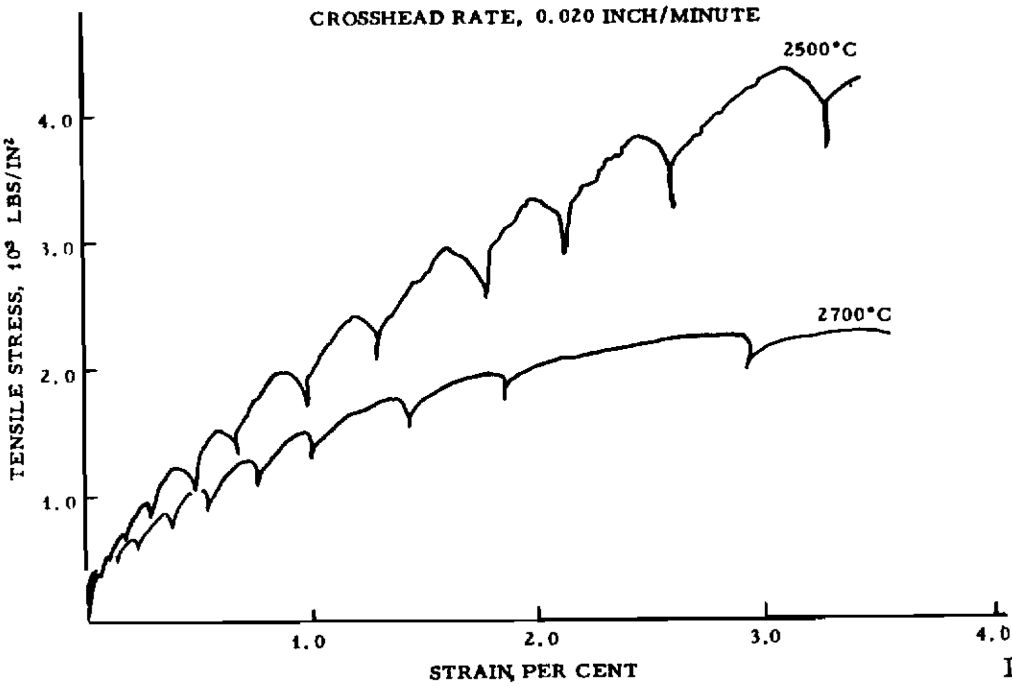
L-614

Figure 190. Across-Grain Tensile Stress-Strain Curves, RVC Graphite, 18-Inch Diameter by 17-Inch Length, Block No. 163, Room Temperature



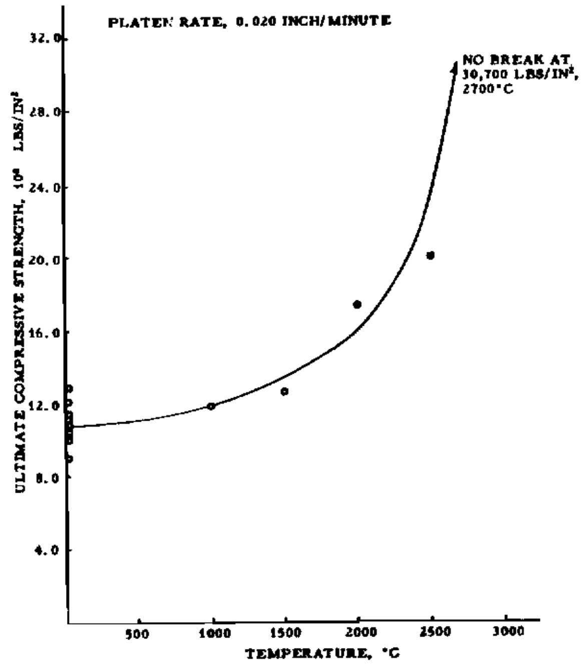
L-615

Figure 191. Across-Grain Tensile Stress-Strain Curves, RVC Graphite, 18-Inch Diameter by 17-Inch Length, Block No. 163, 1000°C, 1500°C, 2000°C



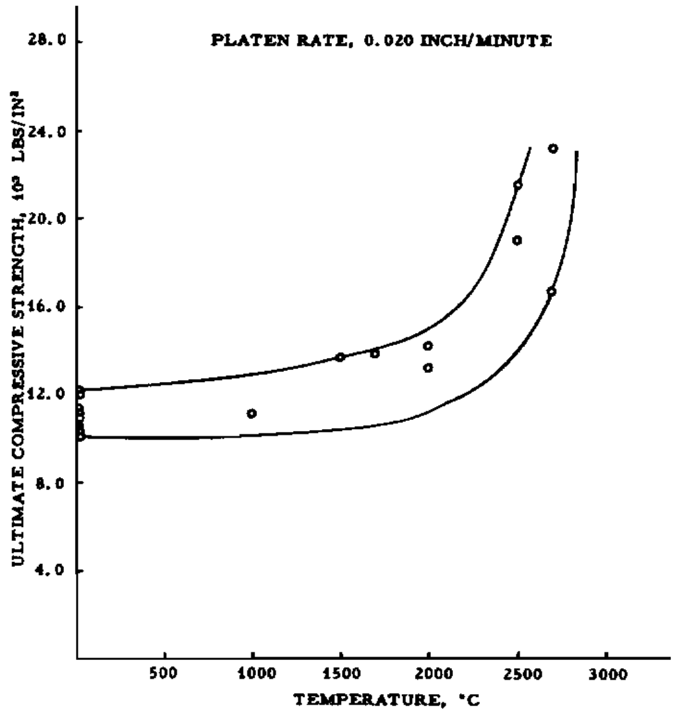
L-616

Figure 192. Across-Grain Tensile Stress-Strain Curves, RVC Graphite, 18-Inch Diameter by 17-Inch Length, Block No. 163, 2500°C, 2700°C



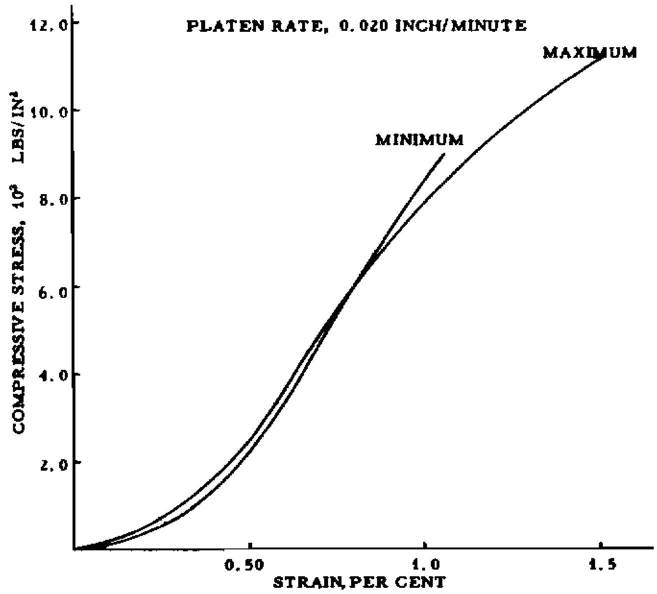
L-617

Figure 193. With-Grain Ultimate Compressive Strength vs. Temperature, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length



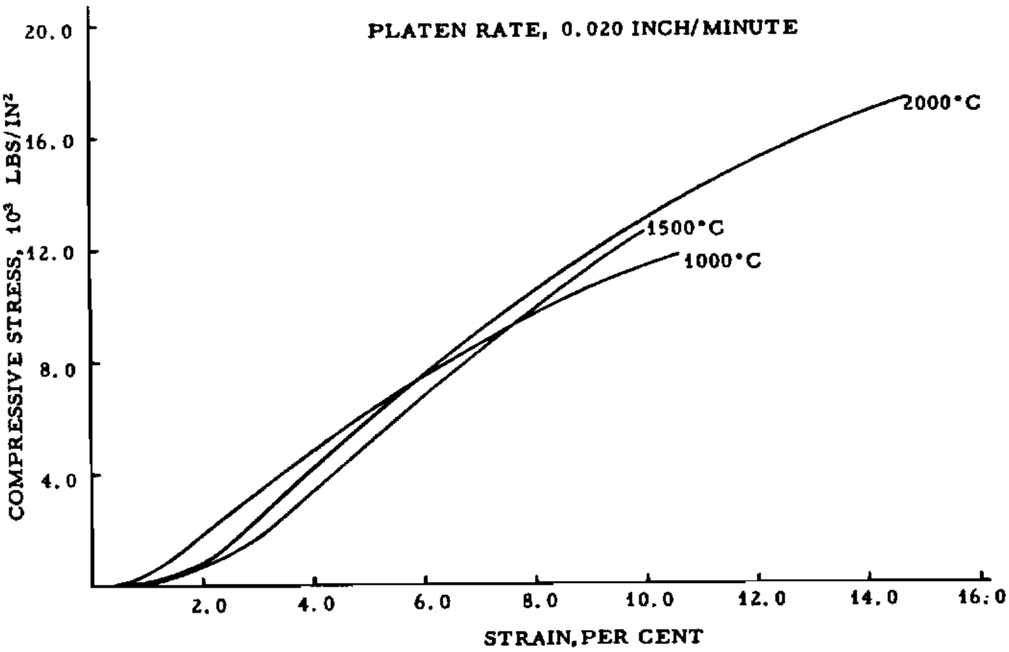
L-618

Figure 194. Across-Grain Ultimate Compressive Strength vs. Temperature, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length



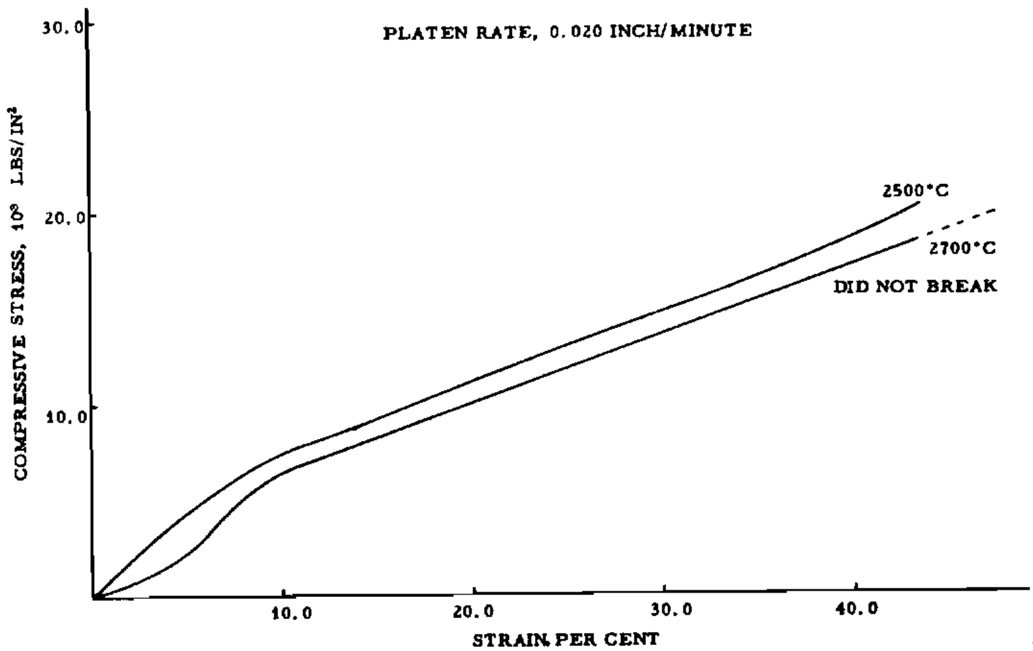
L-619

Figure 195. With-Grain Compressive Stress-Strain Curves, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length, Room Temperature



L-620

Figure 196. With-Grain Compressive Stress-Strain Curves, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length, 1000°C, 1500°C, 2000°C



L-621

Figure 197. With-Grain Compressive Stress-Strain Curves, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length, 2500°C, 2700°C

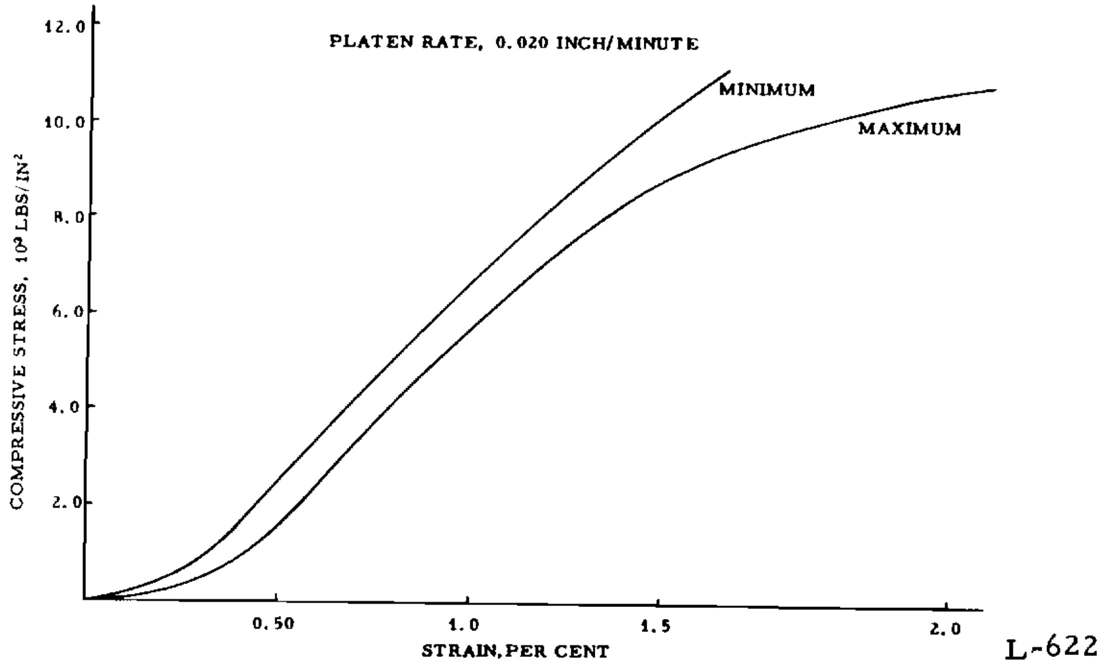


Figure 198. Across-Grain Compressive Stress-Strain Curves, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length, Room Temperature

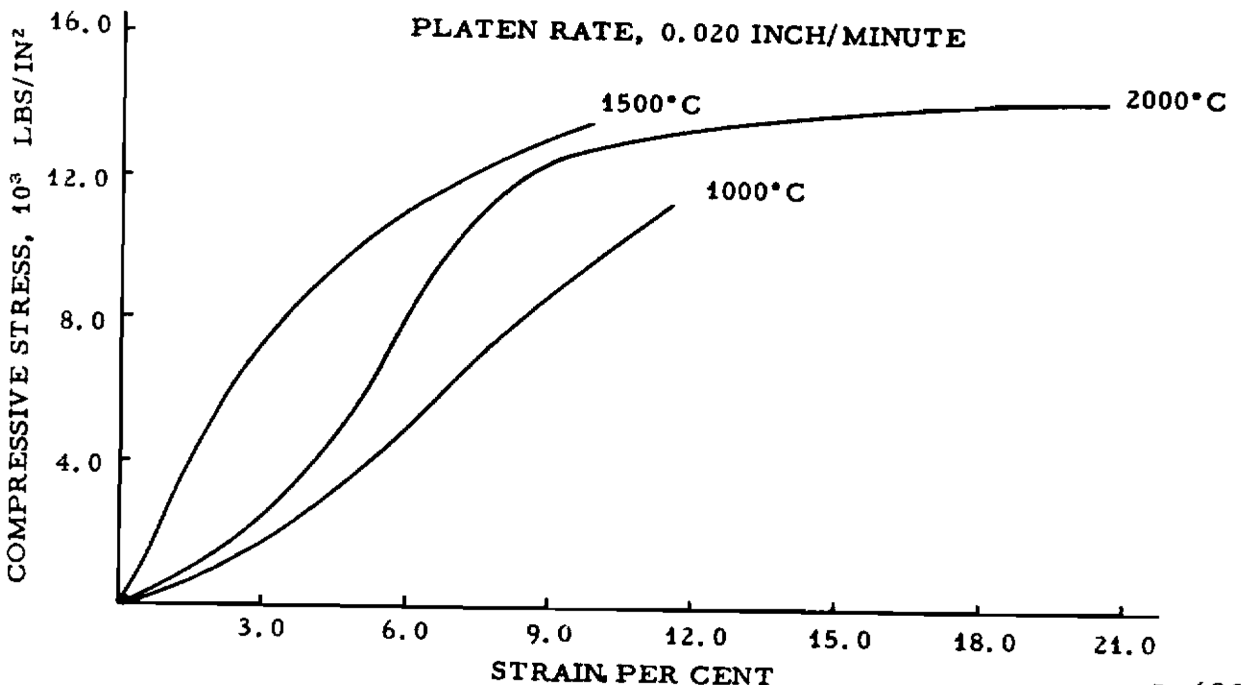


Figure 199. Across-Grain Compressive Stress-Strain Curves, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length, 1000°C, 1500°C, 2000°C

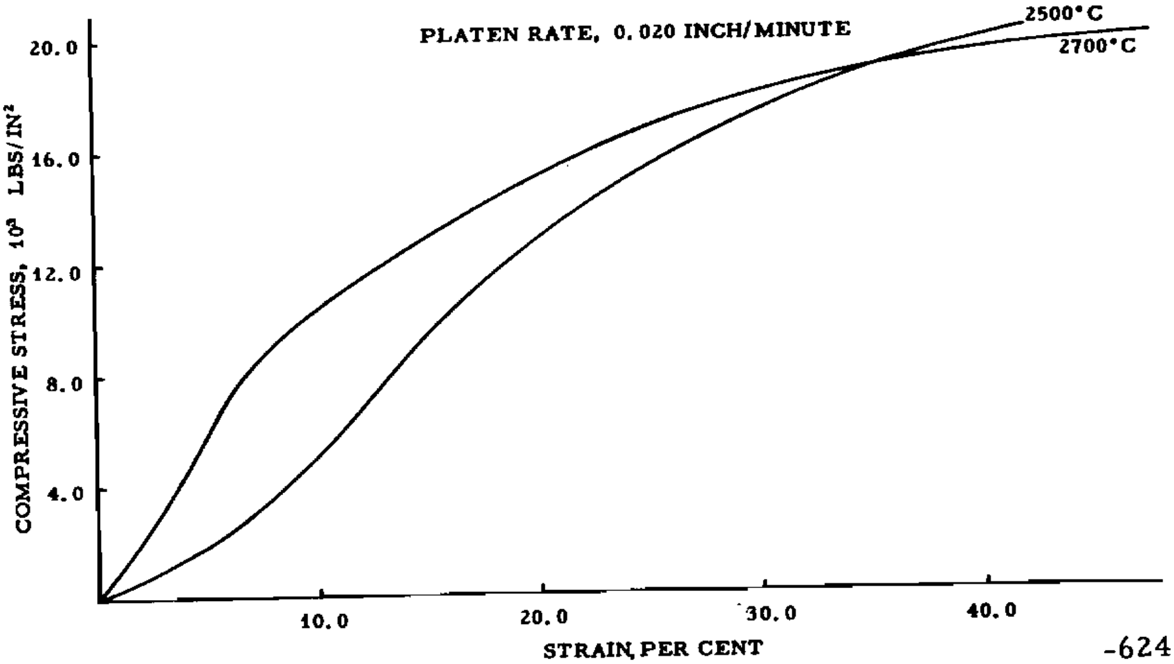


Figure 200. Across-Grain Compressive Stress-Strain Curves, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length, 2500°C, 2700°C

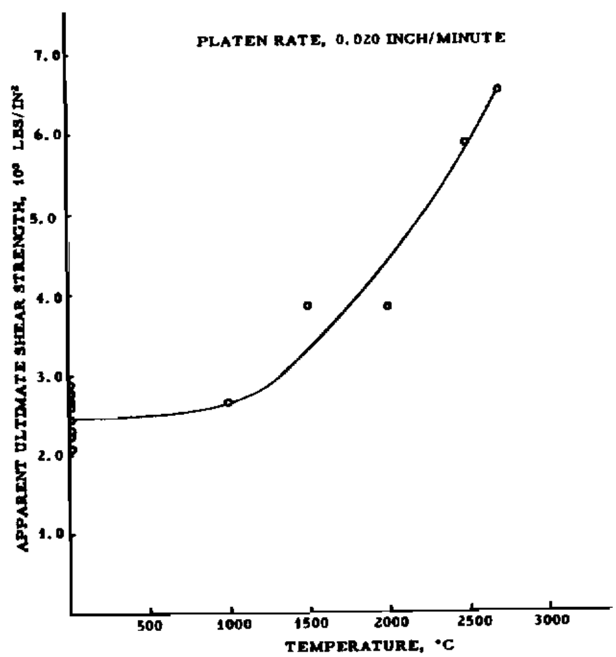
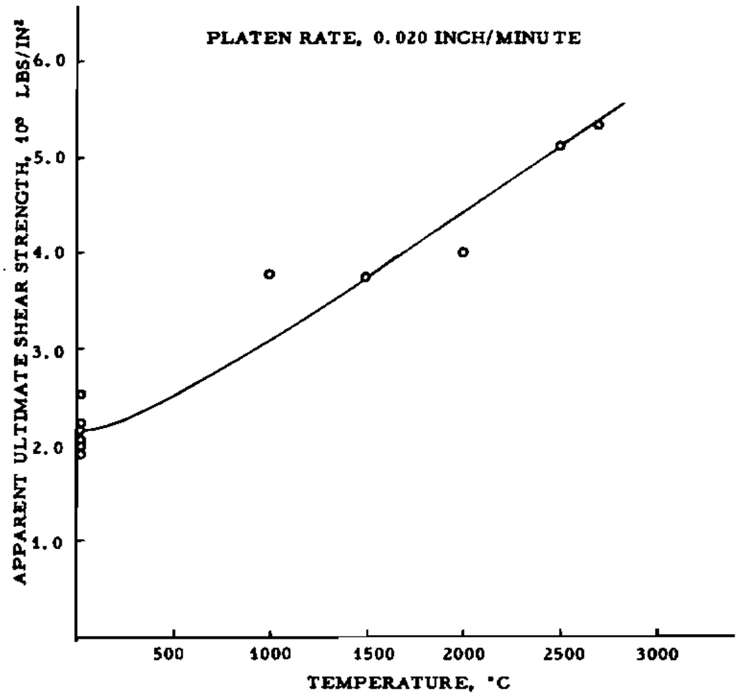
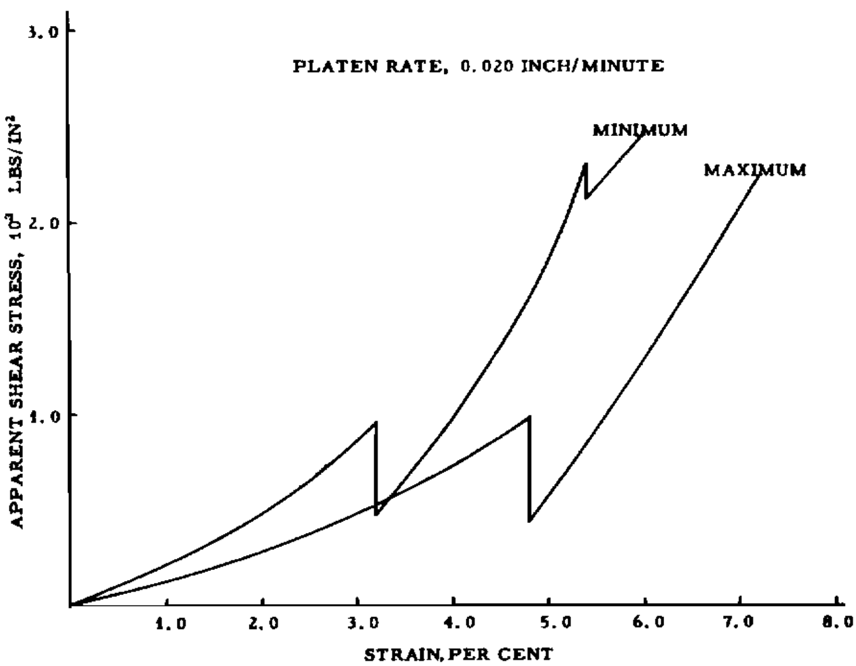


Figure 201. With-Grain Apparent Ultimate Shear Strength vs. Temperature, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length



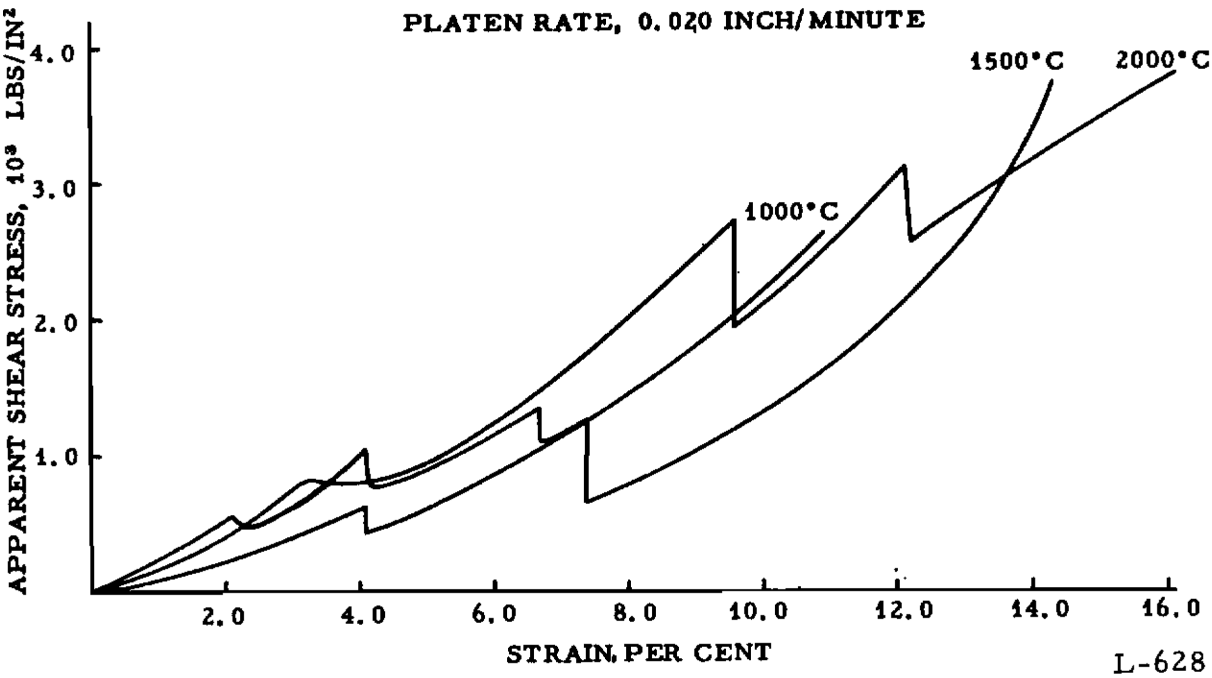
L-626

Figure 202. Across-Grain Apparent Shear Strength, vs. Temperature, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length



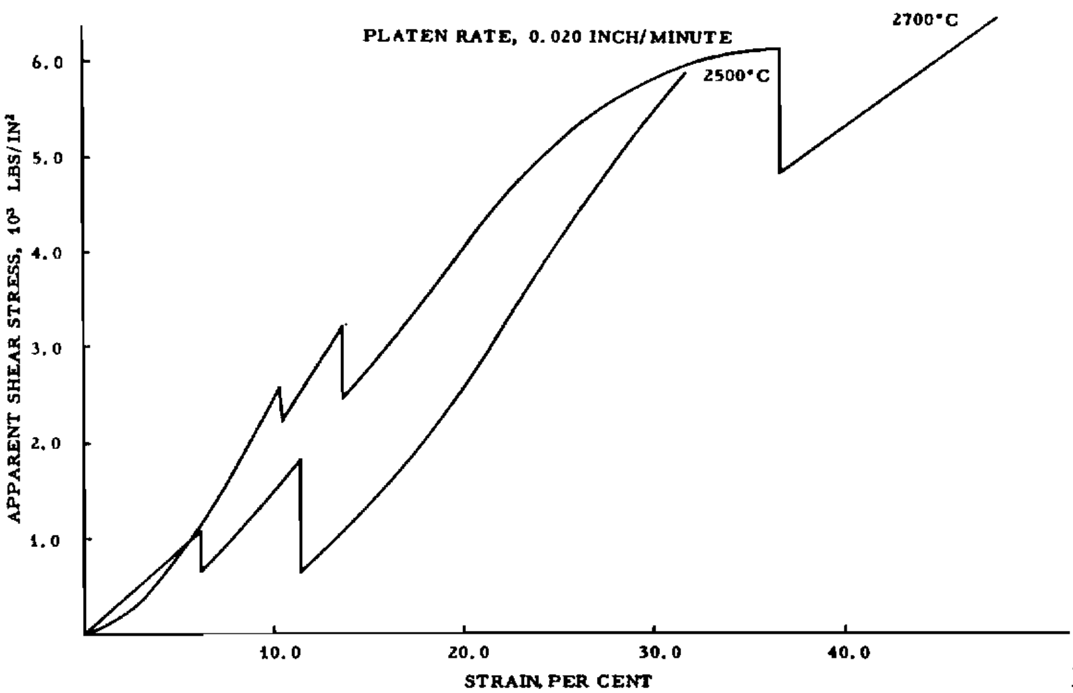
L-627

Figure 203. With-Grain Apparent Shear Stress-Strain Curves, RVC Graphite, Room Temperature, Block No. 163, 18-Inch Diameter by 17-Inch Length



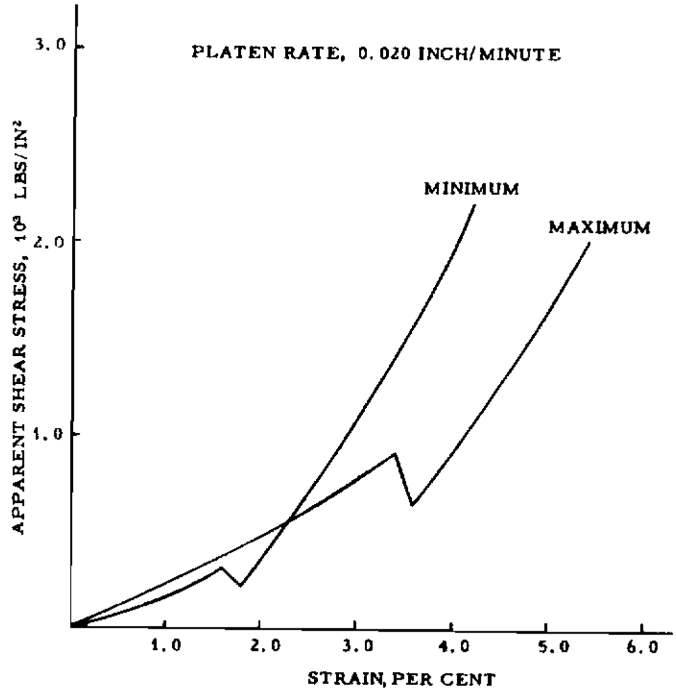
L-628

Figure 204. With-Grain Apparent Shear Stress-Strain Curves, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length, 1000°C, 1500°C, 2000°C



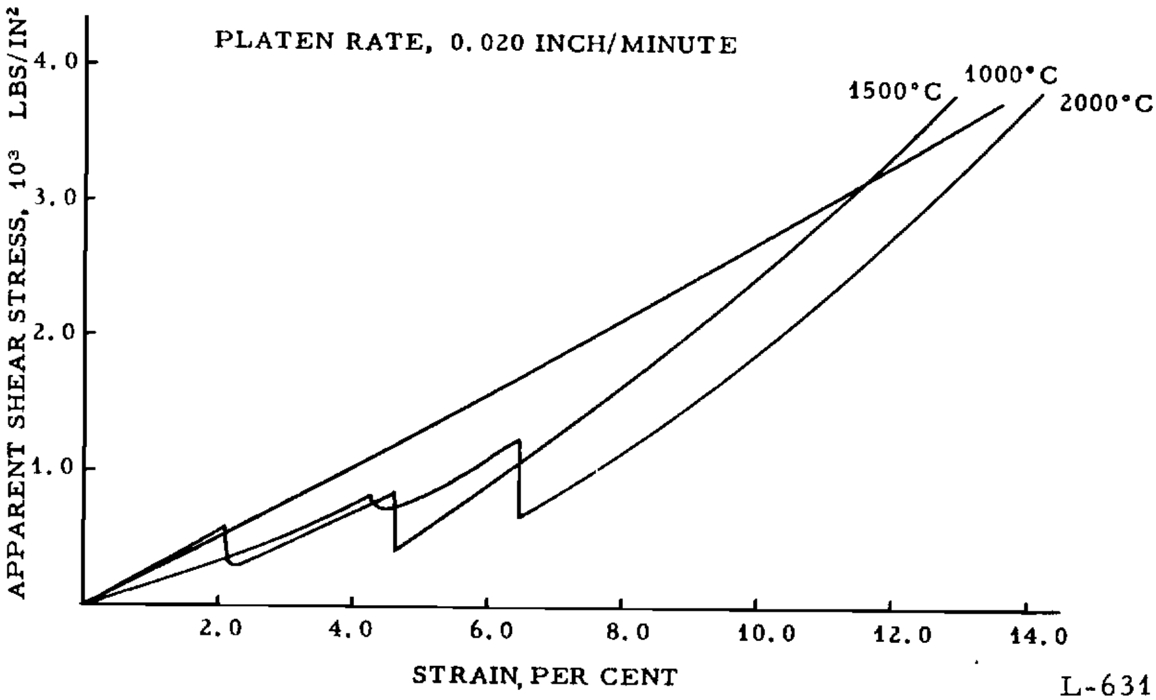
L-629

Figure 205. With-Grain Apparent Shear Stress-Strain Curves, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length, 2500°C, 2700°C



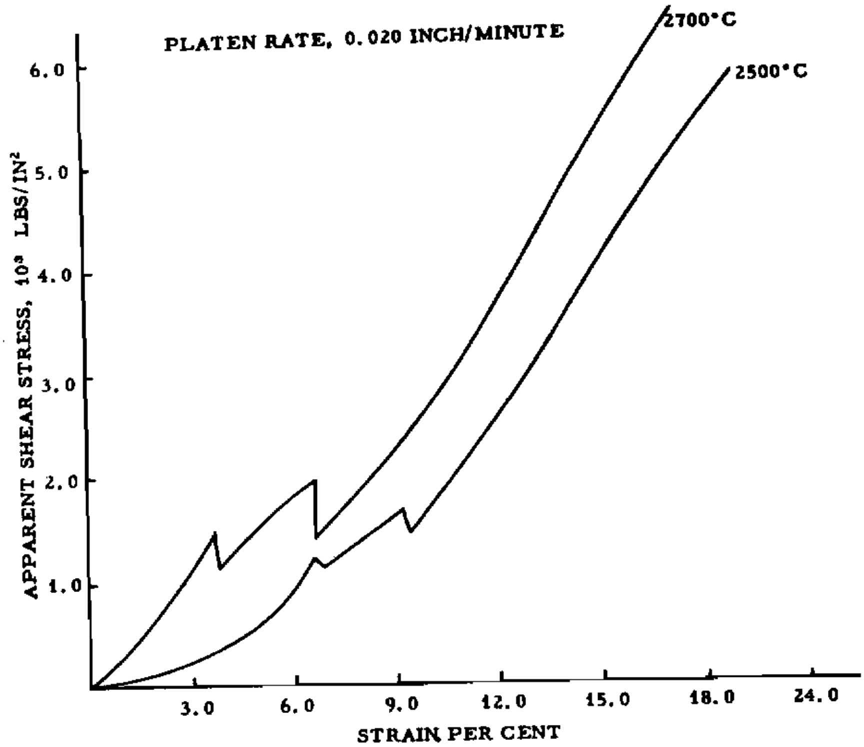
L-630

Figure 206. Across-Grain Apparent Shear Stress-Strain Curves, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length, Room Temperature



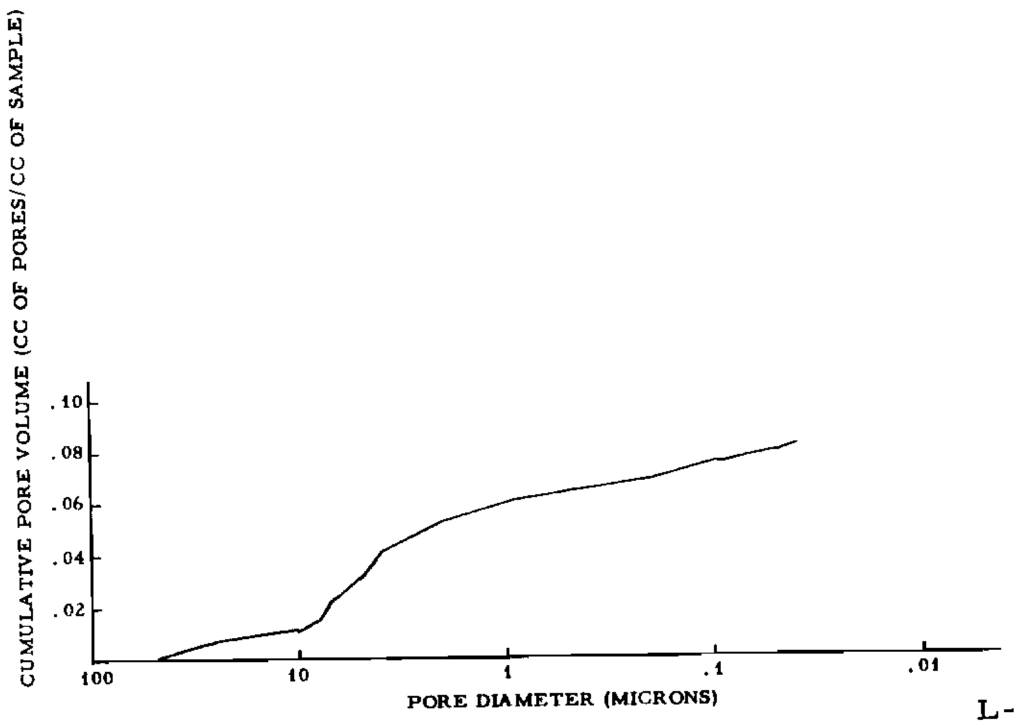
L-631

Figure 207. Across-Grain Apparent Shear Stress-Strain Curves, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length, 1000°C, 1500°C, 1500°C



L-632

Figure 208. Across-Grain Apparent Shear Stress-Strain Curves, RVC Graphite, Block No. 163, 18-Inch Diameter by 17-Inch Length, 2500°C, 2700°C



L-653

Figure 209. Pore Size Distribution, Mercury Porosimetry, RVC Graphite

3.10. Grade RVD Graphite[22]

Two 18-inch diameter by 17-inch length blocks were used to determine the physical properties of RVD graphite. Most of the high-temperature properties were determined on Block No. 200, with thermal expansion being the only high-temperature property measured on both blocks.

The physical property data from both blocks are given in Tables 59 and 60, whereas Tables 61 to 64, inclusive, present the properties of the individual blocks. Figure 211 is a plot of the thermal expansion data from Table 60. The interpretation of stress-strain curves was discussed in section 3.1. All strength measurements were made with a cross-head or platen rate of 0.020 inch per minute.

Table 59. Summary of Room-Temperature Properties, RVD Graphite, 18-Inch Diameter by 17-Inch Length

Properties	With Grain Average	With Grain σ	With Grain n	With Grain No. of Blocks	Across Grain Average	Across Grain σ	Across Grain n	Across Grain No. of Blocks
Bulk Density, g/cc	1.87	0.01	36	2	---	---	--	-
Specific Resistance, 10^{-4} ohm-cm	12.62	0.36	19	2	21.64	0.76	17	2
Young's Modulus, 10^{6} lbs/in^2	2.10	0.05	19	2	1.12	0.05	17	2
Flexural Strength, lbs/in^2	4705	359	19	2	3125	216	17	2
Compressive Strength, 1- by 1- by 1-inch, lbs/in^2	11610	1050	13	2	12400	750	16	2
Compressive Strength, $\frac{1}{2}$-inch diameter by $\frac{1}{2}$-inch, lbs/in^2	.12170	219	10	1	12380	420	10	1
Tensile Strength, lbs/in^2	4095	440	11	1	2705	201	10	1
Apparent Shear Strength, lbs/in^2	3085	412	10	1	2330	180	10	1

Properties	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	With Grain No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n	Across Grain No. of Blocks
CTE, $10^{-6}/°C$, 20-100°C	1.76	1.61	1.70	6	2	3.51	3.27	3.43	6	1
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ °K}$	0.289	0.256	0.273	6	2	0.220	0.185	0.198	6	2
Admittance, cm^2/sec	$1x10^{-2}$	$9x10^{-3}$	$1x10^{-2}$	3	2	$7x10^{-3}$	$4x10^{-3}$	$5x10^{-3}$	3	2
Per Cent Ash	0.167	0.162	0.165	2	2	---	---	---	-	-

Table 60. Summary of High-Temperature Properties, RVD Graphite, 18-Inch Diameter by 17-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	With Grain No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n	Across Grain No. of Blocks
Thermal Expansion,	500	0.155	0.112	0.132	6	2	0.210	0.180	0.194	6	2
Per Cent Elongation,	1000	0.343	0.267	0.298	6	2	0.442	0.427	0.436	6	2
$\frac{\Delta L}{L} \times 100$	1500	0.540	0.441	0.490	6	2	0.735	0.658	0.705	6	2
	2000	0.820	0.719	0.759	6	2	1.106	1.018	1.076	6	2
	2400	1.070	.980	1.016	6	2	1.517	1.420	1.478	6	2
	2800	1.351	1.207	1.286	6	2	1.954	1.842	1.916	6	2
Young's Modulus, 10^6 lbs/in^2	RT	1.76	1.70	1.73	3	1	1.03	0.98	1.00	3	1
	600	1.78	1.72	1.75	3	1	1.05	0.92	1.01	3	1
	1200	1.84	1.76	1.79	3	1	1.08	1.02	1.04	3	1
	1600	1.88	1.80	1.83	3	1	1.10	1.04	1.08	3	1
	2000	1.92	1.83	1.87	3	1	1.12	1.06	1.10	3	1
	2300	1.93	1.86	1.89	3	1	1.14	1.08	1.11	3	1
	2500	1.92	1.86	1.88	3	1	1.13	1.07	1.09	3	1
	2800	1.89	1.83	1.85	3	1	1.11	1.07	1.08	3	1
Tensile Strength, lbs/in^2	1000	---	---	4455	1	1	---	---	3720	1	1
	1500	---	---	5190	1	1	---	---	3045	1	1
	2000	---	---	6100	1	1	4515	3825	4170	2	1
	2500	---	---	6760	1	1	4680	4275	4455	4	1
	2700	---	---	5290	1	1	---	---	3480	1	1
Compressive Strength, ½-inch dia. by ½-inch,	1000	---	---	11455	1	1	---	---	13600	1	1
	1500	---	---	12935	1	1	---	---	12835	1	1
	2000	---	---	13750	1	1	---	---	16805	1	1
	2500	---	---	23455	1	1	---	---	24040	1	1
	2700	---	---	---	-	-	---	---	27860	1	1
Apparent Shear Strength	1000	4735	4390	4565	2	1	---	---	4510	1	1
	1500	6520	5815	6165	2	1	---	---	4550	1	1
	2000	---	---	6560	1	1	5990	4990	5490	2	1
	2500	7735	5860	6795	2	1	5940	5785	5860	2	1
	2700	---	---	8025	1	1	6065	5560	5810	2	1

Table 61. Room-Temperature Properties, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length

Properties	With Grain Average	With Grain σ	With Grain n	Across Grain Average	Across Grain σ	Across Grain n
Bulk Density, g/cc	1.87	0.01	19	---	---	--
Specific Resistance, 10^{-4} ohm-cm	12.52	0.41	10	21.72	0.97	9
Young's Modulus, 10^{6} lbs/in^2	2.10	0.05	10	1.13	0.05	9
Flexural Strength, lbs/in^2	4695	315	10	3155	270	9
Compressive Strength, 1- by 1- by 1-inch, lbs/in^2	11550	1200	6	12000	900	8
Compressive Strength, $\frac{1}{2}$-inch diameter by $\frac{1}{2}$-inch, lbs/in^2	12170	219	10	12380	420	10
Tensile Strength, lbs/in^2	4095	440	11	2705	201	10
Apparent Shear Strength, lbs/in^2	3085	412	10	2330	180	10

Properties	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
CTE, $10^{-6}/^{\circ}C$, 20°-$100^{\circ}C$	1.70	1.61	1.65	3	3.48	3.27	3.43	3
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2/\text{sec}}$	0.289	0.274	0.280	3	0.220	0.185	0.198	3
Admittance, cm^2/sec	---	---	1×10^{-2}	1	7×10^{-3}	6×10^{-3}	6×10^{-3}	2
Per Cent Ash	---	---	0.162	1	---	---	---	--

Table 62. High-Temperature Properties, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	n
Thermal Expansion	500	0.118	0.112	0.115	3	0.196	0.184	0.190	3
Per Cent Elongation	1000	0.324	0.281	0.298	3	0.442	0.427	0.437	3
$\frac{\Delta L}{L} \times 100$	1500	0.518	0.486	0.502	3	0.735	0.658	0.691	3
	2000	0.785	0.728	0.753	3	1.103	1.018	1.058	3
	2400	1.041	0.982	1.016	3	1.517	1.420	1.466	3
	2800	1.336	1.254	1.299	3	1.953	1.842	1.899	3
Young's Modulus, 10^6 lbs/in^2	RT	1.76	1.70	1.73	3	1.03	0.98	1.00	3
	600	1.78	1.72	1.75	3	1.05	0.92	1.01	3
	1200	1.84	1.76	1.79	3	1.08	1.02	1.04	3
	1600	1.88	1.80	1.83	3	1.10	1.04	1.08	3
	2000	1.92	1.83	1.87	3	1.12	1.06	1.10	3
	2300	1.93	1.86	1.89	3	1.14	1.08	1.11	3
	2500	1.92	1.86	1.88	3	1.13	1.07	1.09	3
	2800	1.89	1.83	1.85	3	1.11	1.07	1.08	3
Tensile Strength, lbs/in^2	1000	---	---	4455	1	---	---	3720	1
	1500	---	---	5190	1	---	---	3045	1
	2000	---	---	6100	1	4515	3825	4170	2
	2500	---	---	6760	1	4680	4275	4455	4
	2700	---	---	5290	1	---	---	3480	1
Compressive Strength, ½-inch diameter by ½-inch lbs/in^2	1000	---	---	11455	1	---	---	13600	1
	1500	---	---	12935	1	---	---	12835	1
	2000	---	---	13750	1	---	---	16805	1
	2500	---	---	23455	1	---	---	24040	1
	2700	---	---	---	-	---	---	27860	1
Apparent Shear Strength, lbs/in^2	1000	4735	4390	4565	2	---	---	4510	1
	1500	6520	5815	6165	2	---	---	4550	1
	2000	---	---	6560	1	5990	4990	5490	2
	2500	7735	5680	6795	2	5940	5785	5860	2
	2700	---	---	8025	1	6065	5560	5810	2

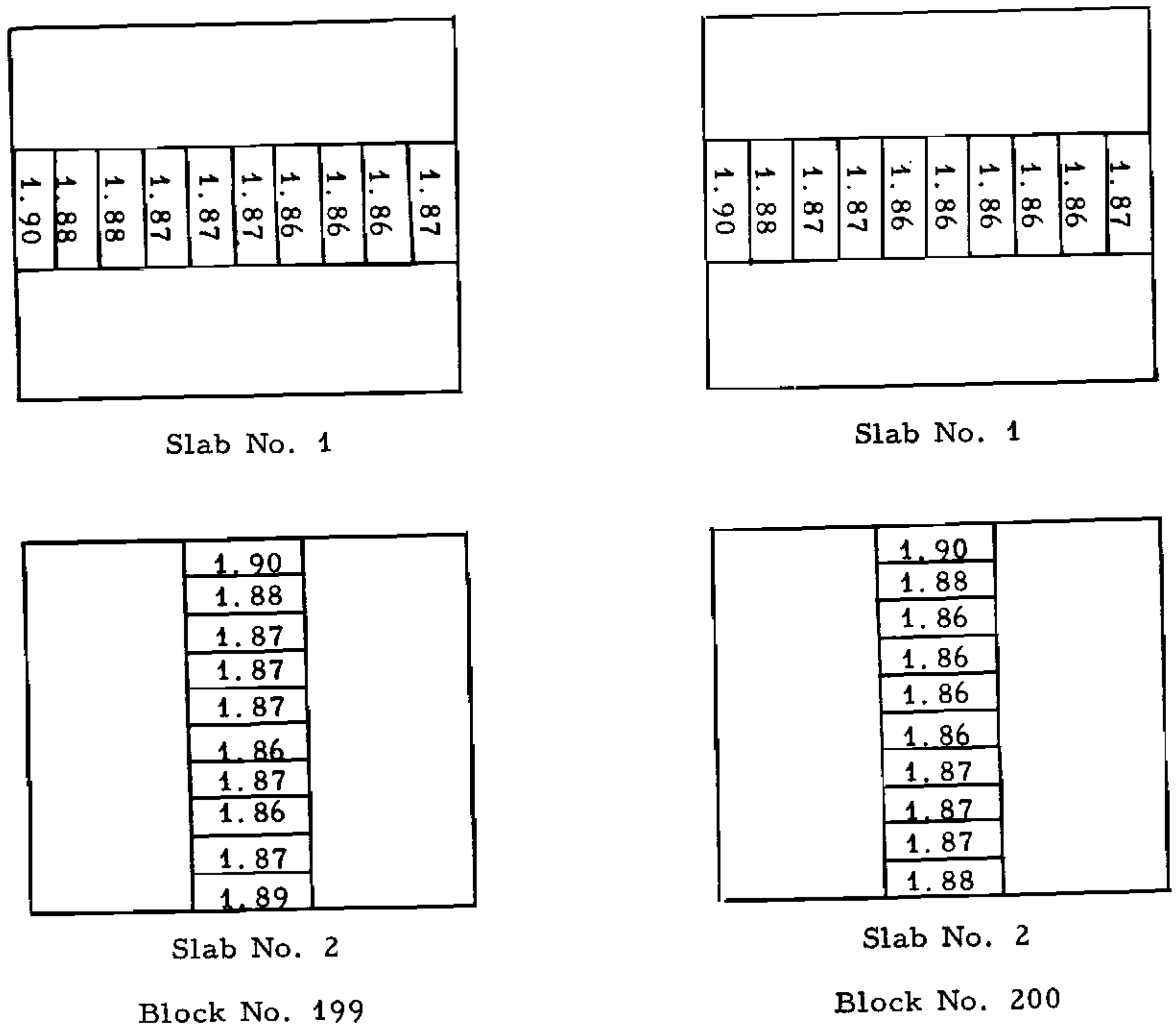
Table 63. Room-Temperature Properties, RVD Graphite, Block No. 200, 18-Inch Diameter by 17-Inch Length

Properties	With Grain Average	With Grain σ	With Grain n	Across Grain Average	Across Grain σ	Across Grain n
Bulk Density, g/cc	1.87	0.01	17	---	---	-
Specific Resistance, 10^{-4} ohm-cm	12.72	0.28	9	21.54	0.47	8
Young's Modulus, 10^{6} lbs/in^2	2.09	0.05	9	1.11	0.04	8
Flexural Strength, lbs/in^2	4720	420	9	3095	145	8
Compressive Strength, 1- by 1- by 1 inch, lbs/in^2	11650	950	7	12850	600	8

Properties	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
CTE, $10^{-6}/°C$, 20°-100°C	1.76	1.73	1.75	3	3.51	3.42	3.46	3
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ °K}$	0.277	0.256	0.267	3	0.206	0.193	0.199	3
Admittance, cm^2/sec	$1x10^{-2}$	$9x10^{-3}$	$1x10^{-2}$	2	---	---	$4x10^{-3}$	1
Per Cent Ash	---	---	0.167	1	---	---	---	-

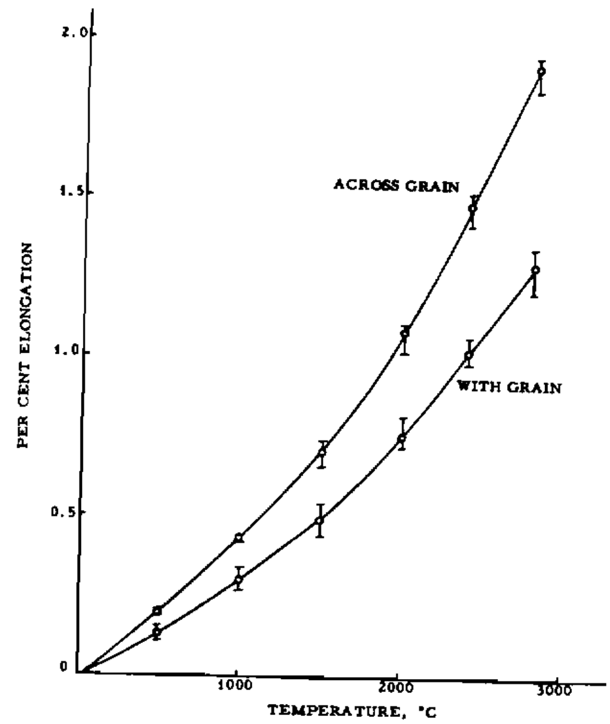
Table 64. High-Temperature Properties, RVD Graphite, Block No. 200, 18-Inch Diameter by 17-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
Thermal Expansion Per Cent Elongation $\frac{\Delta L}{L} \times 100$	500	0.155	0.141	0.149	3	0.210	0.180	0.197	3
	1000	0.343	0.267	0.298	3	0.441	0.429	0.435	3
	1500	0.540	0.441	0.479	3	0.728	0.711	0.720	3
	2000	0.820	0.719	0.765	3	1.106	1.087	1.094	3
	2400	1.070	0.980	1.017	3	1.509	1.471	1.491	3
	2800	1.357	1.207	1.272	3	1.954	1.908	1.932	3



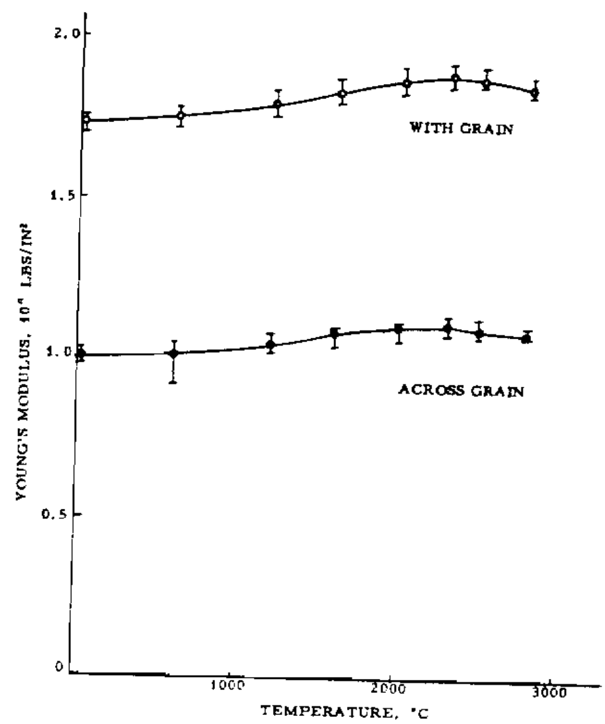
L-654

Figure 210. Density Profile, RVD Graphite, Blocks No. 199 and 200, 18-Inch Diameter by 17-Inch Length



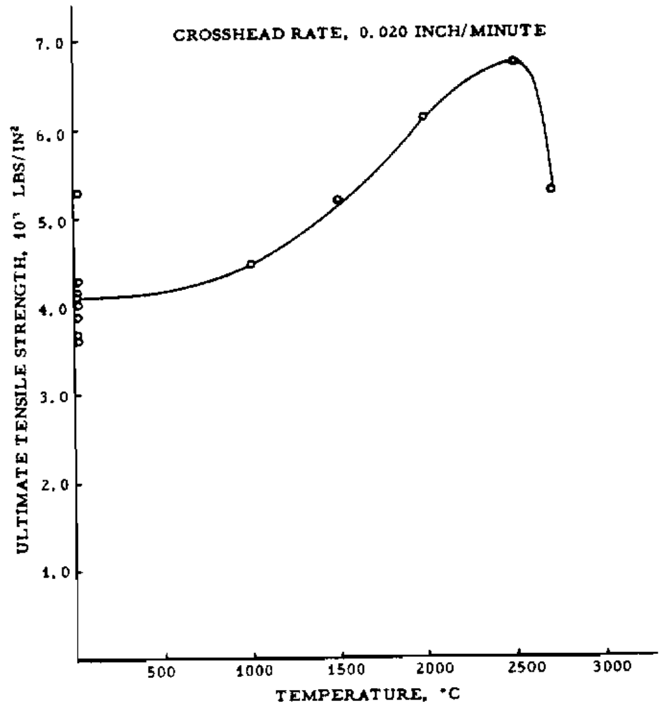
L-633

Figure 211. Thermal Expansion vs. Temperature, RVD Graphite, 18-Inch Diameter by 17-Inch Length



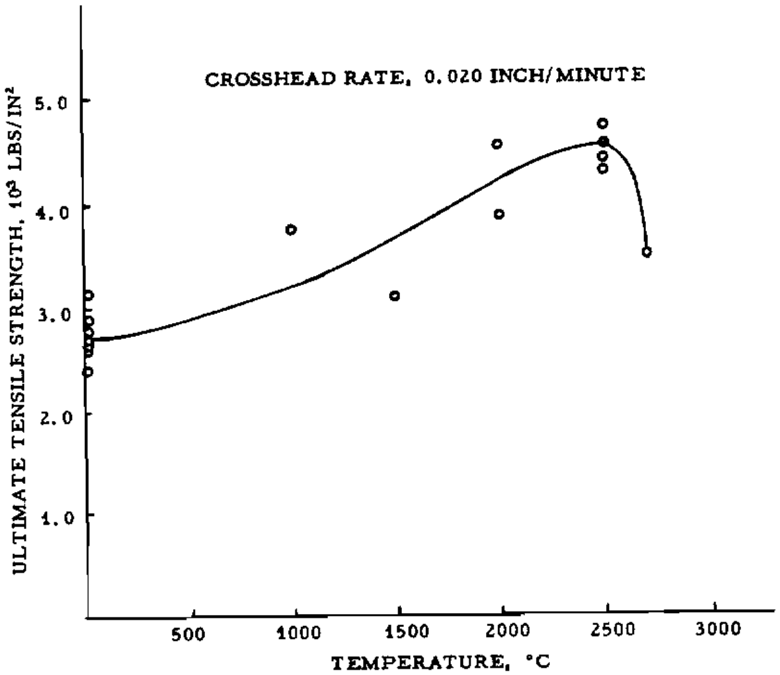
L-634

Figure 212. Young's Modulus vs. Temperature, RVD Graphite, 18-Inch Diameter by 17-Inch Length, Block No. 199



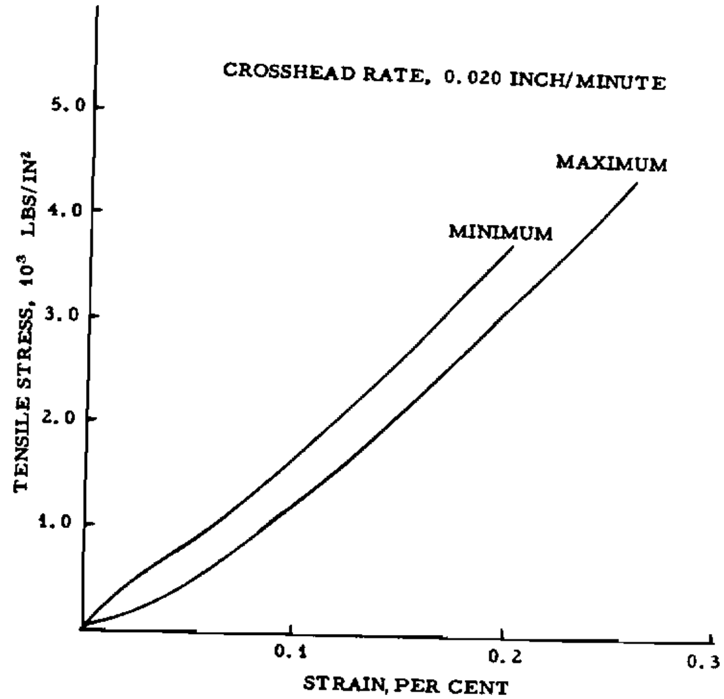
L-635

Figure 213. With-Grain Ultimate Tensile Strength vs. Temperature, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length



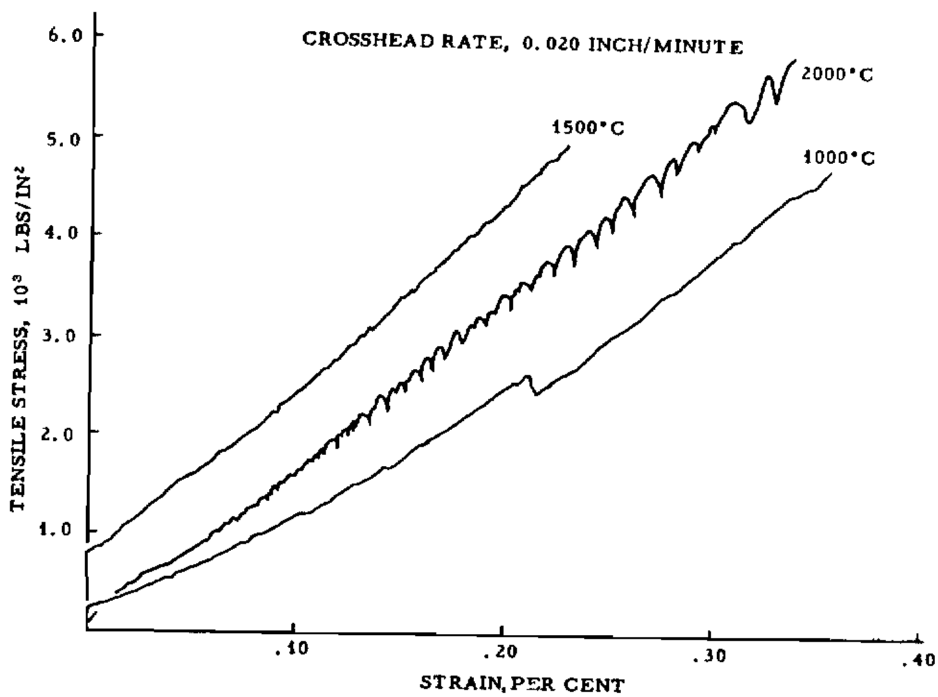
L-636

Figure 214. Across-Grain Ultimate Tensile Strength vs. Temperature, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length



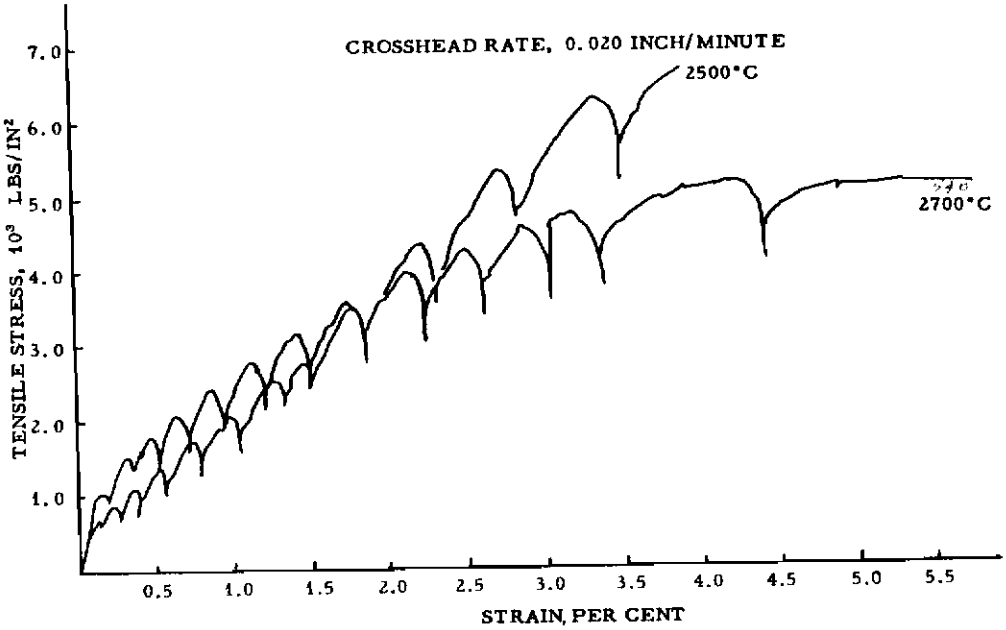
L-637

Figure 215. With-Grain Tensile Stress-Strain Curves, RVD Graphite, 18-Inch Diameter by 17-Inch Length, Block No. 199, Room Temperature



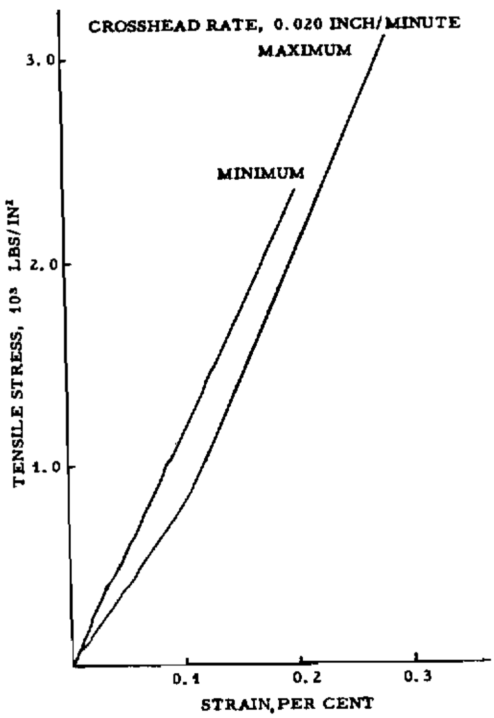
L-638

Figure 216. With-Grain Tensile Stress-Strain Curves, RVD Graphite, 18-Inch Diameter by 17-Inch Length, Block 199, 1000°C, 1500°C, 2000°C



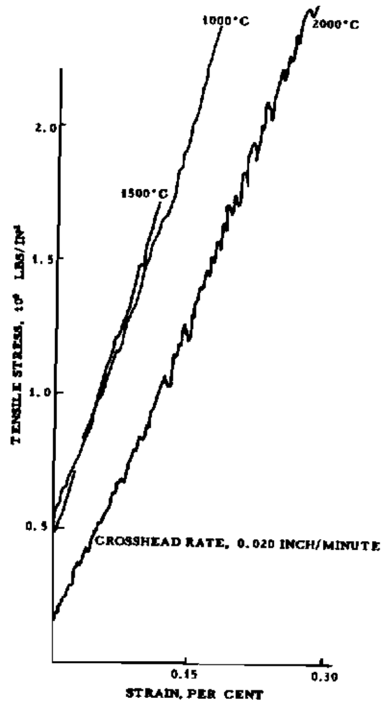
L-639

Figure 217. With-Grain Tensile Stress-Strain Curves, RVD Graphite, 18-Inch Diameter by 17-Inch Length, Block No. 199, 2500°C, 2700°C



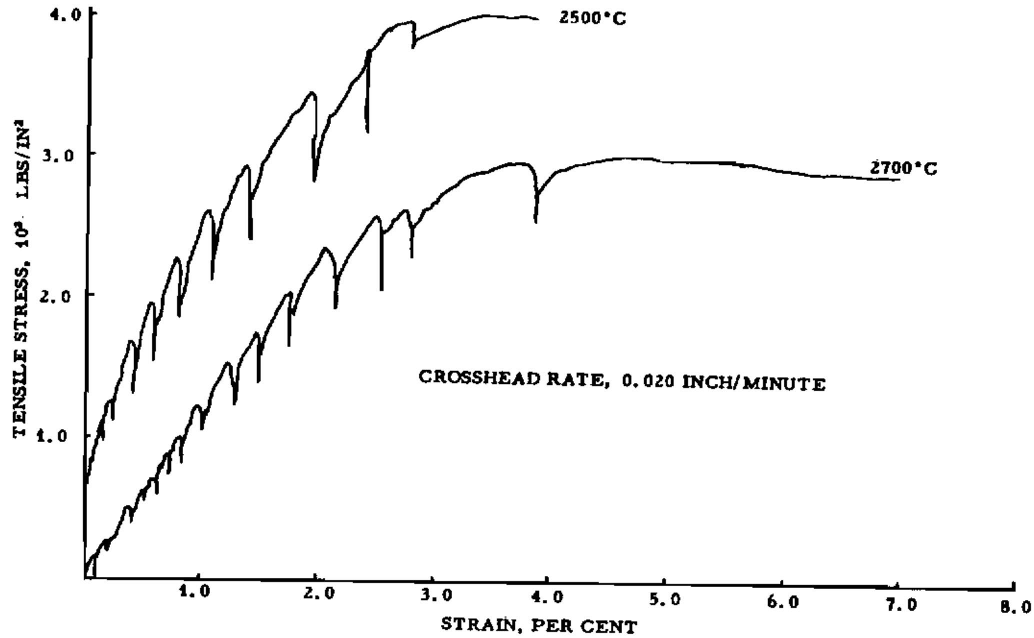
L-640

Figure 218. Across-Grain Tensile Stress-Strain Curves, RVD Graphite, 18-Inch Diameter by 17-Inch Length, Block No. 199, Room Temperature



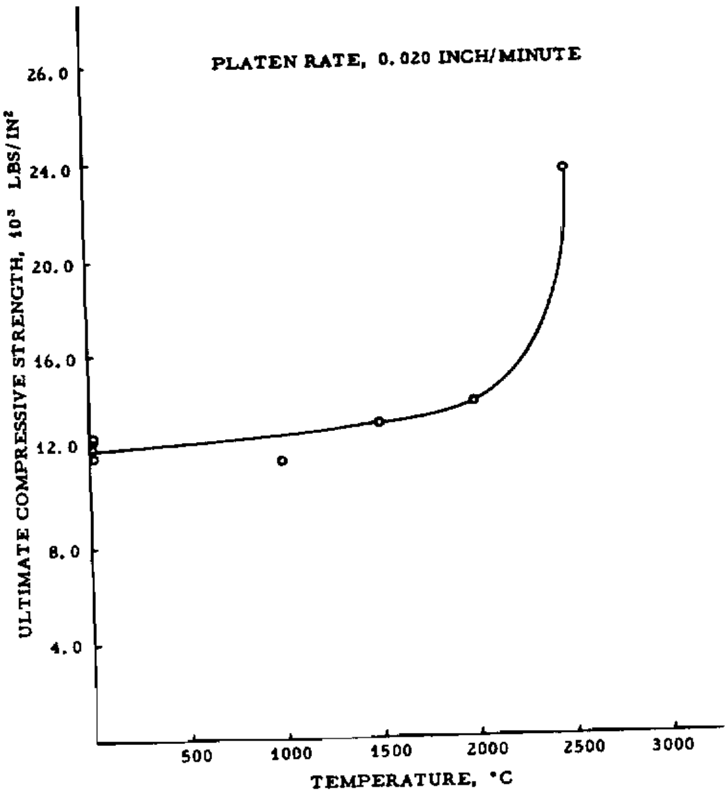
L-641

Figure 219. Across-Grain Tensile Stress-Strain Curves, RVD Graphite, 18-Inch Diameter by 17-Inch Length, Block No. 199, 1000°C, 1500°C, 2000°C



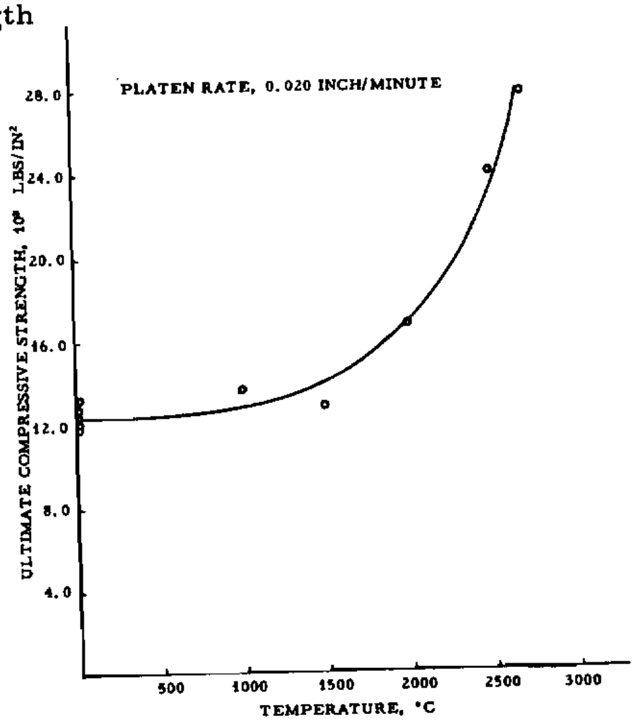
L-642

Figure 220. Across-Grain Tensile Stress-Strain Curves, RVD Graphite, 18-Inch Diameter by 17-Inch Length, Block No. 199, 2500°C, 2700°C



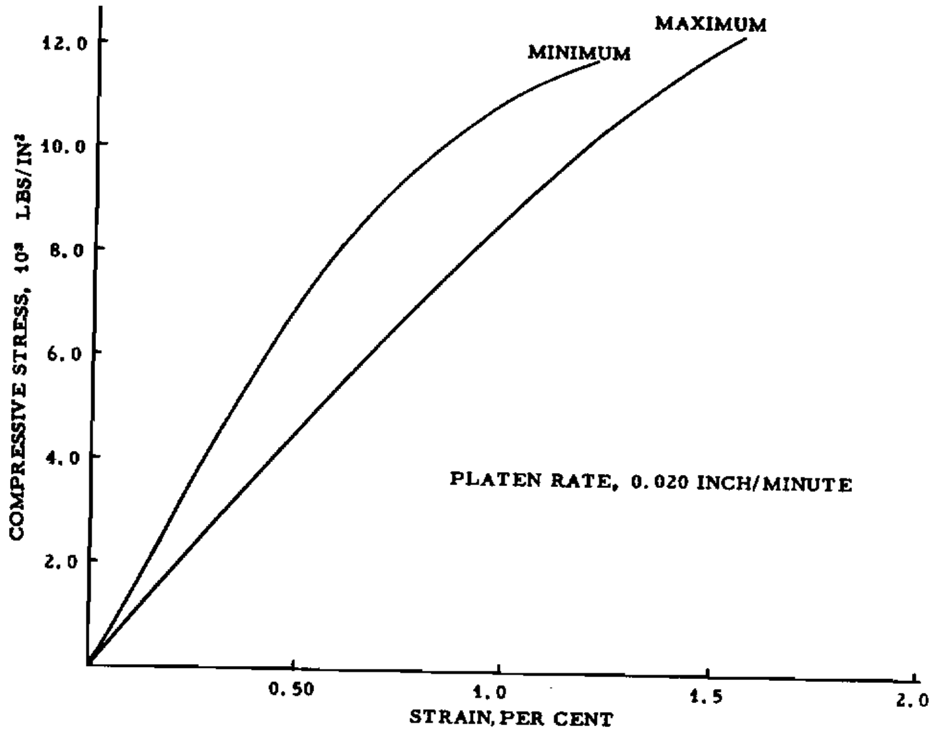
L-643

Figure 221. With-Grain Ultimate Compressive Strength vs. Temperature, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length



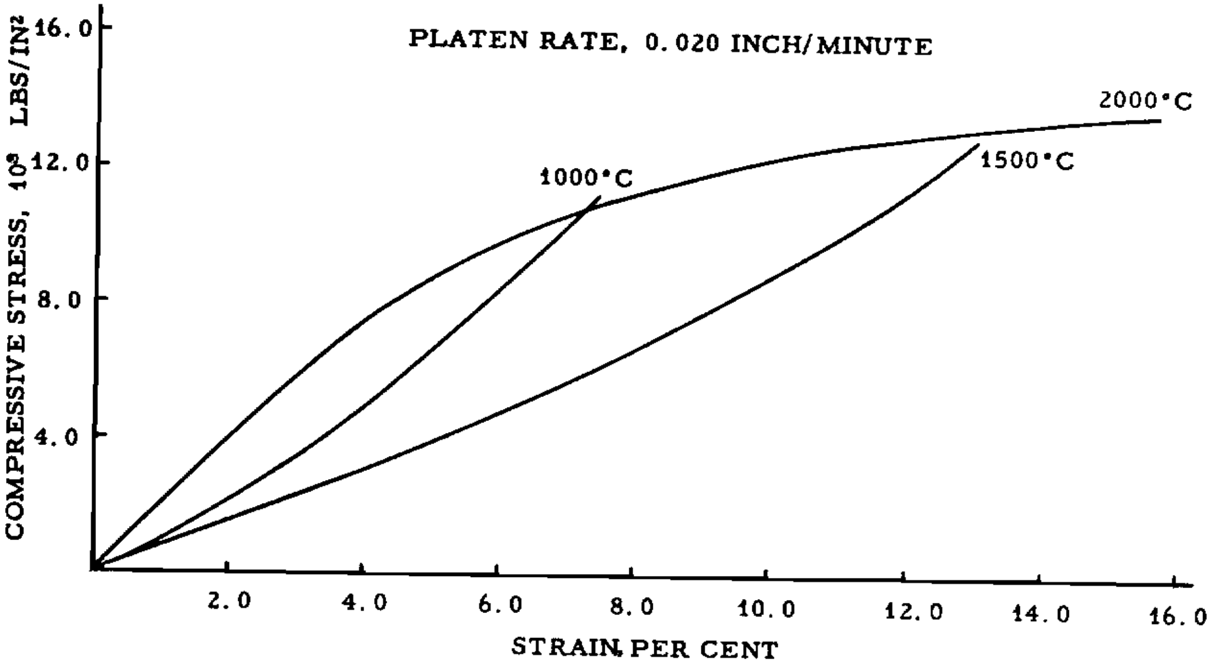
L-644

Figure 222. Across-Grain Ultimate Compressive Strength vs. Temperature, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length



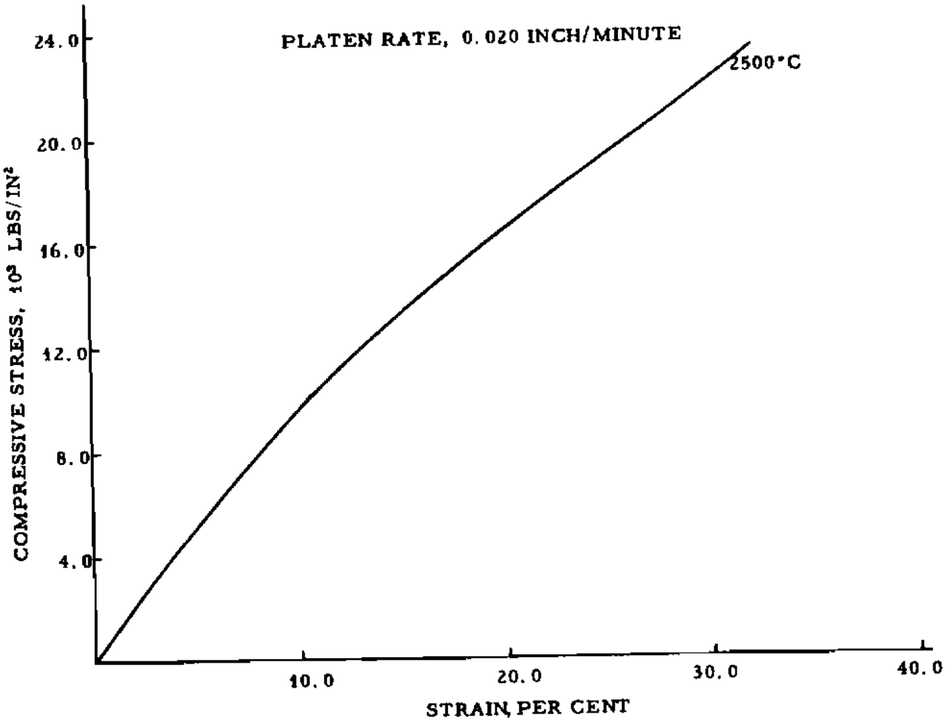
L-645

Figure 223. With-Grain Compressive Stress-Strain Curves, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length, Room Temperature



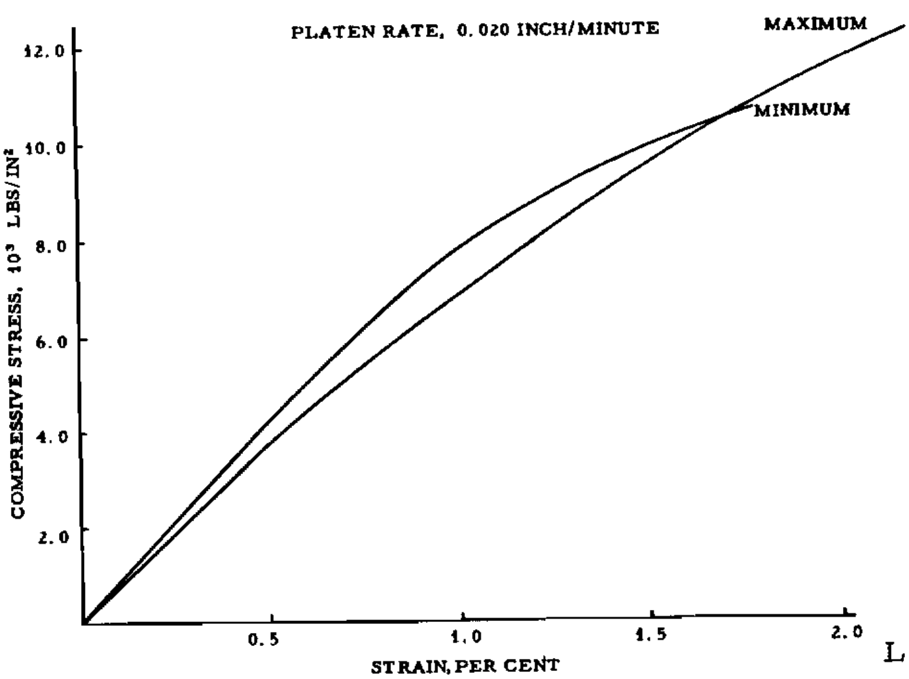
L-646

Figure 224. With-Grain Compressive Stress-Strain Curves, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length, 1000°C, 1500°C, 2000°C



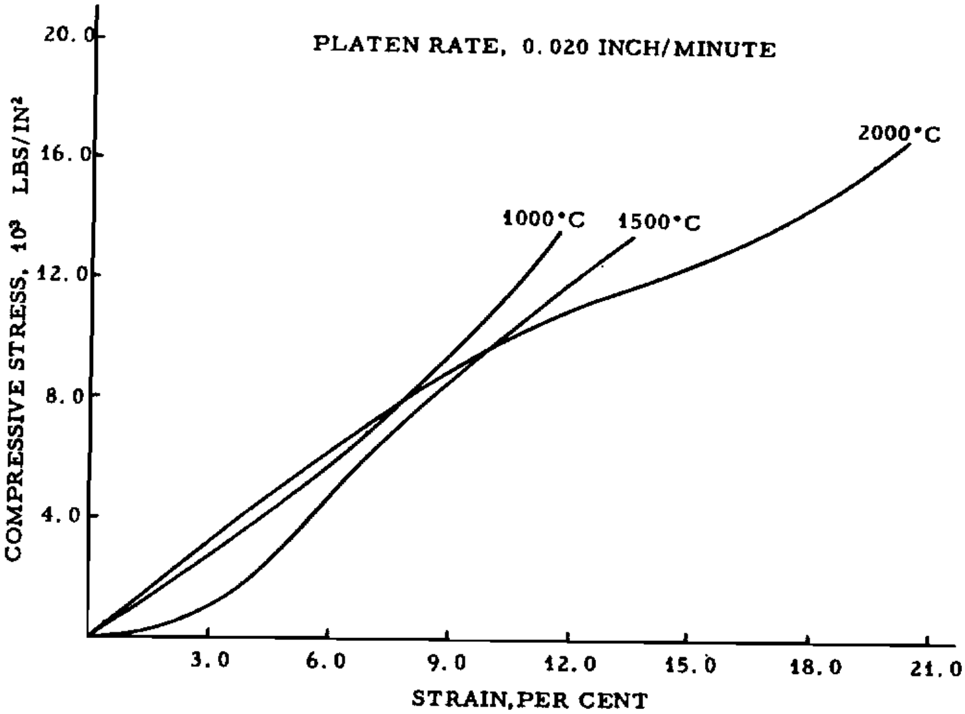
L-647

Figure 225. With-Grain Compressive Stress-Strain Curve, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length, 2500°C



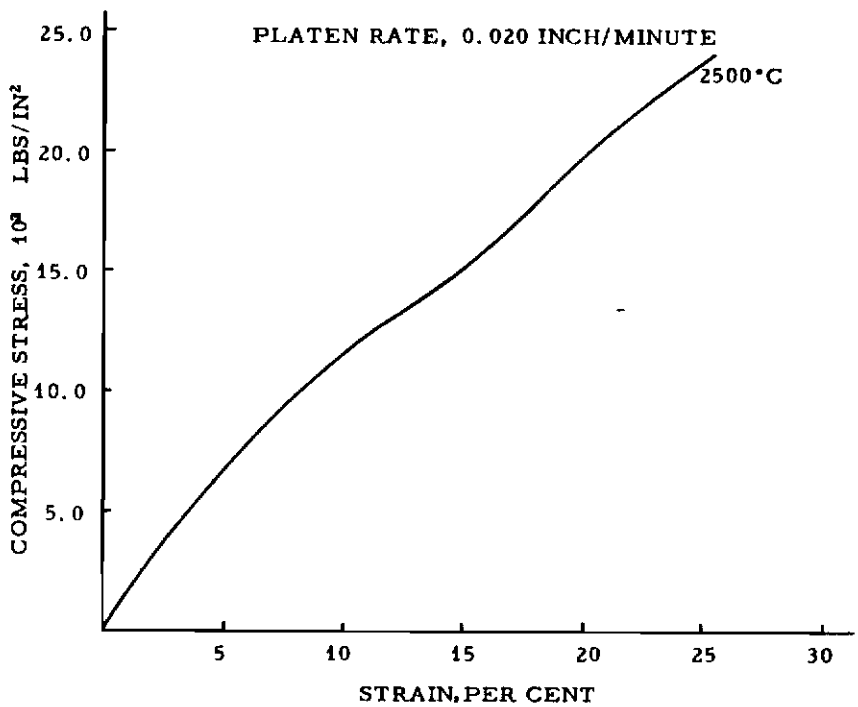
L-648

Figure 226. Across-Grain Compressive Stress-Strain Curves, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length, Room Temperature



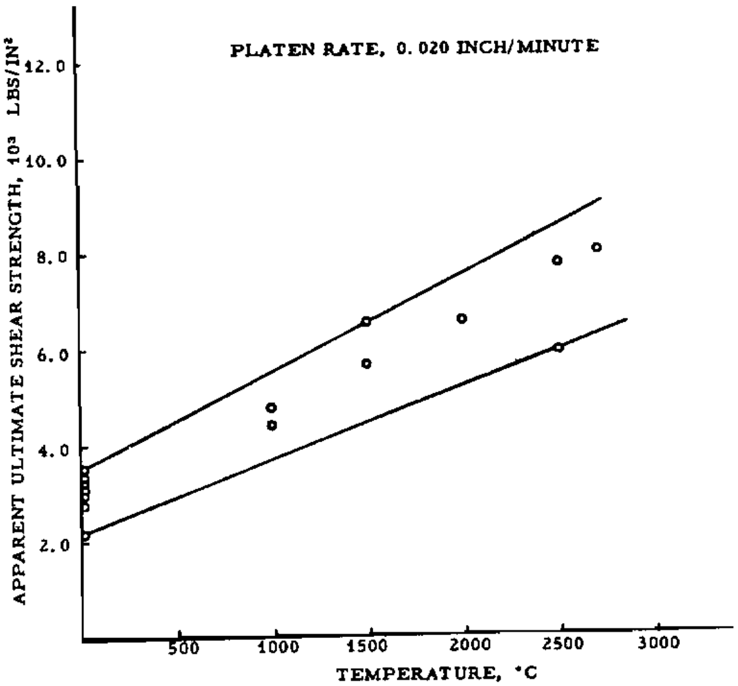
L-649

Figure 227. Across-Grain Compressive Stress-Strain Curves, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length, 1000°C, 1500°C, 2000°C



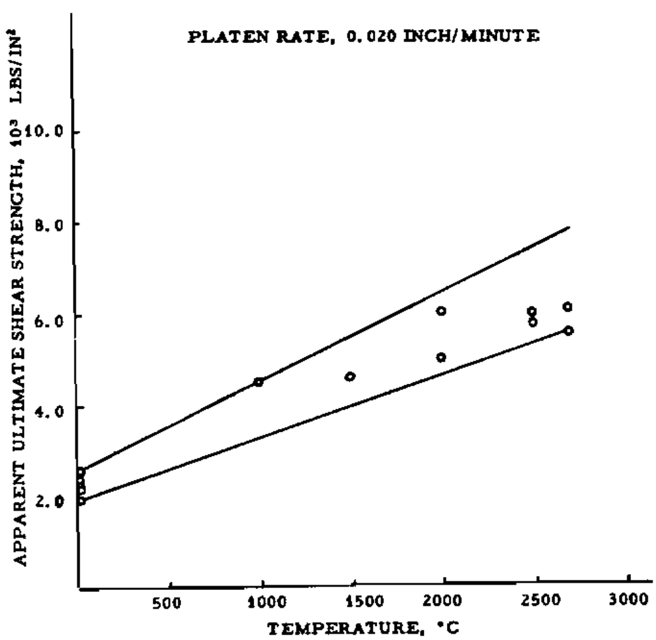
L-650

Figure 228. Across-Grain Compressive Stress-Strain Curve, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length, 2500°C



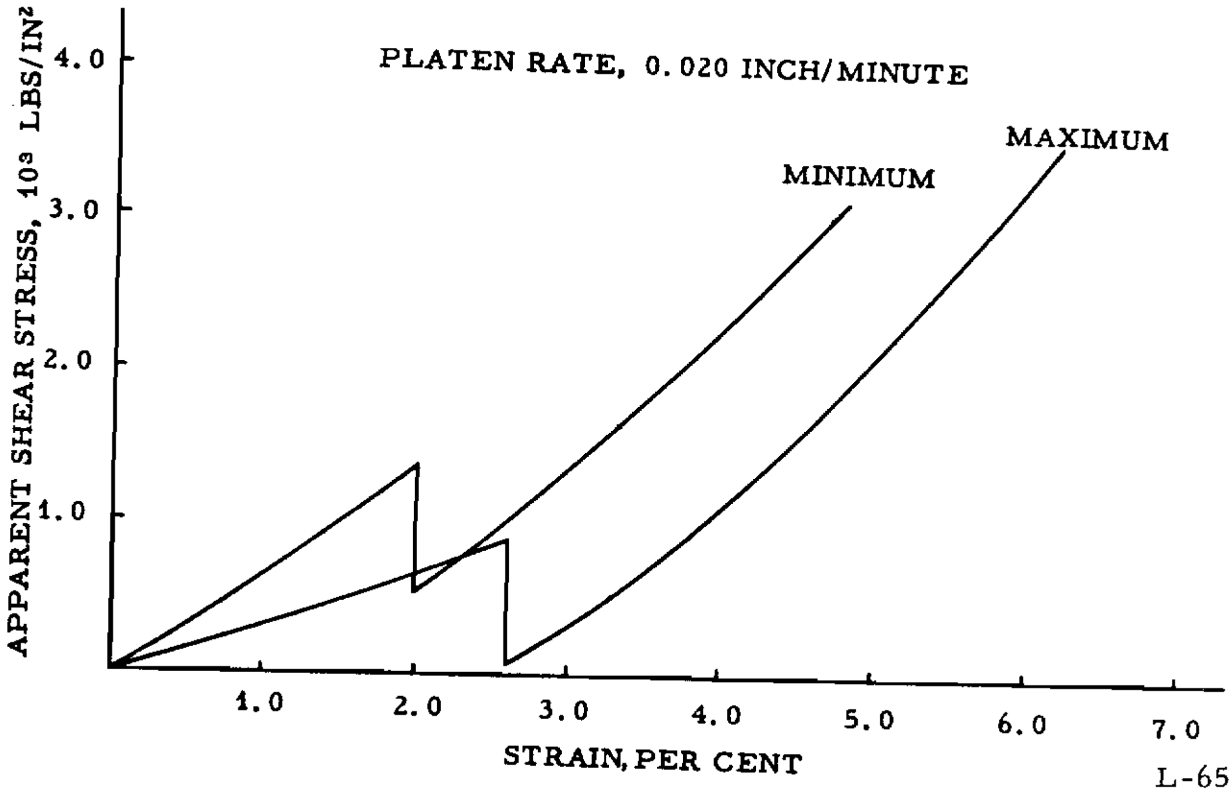
L-651

Figure 229. With-Grain Apparent Ultimate Shear Strength vs. Temperature, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length



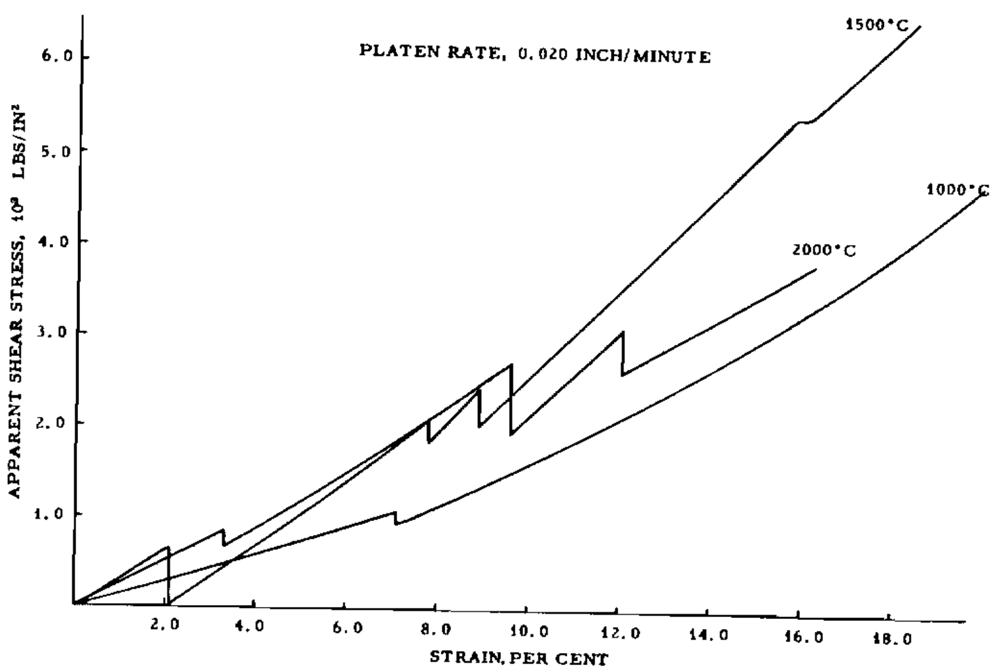
L-652

Figure 230. Across-Grain Apparent Ultimate Shear Strength vs. Temperature, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length



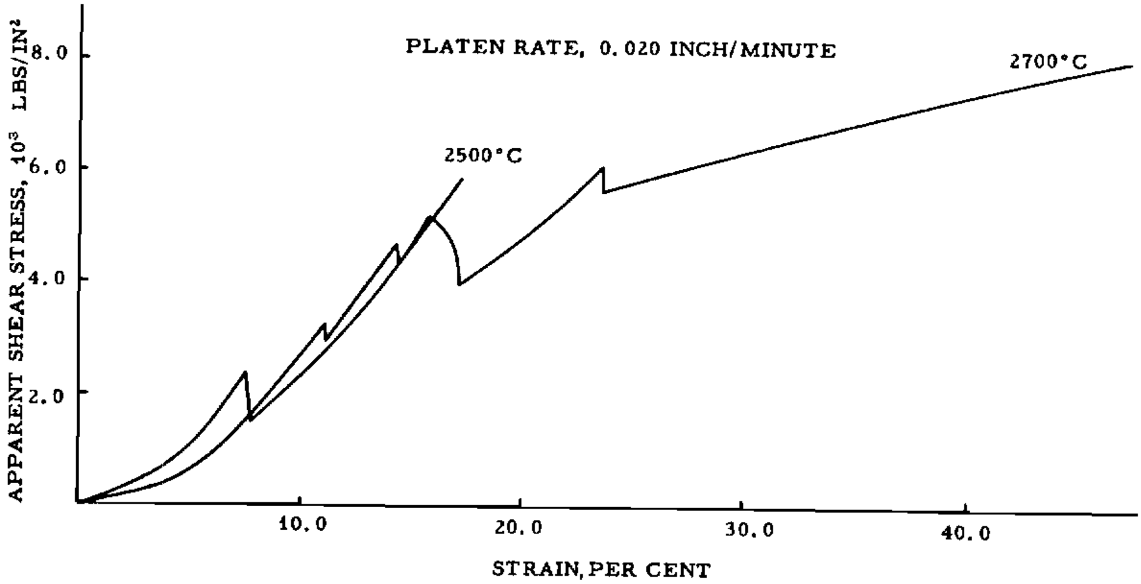
L-655

Figure 231. With-Grain Apparent Shear Stress-Strain Curves, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length, Room Temperature



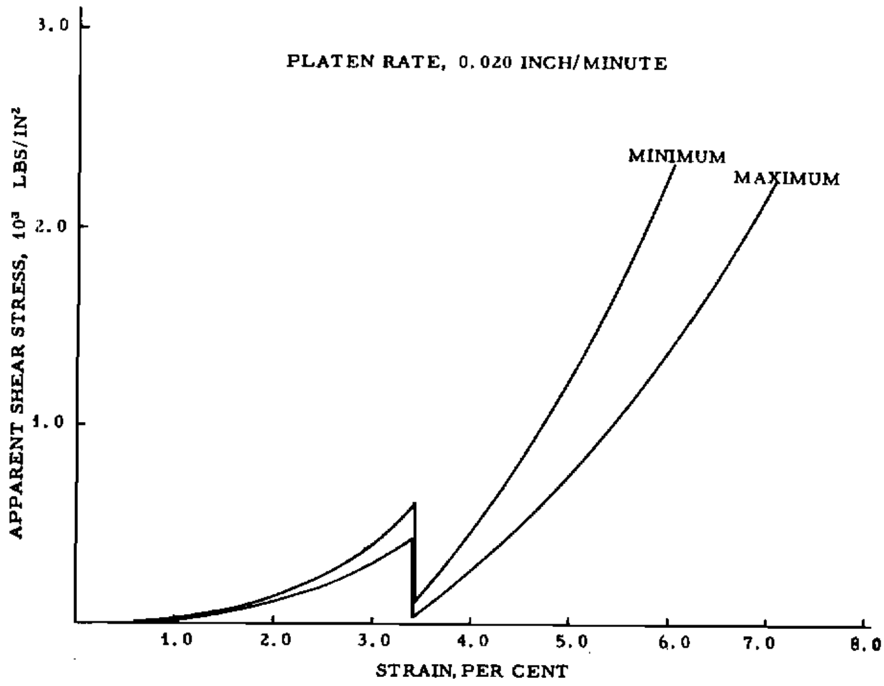
L-656

Figure 232. With-Grain Apparent Shear Stress-Strain Curves, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length, 1000°C, 1500°C, 2000°C



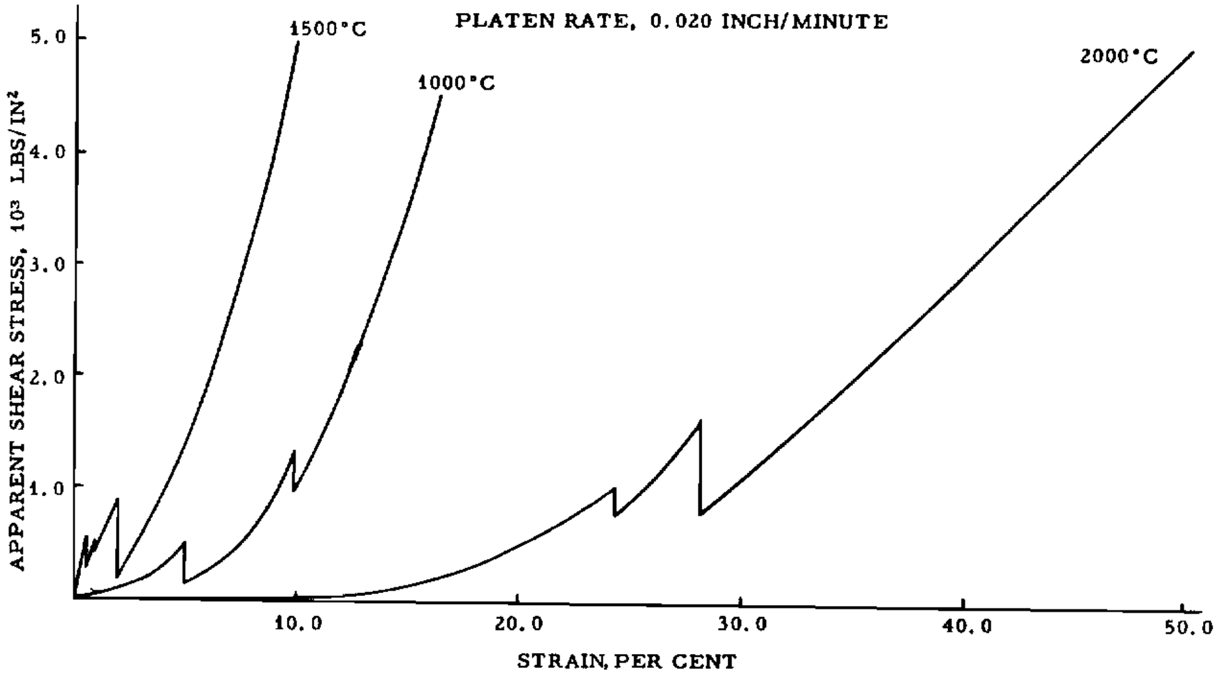
L-657

Figure 233. With-Grain Apparent Shear Stress-Strain Curves, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length, 2500°C, 2700°C



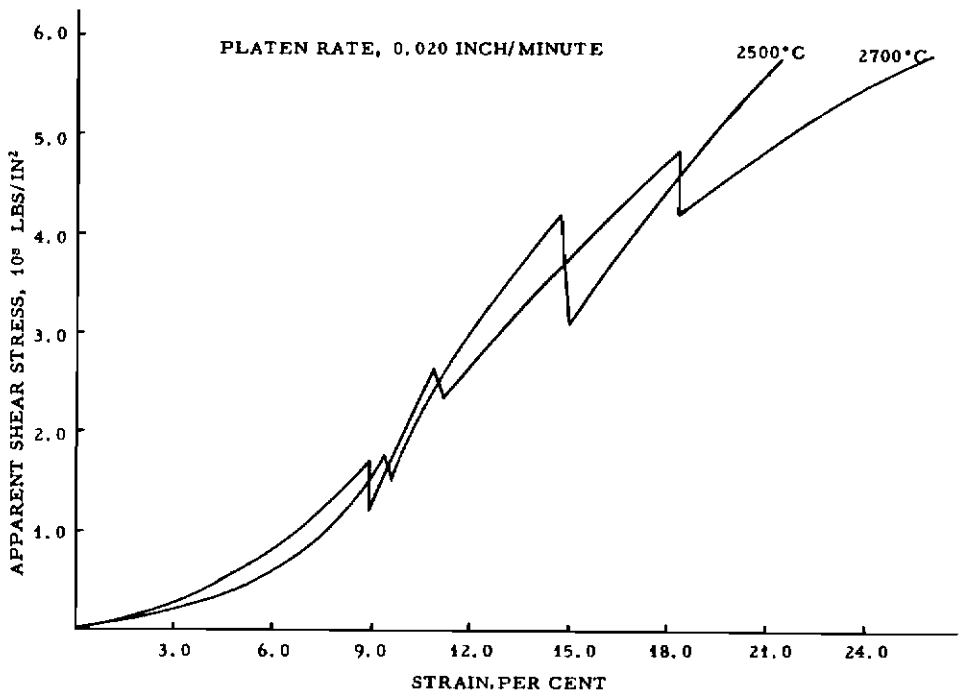
L-658

Figure 234. Across-Grain Apparent Shear Stress-Strain Curves, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length, Room Temperature



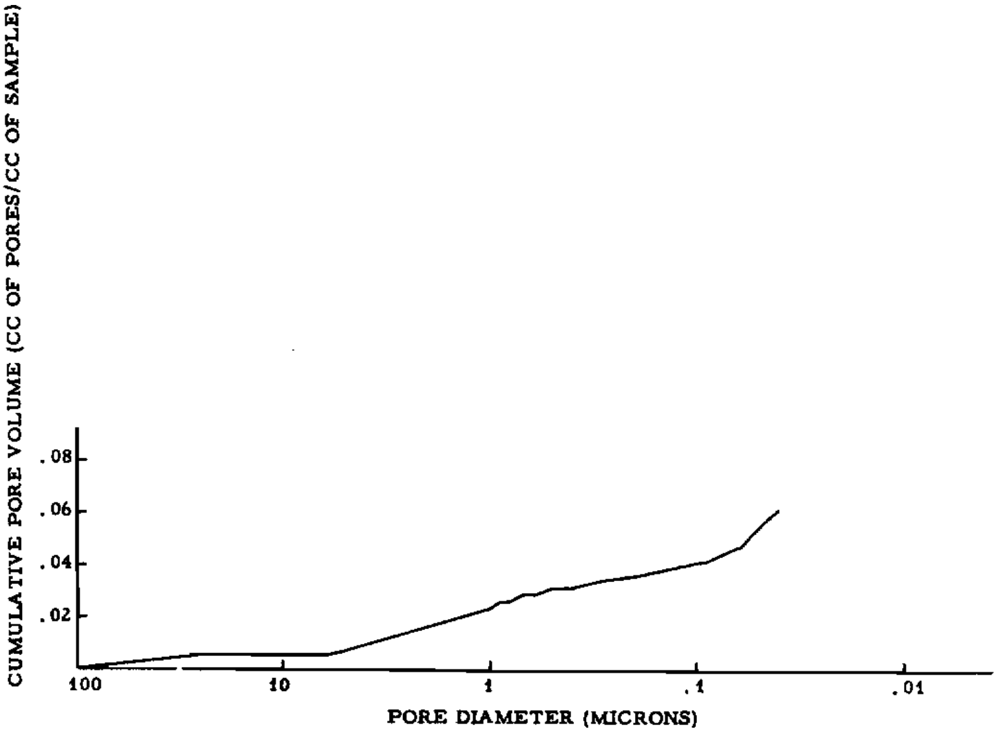
L-659

Figure 235. Across-Grain Apparent Shear Stress-Strain Curves, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length, 1000°C, 1500°C, 2000°C



L-660

Figure 236. Across-Grain Apparent Shear Stress-Strain Curves, RVD Graphite, Block No. 199, 18-Inch Diameter by 17-Inch Length, 2500°C, 2700°C



L-661

Figure 237. Pore Size Distribution, Mercury Porosimetry, RVD Graphite

3.11. Grade CFW Graphite[23]

Physical properties were measured on one block of CFW graphite, 40-inch O. D. by 15-inch I. D. by 20-inch length. The room and high-temperature properties are given in Tables 65 and 66, respectively. The interpretation of stress-strain curves was discussed in Section 3.1. All strength measurements were made with cross-head or platen rates of 0.020 inch per minute.

Table 65. Room-Temperature Properties, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length

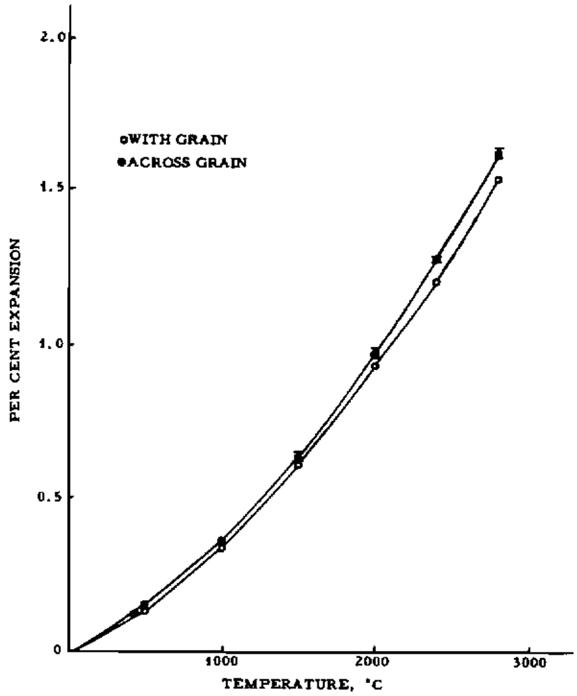
Properties	With Grain Average	With Grain σ	With Grain n	With Grain No. of Blocks	Across Grain Average	Across Grain σ	Across Grain n	Across Grain No. of Blocks
Bulk Density, g/cc	1.90	0.01	39	1	---	---	--	-
Specific Resistance, 10^{-4} ohm-cm	11.98	0.44	19	1	12.60	0.31	20	1
Young's Modulus, 10^6 lbs/in^2	1.53	0.03	19	1	1.42	0.06	20	1
Flexural Strength, lbs/in^2	2195	190	19	1	2185	270	20	1
Compressive Strength*	8280	880	19	1	9065	990	20	1
Compressive Strength**	9005	532	11	1	8190	1276	11	1
Tensile Strength, lbs/in^2	1725	186	10	1	1390	199	10	1
Apparent Shear Strength, lbs/in^2	1605	377	10	1	2025	174	10	1

Properties	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	With Grain No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n	Across Grain No. of Blocks
CTE, $10^{-6}/°C$, 20-100°C	2.44	2.35	2.40	6	1	2.80	2.71	2.75	6	1
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ °K}$	0.325	0.308	0.318	3	1	0.319	1.287	0.300	3	1
Admittance, cm^2/sec.	0.1	0.09	0.1	3	1	0.09	0.02	0.06	3	1
Per Cent Ash	---	---	0.865	1	1	---	---	---	-	-

* 1-by 1- by 1-inch, 1bs/in^2
** $\frac{1}{2}$-inch diameter by $\frac{1}{2}$-inch, lbs/in^2

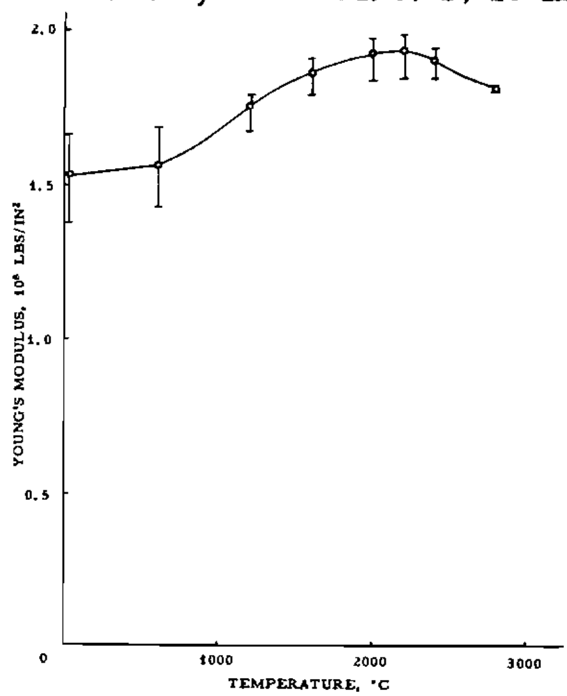
Table 66. High-Temperature Properties, CFW Graphite, 40-Inch O.D. by 15-Inch I.D. by 20-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	With Grain No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n	Across Grain No. of Blocks
Thermal Expansion,	500	0.137	1.130	0.133	3	1	0.162	0.147	0.154	3	1
Per Cent Elongation,	1000	0.343	0.331	0.339	3	1	0.372	0.354	0.361	3	1
$\frac{\Delta L}{L}$ x 100	1500	0.618	0.600	0.608	3	1	0.650	0.622	0.633	3	1
	2000	0.942	0.920	0.934	3	1	0.989	0.960	0.974	3	1
	2400	1.215	1.204	1.210	3	1	1.292	1.274	1.282	3	1
	2800	1.546	1.536	1.542	3	1	1.638	1.606	1.619	3	1
Young's Modulus,	RT	1.67	1.38	1.53	3	1	1.52	1.39	1.43	3	1
10^6 lbs/in^2	600	1.69	1.43	1.57	3	1	1.54	1.44	1.49	3	1
	1200	1.80	1.68	1.76	3	1	1.73	1.53	1.60	3	1
	1600	1.92	1.80	1.87	3	1	1.92	1.60	1.74	3	1
	2000	1.98	1.84	1.93	3	1	2.10	1.63	1.90	3	1
	2200	1.99	1.85	1.94	3	1	2.17	1.64	1.94	3	1
	2400	1.95	1.85	1.91	3	1	2.23	1.63	1.96	3	1
	2800	1.83	1.81	1.82	3	1	2.15	1.61	1.93	3	1
Tensile Strength,	1000	2340	2300	2320	2	1	---	---	2085	1	1
lbs/in^2	1500	---	---	2335	1	1	---	---	1990	1	1
	2000	---	---	2865	1	1	---	---	3045	1	1
	2500	---	---	3415	1	1	---	---	3175	1	1
	2700	---	---	2660	1	1	---	---	3065	1	1
Compressive Strength,	1000	---	---	8660	1	1	---	---	8915	1	1
½-inch diameter by	1500	---	---	11715	1	1	---	---	9030	1	1
½-inch, lbs/in^2	2000	---	---	13910	1	1	---	---	15860	1	1
	2500	---	---	18490	1	1	---	---	18510	1	1
	2700	---	---	20680	1	1	---	---	---	-	-
Apparent Shear Strength,	1000	---	---	1810	1	1	---	---	2950	1	1
lbs/in^2	1500	---	---	2710	1	1	3215	1960	2955	2	1
	2000	---	---	3115	1	1	---	---	4065	1	1
	2500	---	---	3615	1	1	---	---	5685	1	1
	2700	---	---	5080	1	1	---	---	7375	1	1



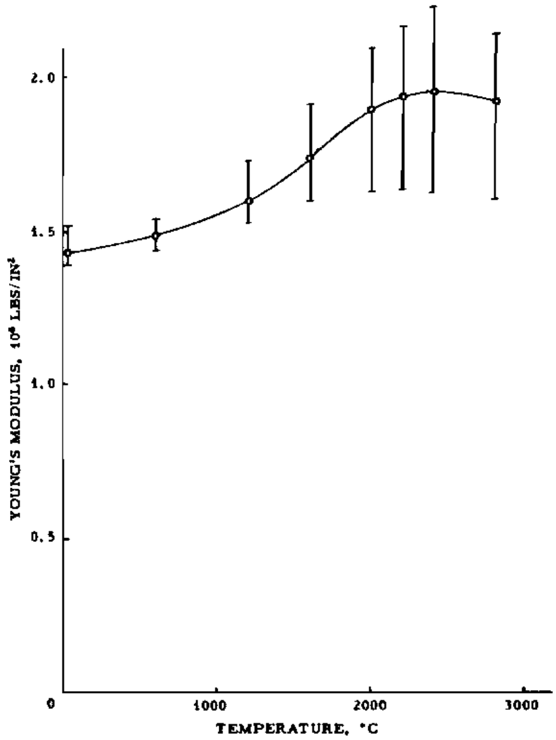
L-662

Figure 238. Thermal Expansion vs. Temperature, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length



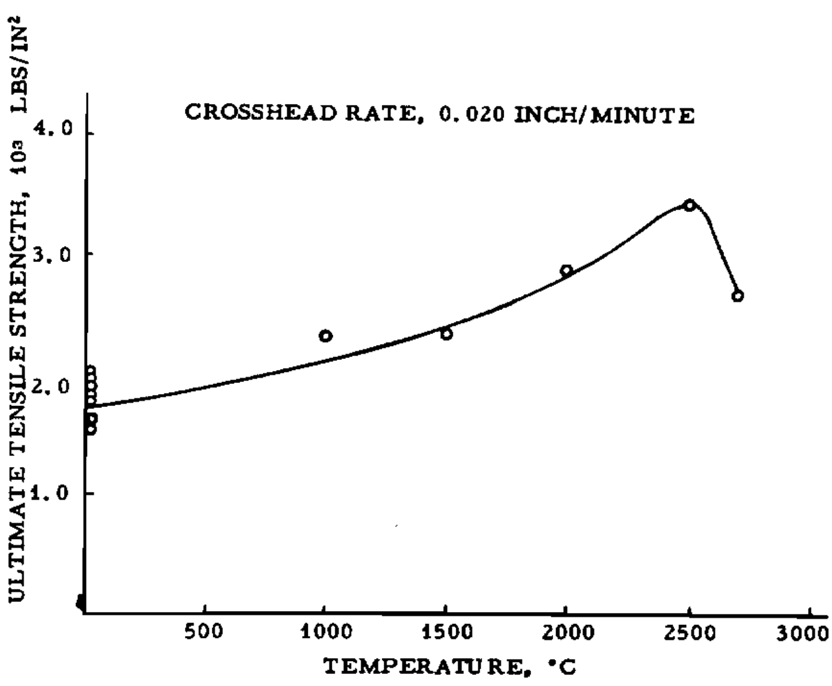
L-663

Figure 239. With-Grain Young's Modulus vs. Temperature, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length



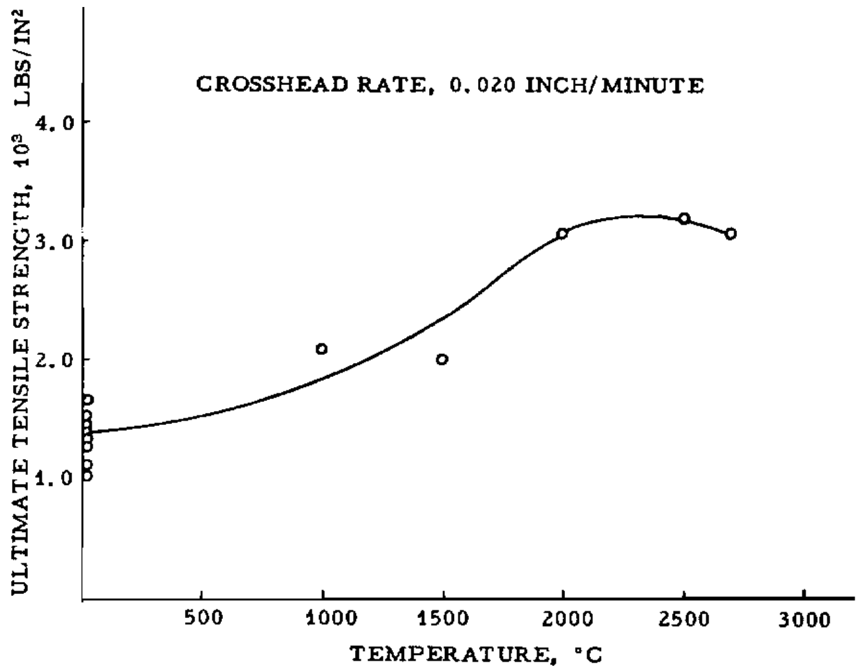
L-664

Figure 240. Across-Grain Young's Modulus vs. Temperature, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length



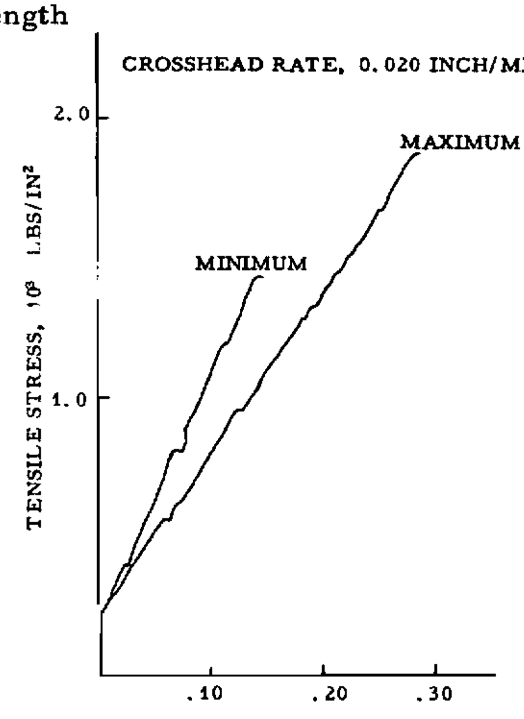
L-665

Figure 241. With-Grain Ultimate Tensile Strength vs. Temperature, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length



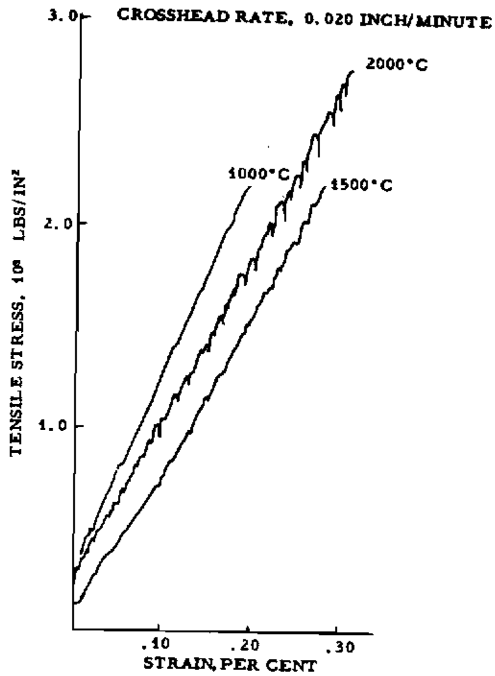
L-666

Figure 242. Across-Grain Ultimate Tensile Strength vs. Temperature, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length



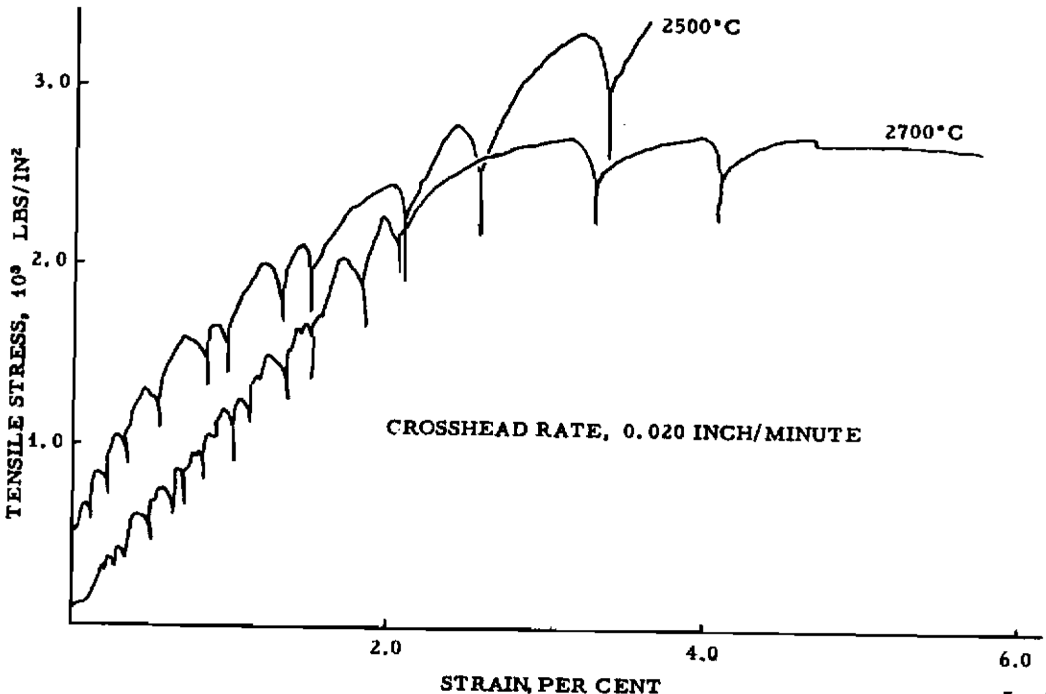
L-667

Figure 243. With-Grain Tensile Stress-Strain Curves, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length, Room Temperature



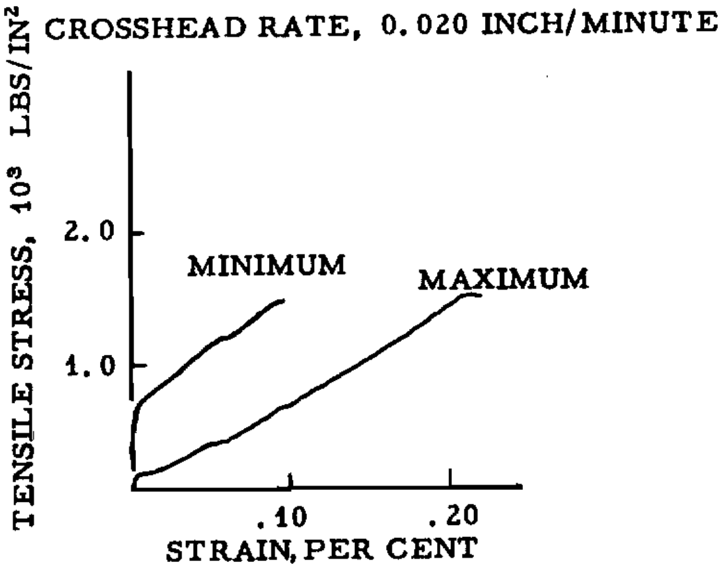
L-669

Figure 244. With-Grain Tensile Stress-Strain Curves, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length, 1000°C, 1500°C, 2000°C



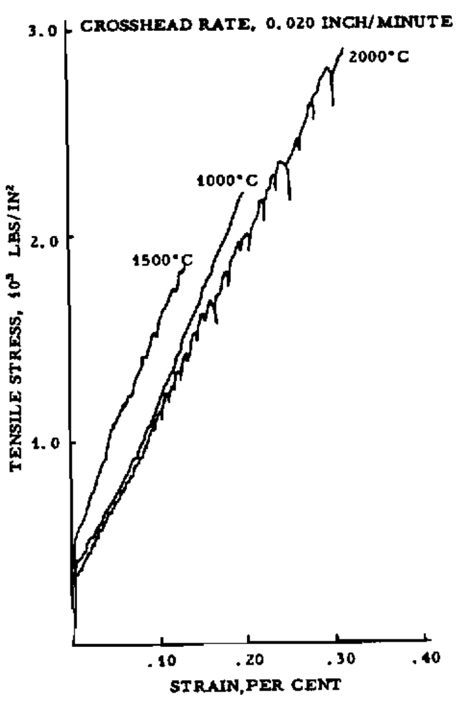
L-668

Figure 245. With-Grain Tensile Stress-Strain Curves, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length, 2500°C, 2700°C



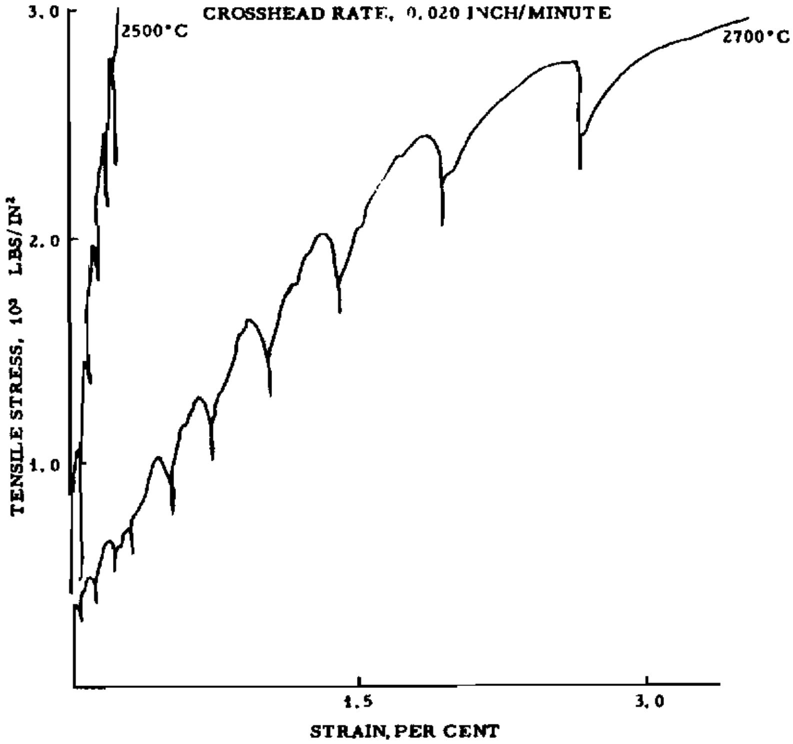
L-670

Figure 246. Across-Grain Tensile Stress-Strain Curves, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length, Room Temperature



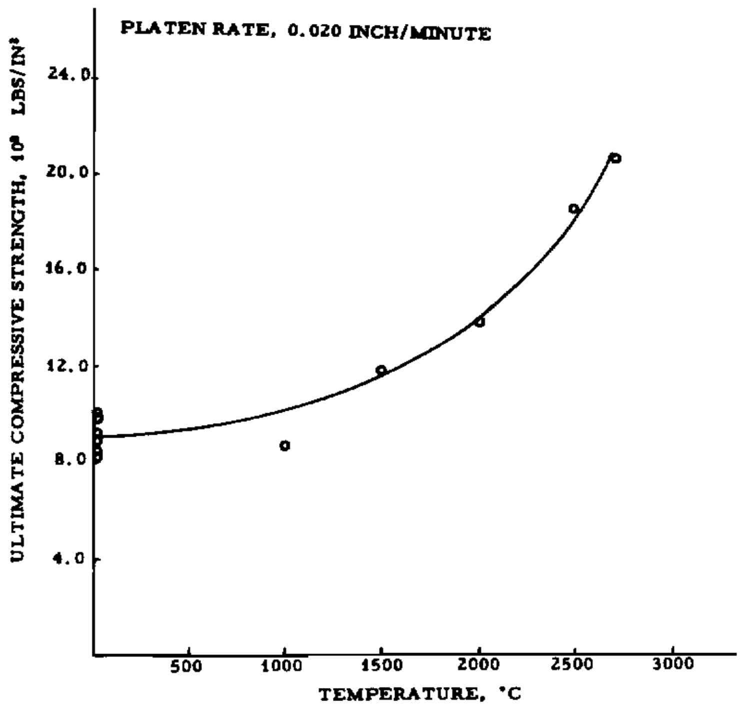
L-671

Figure 247. Across-Grain Stress-Strain Curves, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length, 1000°C, 1500°C, 2000°C



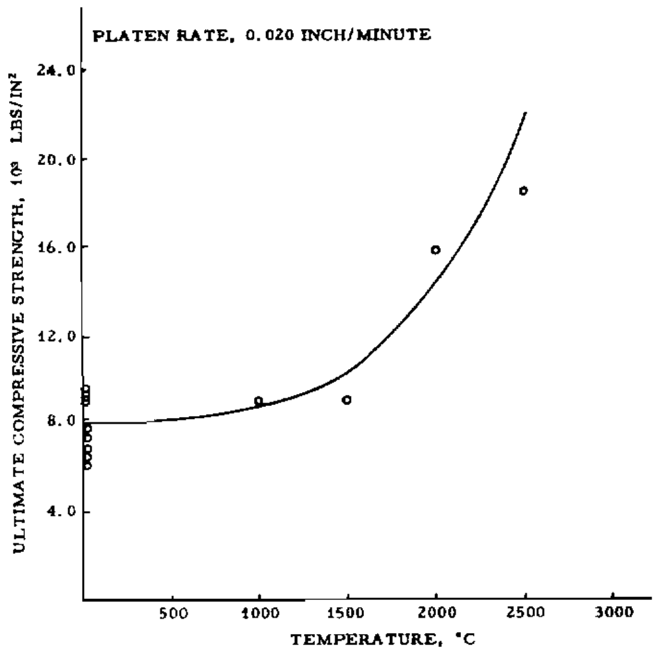
L-672

Figure 248. Across-Grain Tensile Stress-Strain Curves, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length, 2500°C, 2700°C



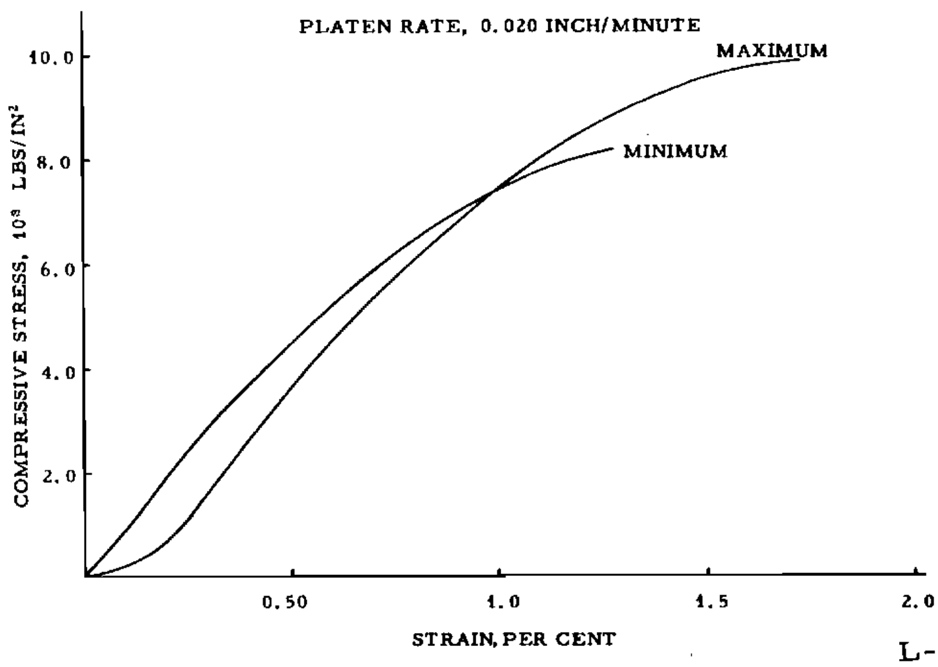
L-673

Figure 249. With-Grain Ultimate Compressive Strength vs. Temperature, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length



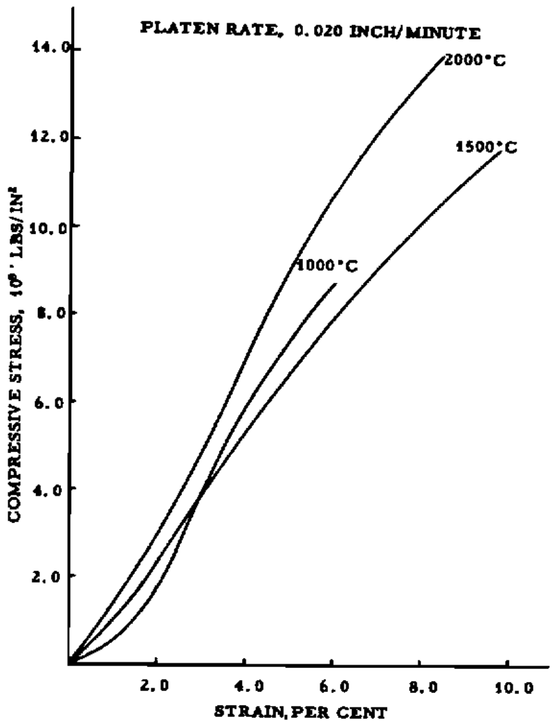
L-674

Figure 250. Across-Grain Ultimate Compressive Strength vs. Temperature, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length



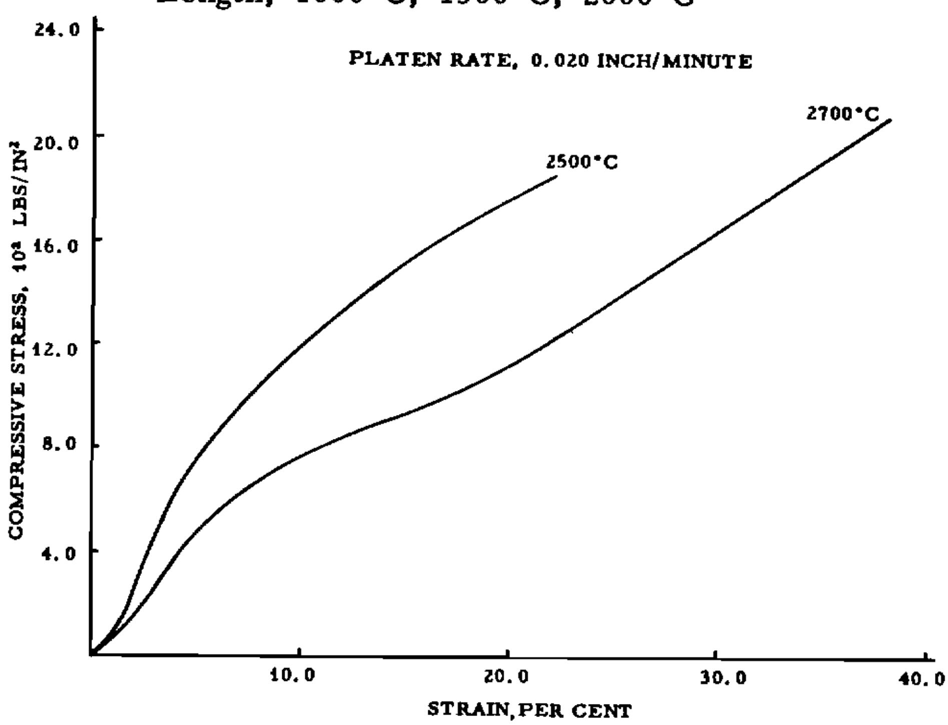
L-675

Figure 251. With-Grain Compressive Stress-Strain Curves, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length, Room Temperature



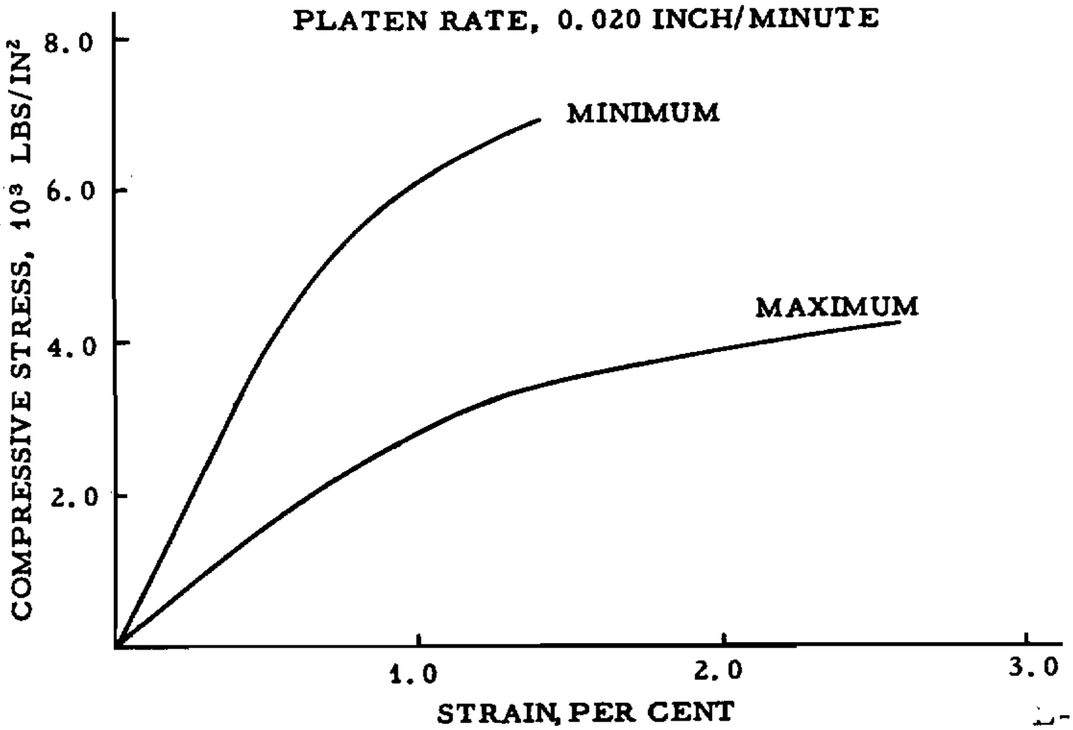
L-676

Figure 252. With-Grain Compressive Stress-Strain Curves, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length, 1000°C, 1500°C, 2000°C



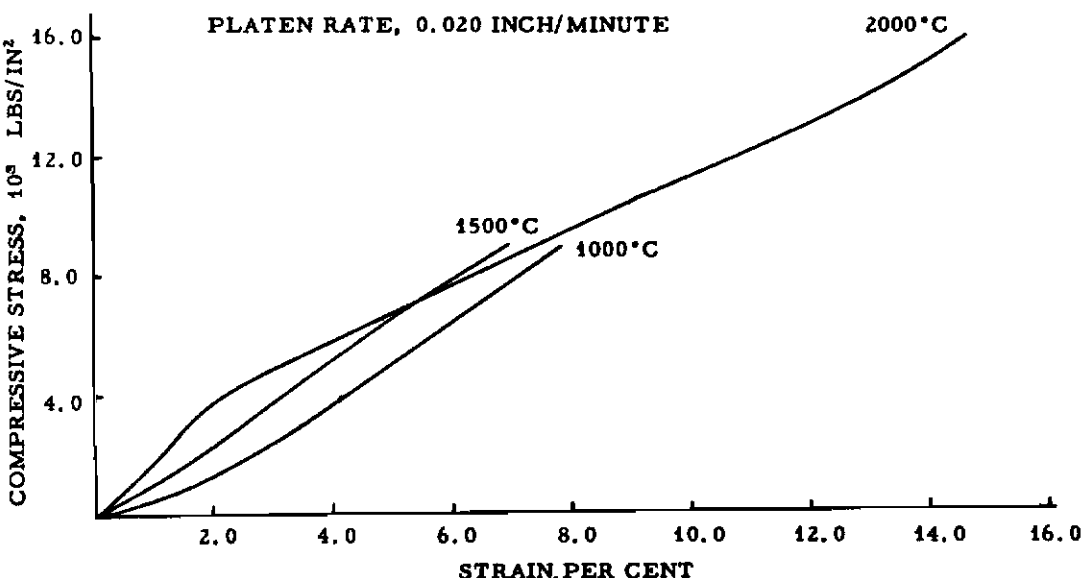
L-677

Figure 253. With-Grain Compressive Stress-Strain Curves, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length, 2500°C, 2700°C



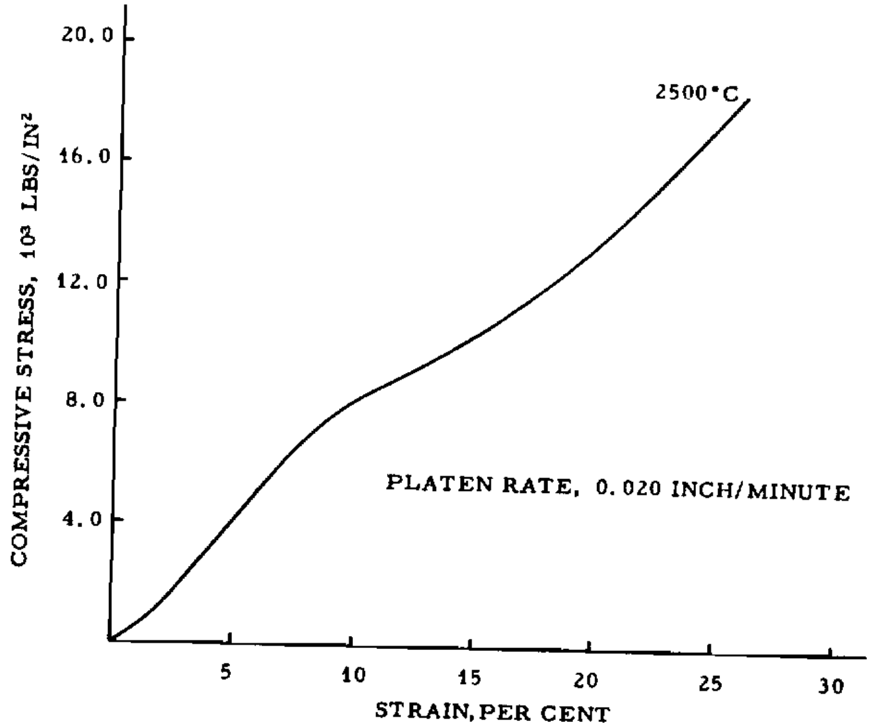
L-678

Figure 254. Across-Grain Compressive Stress-Strain Curves, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length, Room Temperature



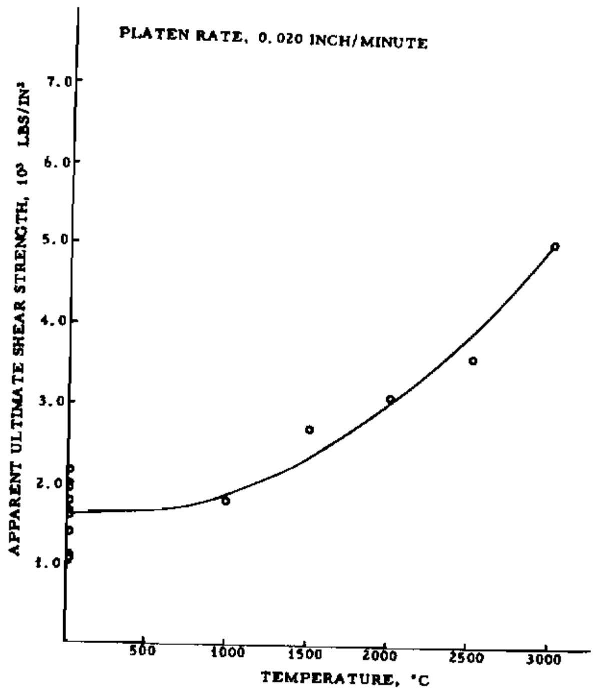
L-679

Figure 255. Across-Grain Compressive Stress-Strain Curves, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length, 1000°C, 1500°C, 2000°C



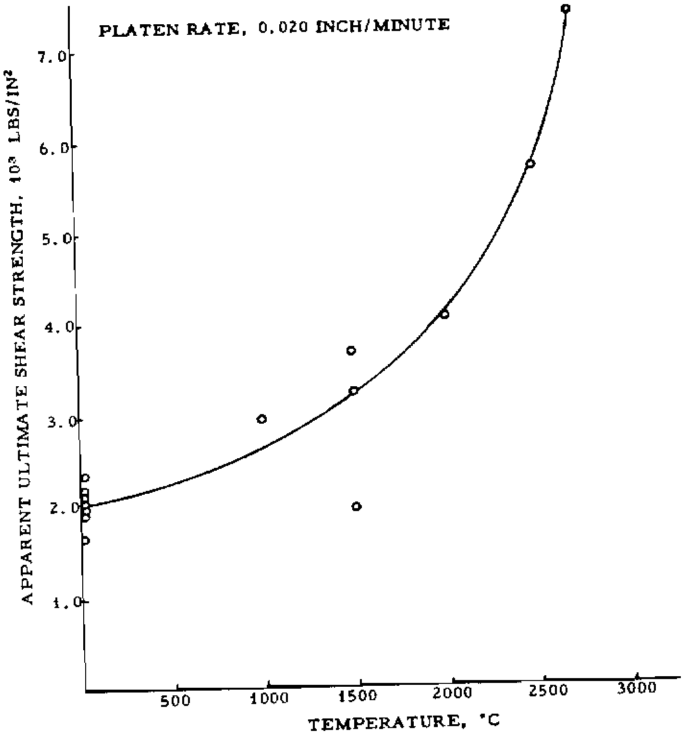
L-680

Figure 256. Across-Grain Compressive Stress-Strain Curves, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length, 2500°C



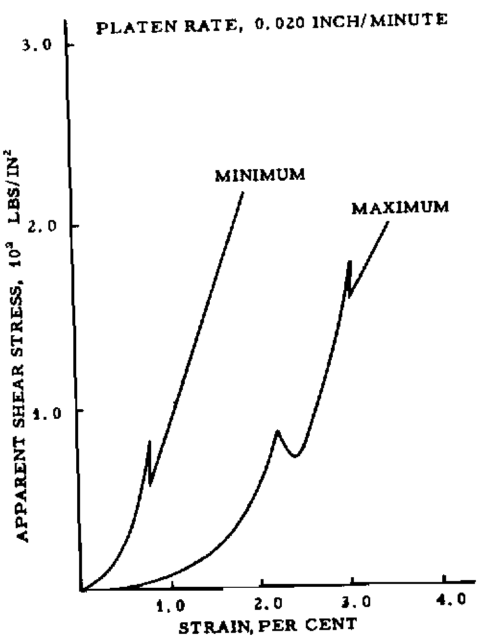
L-681

Figure 257. With-Grain Apparent Ultimate Shear Strength vs. Temperature, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length



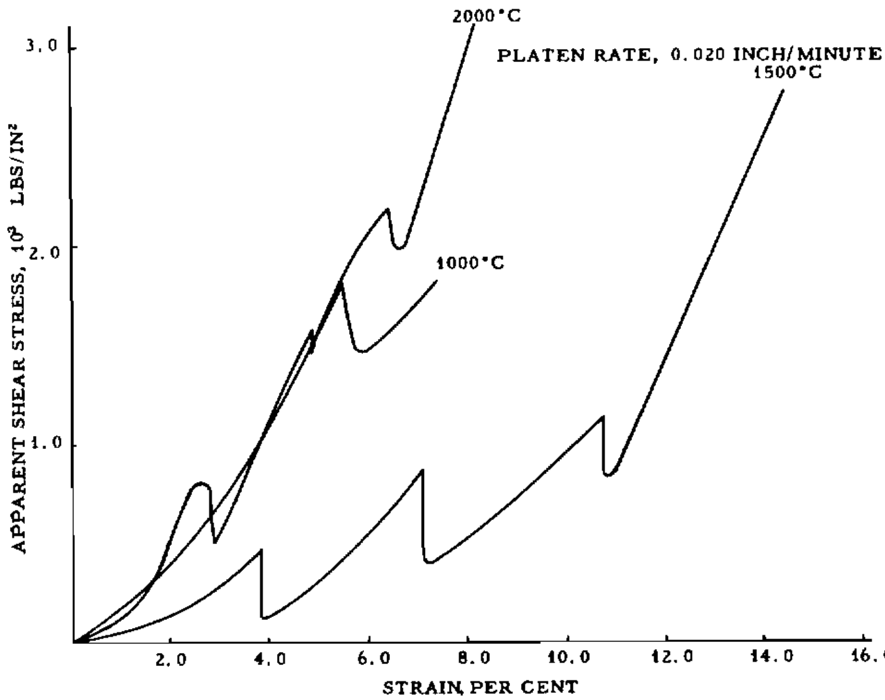
L-682

Figure 258. Across-Grain Apparent Shear Strength vs. Temperature, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length



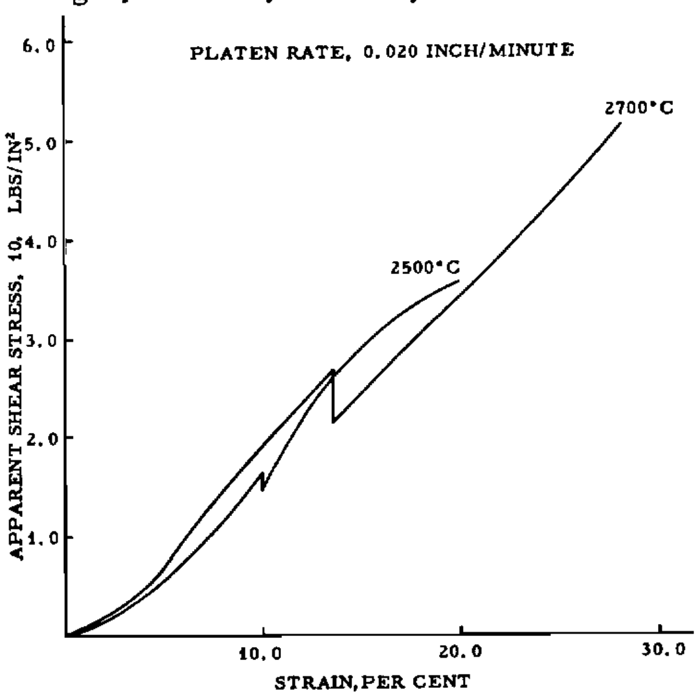
L-683

Figure 259. With-Grain Apparent Shear Stress-Strain Curves, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length, Room Temperature



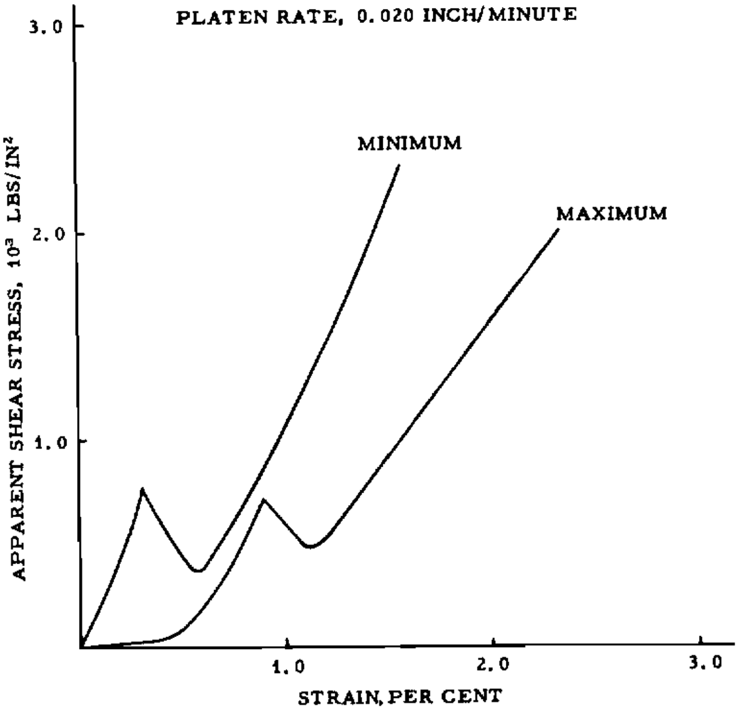
L-684

Figure 260. With-Grain Apparent Shear Stress-Strain Curves, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length, 1000°C, 1500°C, 2000°C



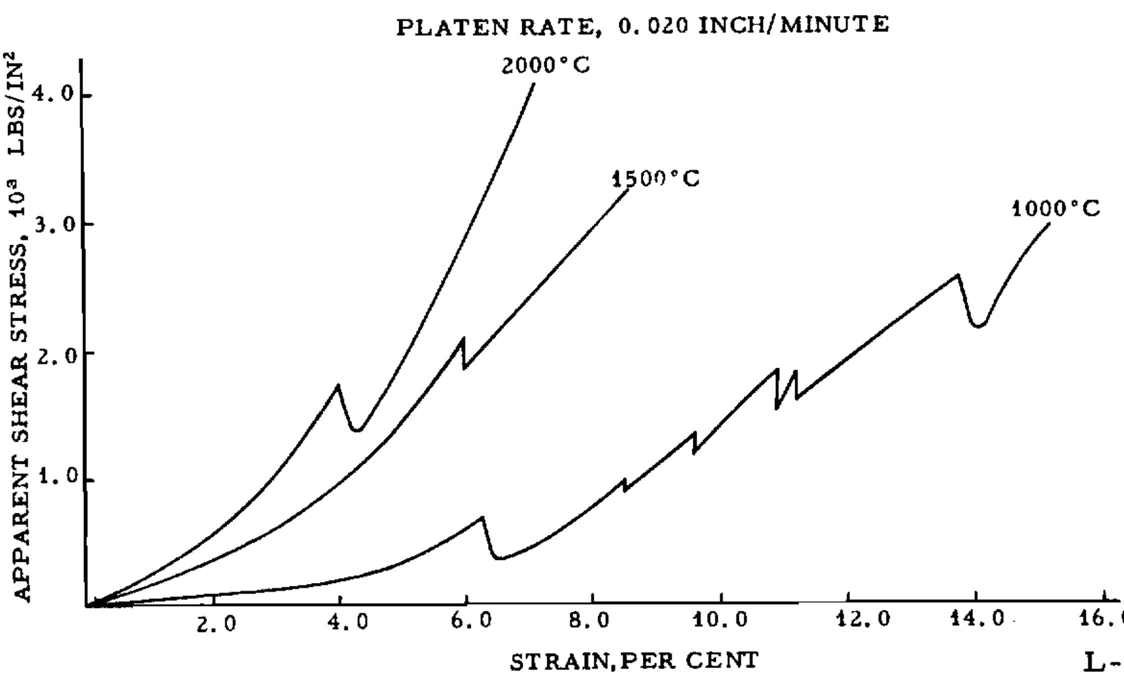
L-685

Figure 261. With-Grain Apparent Shear Stress-Strain Curves, CFW Graphite, 40-Inch O. D. by 15-Inch I. D., by 20-Inch Length, 2500°C, 2700°C



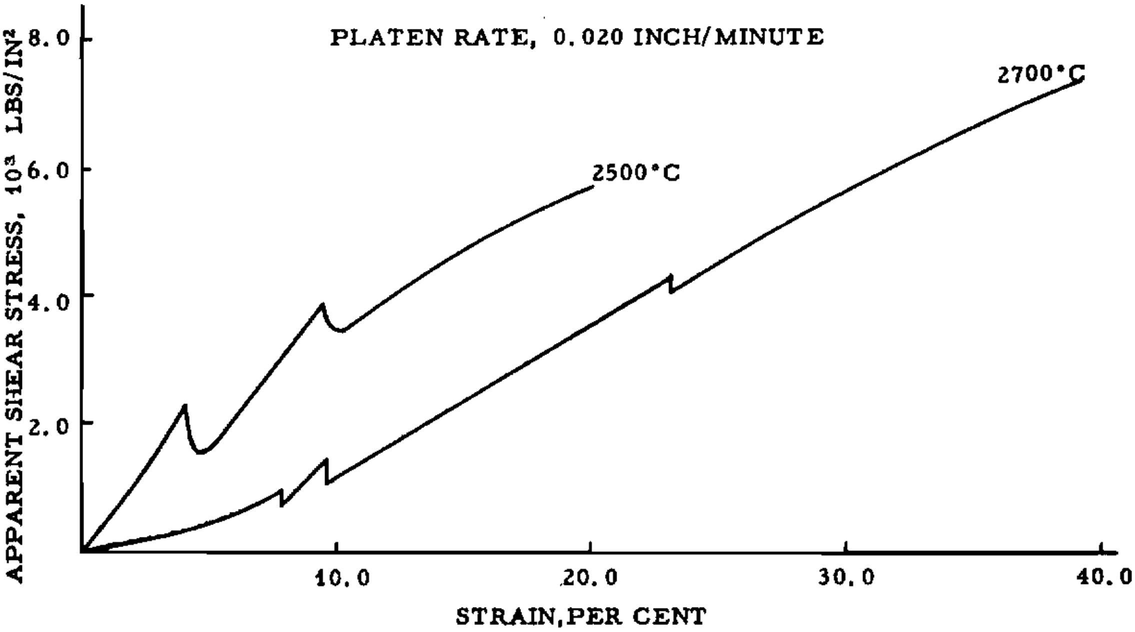
L-686

Figure 262. Across-Grain Apparent Shear Stress-Strain Curves, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length, Room Temperature



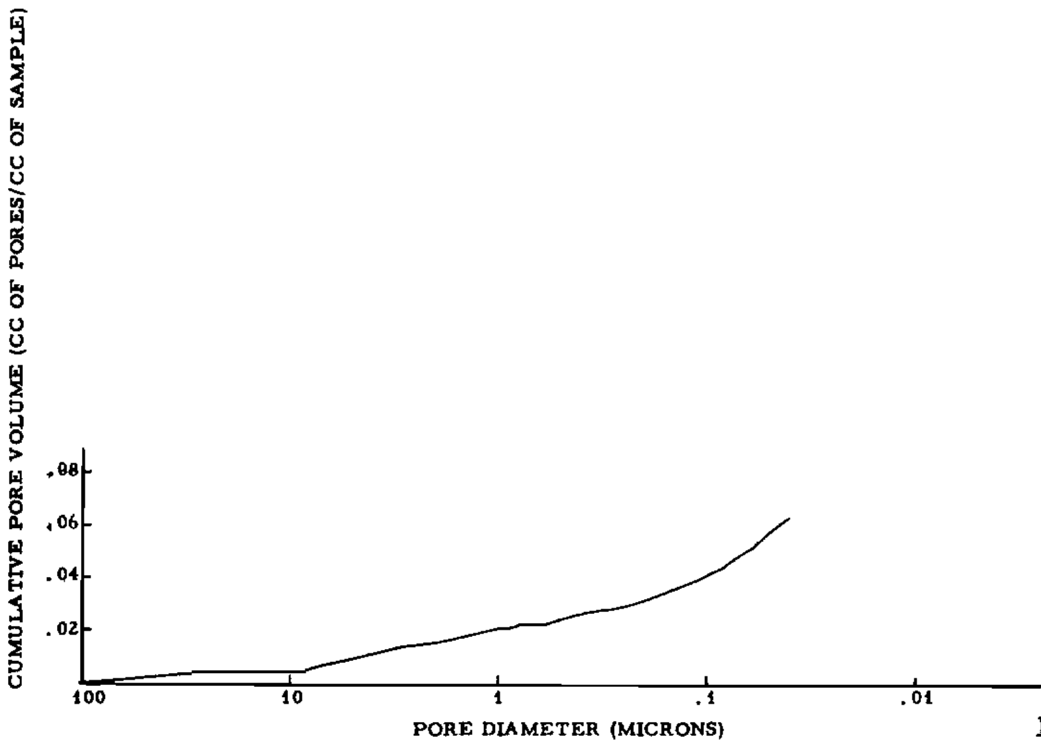
L-687

Figure 263. Across-Grain Apparent Shear Stress-Strain Curves, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length, 1000°C, 1500°C, 2000°C



L-688

Figure 264. Across-Grain Apparent Shear Stress-Strain Curves, CFW Graphite, 40-Inch O. D. by 15-Inch I. D. by 20-Inch Length, 2500°C, 2700°C



L-689

Figure 265. Pore Size Distribution, Mercury Porosimetry, CFW Graphite

3.12 Grade CFZ Graphite [23]

One block of CFZ graphite, 14 inches in diameter by $13\frac{1}{2}$ inches in length, was measured for the complete list of physical properties as outlined in Section 1. Results of these measurements are presented in Tables 67 and 68. The with-grain ultimate tensile strength versus temperature curve in Figure 269 is unusual in that there is not a rapid increase in tensile strength in the transition state (1500-2500°C). Further testing in the transition state is needed, particularly in view of the more normal across-grain ultimate tensile strength curve in Figure 270.

The interpretation of stress-strain curves has been discussed in Section 3.1. All strength tests were made with cross-head or platen rates of 0.020 inch per minute.

Table 67. Room-Temperature Properties, CFZ Graphite, 14-Inch Diameter by $13\frac{1}{2}$-Inch Length

Properties	With Grain Average	With Grain σ	With Grain n	With Grain No. of Blocks	Across Grain Average	Across Grain σ	Across Grain n	Across Grain No. of Blocks
Bulk Density, g/cc	1.91	0.01	40	1	---	---	--	-
Specific Resistance, 10^{-4} ohm-cm	12.77	0.28	14	1	16.08	0.33	16	1
Young's Modulus, 10^6 lbs/in^2	1.89	0.07	14	1	1.50	0.04	16	1
Flexural Strength, lbs/in^2	3980	340	14	1	3410	260	16	1
Compressive Strength*	9990	1420	12	1	12080	750	11	1
Compressive Strength**	12430	513	10	1	12225	197	10	1
Tensile Strength, lbs/in^2	2975	252	9	1	2490	254	10	1
Apparent Shear Strength, lbs/in^2	2815	435	10	1	2525	186	10	1

	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	With Grain No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n	Across Grain No. of Blocks
CTE, $10^{-6}/°C$, 20-100°C	2.05	1.82	1.94	4	1	2.71	2.56	2.64	4	1
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ °K}$	0.334	0.315	0.321	3	1	0.259	0.244	0.253	3	1
Admittance, cm^2/sec	1×10^{-2}	2×10^{-3}	6×10^{-3}	3	1	2×10^{-3}	1×10^{-3}	1×10^{-3}	3	1
Per Cent Ash	---	---	0.180	1	1	---	---	---	-	-

* 1- by 1- by 1-inch, lbs/in^2
** $\frac{1}{2}$-inch diameter by $\frac{1}{2}$-inch, lbs/in^2

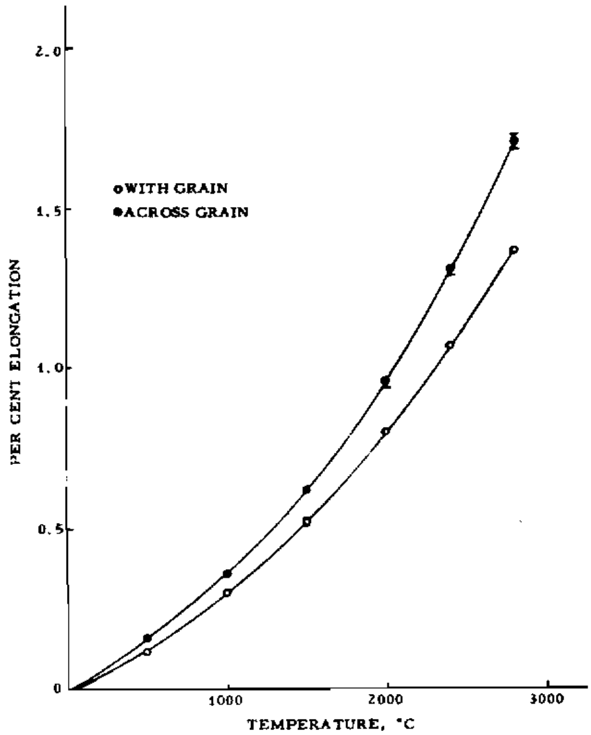
Table 68. High-Temperature Properties, CFZ Graphite, 14-Inch Diameter by $13\frac{1}{2}$-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	With Grain No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n	Across Grain No. of Blocks
Thermal Expansion,	500	0.120	0.117	0.119	3	1	0.167	0.155	0.162	3	1
Per Cent Elongation,	1000	0.305	0.296	0.299	3	1	0.363	0.353	0.357	3	1
$\frac{\Delta L}{L} \times 100$	1500	0.529	0.512	0.523	3	1	0.634	0.611	0.620	3	1
	2000	0.830	0.792	0.799	3	1	0.970	0.943	0.959	3	1
	2400	1.071	1.061	1.066	3	1	1.318	1.291	1.307	3	1
	2800	1.368	1.365	1.367	3	1	1.729	1.684	1.712	3	1
Young's Modulus, Sonic	RT	2.28	1.90	2.03	3	1	1.36	1.24	1.29	3	1
	600	2.40	1.97	2.11	3	1	1.44	1.28	1.36	3	1
	1200	2.47	2.15	2.27	3	1	1.59	1.40	1.47	3	1
	1600	2.60	2.23	2.37	3	1	1.69	1.66	1.68	3	1
	2000	2.73	2.29	2.46	3	1	1.98	1.85	1.92	3	1
	2200	---	---	---	-	-	1.99	1.87	1.93	3	1
	2400	2.77	2.36	2.51	3	1	---	---	---	-	-
	2500	---	---	---	-	-	1.92	1.76	1.84	3	1
	2800	2.63	2.31	2.43	3	1	1.84	1.72	1.78	3	1
Tensile Strength,	1000	---	---	4130	1	1	---	---	2865	1	1
lbs/in^2	1500	---	---	4460	1	1	---	---	2905	1	1
	2000	---	---	4530	1	1	---	---	3845	1	1
	2500	---	---	4515	1	1	---	---	3965		
	2700	---	---	4750	1	1	---	---	3805	1	1
Compressive Strength,	1000	12020	9165	10590	2	1	---	---	12885	1	1
$\frac{1}{2}$-inch diameter by	1500	---	---	13140	1	1	---	---	14260	1	1
$\frac{1}{2}$-inch, lbs/in^2	2000	---	---	14465	1	1	---	---	16755	1	1
	2500	No break at		25670	1	1	---	---	22460	-	-
	2700	---	---	---	-	-	---	---	---	-	-
Apparent Shear Strength,	1000	---	---	3770	1	1	4620	3840	4230	2	1
lbs/in^2	1500	---	---	4580	1	1	---	---	4840	1	1
	2000	---	---	5365	1	1	---	---	4975	1	1
	2500	---	---	7150	1	1	---	---	7210	1	1
	2700	---	---	7150	1	1	---	---	6875	1	1

1.925	1.933	1.931	1.933	1.937	1.934	1.939	1.938	1.938	1.938	1.920	1.919
1.924	1.930	1.933	1.935	1.933	1.938	1.937	1.939	1.938	1.934	1.913	1.914
1.930	1.935	1.934	1.935	1.937	1.938	1.937	1.941	1.939	1.894	1.910	1.908
1.934	1.935	1.937	1.937	1.940	1.939	1.939	1.941	1.941	1.930	1.916	1.915
1.938	1.938	1.938	1.939	1.942	1.946	1.952	1.947	1.943	1.944	1.932	1.933

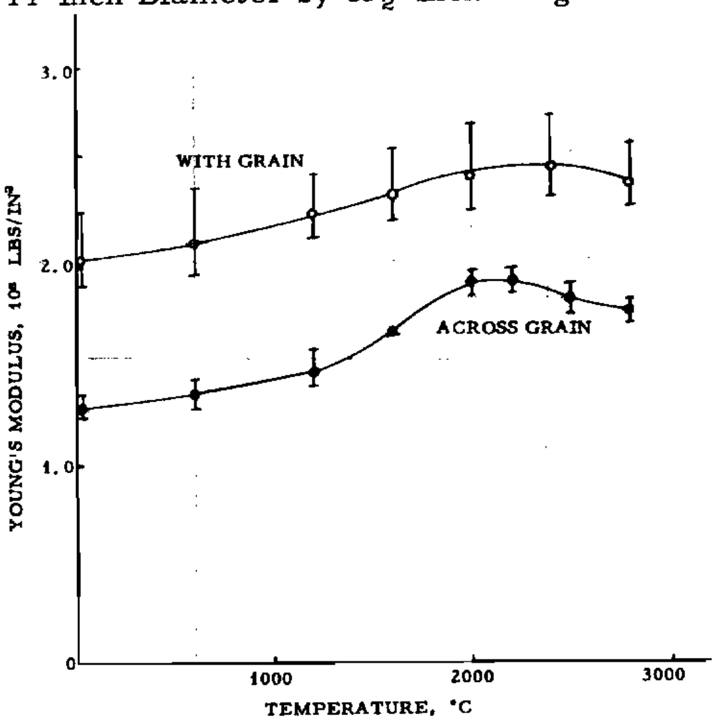
L-693

Figure 266. Density Profile, CFZ Graphite, 14-Inch Diameter by $13\frac{1}{2}$-Inch Length



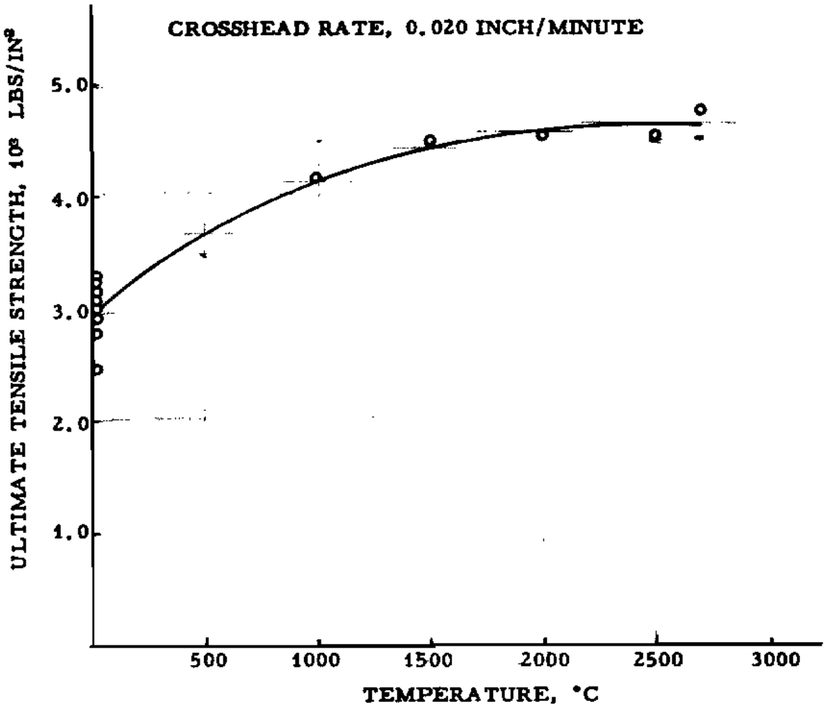
L-694

Figure 267. Thermal Expansion vs. Temperature, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length



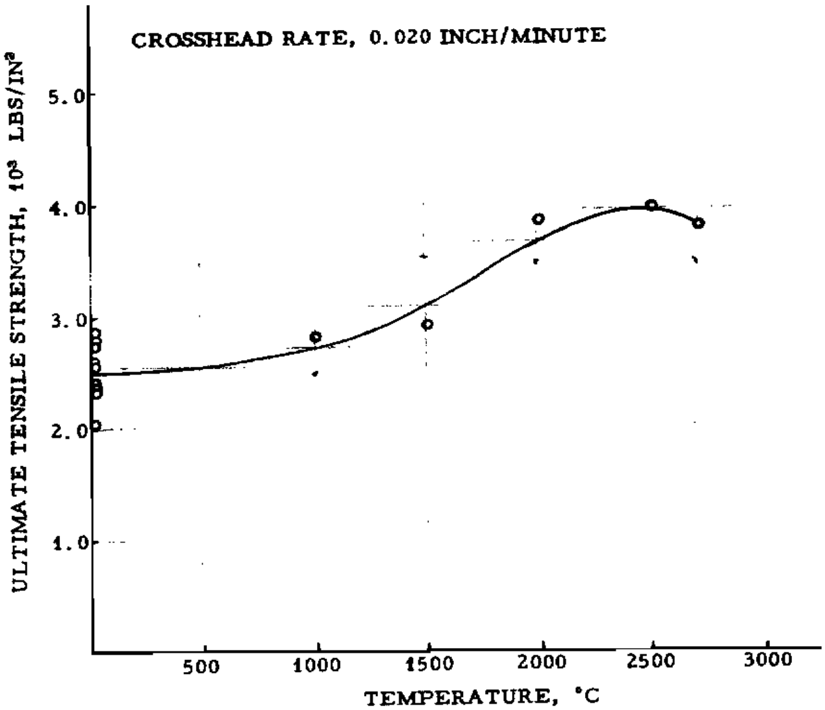
L-695

Figure 268. Young's Modulus vs. Temperature, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length



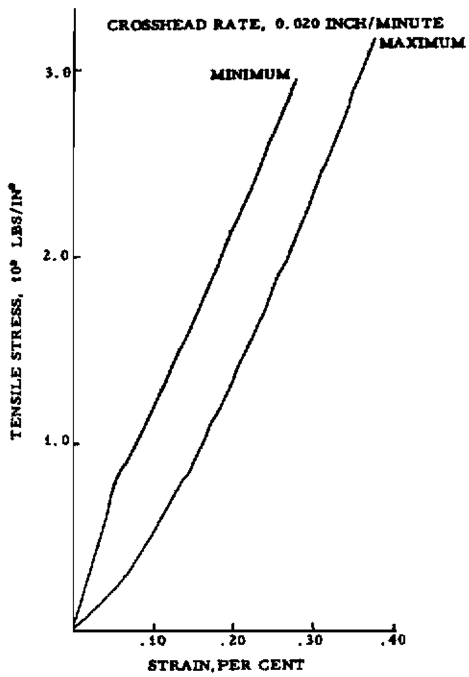
L-696

Figure 269. With-Grain Ultimate Tensile Strength vs. Temperature, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length



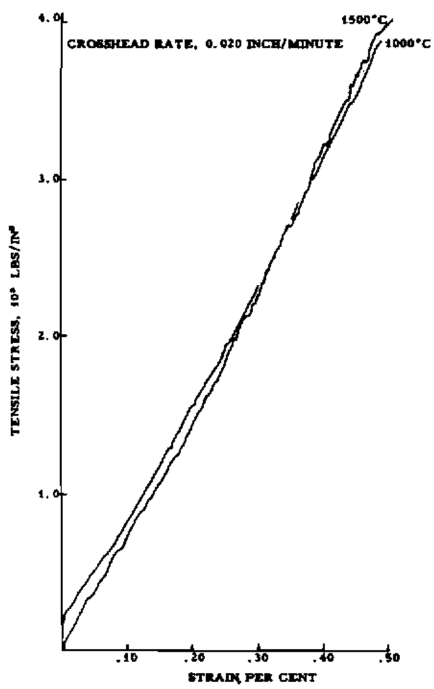
L-697

Figure 270. Across-Grain Ultimate Tensile Strength vs. Temperature, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length



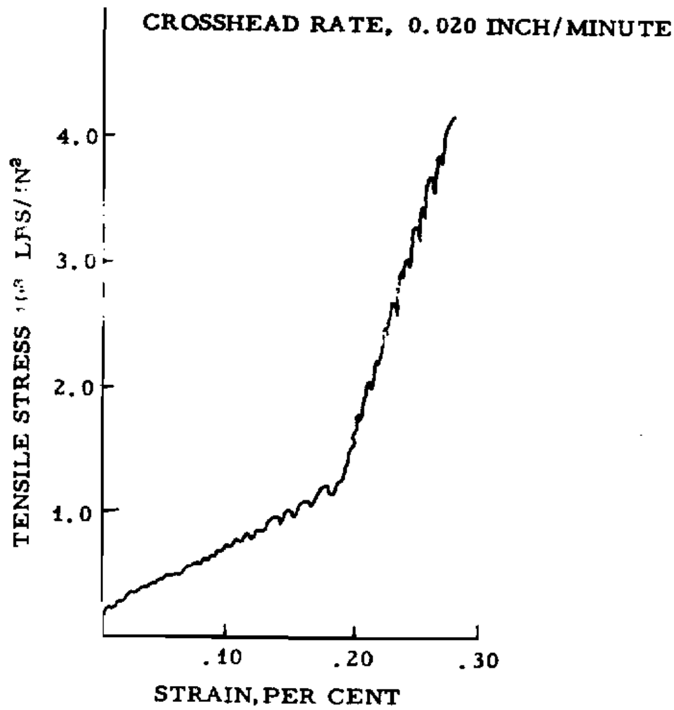
L-698

Figure 271. With-Grain Tensile Stress-Strain Curves, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length, Room Temperature



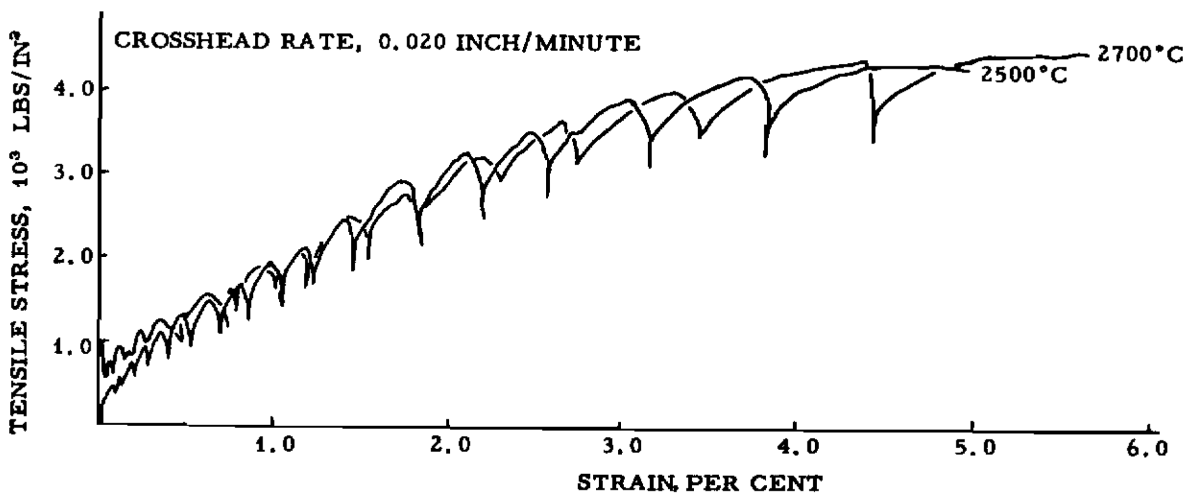
L-699

Figure 272. With-Grain Tensile Stress-Strain Curves, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length, 1000°C, 1500°C



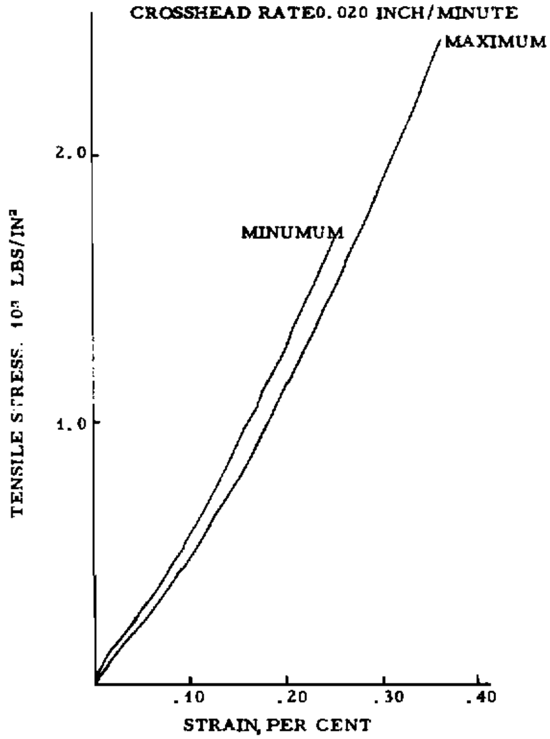
L-700

Figure 273. With-Grain Tensile Stress-Strain Curve, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length, 2000°C



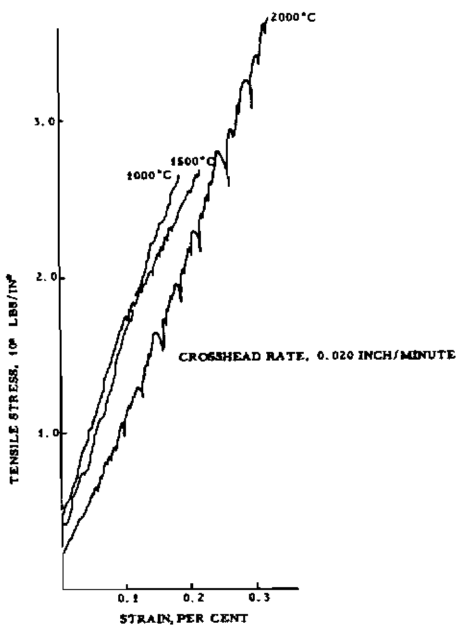
L-701

Figure 274. With-Grain, Tensile Stress-Strain Curves, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length, 2500°C, 2700°C



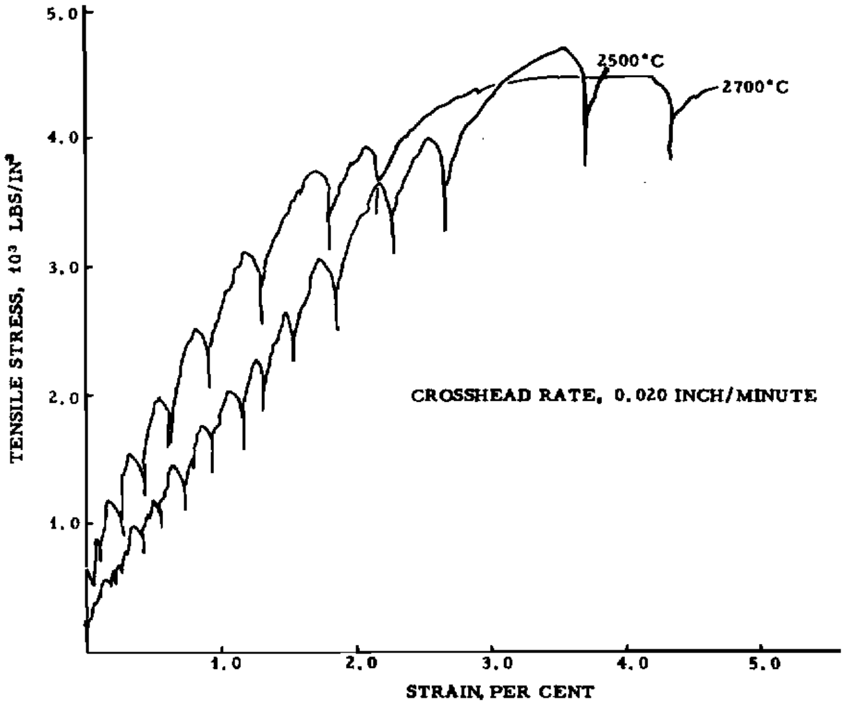
L-702

Figure 275. Across-Grain Tensile Stress-Strain Curves, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length, Room Temperature



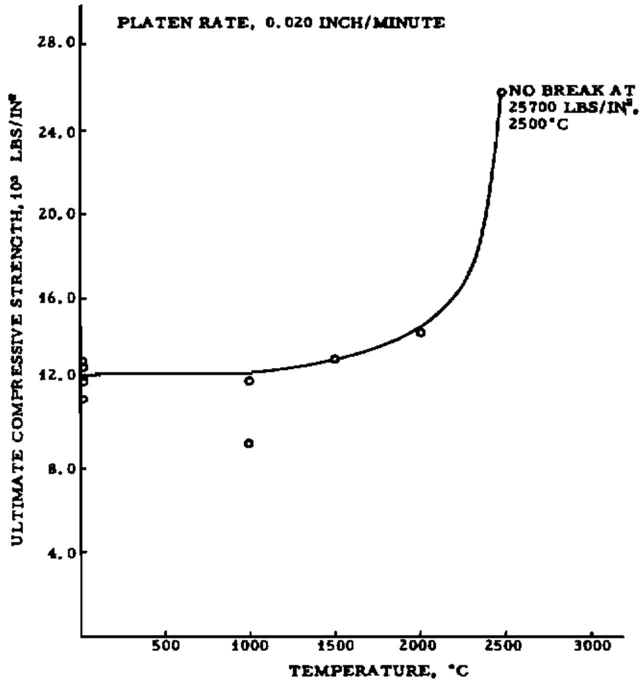
L-703

Figure 276. Across-Grain Tensile Stress-Strain Curves, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length, 1000°C, 1500°C, 2000°C



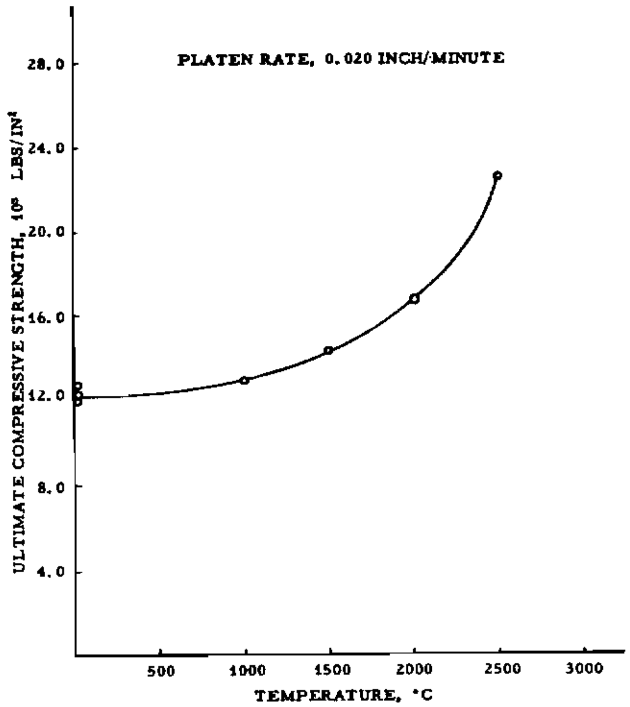
L-704

Figure 277. Across-Grain Tensile Stress-Strain Curves, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length, 2500°C, 2700°C



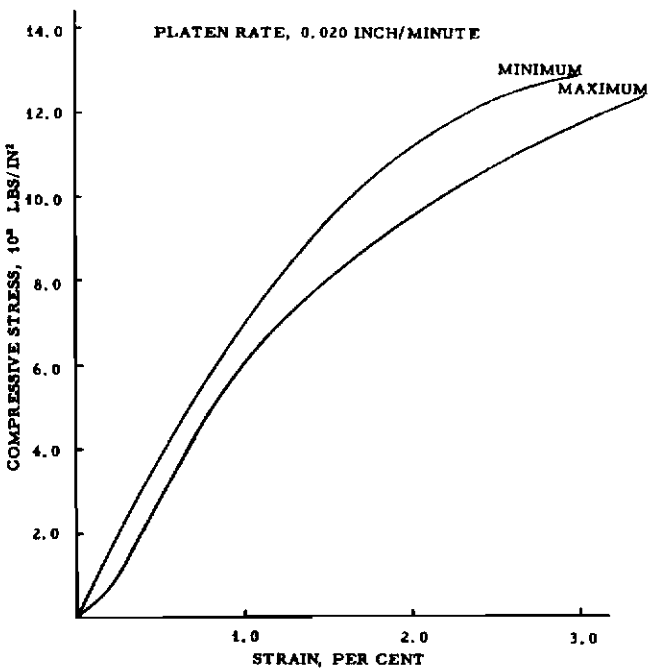
L-705

Figure 278. With-Grain Ultimate Compressive Strength vs. Temperature, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length



L-706

Figure 279. Across-Grain Ultimate Compressive Strength vs. Temperature, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length



L-707

Figure 280. With-Grain Compressive Stress-Strain Curves, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length, Room Temperature

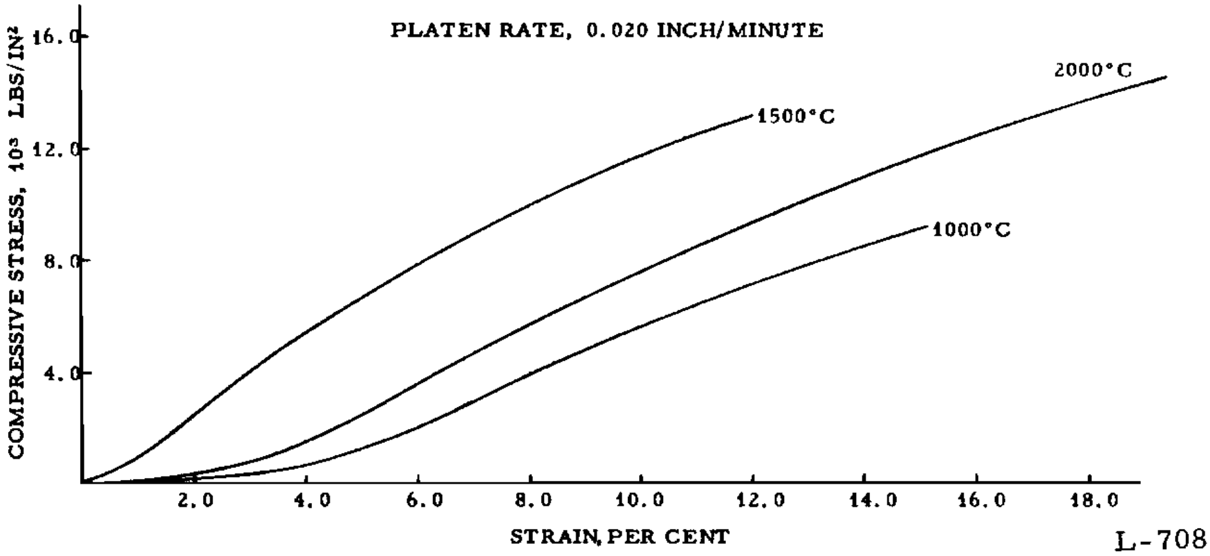


Figure 281. With-Grain Compressive Stress-Strain Curves, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length, 1000°C, 1500°C, 2000°C

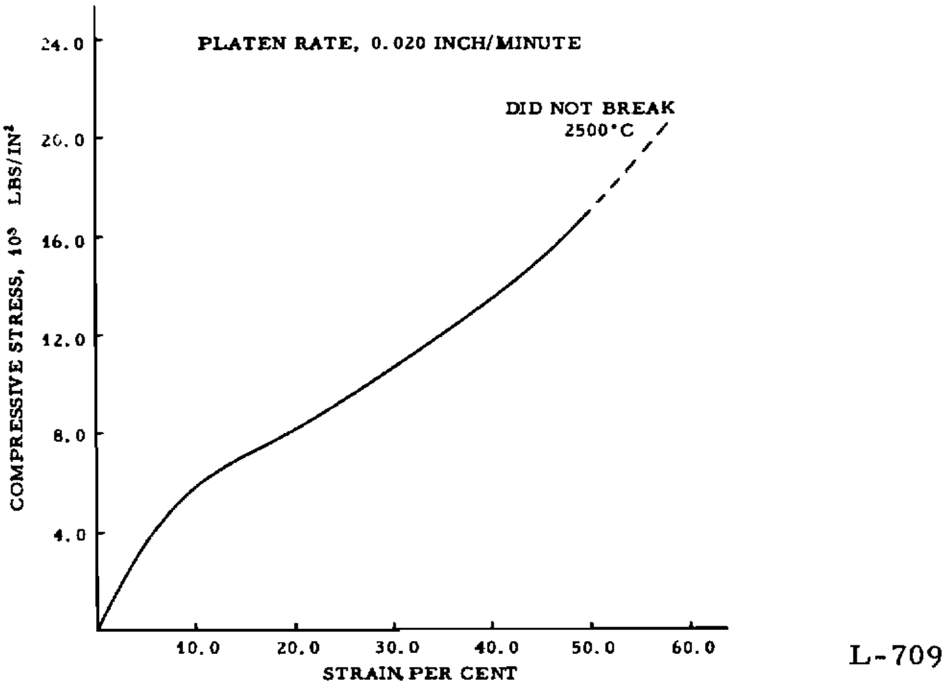


Figure 282. With-Grain Compressive Stress-Strain Curve, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length, 2500°C

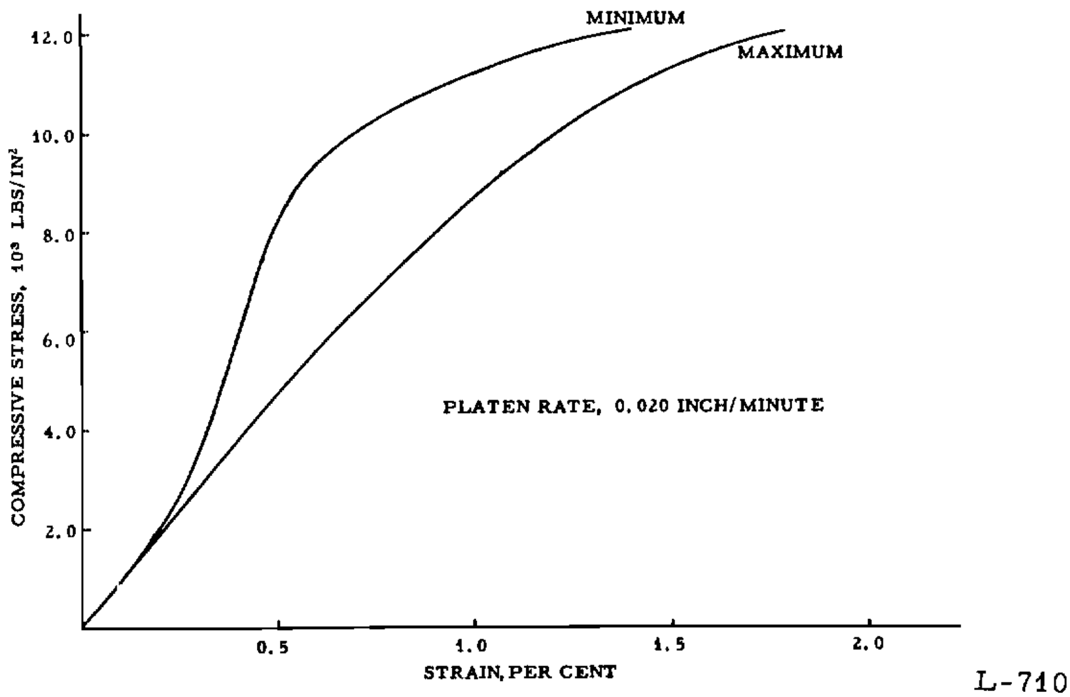


Figure 283. Across-Grain Compressive Stress-Strain Curves, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length, Room Temperature

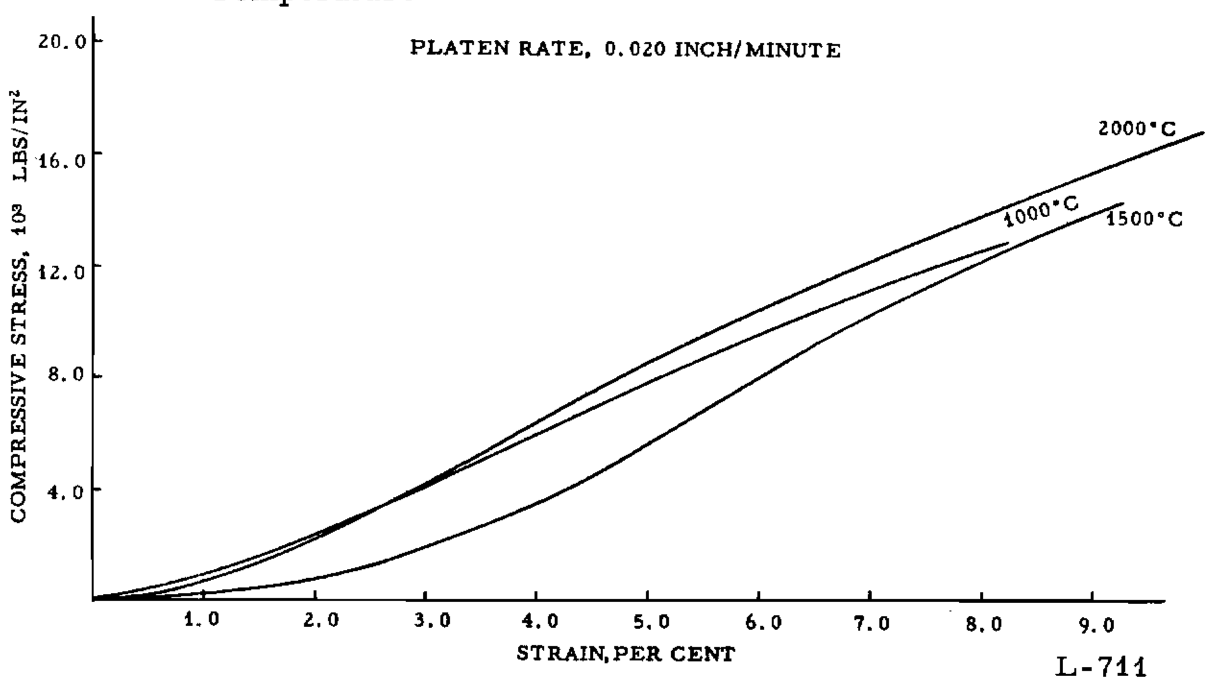
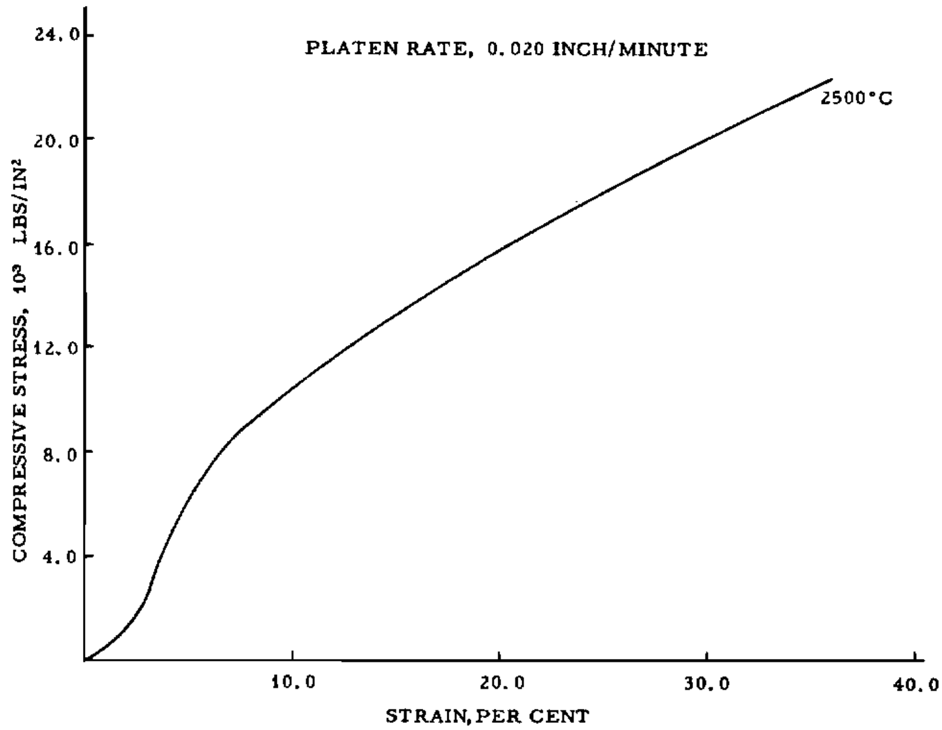
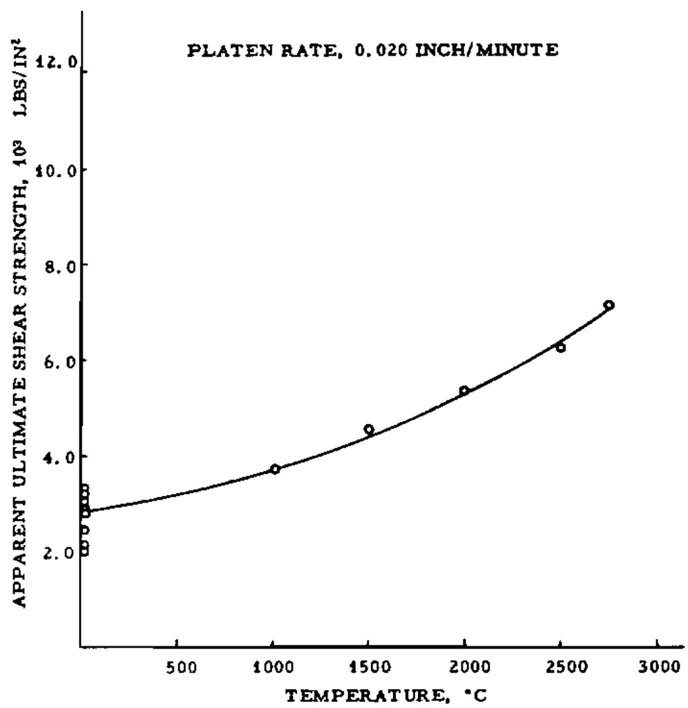


Figure 284. Across-Grain Compressive Stress-Strain Curves, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length, 1000°C, 1500°C, 2000°C



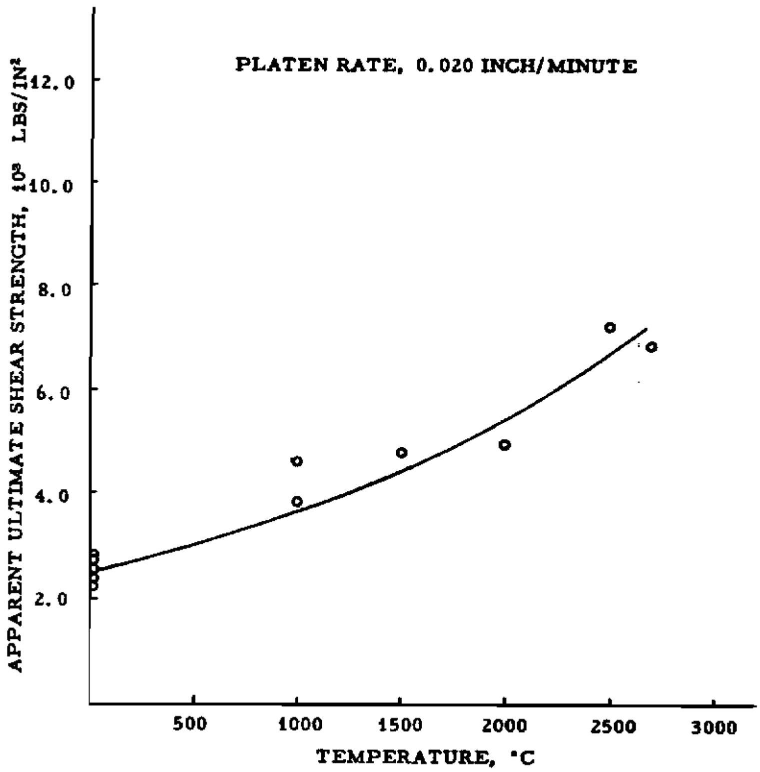
L-712

Figure 285. Across-Grain Compressive Stress-Strain Curve, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length, 2500°C



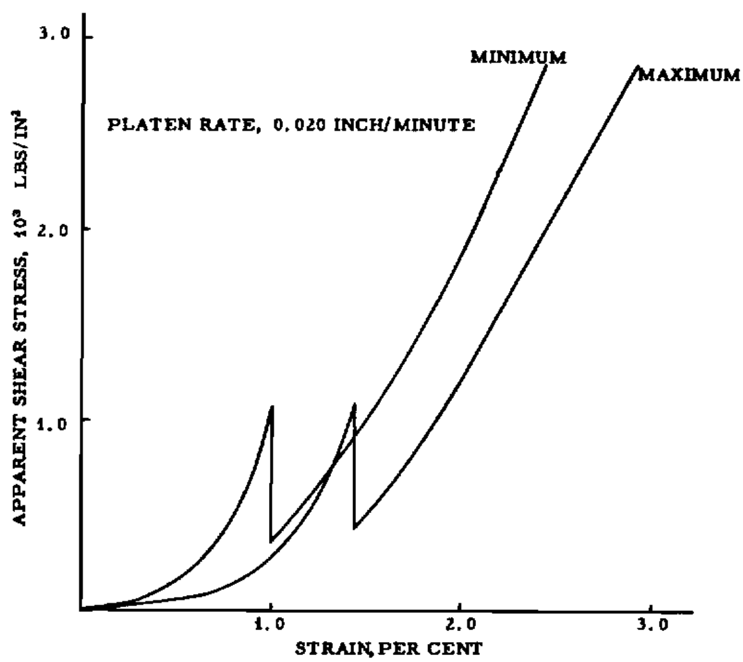
L-713

Figure 286. With-Grain Apparent Ultimate Shear Strength vs. Temperature, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length



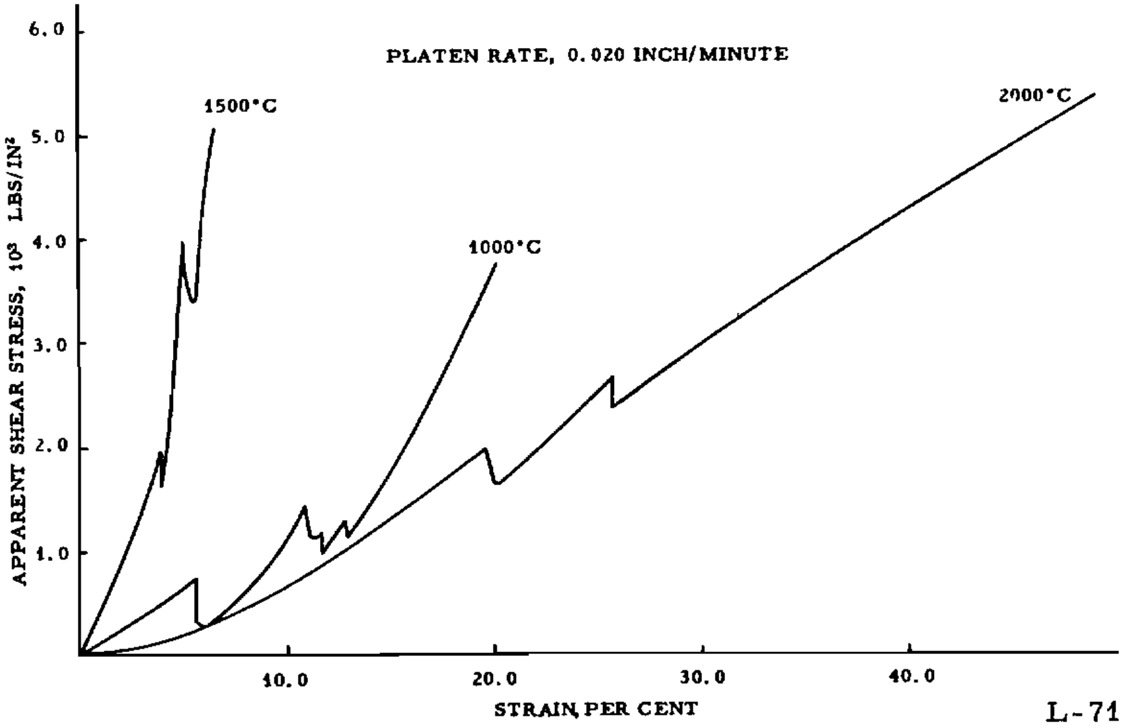
L-721

Figure 287. Across-Grain Apparent Ultimate Shear Strength vs. Temperature, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length



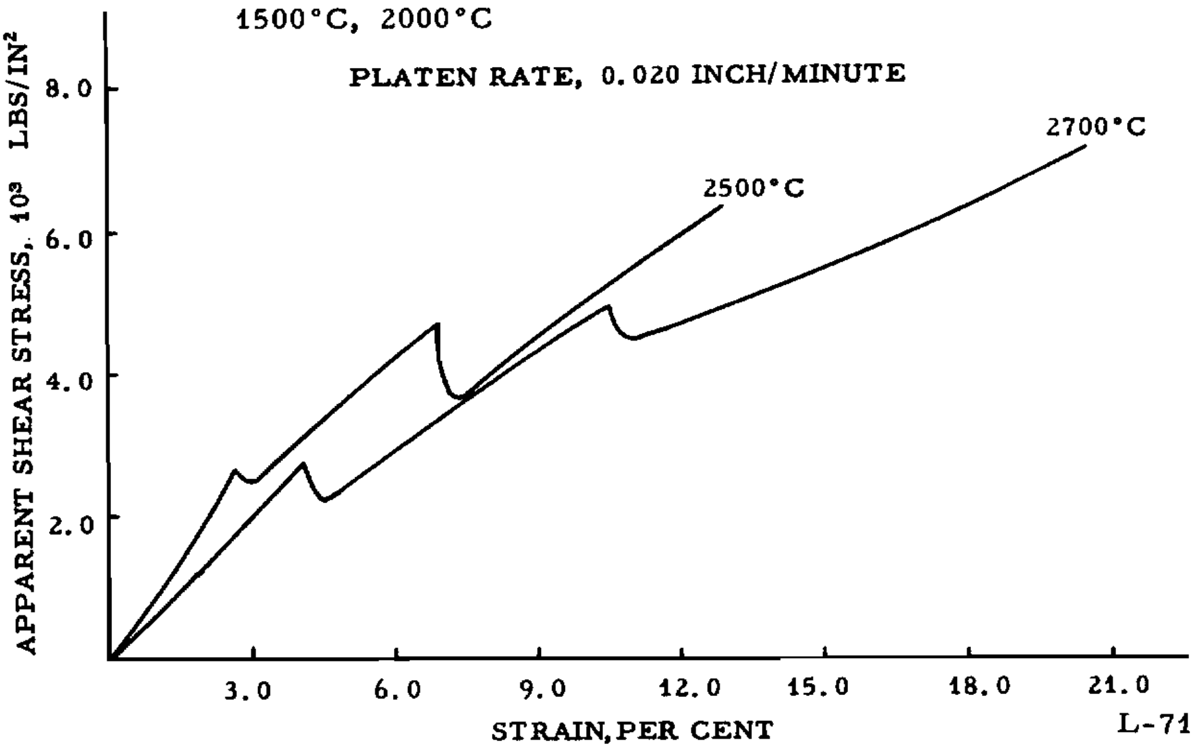
L-722

Figure 288. With-Grain Apparent Shear Stress-Strain Curves, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length, Room Temperature



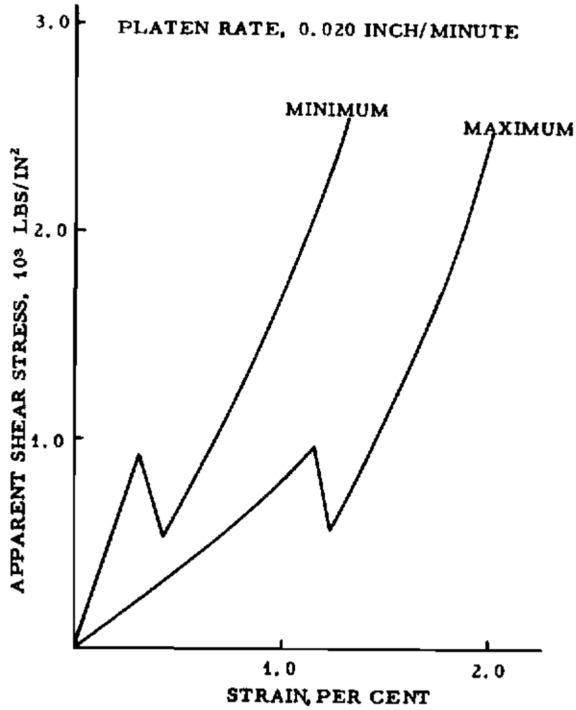
L-714

Figure 289. With-Grain Apparent Shear Stress-Strain Curves, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length, 1000°C, 1500°C, 2000°C



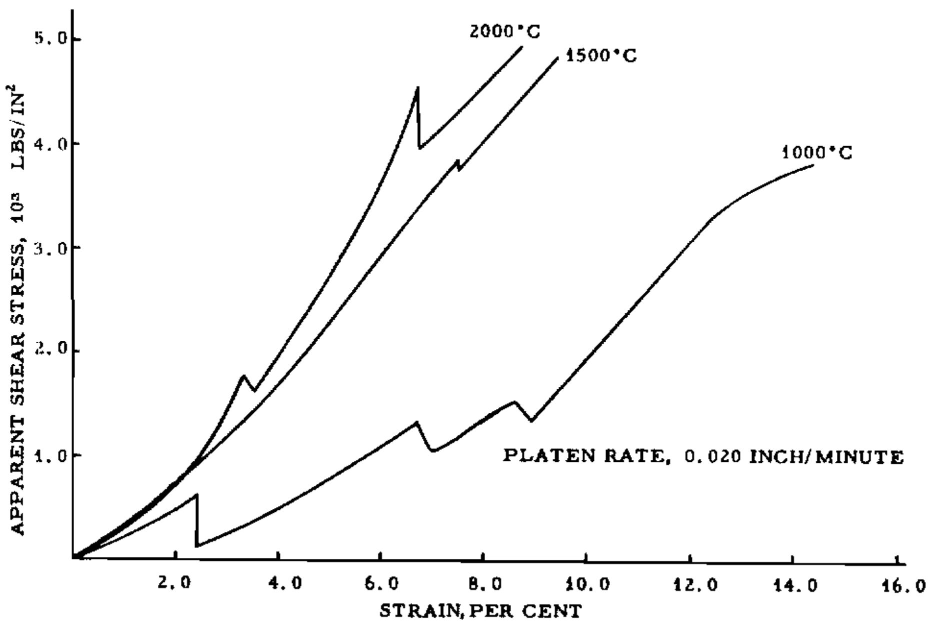
L-715

Figure 290. With-Grain Apparent Shear Stress-Strain Curves, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length, 2500°C, 2700°C



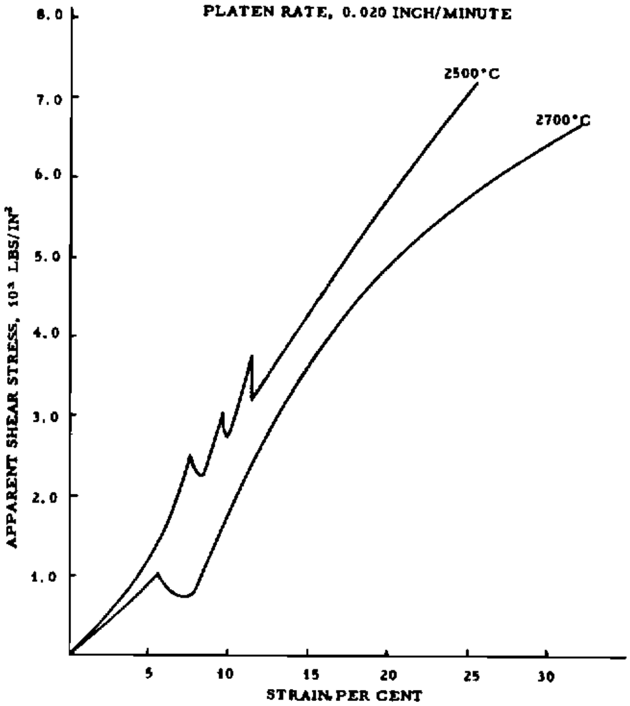
L-716

Figure 291. Across-Grain Apparent Shear Stress-Strain Curves, CFZ Graphite, 14-Inch Diameter by $13\frac{1}{2}$-Inch Length, Room Temperature



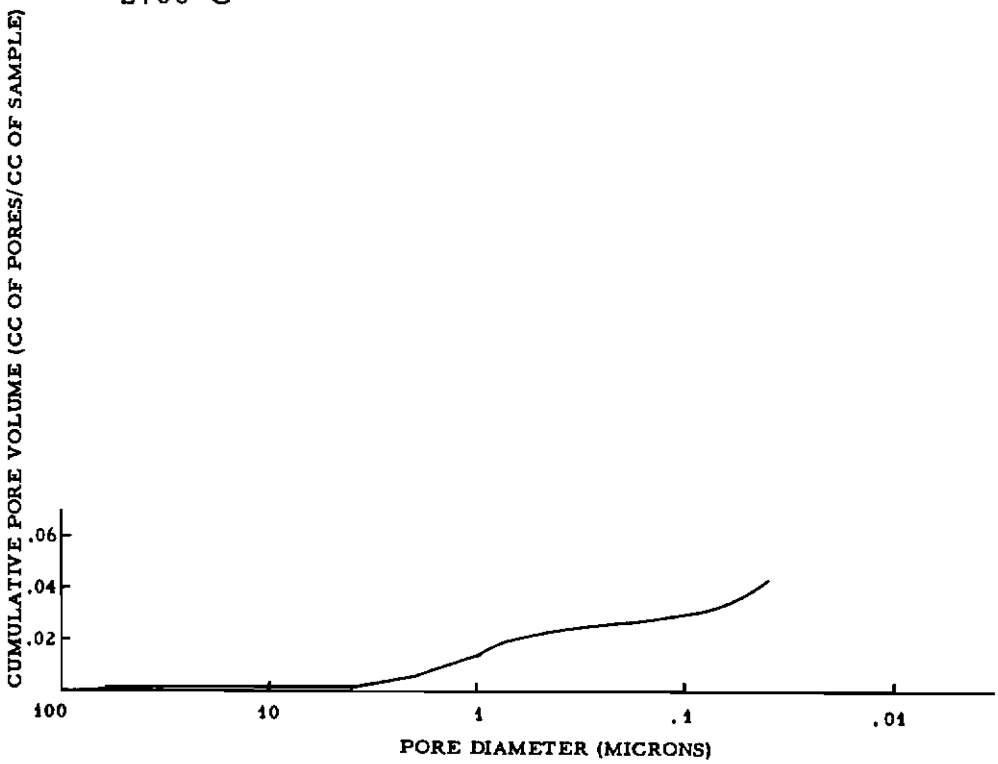
L-717

Figure 292. Across-Grain Apparent Shear Stress-Strain Curves, CFZ Graphite, 14-Inch Diameter by $13\frac{1}{2}$-Inch Length, 1000°C, 1500°C, 2000°C



L-718

Figure 293. Across-Grain Apparent Shear Stress-Strain Curves, CFZ Graphite, 14-Inch Diameter by 13½-Inch Length, 2500°C, 2700°C



L-719

Figure 294. Pore Size Distribution, Mercury Porosimetry, CFZ Graphite

3.13. Grade PT-0113 Graphite-Cloth Composite[24]

PT-0113 is one of the grades containing a shredded or macerated graphite cloth filler. The final process temperature of the composite is 800°C, and as a result its properties are more like those of carbon than graphite. The properties of carbon are conspicuously altered at graphitizing temperatures; consequently, the temperature for measurement of high temperature properties does not exceed 1200°C.

The low temperature thermal conductivity of PT-0113 provided an excellent opportunity to compare the Fitch method with the Meers method of measuring that property. It can be seen in Table 69 that, based upon a limited amount of data, average values obtained by the two methods do not differ by more than 0.003 cal-cm/sec/cm^2/°K. The Fitch method may, therefore, be used when thermal conductivities are not higher than 0.012 cal-cm/sec/cm^2/°K.

Because of the low across-grain flexural strength of grade PT-0113, it was not possible to prepare samples to be used for across-grain CTE measurements.

All strength measurements were made with cross-head or platen rates of 0.020 inch per minute.

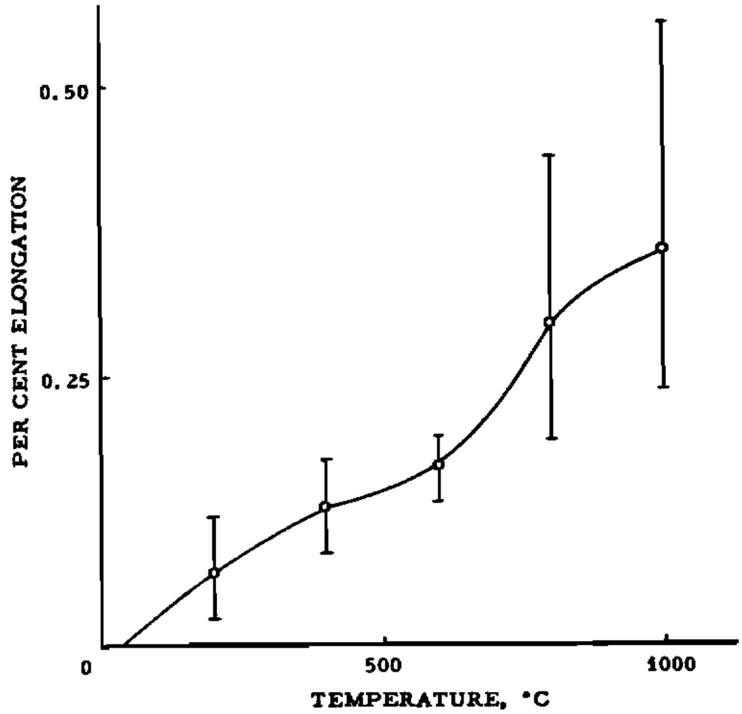
Table 69. Room-Temperature Properties, PT-0113 Carbon, 5-Inch Diameter by 5-Inch Length

Properties	With Grain Average	With Grain σ	With Grain n	With Grain No. of Blocks	Across Grain Average	Across Grain σ	Across Grain n	Across Grain No. of Blocks
Bulk Density, g/cc	1.18	0.04	44	6	---	---	--	-
Specific Resistance, 10^{-4} ohm-cm	120	15	32	6	289	46	17	6
Young's Modulus, 10^6 lbs/in^2	1.23	0.13	29	6	0.43	0.06	15	6
Flexural Strength, lbs/in^2	2060	230	14	6	440	60	8	6
Compressive Strength, 1- by 1- by 1-inch, lbs/in^2	2970	340	6	6	3710	250	6	6

Properties	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	With Grain No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n	Across Grain No. of Blocks
Permeability, Darcy's	0.016	0.004	0.0055	15	5	0.004	0.002	0.003	15	5
CTE, 20°-100°C, 10^{-6}/°C	1.41	1.21	1.32	4	3	Could not prepare samples				
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ \text{°K}}$ (Fitch)	0.011	0.010	0.010	3	2	0.005	0.004	0.005	3	1
" " (Meers)	0.013	0.012	0.013	2	1	0.007	0.007	0.007	2	1
Per Cent Ash	0.200	0.111	0.134	6	6	---	---	---	-	-

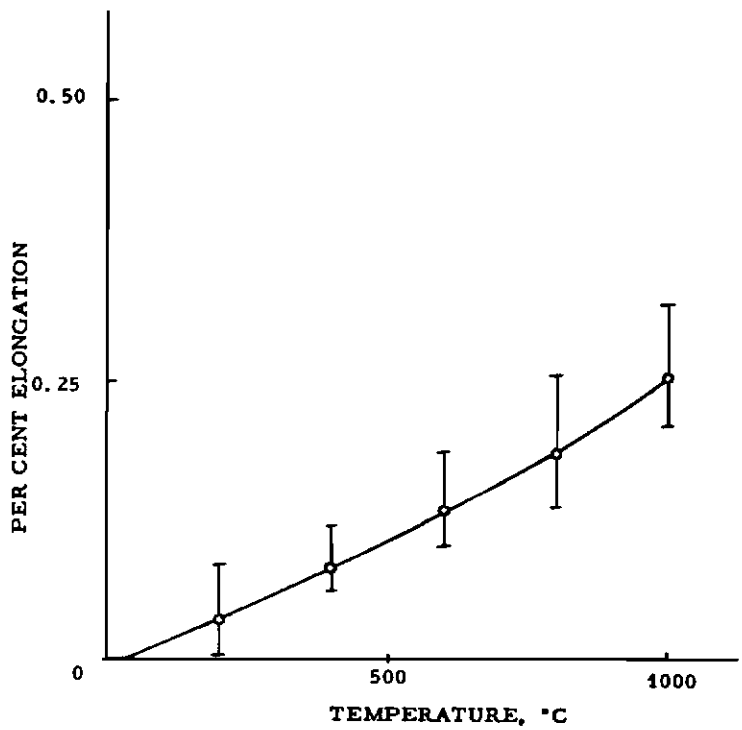
Table 70. High-Temperature Properties, PT-0113 Carbon, 5-Inch Diameter by 5-Inch Length

Properties	Temp. °C	With Grain					Across Grain				
		Max.	Min.	Ave.	n	No. of Blocks	Max.	Min.	Ave.	n	No. of Blocks
CTE, Per Cent Elongation, $\frac{\Delta L}{L} \times 100$	200	0.087	0.002	0.035	3	1	0.117	0.023	0.064	3	1
	400	0.120	0.061	0.081	3	1	0.167	0.081	0.121	3	1
	600	0.186	0.102	0.131	3	1	0.186	0.128	0.159	3	1
	800	0.254	0.136	0.183	3	1	0.434	0.181	0.283	3	1
	1000	0.318	0.210	0.252	3	1	0.553	0.227	0.350	3	1
Young's Modulus, 10^6 lbs/in^2	RT	1.32	1.10	1.20	3	1	0.53	0.43	0.49	3	1
	600	1.33	1.14	1.22	3	1	0.54	0.43	0.50	3	1
	1200	1.36	1.19	1.27	3	1	0.56	0.44	0.52	3	1



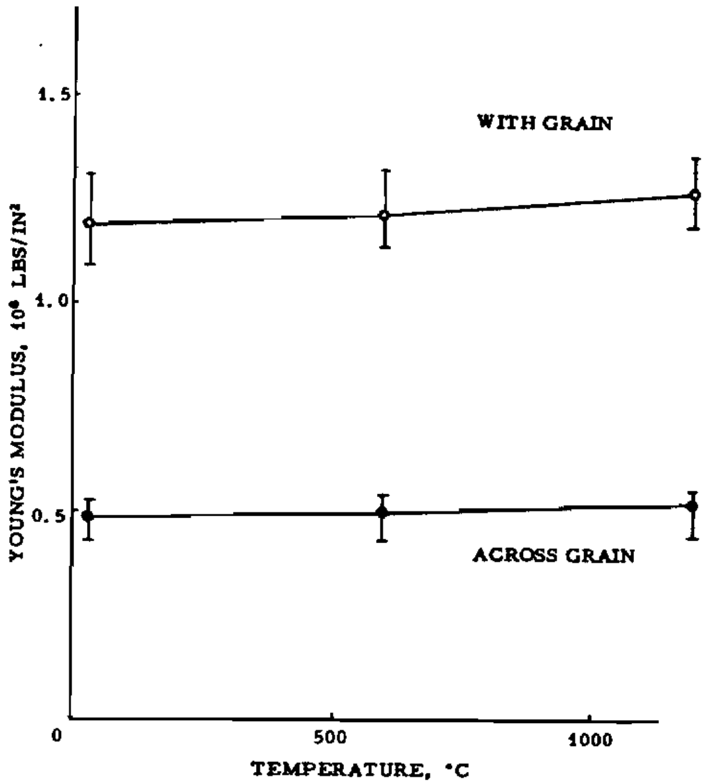
L-720

Figure 295. With-Grain Thermal Expansion vs. Temperature, PT-0113 Carbon, 5-Inch Diameter by 5-Inch Length



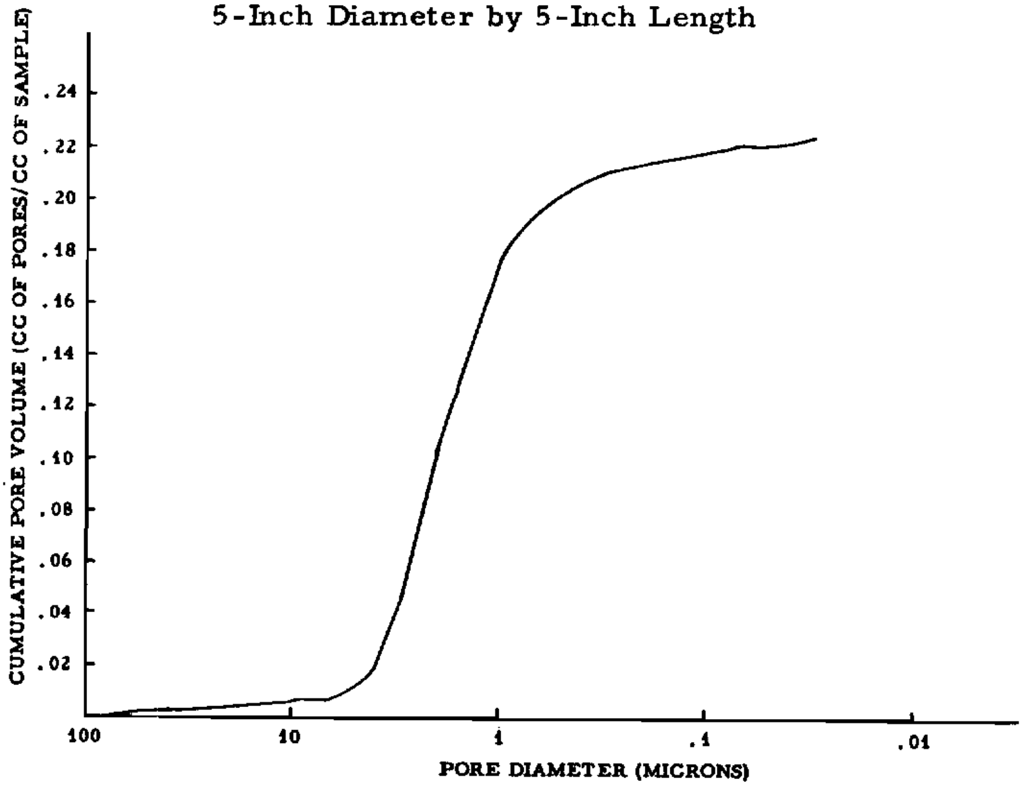
L-723

Figure 296. Across-Grain Thermal Expansion vs. Temperature, PT-0113 Carbon, 5-Inch Diameter by 5-Inch Length



L-724

Figure 297. Young's Modulus vs. Temperature, PT-0113 Carbon, 5-Inch Diameter by 5-Inch Length



L-725

Figure 298. Pore Size Distribution, Mercury Porosimetry, PT-0113 Carbon

3.14. Grade PT-0114 Graphite-Cloth Composite [24]

Grade PT-0114 contains a macerated graphite cloth filler and the composite has been baked to graphitizing temperature. The grade was completely characterized as outlined in Section 1, except for across-grain room temperature CTE. Difficulty was encountered in preparing across-grain CTE samples due to breakage as a result of the low across-grain flexural strength.

The with-grain ultimate tensile strength, Figure 301, appears to be lower at 1000°C than at room temperature. There is insufficient data to determine whether or not the decrease in strength in the room temperature to 1000°C range is real.

Interpretation of stress-strain curves has been discussed in Section 3.1. In addition to the discontinuities, portions of some of the apparent shear stress-strain curves for this grade are serrated. The serrations may be caused by the displacement or fracture of fibers comprising the filler. Another distinctive feature is that some of the specimens appear to have a residual strength after maximum stress has been applied. In these cases the maximum stress is the ultimate apparent shear strength and the stress at maximum strain is the breaking strength[25]. The ultimate and breaking strengths are identical for all graphite grades for which stress-strain data have been presented in Sections 3.1. - 3.18., with the exception of grade PT-0114 in shear. These features may be characteristics of all PT carbons and graphites.

All strength measurements were made with cross-head or platen rates of 0.020 inch per minute. The across-grain ultimate tensile strength was so low that it was not possible to obtain meaningful stress-strain curves.

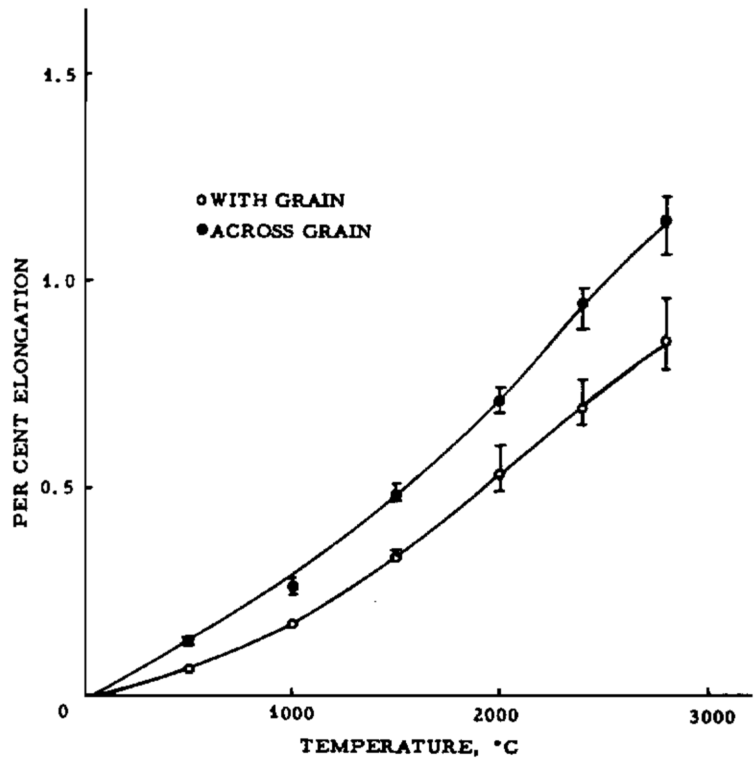
Table 71. Room-Temperature Properties, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length

Properties	With Grain				Across Grain			
	Average	σ	n	No. of Blocks	Average	σ	n	No. of Blocks
Bulk Density, g/cc	1.15	0.02	67	6	---	---	--	-
Specific Resistance, 10^{-4} ohm	30.9	2.0	35	6	62.0	4.7	32	6
Young's Modulus, 10^6 lbs/in^2	0.89	0.07	35	6	0.28	0.03	32	6
Flexural Strength, lbs/in^2	2450	340	12	6	730	80	13	6
Compressive Strength, 1- by 1- by 1 inch, lbs/in^2	2040	380	6	6	2520	350	6	6
Compressive Strength, $\frac{1}{2}$-inch diameter by $\frac{1}{2}$ inch, lbs/in^2	1420	229	10	6	2850	462	10	6
Tensile Strength, lbs/in^2	1060	125	9	6	305	62	11	6
Apparent Shear Strength, lbs/in^2	1380	183	10	6	490	43	9	6

Properties	With Grain					Across Grain				
	Max.	Min.	Ave.	n	No. of Blocks	Max.	Min.	Ave.	n	No. of Blocks
CTE, 20-100°C, 10^{-6}/°C	1.10	0.91	1.00	4	4	(Can not cut without breaking)				
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ \text{°K}}$	---	---	0.0504	1	1	0.0273	0.0263	0.0268	2	1
Permeability, Darcy's	0.0079	0.0051	0.0062	6	1	0.0051	0.0018	0.0031	6	1
Per Cent Ash	0.751	0.290	0.436	4	4	---	---	---	-	-

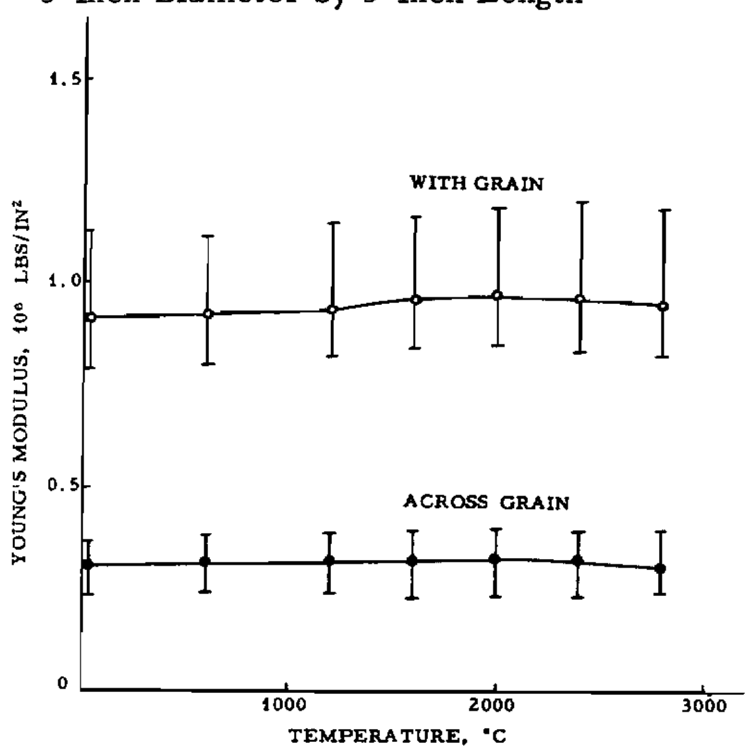
Table 72. High-Temperature Properties, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	n	No. of Blocks	Across Grain Max.	Across Grain Min.	Across Grain Ave.	n	No. of Blocks
CTE, Per Cent Elongation,	500	0.066	0.062	0.064	3	1	0.138	0.122	0.129	3	1
$\frac{\Delta L}{L} \times 100$	1000	0.172	0.162	0.167	3	1	0.280	0.240	0.262	3	1
	1500	0.346	0.321	0.333	3	1	0.508	0.468	0.480	3	1
	2000	0.600	0.486	0.528	3	1	0.742	0.681	0.714	3	1
	2400	0.762	0.646	0.686	3	1	0.985	0.879	0.936	3	1
	2800	0.964	0.784	0.850	3	1	1.204	1.063	1.139	3	1
Young's Modulus,	RT	1.12	0.79	0.91	3	1	0.37	0.23	0.30	3	1
10^6 lbs/in^2	600	1.13	0.80	0.92	3	1	0.38	0.24	0.31	3	1
	1200	1.15	0.82	0.94	3	1	0.38	0.23	0.31	3	1
	1600	1.17	0.84	0.96	3	1	0.39	0.22	0.31	3	1
	2000	1.19	0.85	0.97	3	1	0.40	0.23	0.32	3	1
	2400	1.21	0.84	0.97	3	1	0.40	0.23	0.32	3	1
	2800	1.19	0.82	0.95	3	1	0.40	0.24	0.30	3	1
Tensile Strength,	1000	785	540	665	2	1	---	---	350	1	1
lbs/in^2	1500	---	---	1255	1	1	---	---	---	-	-
	2000	---	---	1135	1	1	---	---	---	-	-
	2400	---	---	1525	1	1	---	---	---	-	-
	2500	---	---	---	-	-	---	---	675	1	1
	2700	---	---	1835	1	1	---	---	360	1	1
	2900	278	151	215	2	1	---	---	---	-	-
Compressive Strength,	1000	---	---	1835	1	1	---	---	3265	1	1
½-inch Diameter by ½-inch,	1500	---	---	1955	1	1	---	--	3720	1	1
lbs/in^2	2000	---	---	2285	1	1	---	---	4735	1	1
	2500	---	---	3845	1	1	---	---	14135	1	1
	2700	---	---	3955	1	1	---	---	23990	1	1
	2800	---	---	5580	1	1	---	---	---	-	-
	2900	Did not break at 28000			1	1	---	---	---	-	-
Apparent Shear Strength,	1000	---	---	1350	1	1	---	---	240	1	1
½-inch Diameter by ½-Inch,	1500	---	---	1375	1	1	---	---	490	1	1
lbs/in^2	2000	---	---	1775	1	1	---	---	555	1	1
	2500	---	---	2545	1	1	---	---	1265	1	1
	2700	---	---	5470	1	1	---	---	1810	1	1



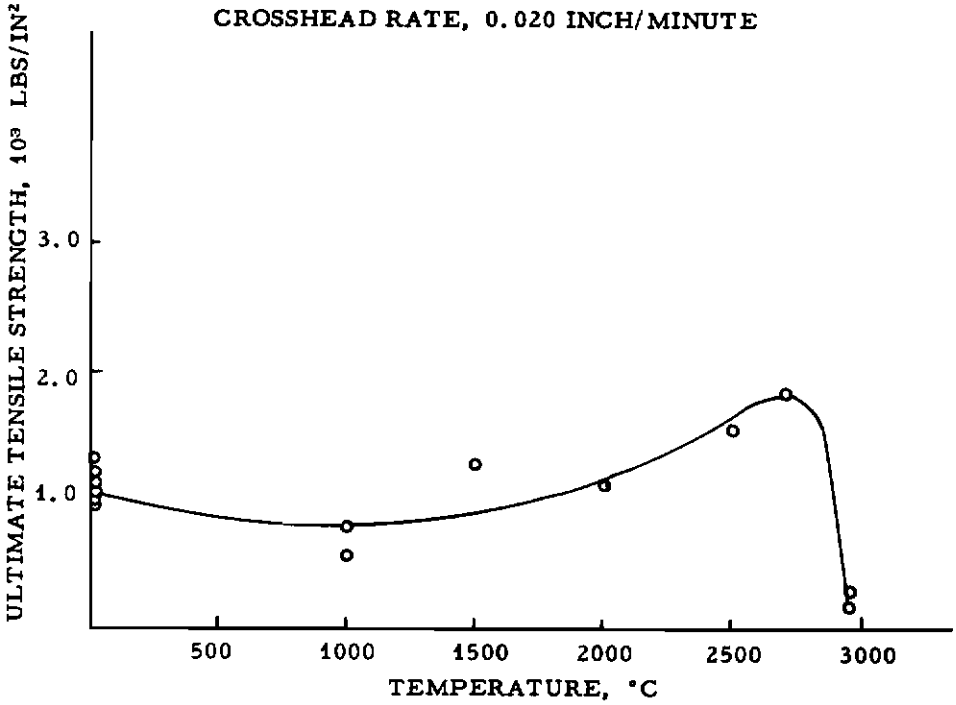
L-726

Figure 299. Thermal Expansion vs. Temperature, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length



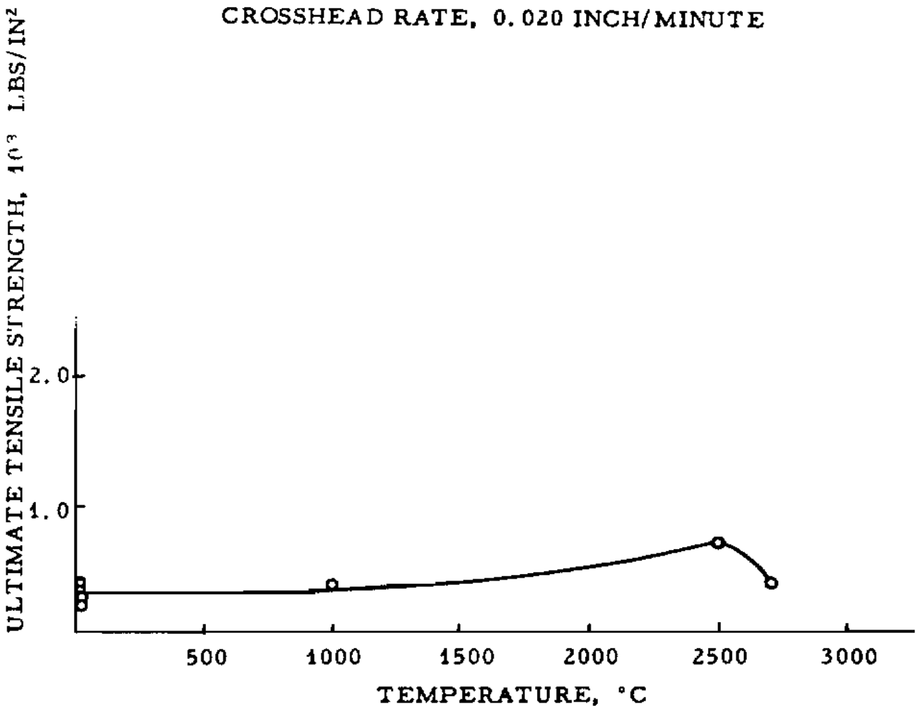
L-727

Figure 300. Young's Modulus vs. Temperature, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length



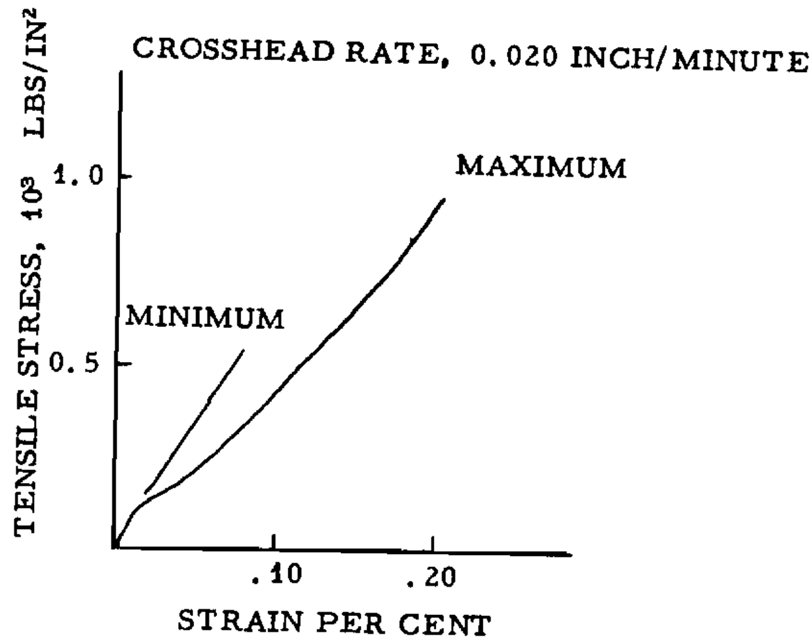
L-728

Figure 301. With-Grain Ultimate Tensile Strength vs. Temperature, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length



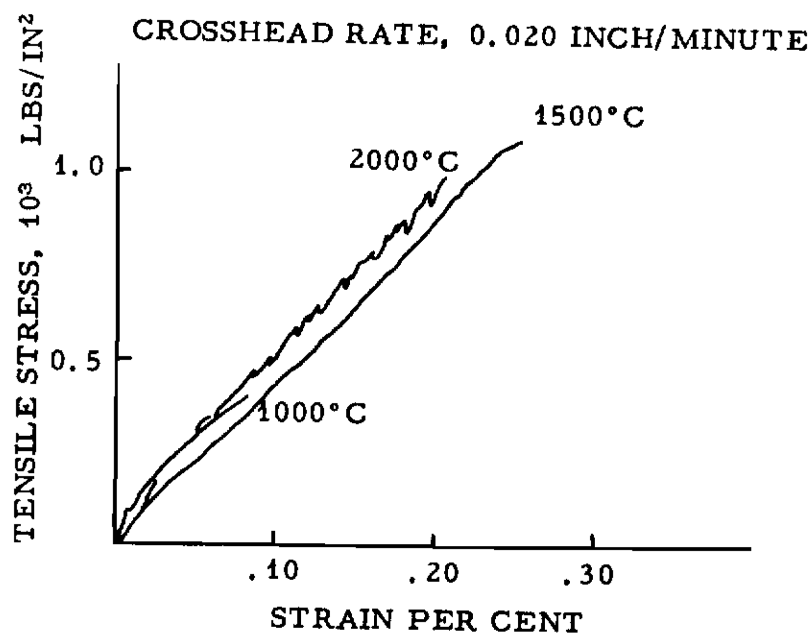
L-729

Figure 302. Across-Grain Ultimate Tensile Strength vs. Temperature, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length



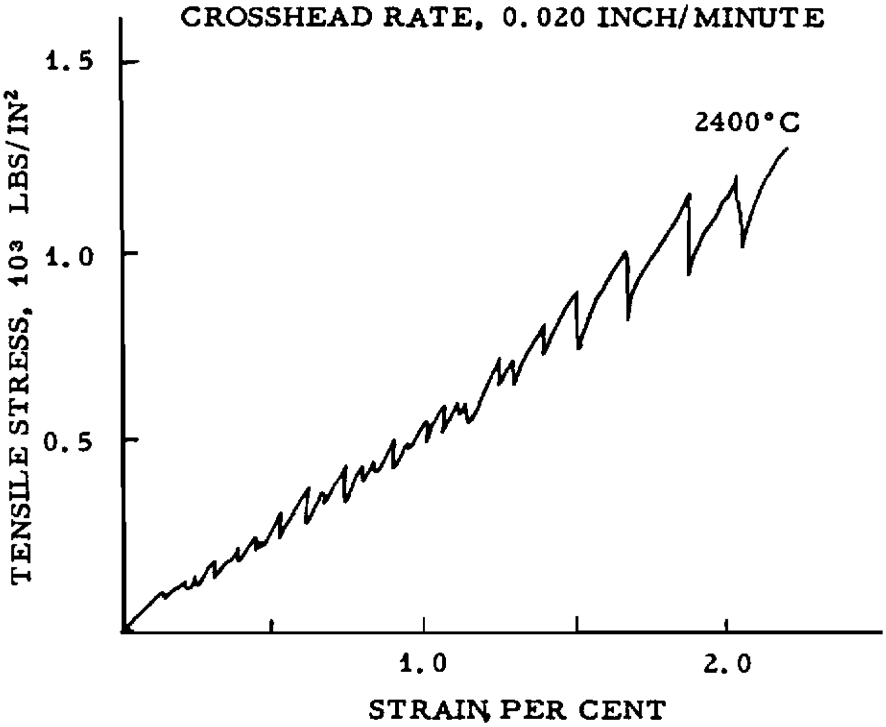
L-730

Figure 303. With-Grain Tensile Stress-Strain Curves, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length



L-760

Figure 304. With-Grain Tensile Stress-Strain Curves, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length



L-731

Figure 305. With-Grain Tensile Stress-Strain Curve, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length, 2400°C

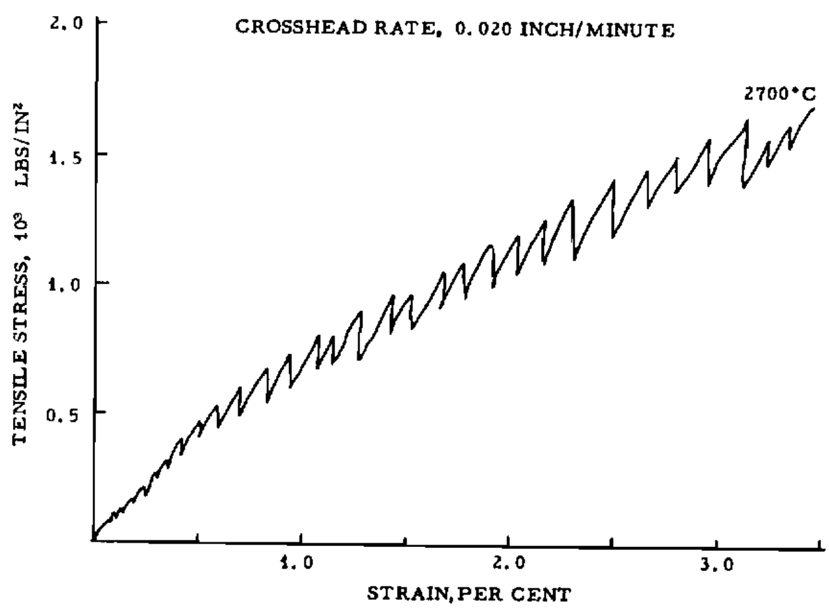
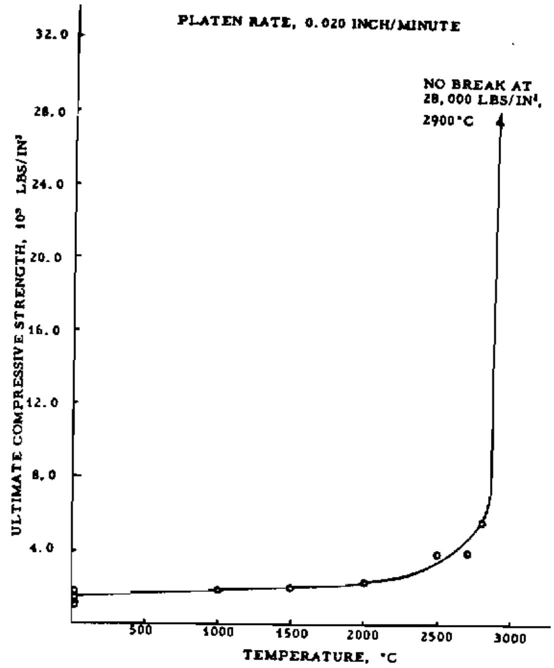
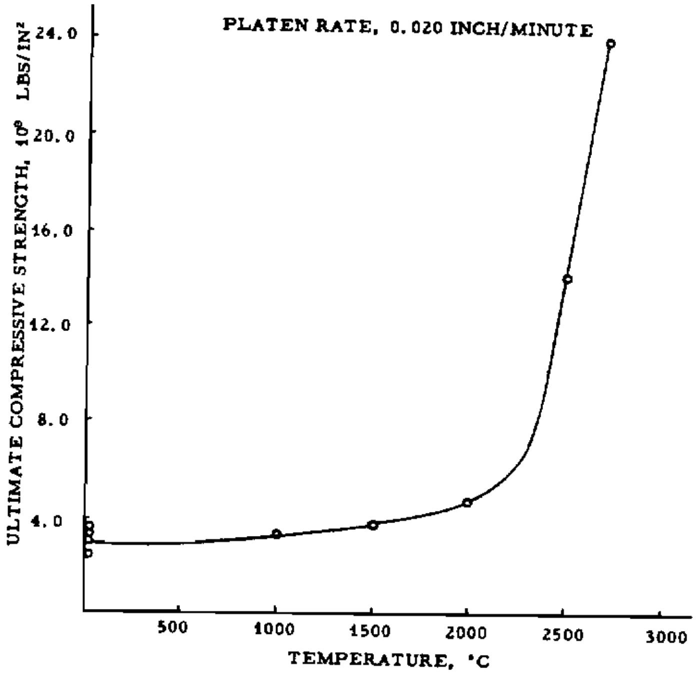


Figure 306. With-Grain Tensile Stress-Strain Curve, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length, 2700°C



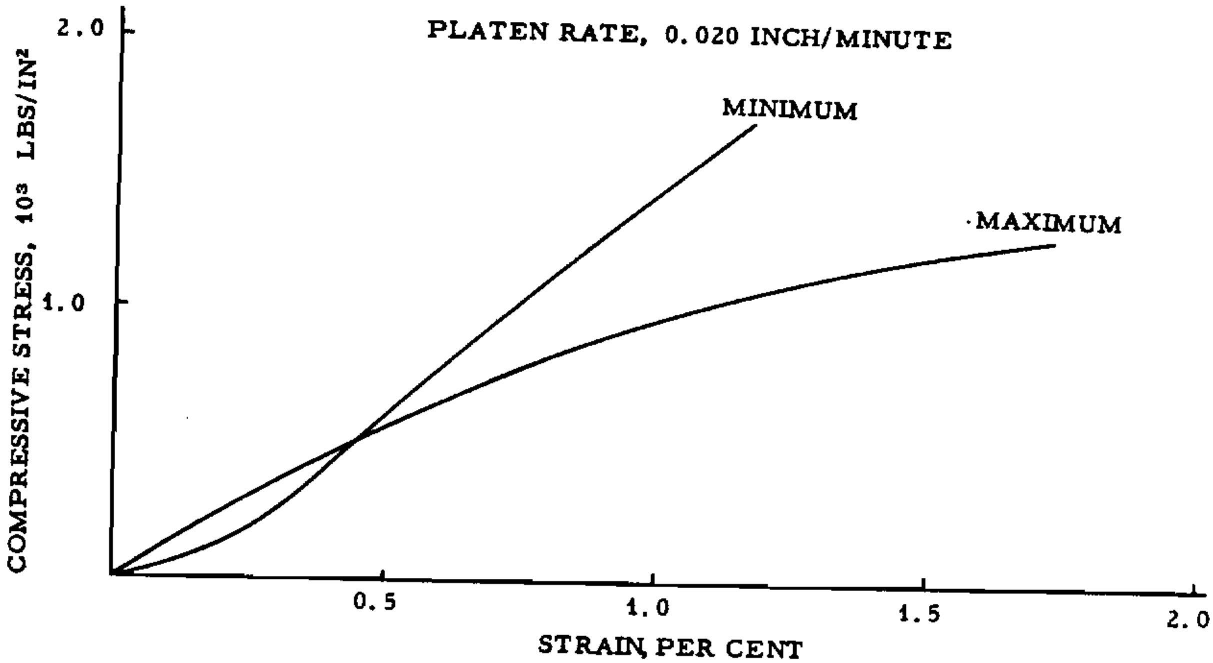
L-732

Figure 307. With-Grain Ultimate Compressive Strength vs. Temperature, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length



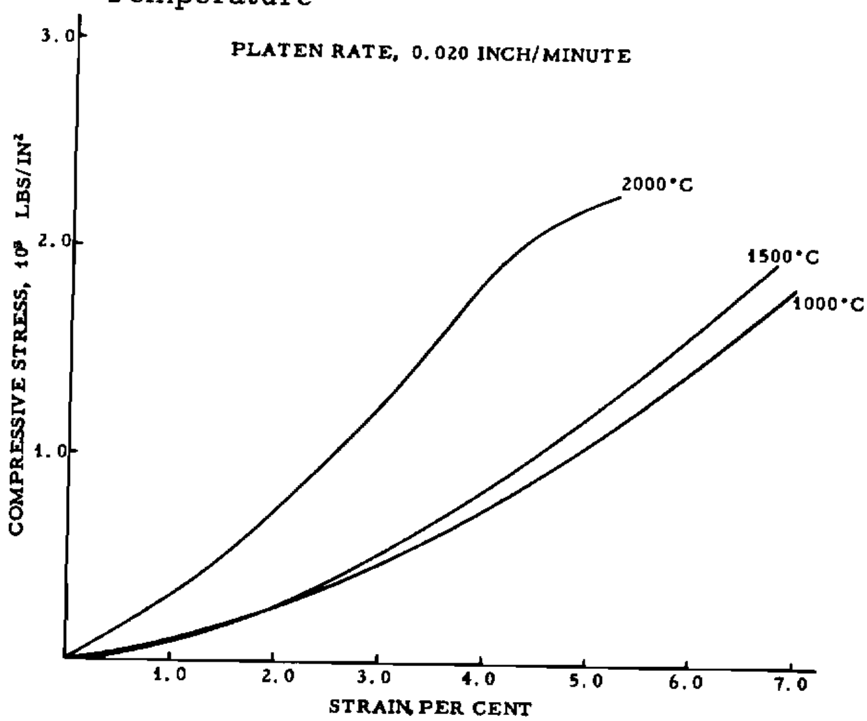
L-733

Figure 308. Across-Grain Ultimate Compressive Strength vs. Temperature, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length



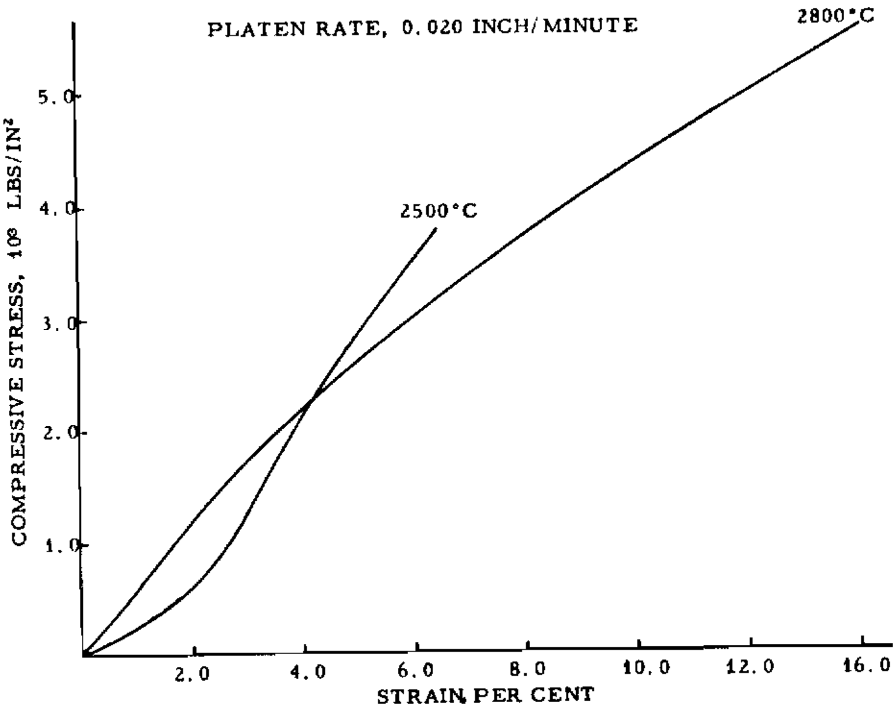
L-734

Figure 309. With-Grain Compressive Stress-Strain Curves, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length, Room Temperature



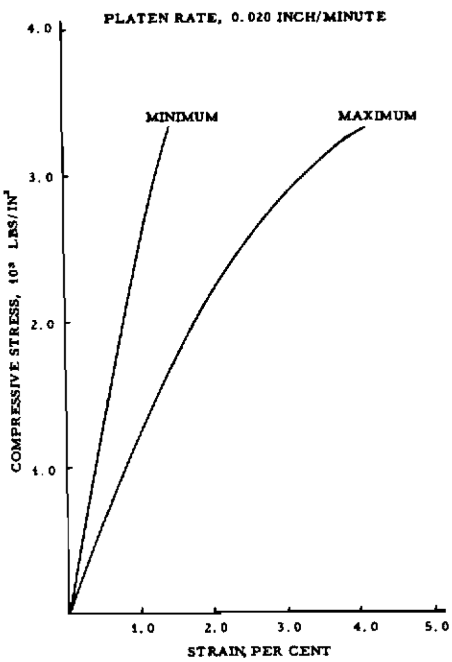
L-735

Figure 310. With-Grain Compressive Stress-Strain Curves, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length, 1000°C, 1500°C, 2000°C



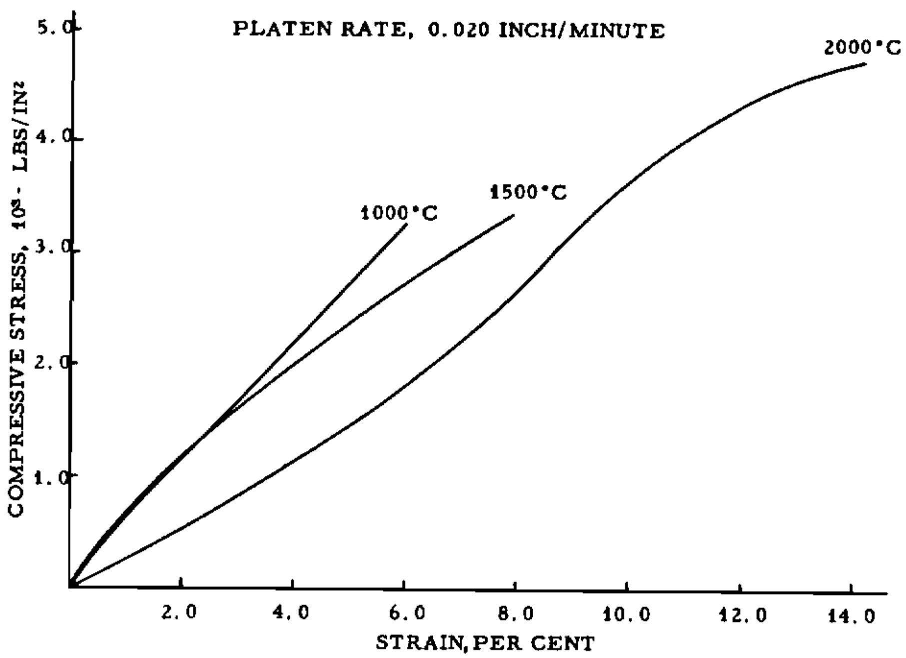
L-736

Figure 311. With-Grain Compressive Stress-Strain Curves, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length, 2500°C, 2800°C



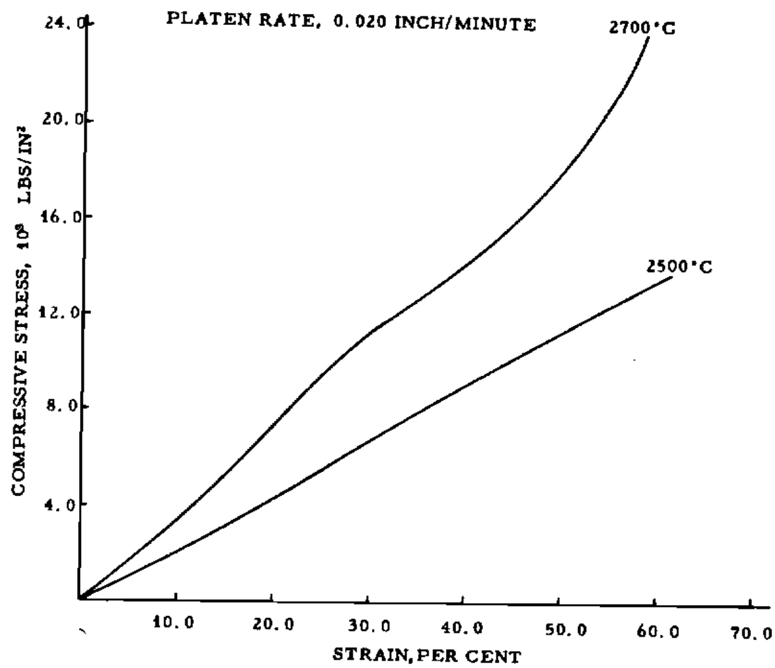
L-737

Figure 312. Across-Grain Compressive Stress-Strain Curves, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length, Room Temperature



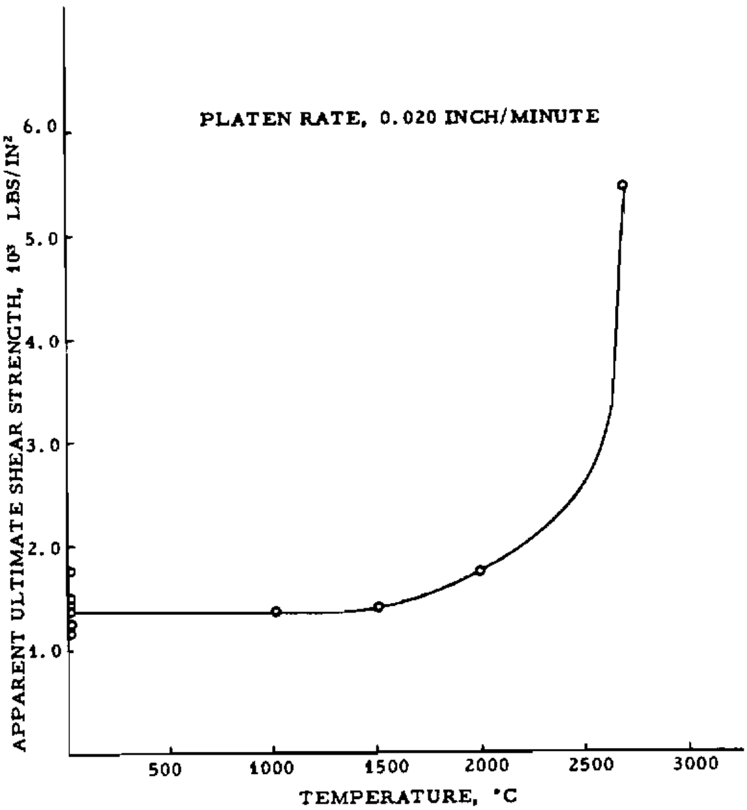
L-738

Figure 313. Across-Grain Compressive Stress-Strain Curves, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length, 1000°C, 1500°C, 2000°C



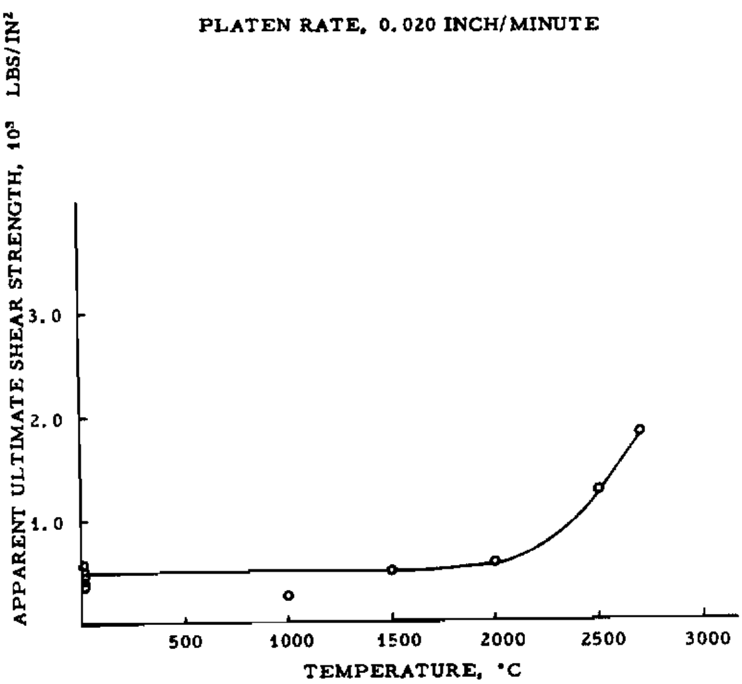
L-739

Figure 314. Across-Grain Compressive Stress-Strain Curves, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length, 2500°C, 2700°C



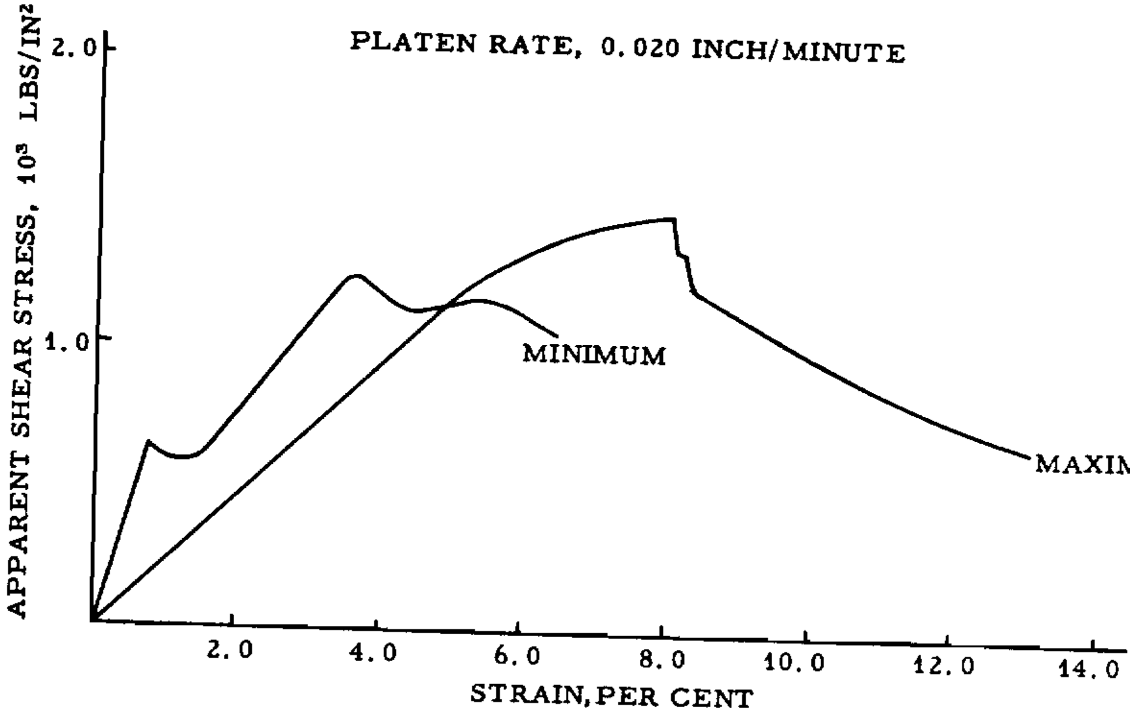
L-740

Figure 315. With-Grain Apparent Ultimate Shear Strength vs. Temperature, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length



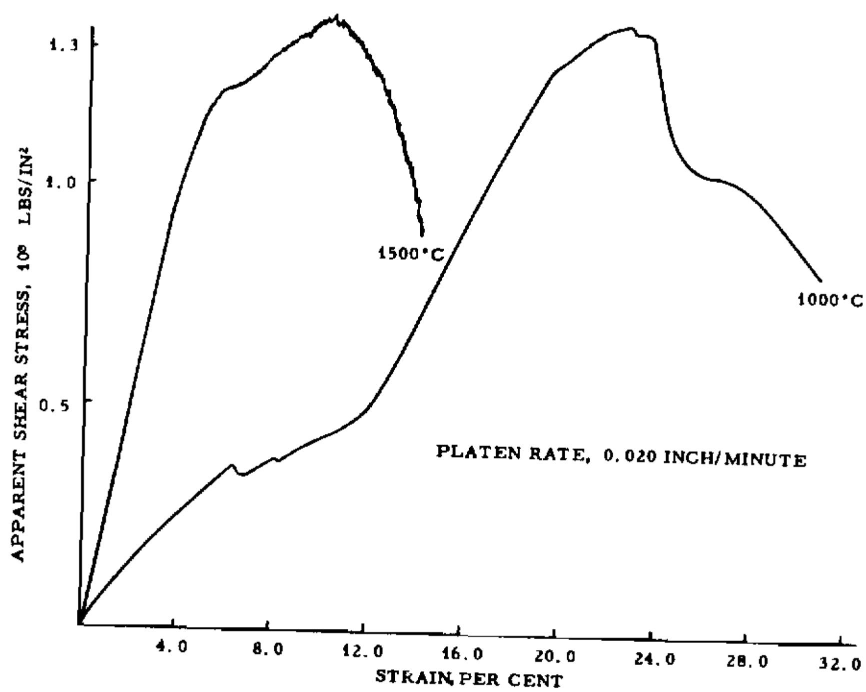
L-741

Figure 316. Across-Grain Apparent Ultimate Shear Strength vs. Temperature, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length



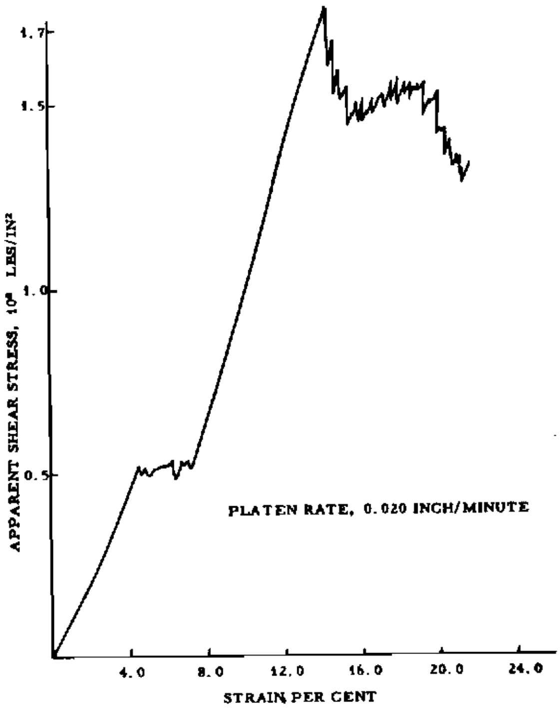
L-742

Figure 317. With-Grain Apparent Shear Stress-Strain Curves, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length, Room Temperature



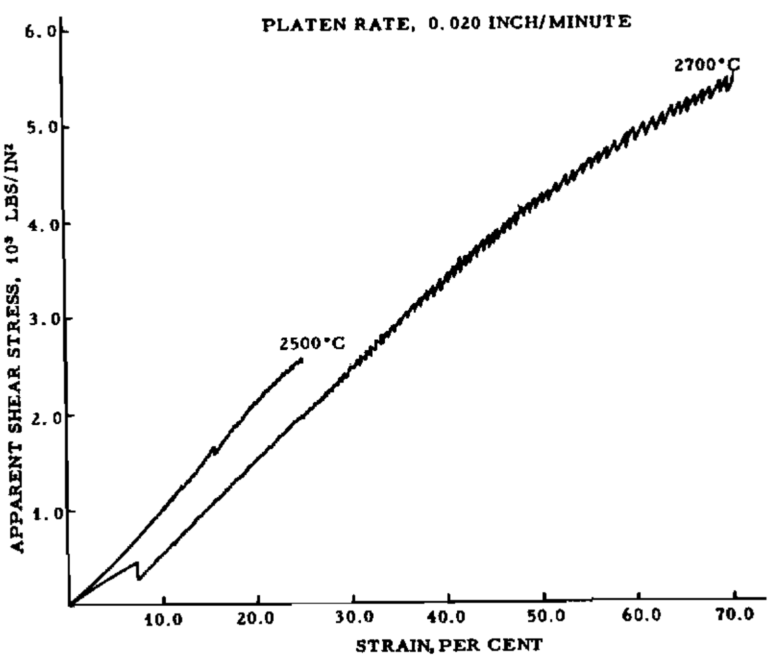
L-743

Figure 318. With-Grain Apparent Shear Stress-Strain Curves, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length, 1000°C, 1500°C



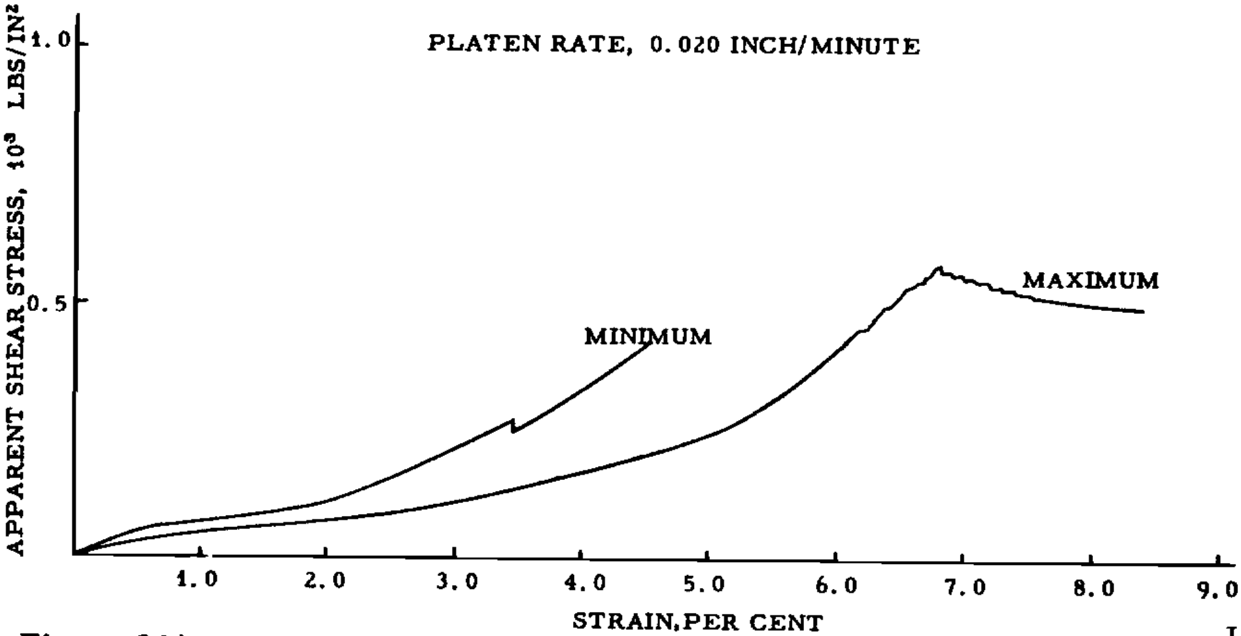
L-744

Figure 319. With-Grain Apparent Shear Stress-Strain Curve, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length, 2000°C



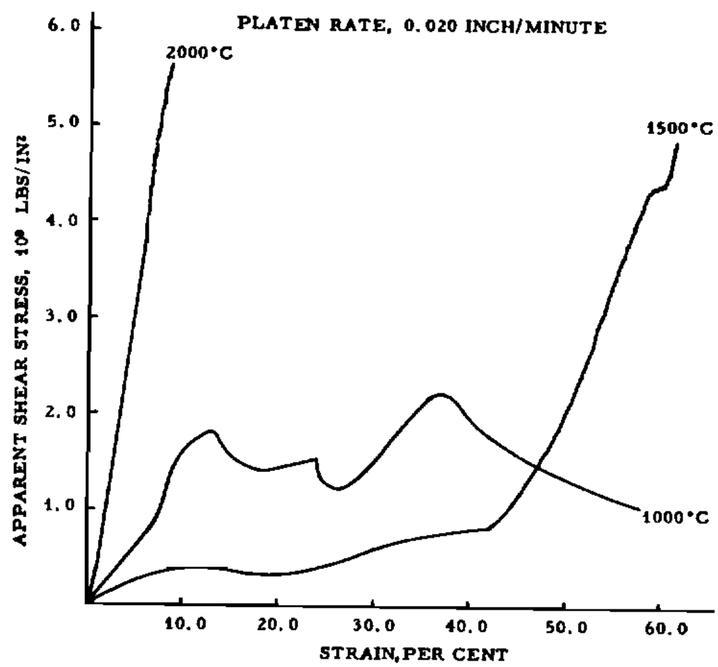
L-745

Figure 320. With-Grain Apparent Shear Stress-Strain Curves, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length, 2500°C, 2700°C



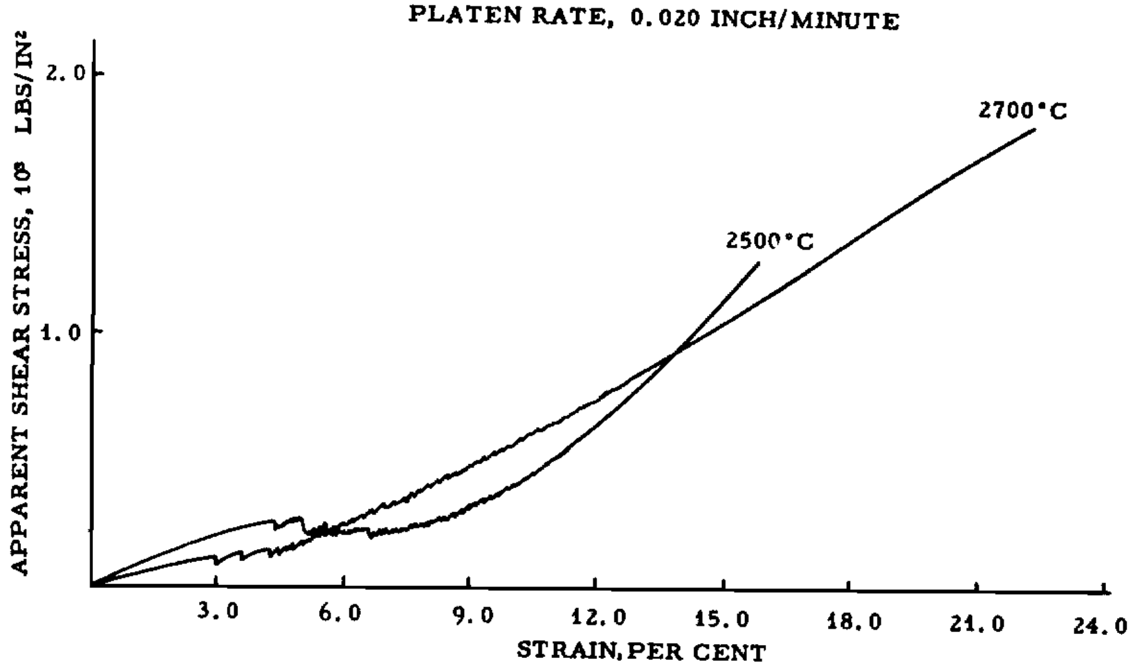
L-746

Figure 321. Across-Grain Apparent Shear Stress-Strain Curves, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length, Room Temperature



L-747

Figure 322. Across-Grain Apparent Shear Stress-Strain Curves, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length, 1000°C, 1500°C, 2000°C



L-748

Figure 323. Across-Grain Apparent Shear Stress-Strain Curves, PT-0114 Graphite, 5-Inch Diameter by 5-Inch Length, 2500°C, 2700°C

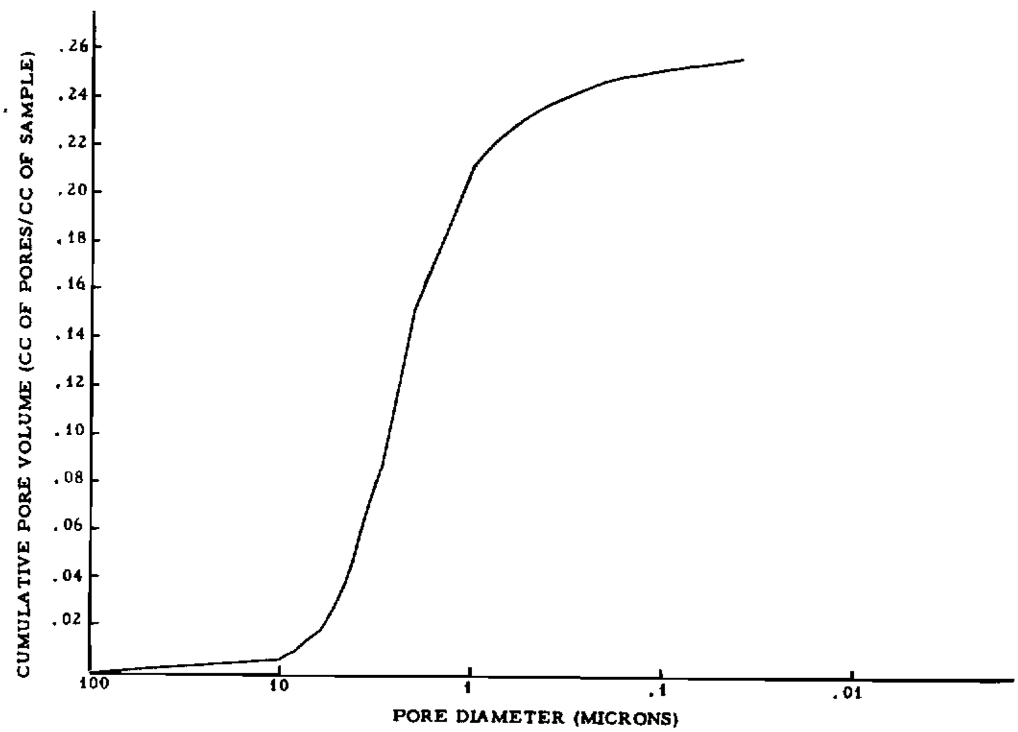


Figure 324. Pore Size Distribution, Mercury Porosimetry, PT-0114 Graphite L-749

3.15. Grade PT-0154 Graphite-Cloth Composite (24)

Grade PT-0154 is a graphite which contains a shredded graphite cloth filler. In processing this grade, the composite is fully graphitized after which it is impregnated and rebaked. Tensile and shear strengths at room and elevated temperatures and compressive strength at elevated temperatures were not measured. Figures 325 and 326, respectively, are plots of the thermal expansion and Young's modulus data in Table 74. All strength measurements were made with cross-head or platen rates of 0.020 inch per minute.

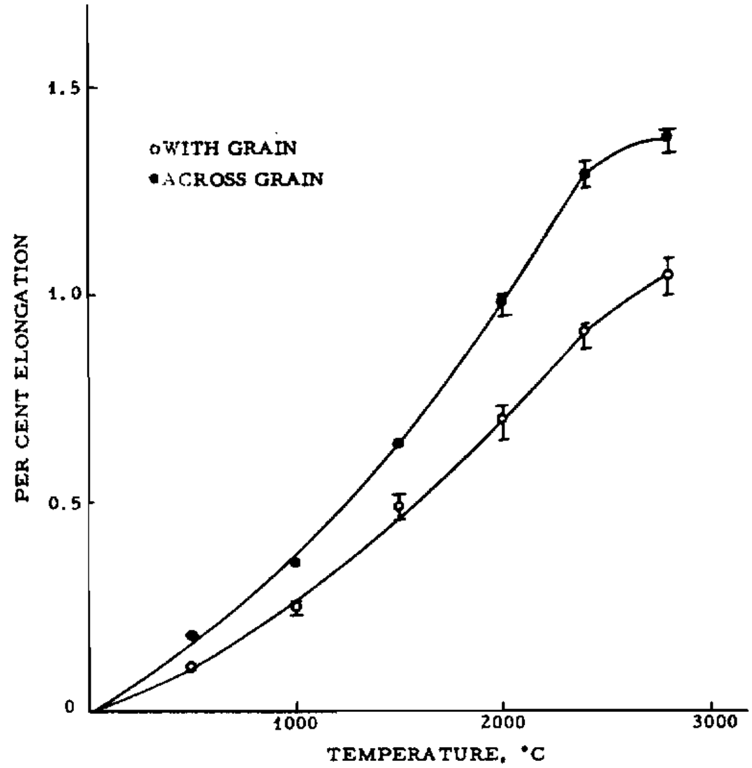
Table 73. Room-Temperature Properties, PT-0154 Graphite, 5-Inch Diameter by 5-Inch Length

Properties	With Grain: Average	With Grain: σ	With Grain: n	With Grain: No. of Blocks	Across Grain: Average	Across Grain: σ	Across Grain: n	Across Grain: No. of Blocks
Bulk Density, g/cc	1.38	0.01	62	6	---	---	--	-
Specific Resistance, 10^{-4} ohm-cm	27.5	0.5	31	6	50.5	2.1	31	6
Young's Modulus, 10^{6} lbs/in^2	1.71	0.13	31	6	0.98	0.11	31	6
Flexural Strength, lbs/in^2	5570	580	7	6	1800	255	12	6
Compressive Strength	6950	2010	6	6	9570	1630	6	6

Properties	With Grain: Max.	With Grain: Min.	With Grain: Ave.	With Grain: n	With Grain: No. of Blocks	Across Grain: Max.	Across Grain: Min.	Across Grain: Ave.	Across Grain: n	Across Grain: No. of Blocks
CTE, 20-100°C, 10^{-6}/°C	2.13	1.79	1.92	3	3	(Can not cut without breaking)				
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ {}^\circ\text{K}}$	0.102	0.100	0.101	2	1	0.061	0.057	0.059	2	1
Permeability, Darcy's	0.057	0.023	0.043	5	1	0.036	0.013	0.019	5	1
Per Cent Ash	0.125	0.092	0.113	5	5	---	---	---	-	-

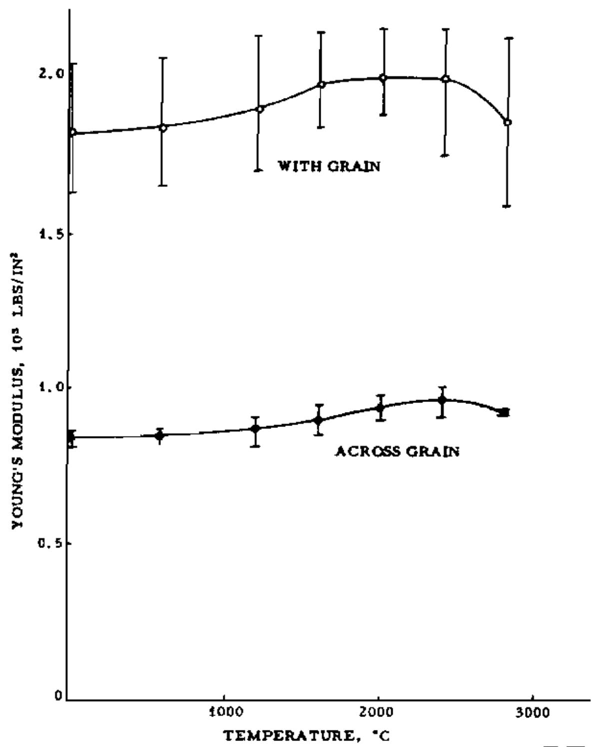
Table 74. High-Temperature Properties, PT-0154 Graphite, 5-Inch Diameter by 5-Inch Length

Properties	Temp. °C	With Grain Max.	With Grain Min.	With Grain Ave.	With Grain n	Across Grain Max.	Across Grain Min.	Across Grain Ave.	Across Grain n
Thermal Expansion Per Cent Elongation $\frac{\Delta L}{L} \times 100$	500	0.108	0.095	0.102	3	0.184	0.172	0.178	3
	1000	0.258	0.233	0.247	3	0.364	0.339	0.350	3
	1500	0.516	0.458	0.492	3	0.651	0.632	0.644	3
	2000	0.762	0.650	0.698	3	1.000	0.948	0.976	3
	2400	0.928	0.874	0.910	3	1.317	1.255	1.292	3
	2800	1.098	1.002	1.053	3	1.400	1.345	1.377	3
Young's Modulus, 10^6 lbs/in^2	RT	2.04	1.63	1.82	3	0.86	0.81	0.84	3
	600	2.06	1.65	1.84	3	0.87	0.82	0.85	3
	1200	2.13	1.70	1.90	3	0.91	0.81	0.87	3
	1600	2.15	1.84	1.98	3	0.95	0.85	0.90	3
	2000	2.16	1.88	2.00	3	0.98	0.90	0.94	3
	2400	2.16	1.76	2.00	3	1.01	0.91	0.97	3
	2800	2.13	1.59	1.86	3	0.94	0.92	0.93	3



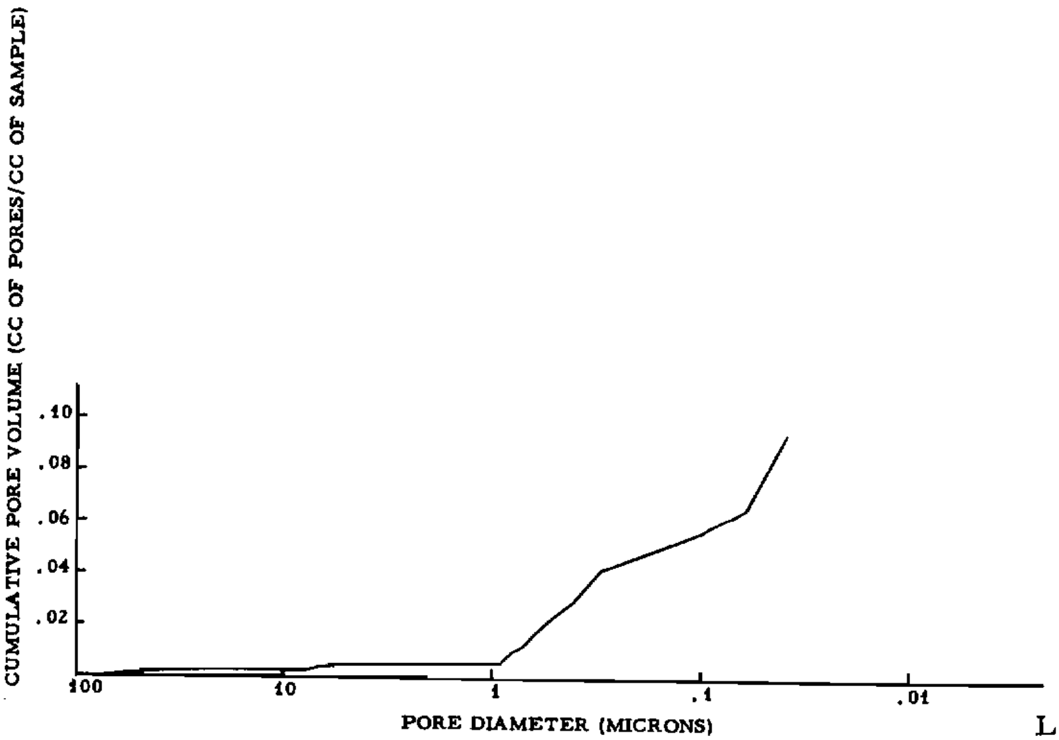
L-750

Figure 325. Thermal Expansion vs. Temperature, PT-0154 Graphite, 5-Inch Diameter by 5-Inch Length



L-751

Figure 326. Young's Modulus vs. Temperature, PT-0154 Graphite, 5-Inch Diameter by 5-Inch Length



L-752

Figure 327. Pore Size Distribution, Mercury Porosimetry, PT-0154 Graphite

3.16. Grade PT-0110 Graphite-Cloth Laminate [24]

Grade PT-0110 consists of layers of graphite cloth bonded together by a suitable carbonaceous binder and baked to 800°C. Carbon shrinks during graphitization; consequently, high-temperature property measurements do not exceed 1200°C. Thermal expansion and Young's modulus are the only high-temperature properties measured.

The thickness of PT-0110 blocks in an across-grain direction were limited to one-half inch, because of processing difficulties; therefore, only a few across-grain properties could be measured. With-grain thermal conductivity could not be measured and compressive strength and permeability samples were reduced in size from 1- by 1- by 1-inch to $\frac{1}{2}$- by $\frac{1}{2}$- by $\frac{1}{2}$-inch and $\frac{1}{2}$- by 1- by 1-inch, respectively, because of block-size limitations.

In the measurement of room temperature CTE, the upper temperature limit (100°C) is obtained by steam. However, in the case of grade PT-0110, steam caused the layers of graphite to delaminate making it impossible to measure room-temperature CTE. All strength measurements were made with cross-head or platen rates of 0.020 inch per minute.

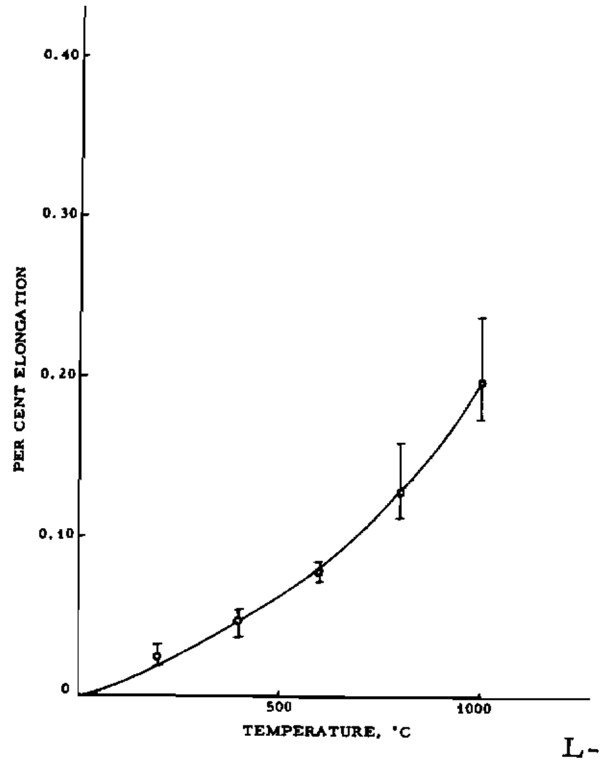
Table 75. Room-Temperature Properties, PT-0110 Carbon, $\frac{1}{2}$-Inch by 6-Inch by 6-Inch Blocks

Properties	With Grain				Across Grain			
	Average	σ	n	No. of Blocks	Average	σ	n	No. of Blocks
Bulk Density, g/cc	1.14	0.01	23	6	---	---	--	-
Specific Resistance, 10^{-4} ohm-cm	116	6	23	6	---	---	--	-
Young's Modulus, 10^{6} lbs/in^{2}	1.22	0.05	23	6	---	---	--	-
Flexural Strength, lbs/in^{2}	2540	800	8	6	---	---	--	-
Compressive Strength, lbs/in^{2} $\frac{1}{2}$- by $\frac{1}{2}$- by $\frac{1}{2}$-inch sample	2090	340	8	6	8160	680	7	6

	With Grain					Across Grain				
	Max.	Min.	Ave.	n	No. of Blocks	Max.	Min.	Ave.	n	No. of Blocks
CTE, 20°-100°C, 10^{-6}/°C	Samples Delaminated					---	---	---	--	-
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ {}^\circ\text{K}}$ (Fitch)	Blocks not thick enough for w.g. sample					---	---	0.003	1	1
Permeability, Darcy's $\frac{1}{2}$- by 1- by 1-inch sample	0.203	0.164	0.178	4	1	0.066	0.024	0.049	5	1
Per Cent Ash	0.282	0.124	0.180	6	6	---	---	---	-	-

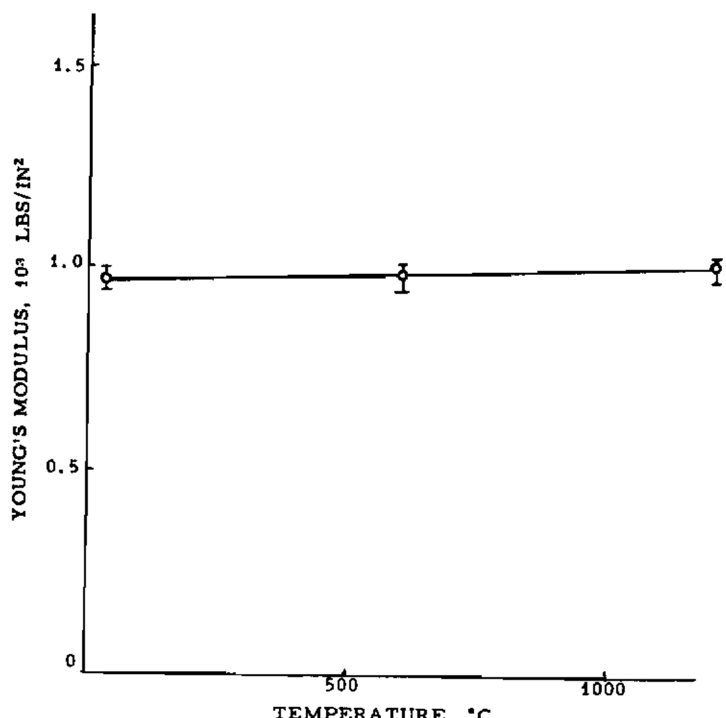
Table 76. High-Temperature Properties, PT-0110 Carbon, $\frac{1}{2}$-Inch by 6-Inch by 6-Inch Blocks

Properties	Temp. °C	With-Grain				
		Max.	Min.	Ave.	n	No. of Blocks
Thermal Expansion, Per Cent Elongation, $\frac{\Delta L}{L}$ x 100	200	0.032	0.018	0.023	3	1
	400	0.054	0.037	0.047	3	1
	600	0.084	0.071	0.078	3	1
	800	0.158	0.111	0.128	3	1
	1000	0.238	0.173	0.197	3	1
Young's Modulus, 10^6 lbs/in^2	RT	1.00	0.94	0.97	3	1
	600	1.02	0.95	0.99	3	1
	1200	1.04	0.98	1.02	3	1



L-753

Figure 328. With-Grain Thermal Expansion vs. Temperature, PT-0110 Carbon, ½-Inch by 6-Inch by 6-Inch Blocks.



L-754

Figure 329. With-Grain Young's Modulus vs. Temperature, PT-0110 Carbon, ½-Inch by 6-Inch by 6-Inch Blocks

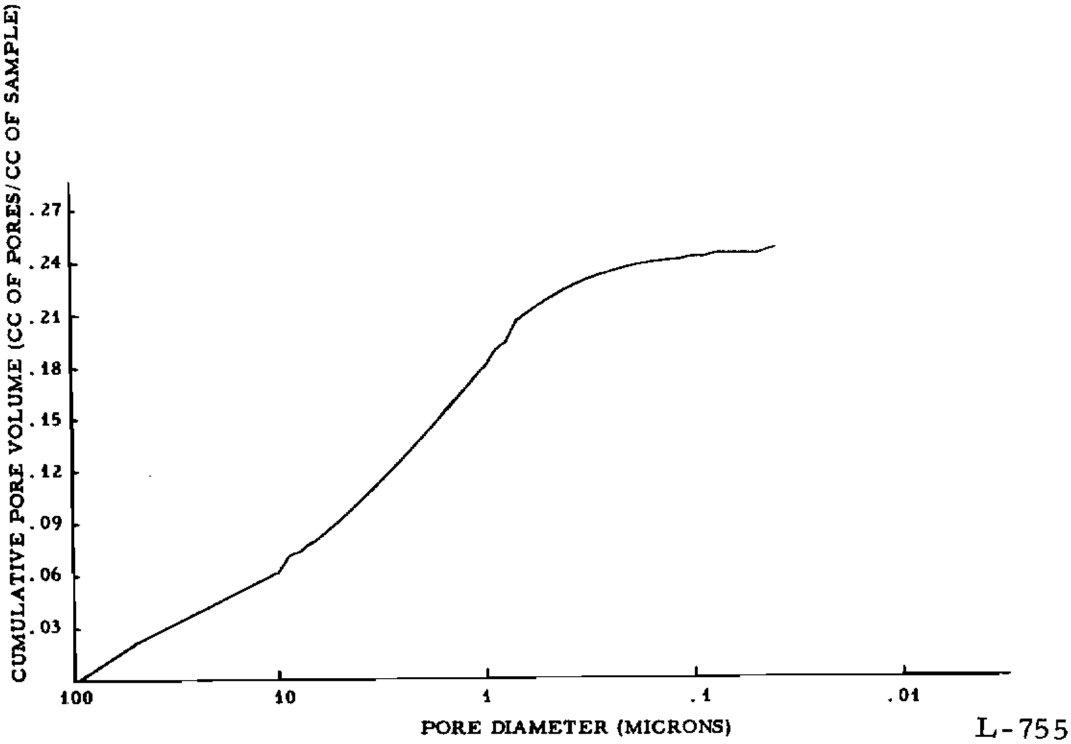


Figure 330. Pore Size Distribution, Mercury Porosimetry, Grade PT-0110

3.17. Grade PT-0111 Graphite-Cloth Laminate[24]

Grade PT-0111 is a laminated graphite cloth bonded together by a suitable carbonaceous binder and graphitized. The reasons for limited across-grain data, for no room-temperature CTE data, and for reduction in compressive strength and permeability sample dimensions are discussed in Section 3.16.

The thermal conductivity of PT-0111 was too great to be measured by the Fitch method, and block-size limitations made it impossible to prepare samples for the Meers method; consequently, room-temperature data are not available. High-temperature data were limited to thermal expansion and Young's modulus. All strength measurements were made with cross-head or platen rates of 0.020 inch per minute.

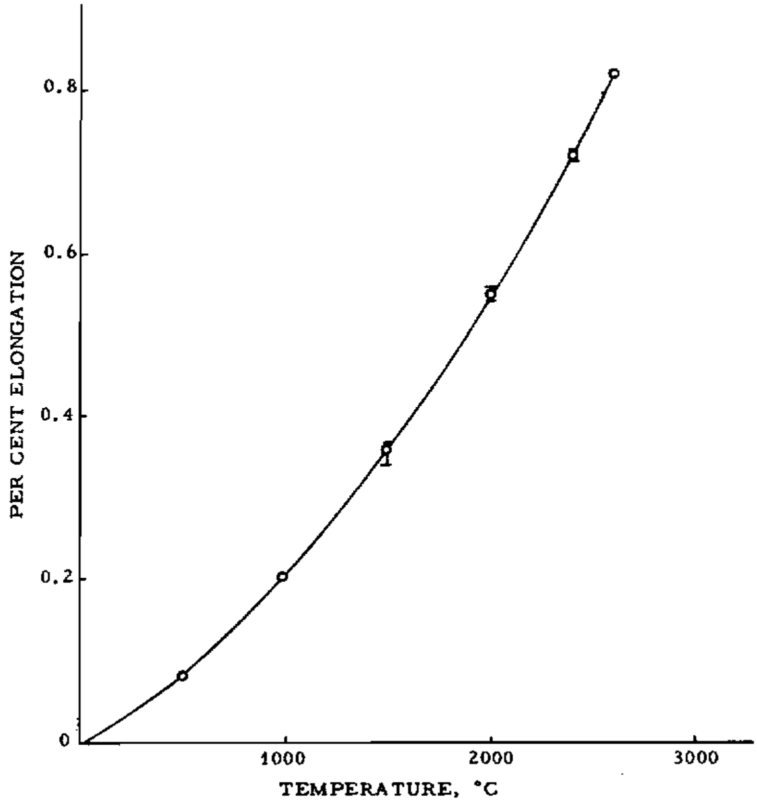
Table 77. Room-Temperature Properties, PT-0111 Graphite, $\frac{1}{2}$-Inch by 6-Inch by 6-Inch Blocks

Properties	With Grain				Across Grain			
	Average	σ	n	No. of Blocks	Average	σ	n	No. of Blocks
Bulk Density, g/cc	1.11	0.02	21	6	---	---	-	-
Specific Resistance, 10^{-4} ohm-cm	32.4	2.0	21	6	---	---	-	-
Young's Modulus	0.87	0.08	21	6	---	---	-	-
Flexural Strength, lbs/in²	2130	495	8	6	---	---	-	-
Compressive Strength, $\frac{1}{2}$- by $\frac{1}{2}$- by $\frac{1}{2}$-inch, lbs/in²	2000	400	8	6	5080	570	8	6

Properties	With Grain					Across Grain				
	Max.	Min.	Ave.	n	No. of Blocks	Max.	Min.	Ave.	n	No. of Blocks
CTE, 20-100°C, 10^{-6}/°C	Samples Delaminated									
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ {}^\circ\text{K}}$	Blocks not thick enough for required sample size									
Permeability, Darcy's, $\frac{1}{2}$- by 1- by 1-inch sample	1.60	0.82	1.21	4	1	0.114	0.069	0.088	6	1
Per Cent Ash	0.454	0.256	0.350	5	5	---	---	---	-	-

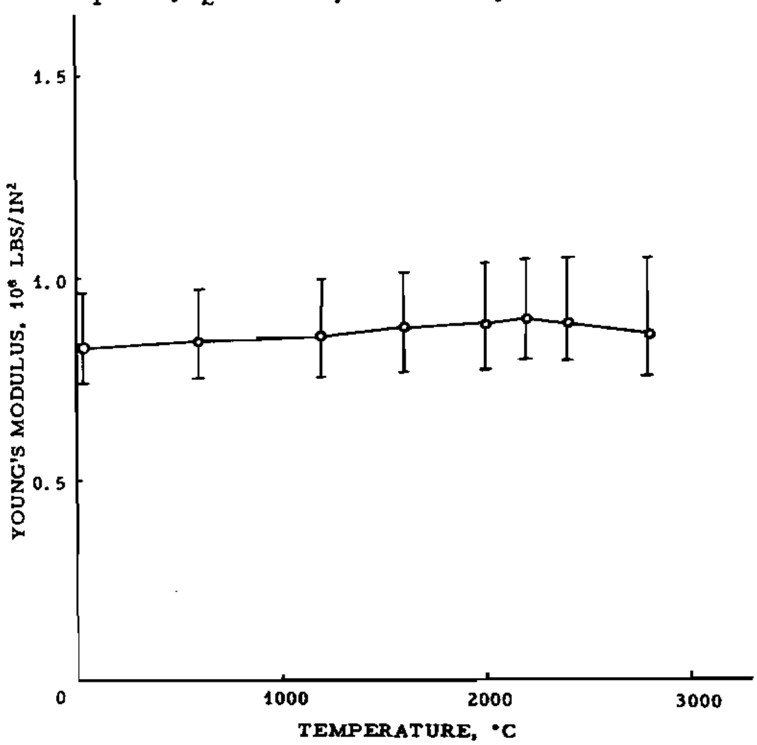
Table 78. High-Temperature Properties, PT-0111 Graphite, $\frac{1}{2}$-Inch by 6-Inch by 6-Inch Blocks

Properties	Temp. °C	With Grain Max.	Min.	Ave.	n	No. of Blocks
Thermal Expansion Per Cent Elongation $\frac{\Delta L}{L}$ x 100	500	0.078	0.075	0.076	3	1
	1000	0.202	0.191	0.098	3	1
	1500	0.368	0.342	0.358	3	1
	2000	0.560	0.540	0.551	3	1
	2400	0.727	0.716	0.722	3	1
	2600	0.827	0.818	0.823	3	1
Young's Modulus, 10^6 lbs/in^2	RT	0.96	0.74	0.83	3	1
	600	0.97	0.75	0.84	3	1
	1200	0.99	0.75	0.85	3	1
	1600	1.01	0.76	0.87	3	1
	2000	1.03	0.77	0.88	3	1
	2200	1.04	0.79	0.89	3	1
	2400	1.04	0.79	0.88	3	1
	2800	1.04	0.75	0.85	3	1



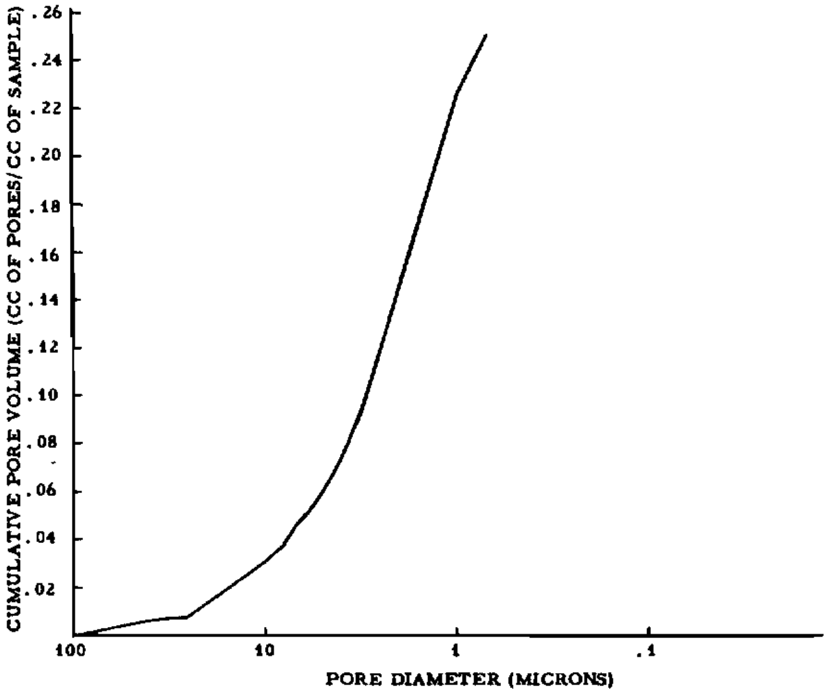
L-756

Figure 331. With-Grain Thermal Expansion vs. Temperature, PT-0111 Graphite, ½-Inch by 6-Inch by 6-Inch Blocks



L-757

Figure 332. With-Grain Young's Modulus vs. Temperature, PT-0111 Graphite, ½-Inch by 6-Inch by 6-Inch Blocks



L-758

Figure 333. Pore Size Distribution, Mercury Porosimetry, Grade PT-0111

3.18. Grade PT-0156 Graphite-Cloth Laminate[24]

Grade PT-0156 is another of the graphite cloth laminates bonded by a carbonaceous binder and graphitized. The reasons for limited across-grain data, for no room-temperature CTE data, and for reduction in compressive strength and permeability sample dimensions are discussed in Section 3.16. The reasons for no thermal conductivity data were explained in Section 3.17. High-temperature properties are limited to thermal expansion and Young's modulus. All strength measurements are made with cross-head or platen rates of 0.020 inch per minute.

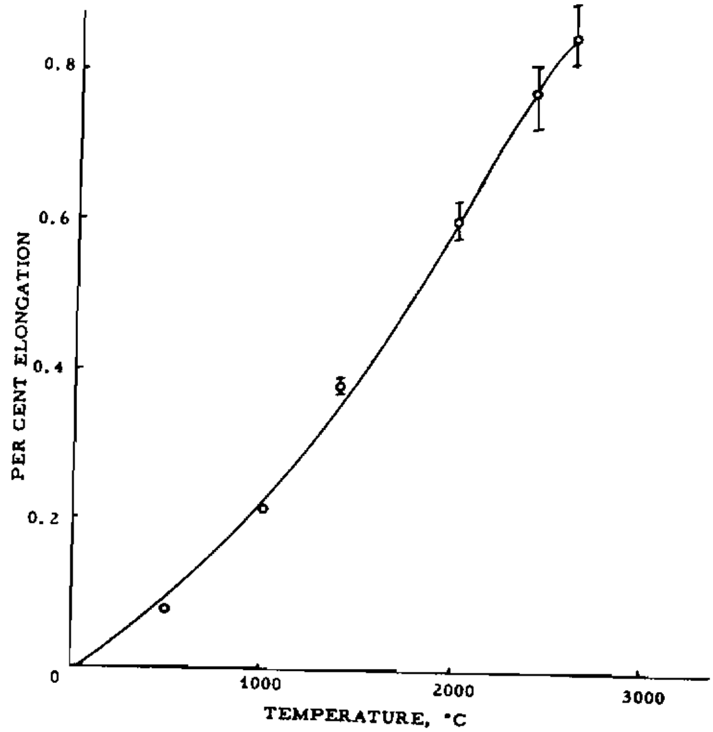
Table 79. Room-Temperature Properties, PT-0156 Graphite, $\frac{1}{2}$-Inch by 6-Inch by 6-Inch Blocks

Properties	With Grain				Across Grain			
	Average	σ	n	No. of Blocks	Average	σ	n	No. of Blocks
Bulk Density, g/cc	1.29	0.01	27	6	---	---	--	-
Specific Resistance, 10^{-4} ohm-cm	30.6	5.1	27	6	---	---	--	-
Young's Modulus, 10^6 lbs/in^2	1.62	0.06	27	6	---	---	--	-
Flexural Strength, lbs/in	5170	1280	8	6	---	---	--	-
Compressive Strength, $\frac{1}{2}$- by $\frac{1}{2}$- by $\frac{1}{2}$-inch, lbs/in^2	3900	440	8	6	11460	1340	9	6

	With Grain					Across Grain				
	Max.	Min.	Ave.	n	No. of Blocks	Max.	Min.	Ave.	n	No. of Blocks
CTE 20-100°C, 10^{-6}/°C	- - - -Samples delaminated in steam -									
Thermal Conductivity, $\frac{\text{cal-cm}}{\text{sec cm}^2\ °\text{K}}$	Blocks not large enough for required sample size									
Permeability, Darcy's, $\frac{1}{2}$- by 1- by 1-inch sample	0.063	0.013	0.030	5	1	0.043	0.023	0.043	4	1
Per Cent Ash	0.610	0.140	0.343	5	5	---	---	---	-	-

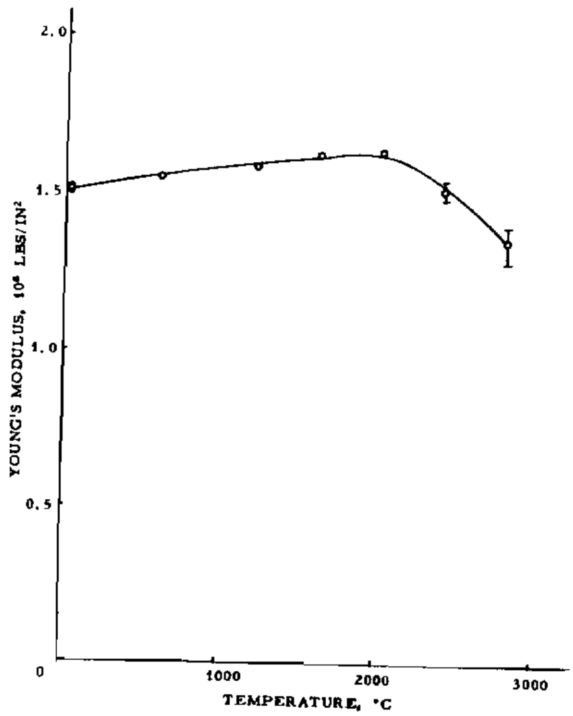
Table 80. High-Temperature Properties, PT-0156 Graphite, $\frac{1}{2}$-Inch by 6-Inch by 6-Inch Blocks

Properties	Temp. °C	With Grain Max.	Min.	Ave.	n	No. of Blocks
Thermal Expansion, Per Cent Elongation, $\frac{\Delta L \Delta}{L}$ x 100	500	0.079	0.077	0.078	3	1
	1000	0.215	0.214	0.215	3	1
	1500	0.389	0.370	0.377	3	1
	2000	0.625	0.574	0.597	3	1
	2400	0.819	0.744	0.778	3	1
	2600	0.891	0.813	0.850	3	1
Young's Modulus, 10^6 lbs/in	RT	1.53	1.52	1.52	3	1
	600	1.56	1.55	1.56	3	1
	1200	1.59	1.58	1.59	3	1
	1600	1.63	1.63	1.63	3	1
	2000	1.64	1.63	1.64	3	1
	2400	1.55	1.49	1.52	3	1
	2800	1.42	1.29	1.36	3	1



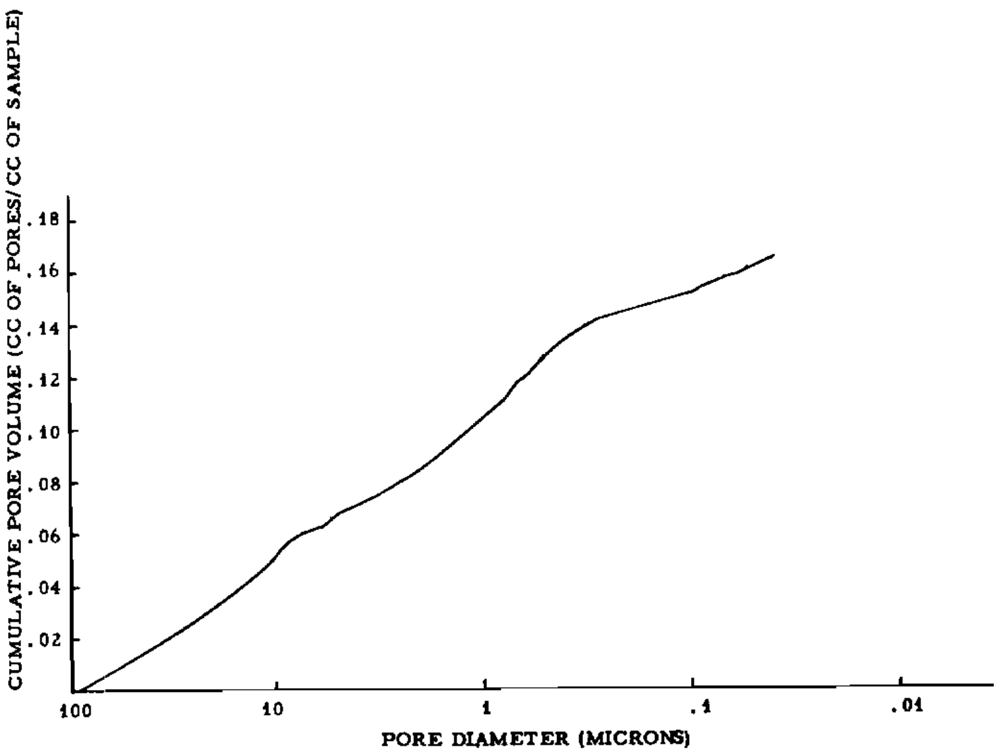
L-761

Figure 334. With-Grain Thermal Expansion vs. Temperature, PT-0156 Graphite, $\frac{1}{2}$-Inch by 6-Inch by 6-Inch Blocks



L-762

Figure 335. With-Grain Young's Modulus vs. Temperature, PT-0156 Graphite, $\frac{1}{2}$-Inch by 6-Inch by 6-Inch Blocks



L-763

Figure 336. Pore Size Distribution, Mercury Porosimetry, PT-0156 Graphite

4. LIST OF REFERENCES

(1) Dull, R. B. and S. O. Johnson, A Method for Determining Young's Modulus of Graphite at Elevated Temperatures, WADD Technical Report 61-72, Volume XXIII.

(2) "Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)", ASTM Standards, Part 4, Standard C78-59 (1961), pp. 734-736.

(3) Dull, R. B. and M. B. Manofsky, Methods of Measuring Mechanical Properties of Graphite in the 20° to 2700°C Temperature Range, WADD Technical Report 61-72, Volume XXXV.

(4) Kingsly, W. D., Property Measurements at High Temperatures, (John Wiley and Sons, New York, 1961), p. 167.

(5) Timoshenko, S., Strength of Materials, 3rd Ed., (D. Van Nostrand Co., New York) Part I, p. 72.

(6) Reference (5), pp. 62-63.

(7) Meers, J. T., Room-Temperature Thermal Conductivity Apparatus, National Carbon Company, Technical Memorandum, TM-345, (1958).

(8) Perry, J. H., Chemical Engineer's Handbook, Textbook Edition, Third Edition, (McGraw-Hill Book Co., Inc., New York, 1950), p. 456.

(9) Reference (8), p. 460.

(10) Eaton, V. E., et al, Selected Experiments in Physics-Thermal Conductivity, (Central Scientific Co., 1940).

(11) The International Dictionary of Applied Mathematics, (D. Van Nostrand Co., New York, 1960), p. 212.

(12) Nightingale, R. E., Nuclear Graphite, (Academic Press, New York, 1962), p. 178.

(13) Wahsburn, E. W., Proc. National Aca. Sci. U. L., 7, (1921), pp. 115-116.

4. LIST OF REFERENCES (CONT'D)

(14) Martens, H. H., Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, Private Communication.

(15) Lubahn, J. B., Mechanical Behavior of Materials at Elevated Temperatures, (Edited by J. E. Dorn, McGraw-Hill Book Co., Inc., New York, 1961), pp. 326-327.

(16) Kellar, A. A., E. A. Neel, and K. J. Zeitsch, High Density Recrystallized Graphite by Hot-Forming, WADD Technical Report 61-72, Volume VII.

(17) Carter, M. B., and G. L. Rowe, High Density Recrystallized Graphite by Hot-Forming, WADD Technical Report 61-72, Supplement to Volume VII.

(18) Piper, E. L. and C. W. Waters, Development of an Improved Large Diameter Fine-Grain Graphite for Aerospace Applications, WADD Technical Report 61-72, Volume XII.

(19) Racicot, R. L., and C. W. Waters, Development of an Improved Large Diameter Fine-Grain Graphite for Aerospace Applications, WADD Technical Report 61-72, Supplement to Volume XII.

(20) Howard, R. A., and E. L. Piper, Development of a Fine-Grain Isotropic Graphite for Structural and Substrate Applications, WADD Technical Report 61-72, Volume XIII.

(21) Howard, R. A., and R. L. Racicot, Development of a Fine-Grain Isotropic Graphite for Structural and Substrate Applications, WADD Technical Report 61-72, Supplement to Volume XIII.

(22) Howard, R. A., and R. L. Racicot, Development of an Improved Large Diameter Ultra Fine-Grain Graphite, WADD Technical Report 61-72, Volume XXXVIII.

(23) Carter, M. B., M. A. Spring, and C. E. Waylett, High Performance Graphite by Liquid Impregnation, WADD Technical Report 61-72, Volume XXXI.

(24) Beasley, W. C., and E. L. Piper, Fabrication and Properties of Carbonized Cloth Composites, WADD Technical Report 61-72, Volume IX.

4. LIST OF REFERENCES (CONT'D)

(25) Nash, W. N., Theory and Problems of Strength of Materials, (Schaum Publishing Co., 1957), pp. 4-5.

(26) Manson, S. S., Mechanical Behavior of Materials at Elevated Temperatures, Edited by J. E. Dorn, (McGraw-Hill Book Co., Inc., New York, 1961), pp. 400-401

(27) The International Dictionary of Applied Mathematics, (D. Van Nostrand Co., 1960), p. 641.

(28) Reference (27), p. 839.

(29) Reference (27), p. 515.

(30) Waugh, A. E., Elements of Statistical Methods, (McGraw-Hill Book Co., Inc., New York, 1952), pp. 187-188.

APPENDIX I

STRAIN CONTOUR PLOTS

A series of curves showing stress-strain for a number of graphite grades measured at room temperature, 1000, 1500, 2000, 2500 and 2700°C have been presented in previous sections of this report. The wide range in strain has made it necessary to present these curves in three or more figures for each grade, and on different scales; consequently, it is difficult to compare stress-strain data at different temperatures. These data may be easily compared in a single figure by plotting a series of stress-temperature curves, each at a constant strain, to form a strain contour plot. In this appendix, Figures 337 to 357 and 358 to 377, inclusive, are tensile and compressive-strain contour plots, respectively, for the graphite grades on which high-temperature tensile and compressive measurements have been made. The strain associated with each curve is indicated in the figures. For example, the bottom curve in Figure 337 shows the stress required to produce a with-grain strain of 0.10 per cent in ATJ graphite over the room temperature to 2700°C temperature range. The ultimate stress or strength curve, shown in each figure, is an average or curve of best fit; hence the stress at fracture taken from a specific stress-strain curve may not fall on the "ultimate" curve but may be above or below it.

It is possible to construct an approximate stress-strain curve at any temperature between room temperature and 2700°C from the data presented in a strain contour plot. Suppose an across-grain tensile stress-strain curve is required for RVC graphite at 1800°C. Turn to Figure 350 and read the stress at 1800°C off each strain curve and the "ultimate" curve. These data may then be plotted to form the approximate stress-strain curve.

The relationship between stress, strain and temperature is not a simple one. An examination of the strain contour plots shows that in general the curves have one or more maxima and minima. In Figure 337, for example, the with-grain tensile strain curves have a minimum at 1500°C and a maximum at 2000°C. Figure 353, with-grain CFW strain contour plot, is an example of curves which have two maxima.

The presence of maxima in the stress-temperature curves verify some apparent anomalies in the stress-strain relationship. For example, Figure 29, Section 3.1, shows that at 1500°C the strain at fracture is not only less than that at 2000°C but also less than that at 1000°C. The presence of the maximum at 1500°C in Figure 338 would have led to the prediction that strain at fracture is less at 1500°C than at 1000°C or 2000°C even if all tests were terminated before failure.

The maxima indicate that there are temperature ranges in which the brittleness of graphite appears to increase with temperature. The mechanism responsible for the phenomenon is not understood. It may be associated with a realignment of particles or a reduction in pore volume, as suggested by an increase in the relative height of the maximum as the strain increases.

A number of contour plots, Figures 338 and 351 for example, show a minimum between 2500 and 2700°C; i.e., in the plastic range. Wide sample-to-sample variation in the stress-strain relationship in the plastic state is common. This variation plus the limitation of strain measurements to one sample per grain direction per graphite block creates doubt of the existence of a minimum between 2500 and 2700°C. If the minimum is real, it may have a tendency to shift to higher temperatures as the strain increases, and disappear altogether as the strain approaches the ultimate, as illustrated in Figure 351. More extensive testing on a single block of graphite is needed to establish the shape of the curves between 2500 and 2700°C.

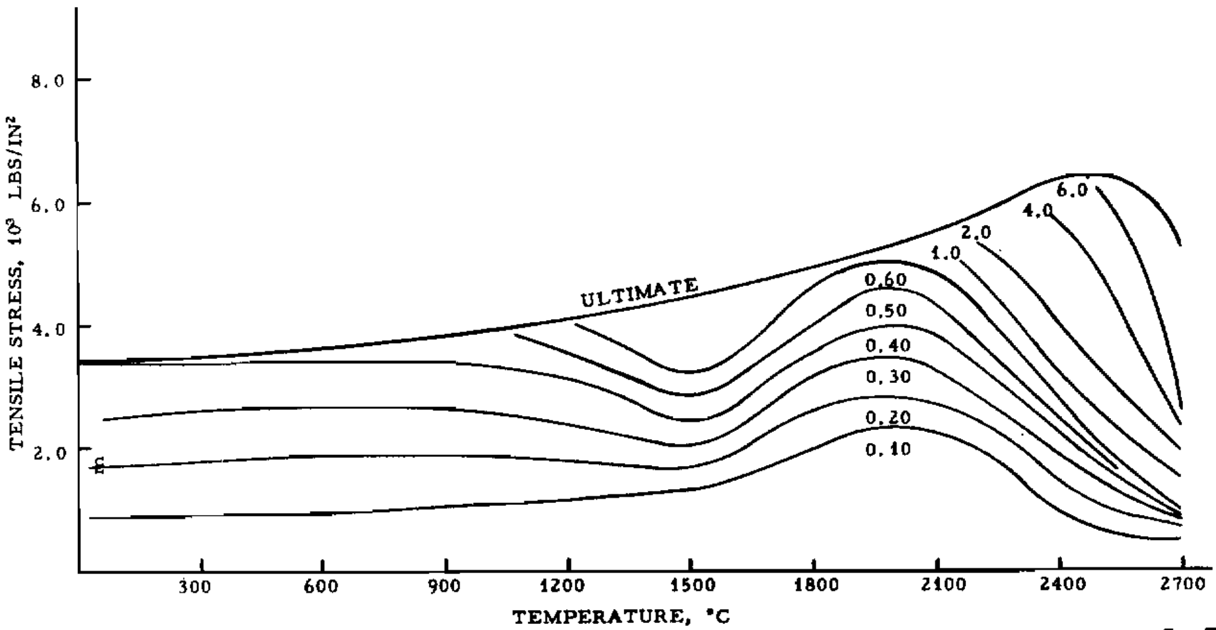


Figure 337. With-Grain Tensile Strain Contour Plot, Stress vs. Temperature, ATJ Graphite

L-764

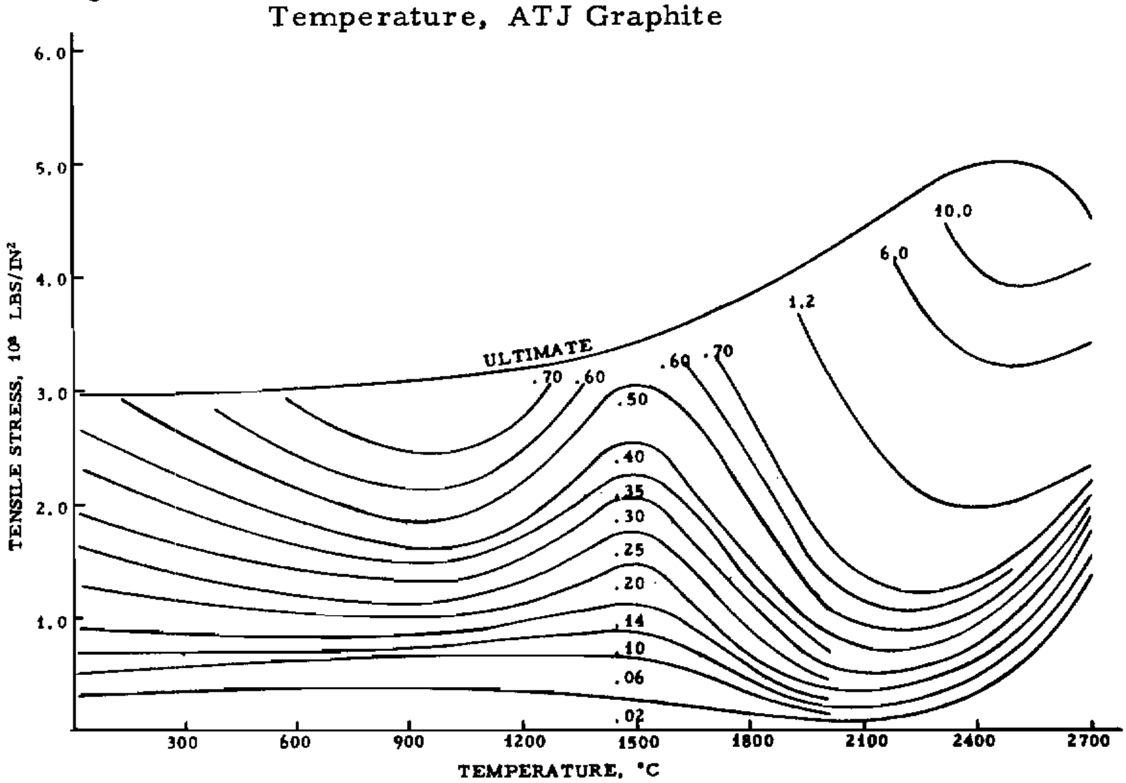


Figure 338. Across-Grain Tensile Strain Contour Plot, Stress vs. Temperature, ATJ Graphite

L-765

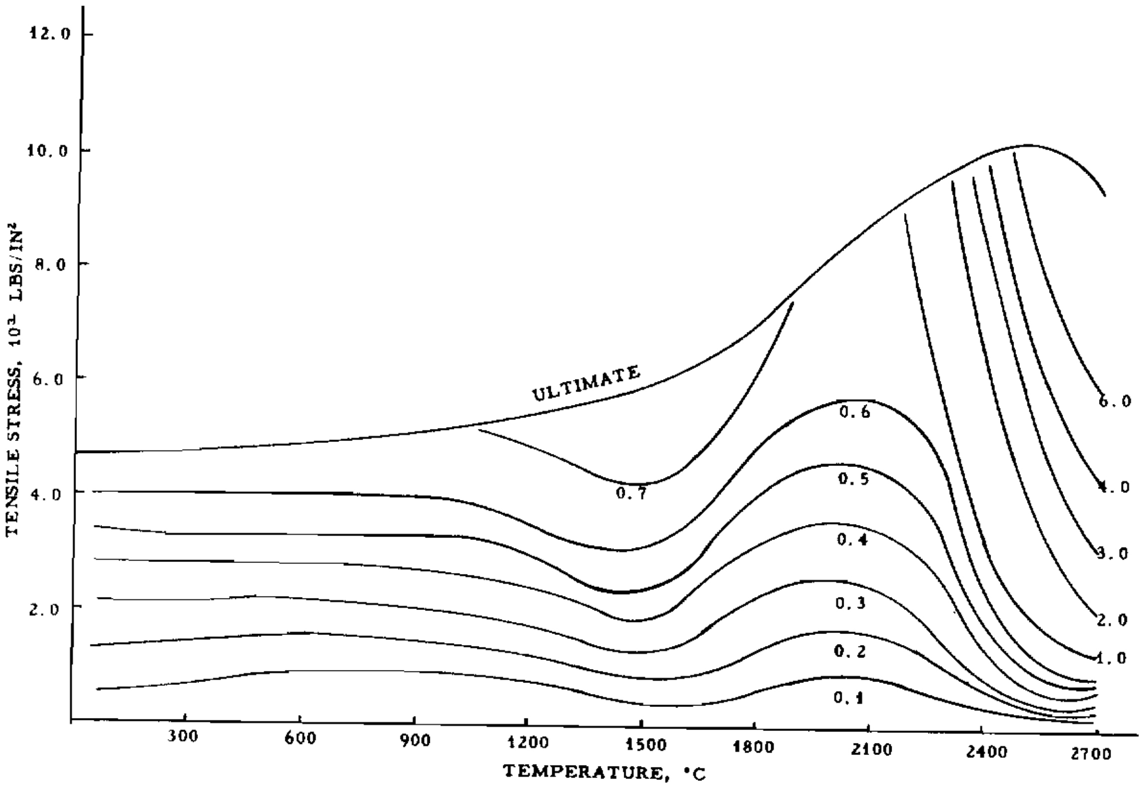


Figure 339. With-Grain Tensile Strain Contour Plot, Stress vs. Temperature, ZTA Graphite, Block No. 111 L-766

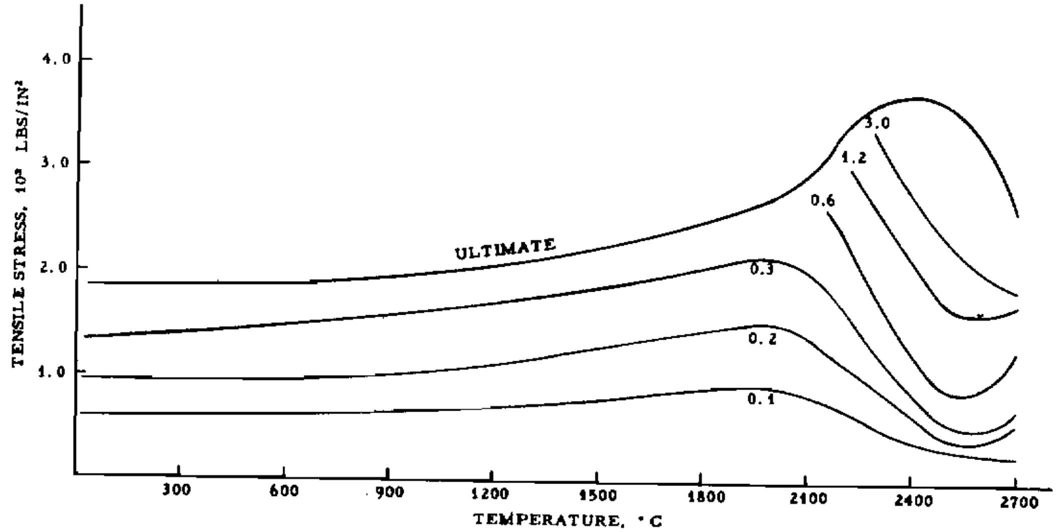
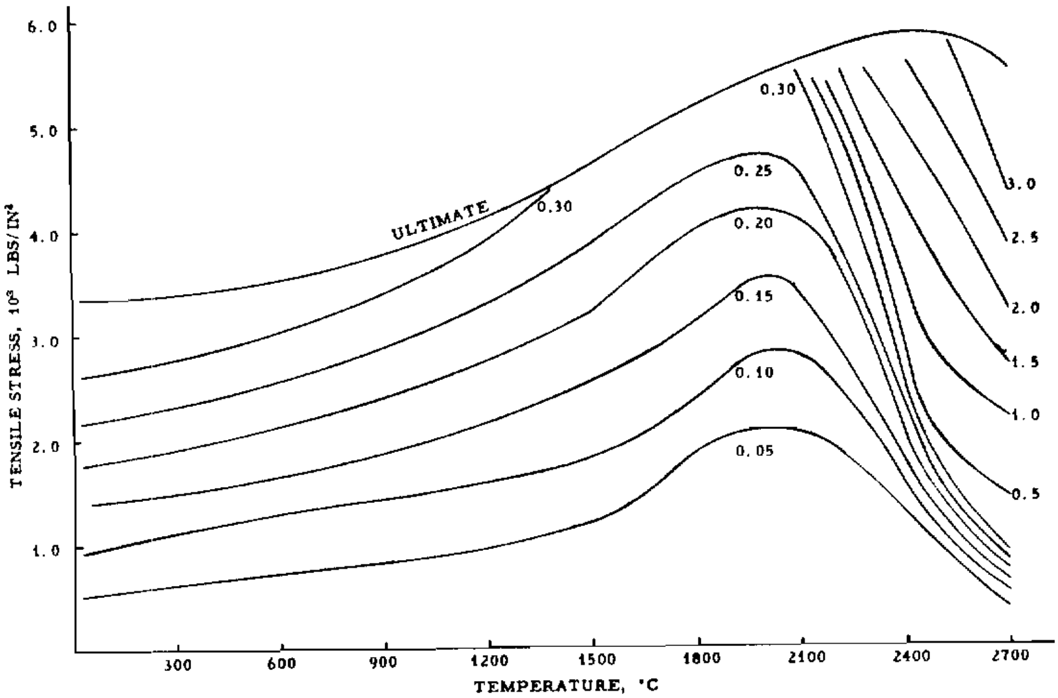
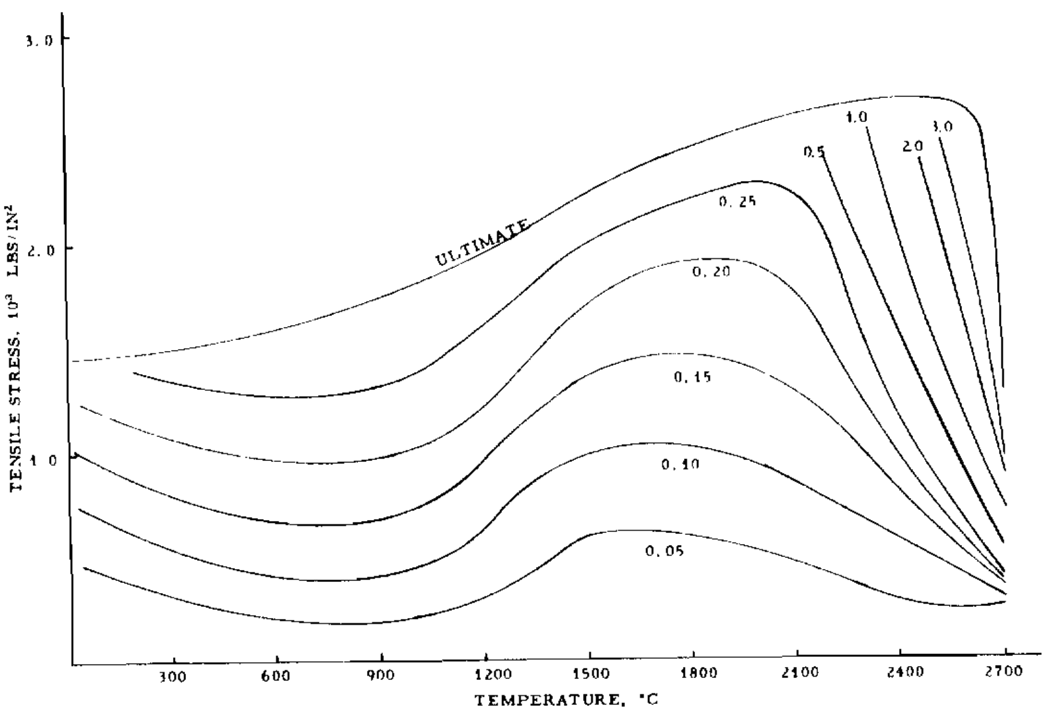


Figure 340. Across-Grain Tensile Strain Contour Plot, Stress vs. Temperature, ZTA Graphite, Block No. 111 L-767



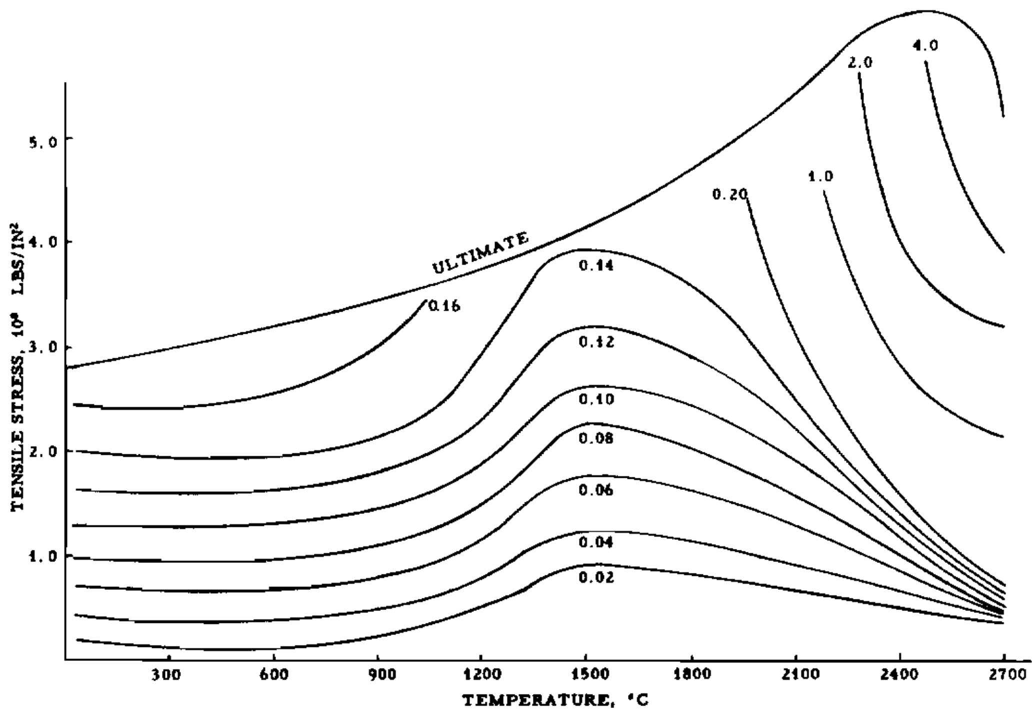
L-768

Figure 341. With-Grain Tensile Strain Contour Plot, Stress vs. Temperature, ZTE Graphite



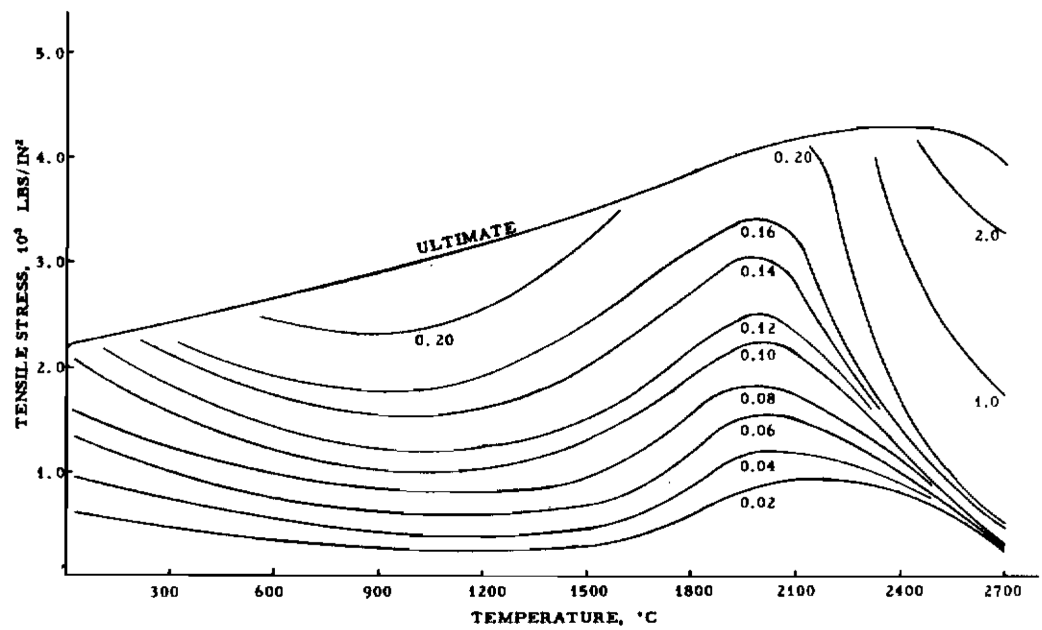
L-769

Figure 342. Across-Grain Tensile Strain Contour Plot, Stress vs. Temperature, ZTE Graphite



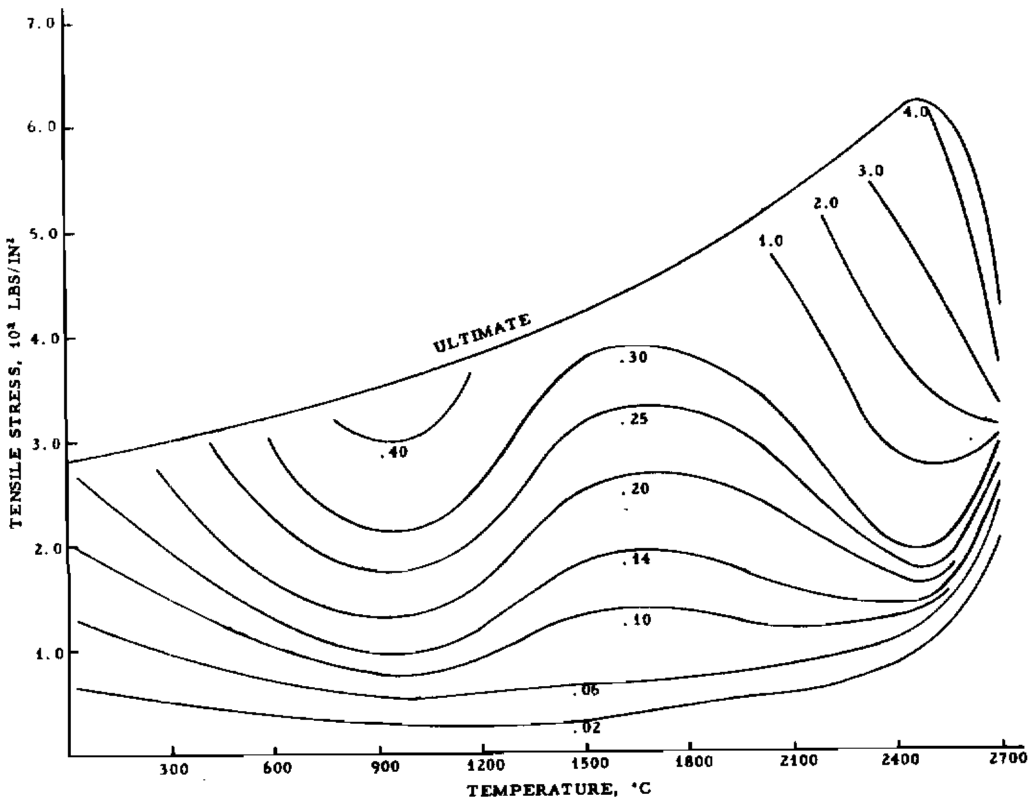
L-770

Figure 343. With-Grain Tensile Strain Contour Plot, Stress vs. Temperature, RVA Graphite, Block No. 19



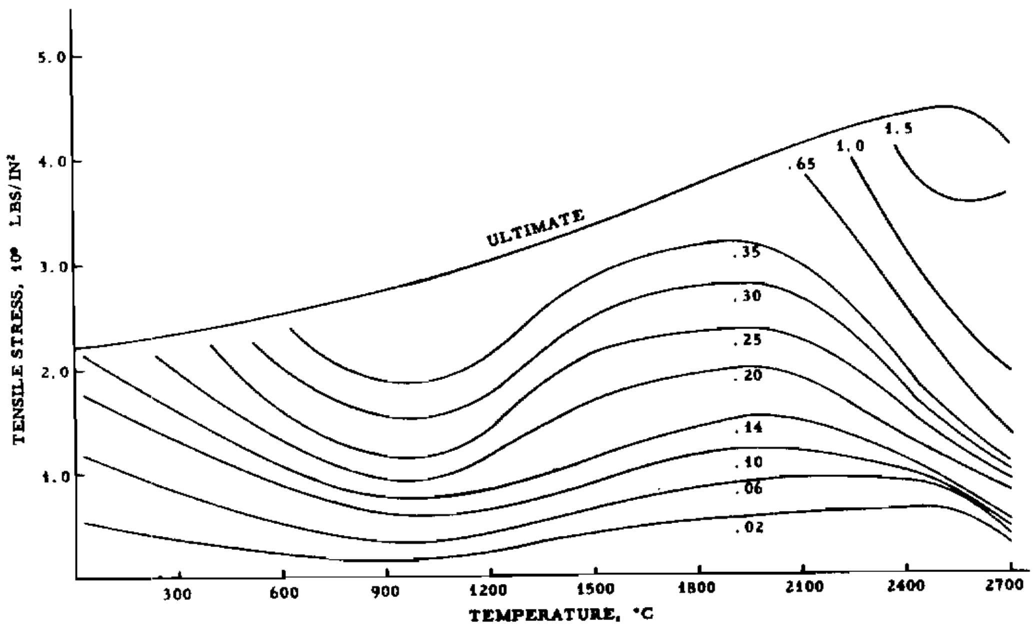
L-771

Figure 344. Across-Grain Tensile Strain Contour Plot, Stress vs. Temperature, RVA Graphite, Block No. 19



L-772

Figure 345. With-Grain Tensile Strain Contour Plot, Stress vs. Temperature, RVA Graphite, Block No. 20



L-773

Figure 346. Across-Grain Tensile Strain Contour Plot, Stress vs. Temperature, RVA Graphite, Block No. 20

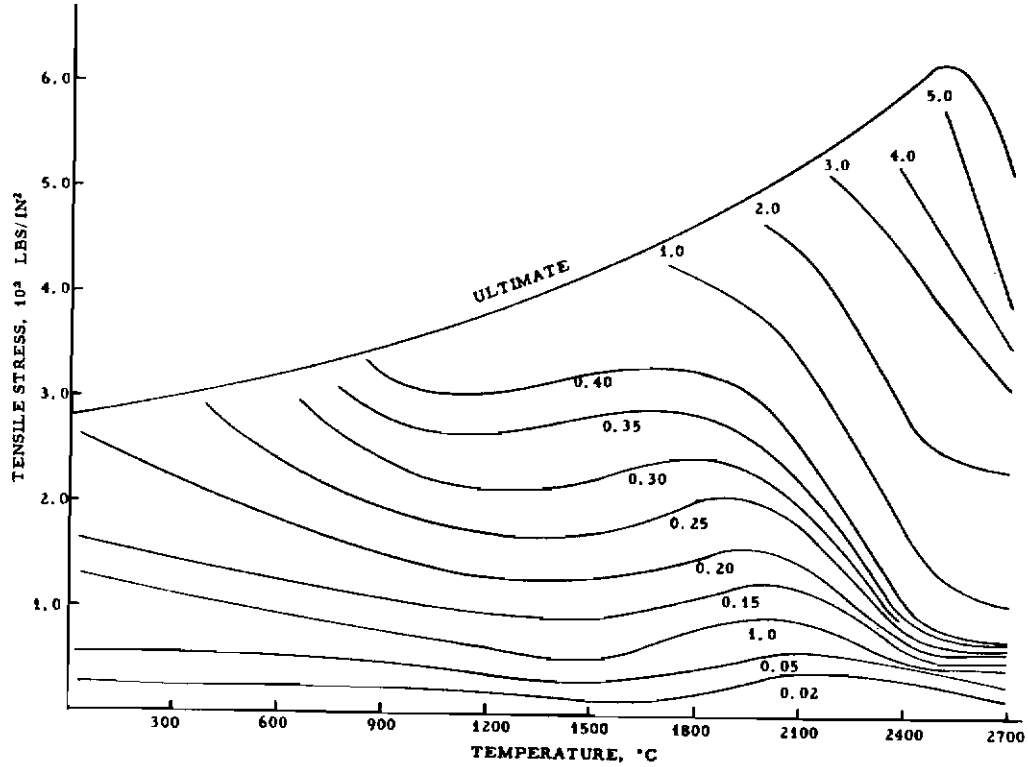


Figure 347. With-Grain Tensile Strain Contour Plot, Stress vs. Temperature, RVA Graphite, Block No. 24 L-775

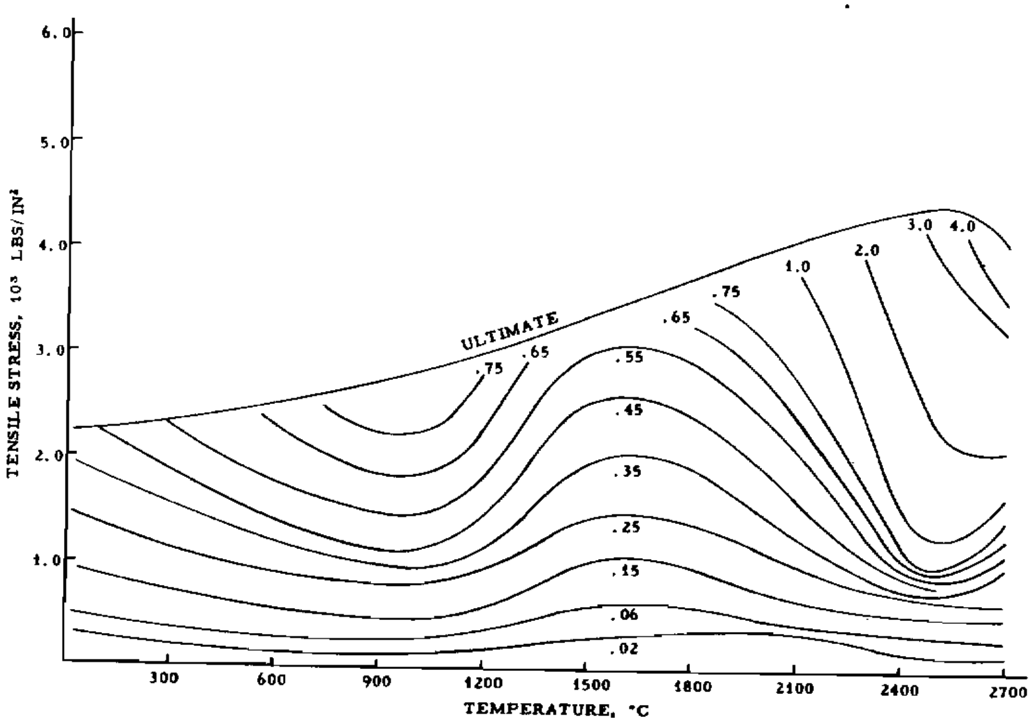
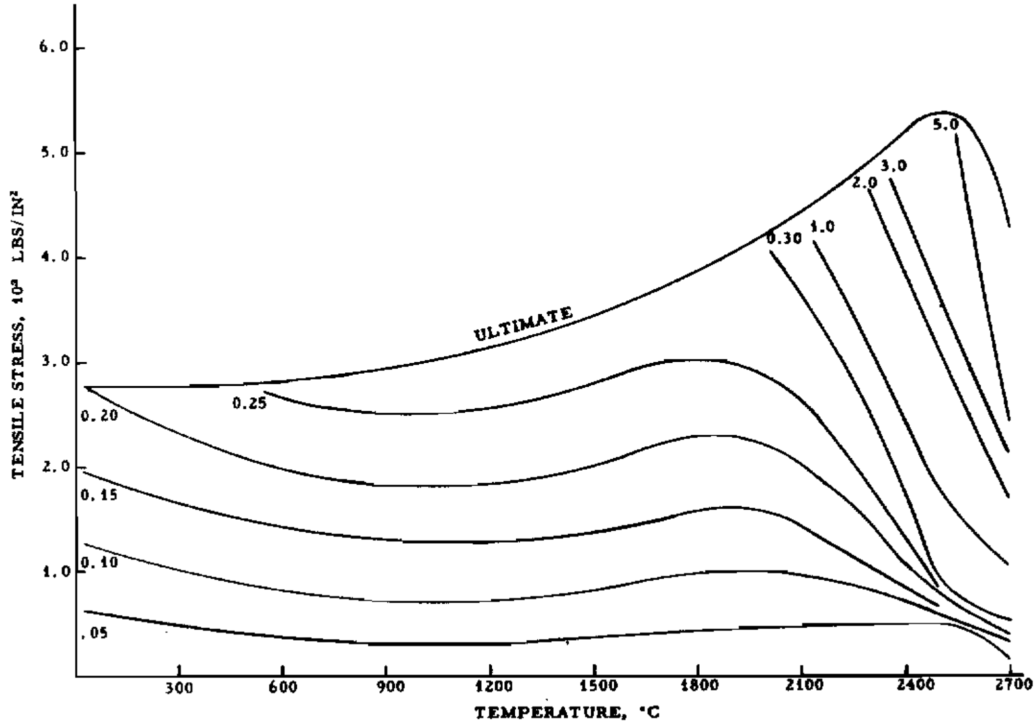
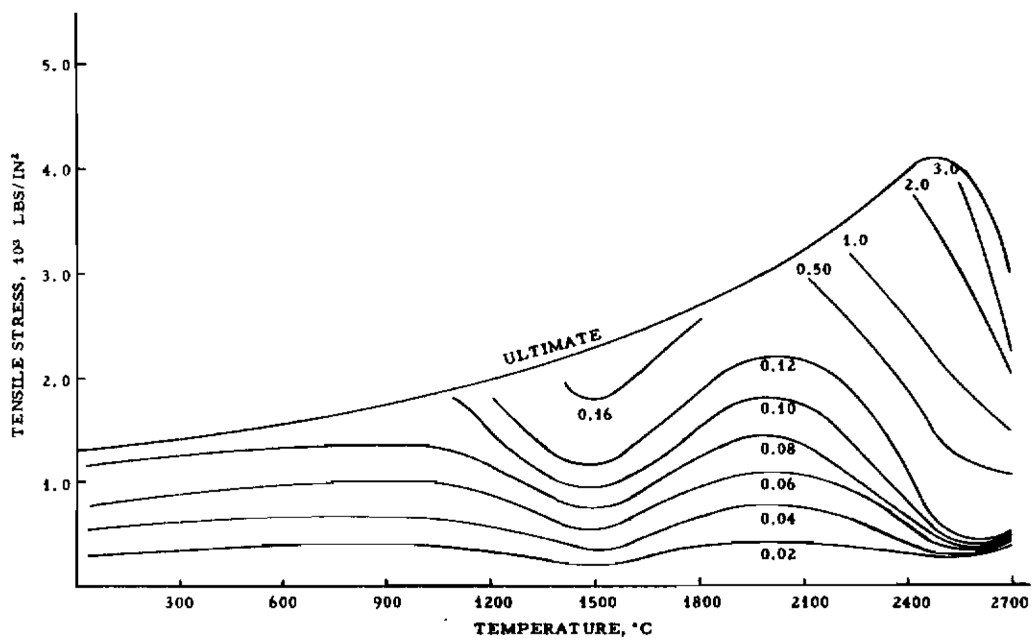


Figure 348. Across-Grain Tensile Strain Contour Plot, Stress vs. Temperature, RVA Graphite, Block No. 24 L-776



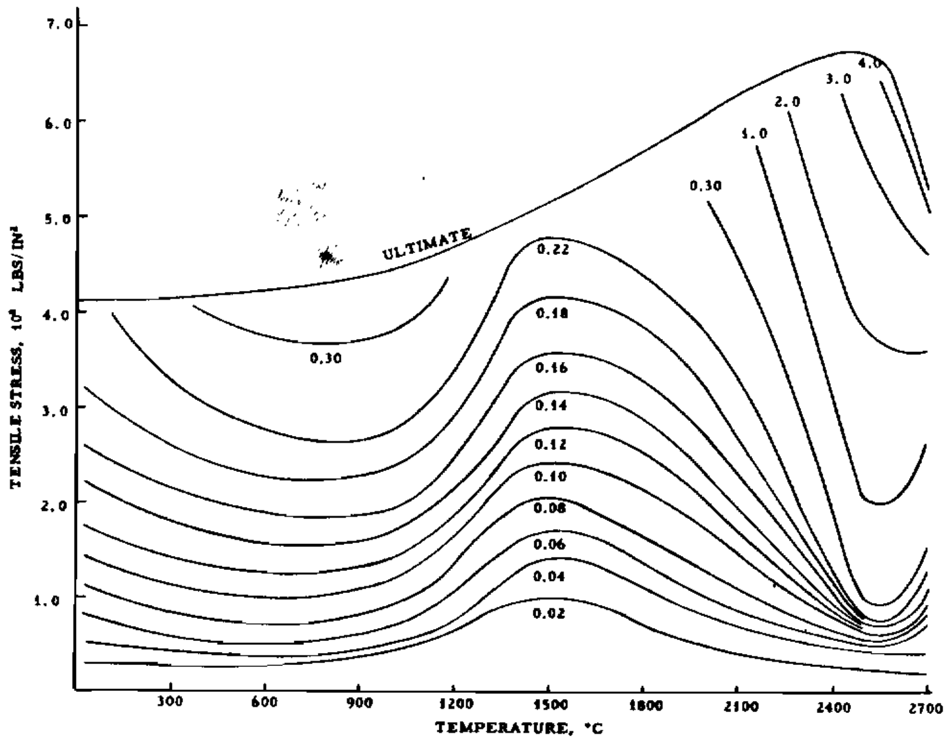
L-777

Figure 349. With-Grain Tensile Strain Contour Plot, Stress vs. Temperature, RVC Graphite



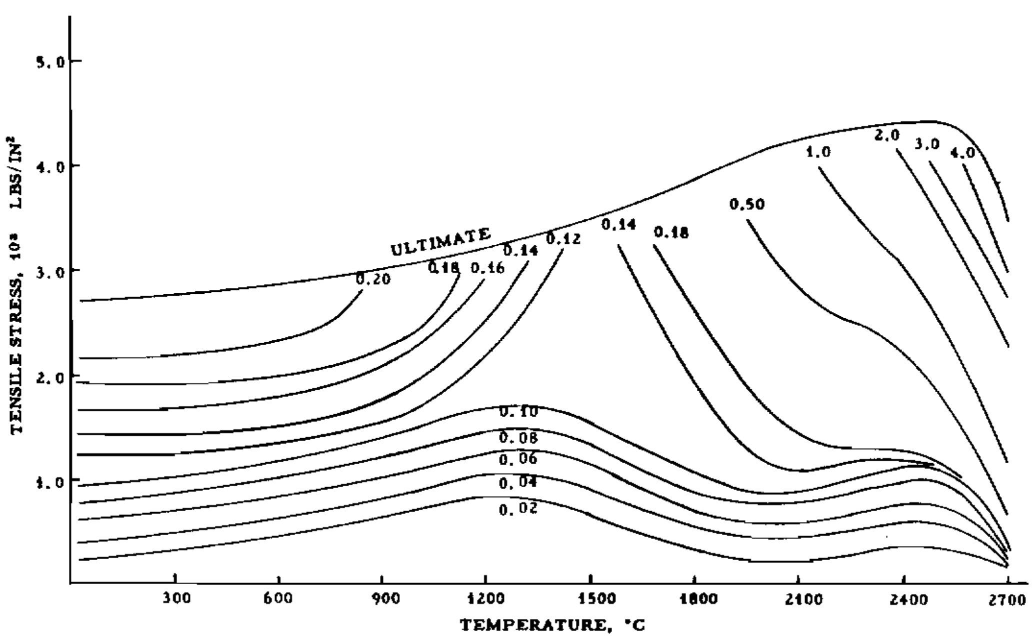
L-778

Figure 350. Across-Grain Tensile Strain Contour Plot, Stress vs. Temperature, RVC Graphite



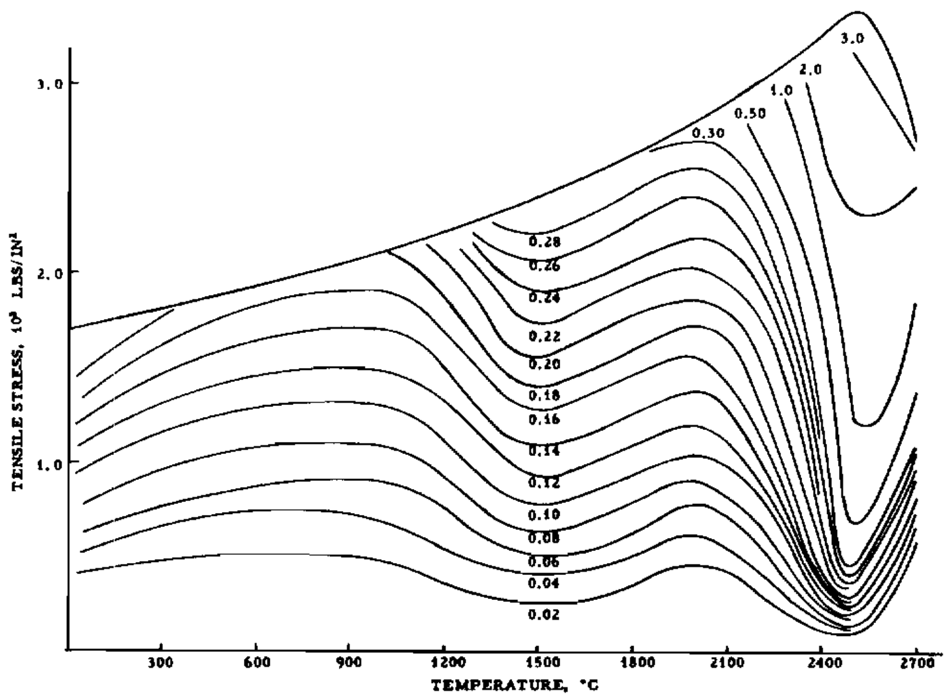
L-779

Figure 351. With-Grain Tensile Strain Contour Plot, Stress vs. Temperature, RVD Graphite



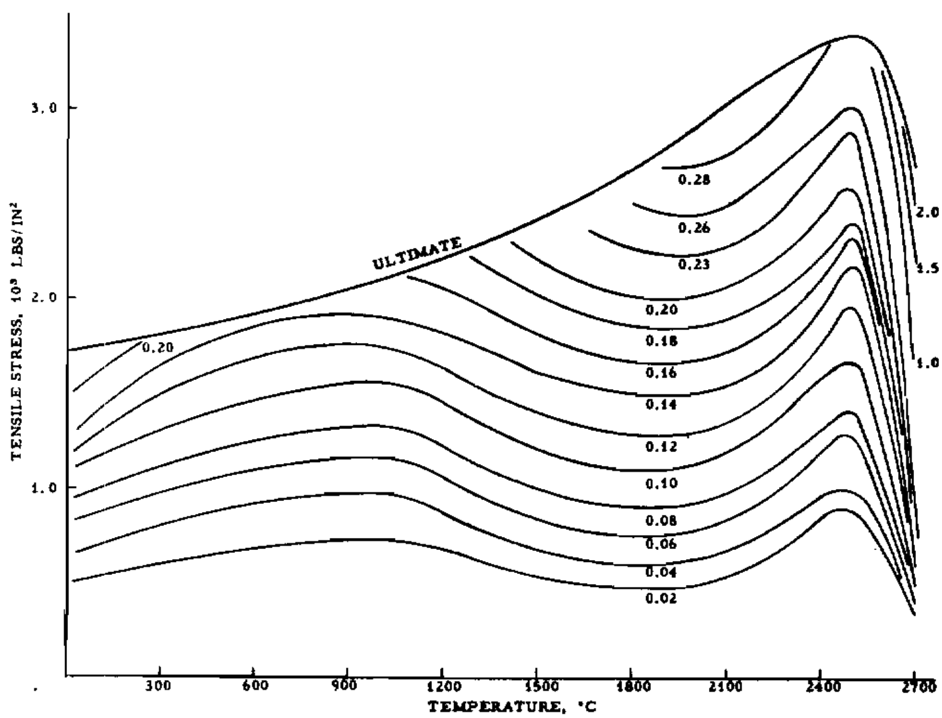
L-780

Figure 352. Across-Grain Tensile Strain Contour Plot, Stress vs. Temperature, RVD Graphite



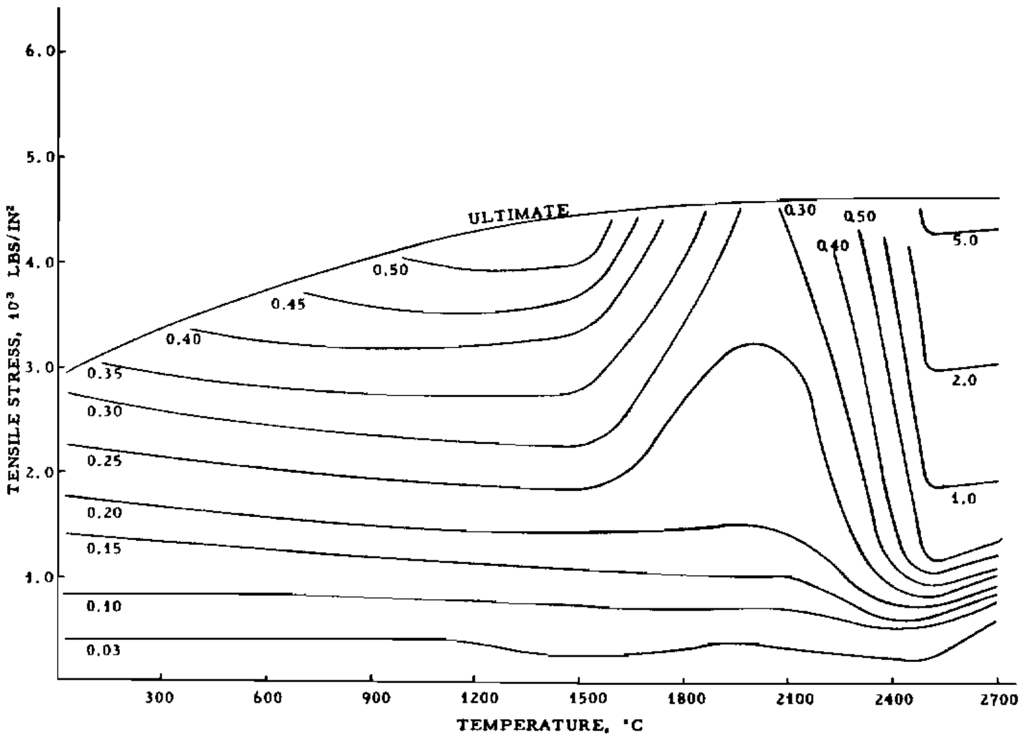
L-781

Figure 353. With-Grain Tensile Strain Contour Plot, Stress vs. Temperature, CFW Graphite



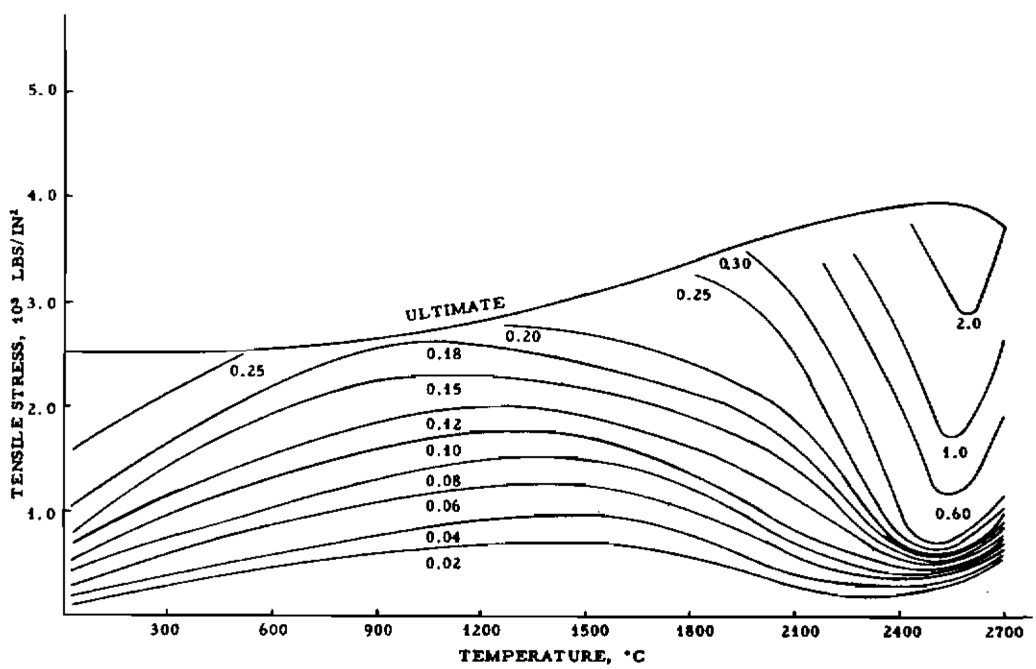
L-782

Figure 354. Across-Grain Tensile Strain Contour Plot, Stress vs. Temperature, CFW Graphite



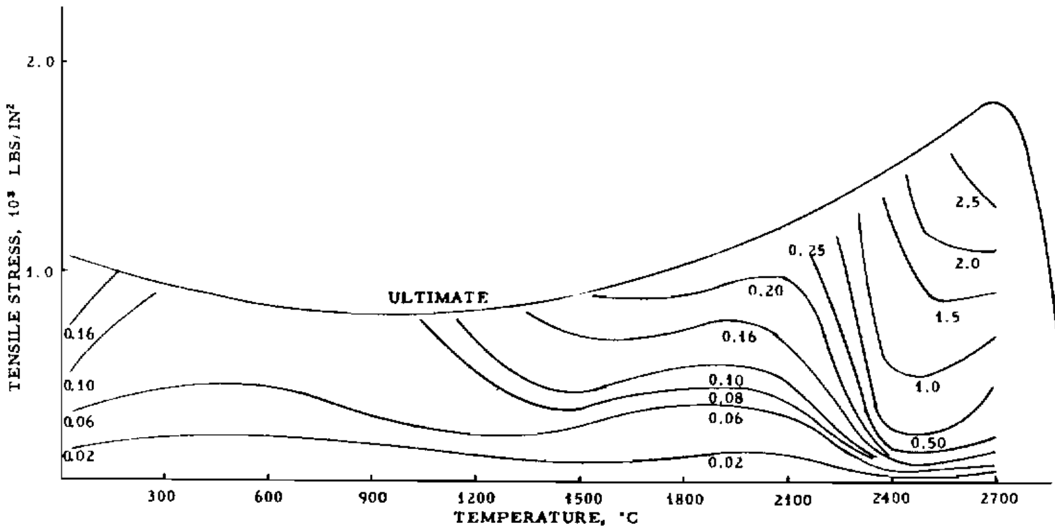
L-784

Figure 355. With-Grain Tensile Strain Contour Plot, Stress vs. Temperature, CFZ Graphite



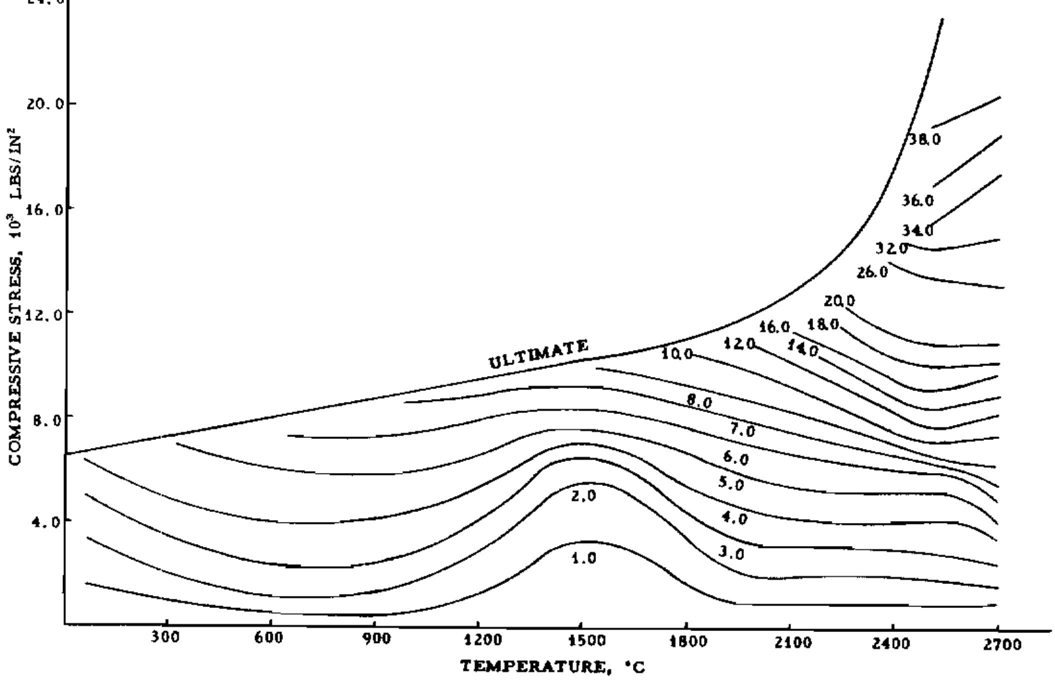
L-783

Figure 356. Across-Grain Tensile Strain Contour Plot, Stress vs. Temperature, CFZ Graphite



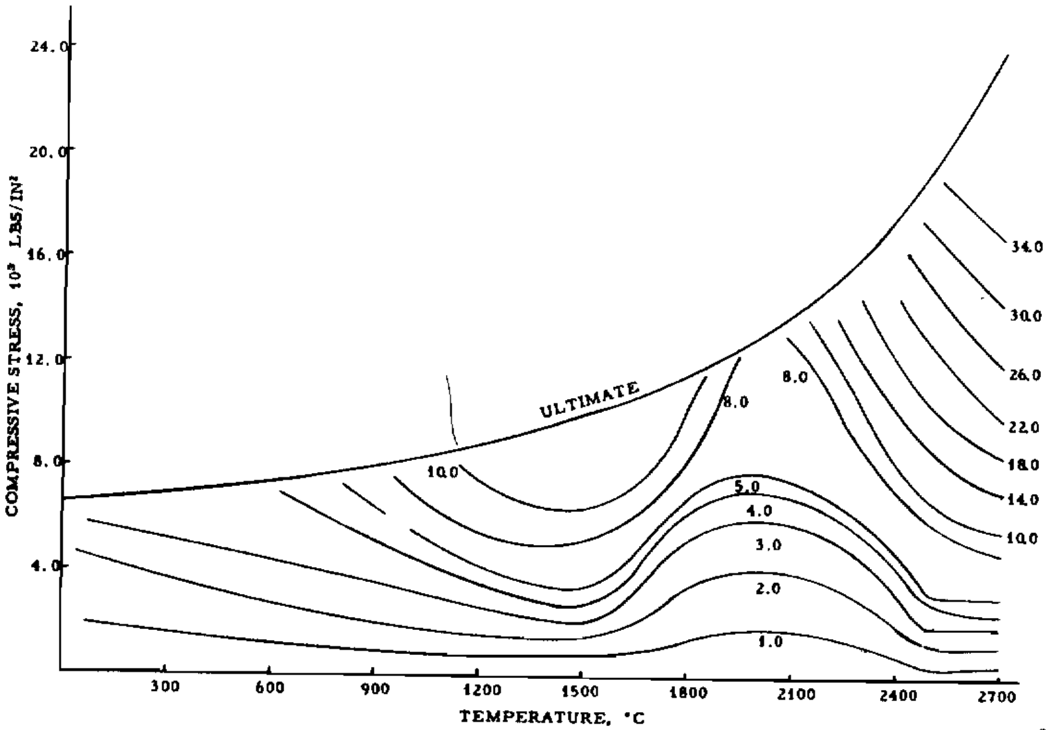
L-785

Figure 357. With-Grain Tensile Strain Contour Plot, Stress vs. Temperature, PT-0114 Graphite



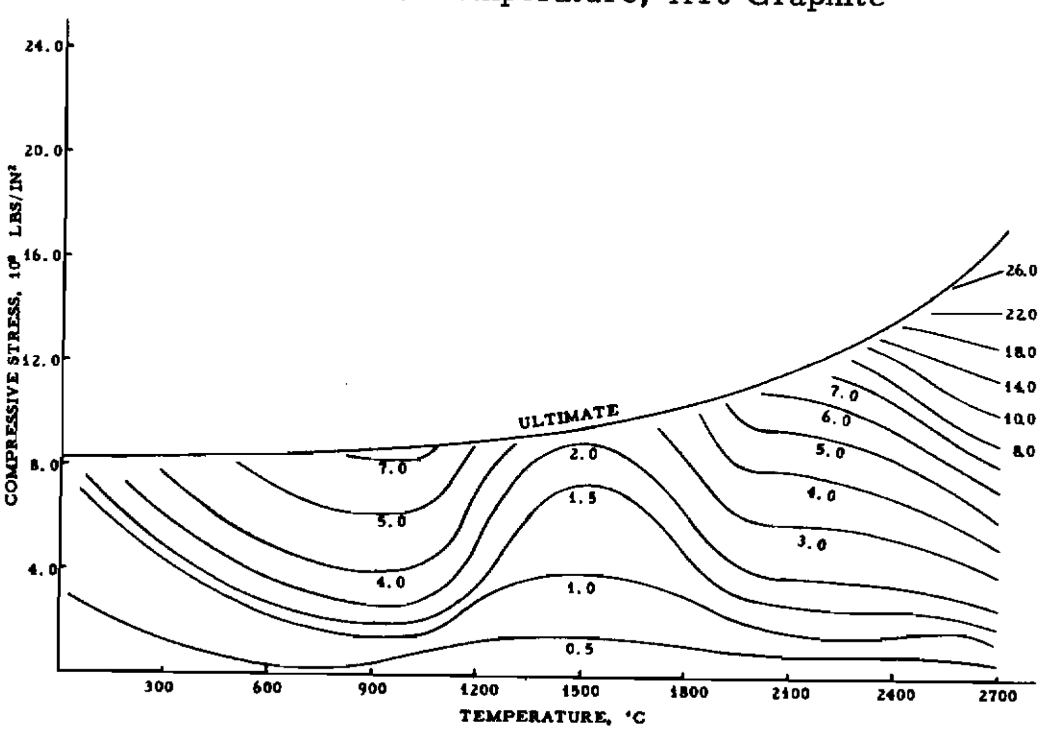
L-786

Figure 358. With-Grain Compressive Strain Contour Plot, Stress vs. Temperature, ATJ Graphite



L-787

Figure 359. Across-Grain Compressive Strain Contour Plot, Stress vs. Temperature, ATJ Graphite



L-788

Figure 360. With-Grain Compressive Strain Contour Plot, Stress vs. Temperature, ZTE Graphite

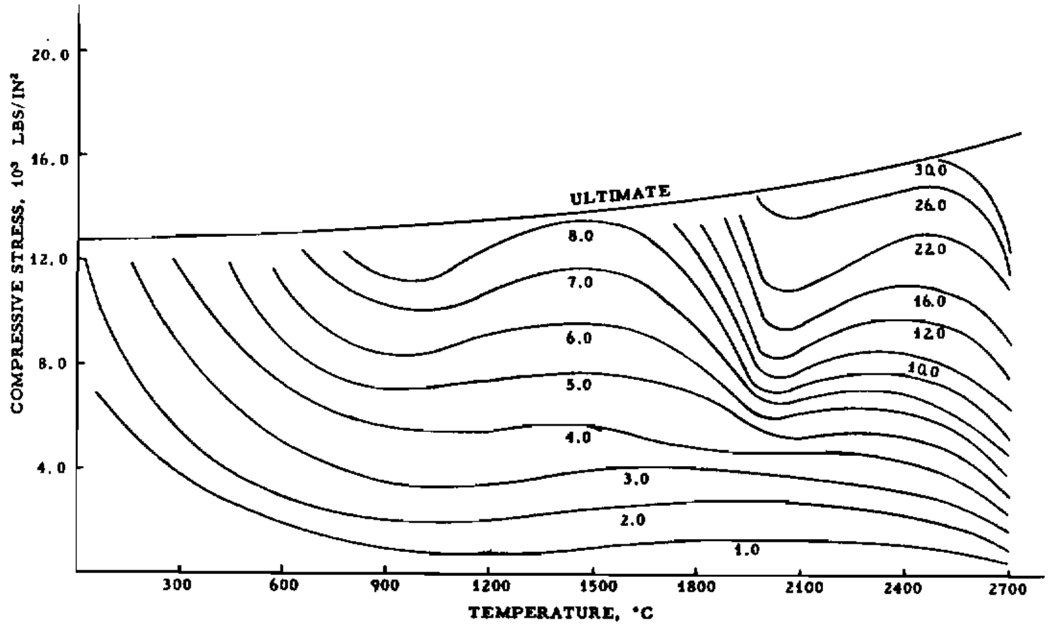


Figure 361. Across-Grain Compressive Strain Contour Plot, Stress vs. Temperature, ZTE Graphite

L-789

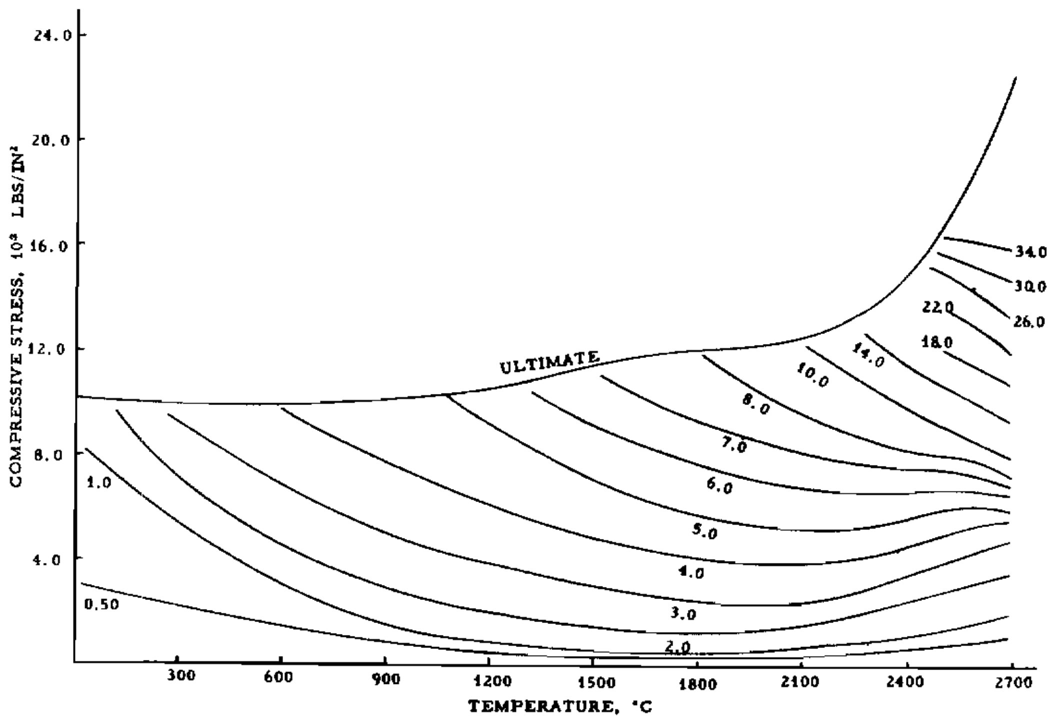
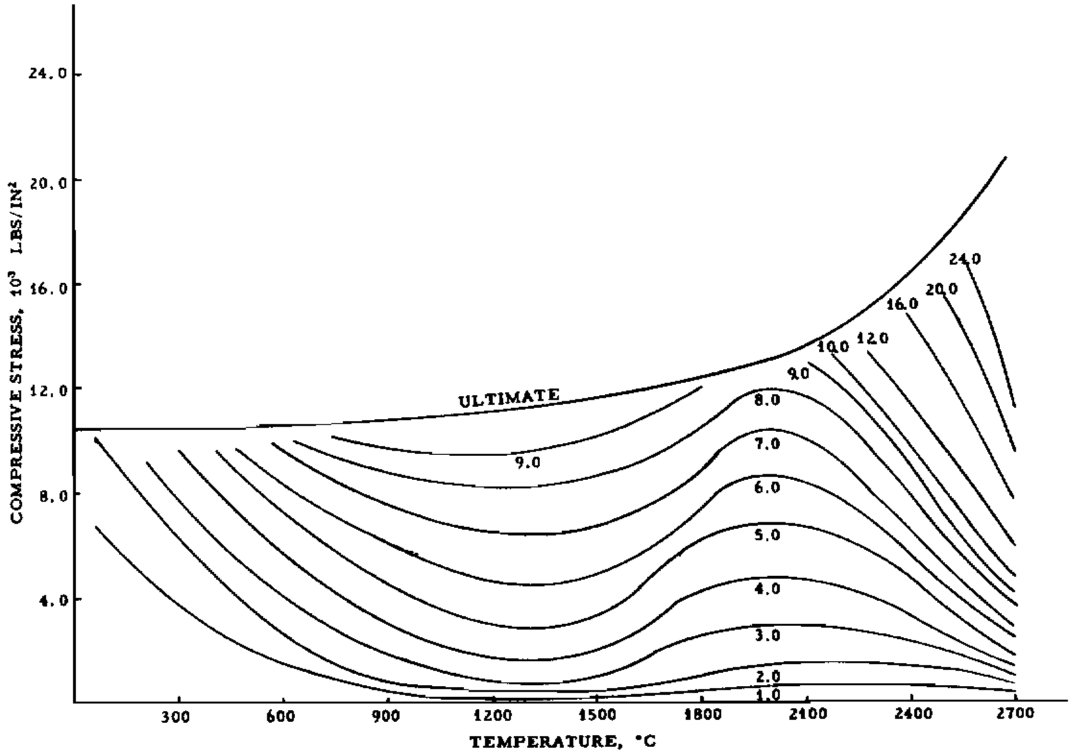


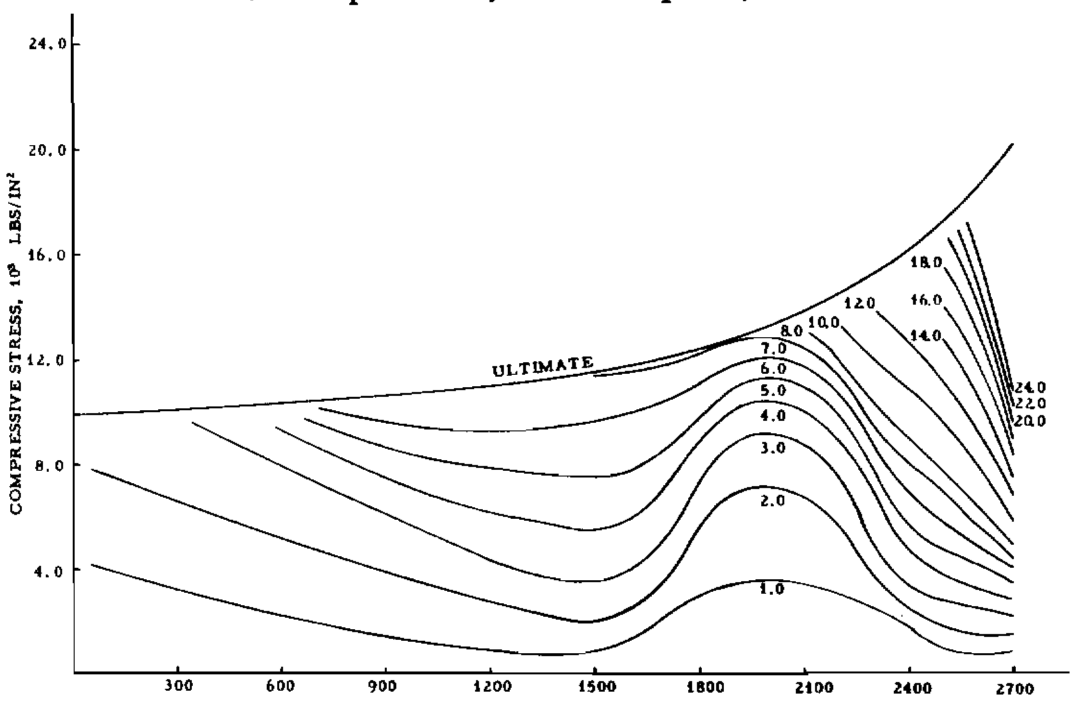
Figure 362. With-Grain Compressive Strain Contour Plot, Stress vs. Temperature, RVA Graphite, Block No. A-19

L-790



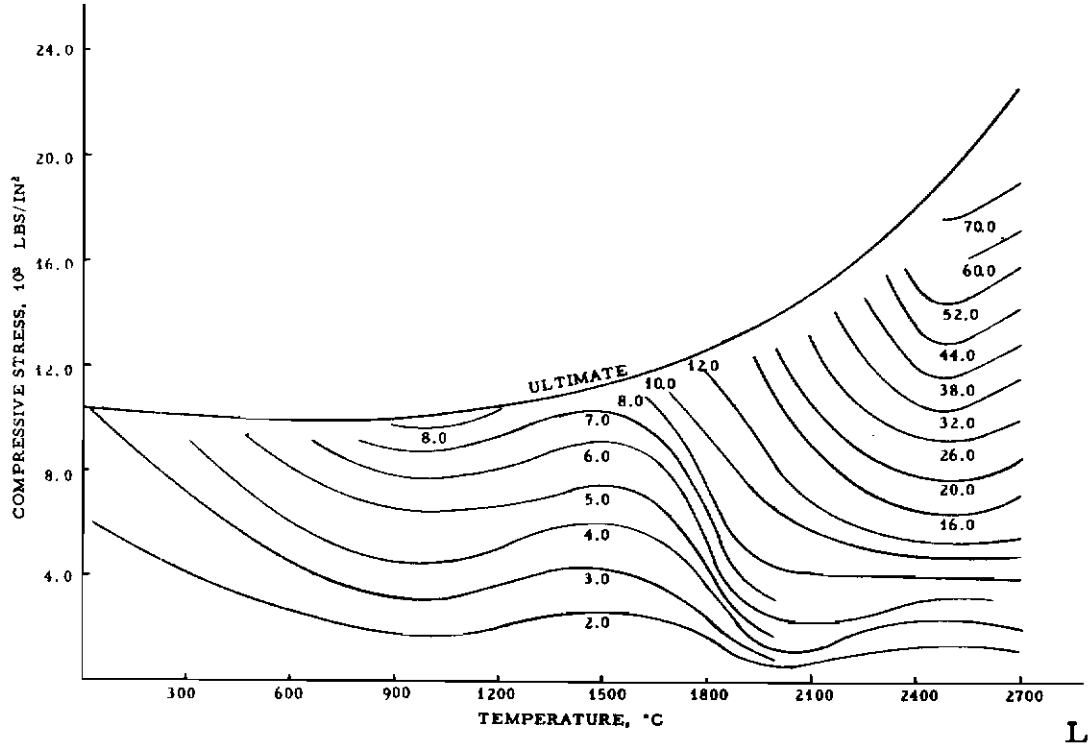
L-791

Figure 363. Across-Grain Compressive Strain, Contour Plot, Stress vs. Temperature, RVA Graphite, Block No. A-19



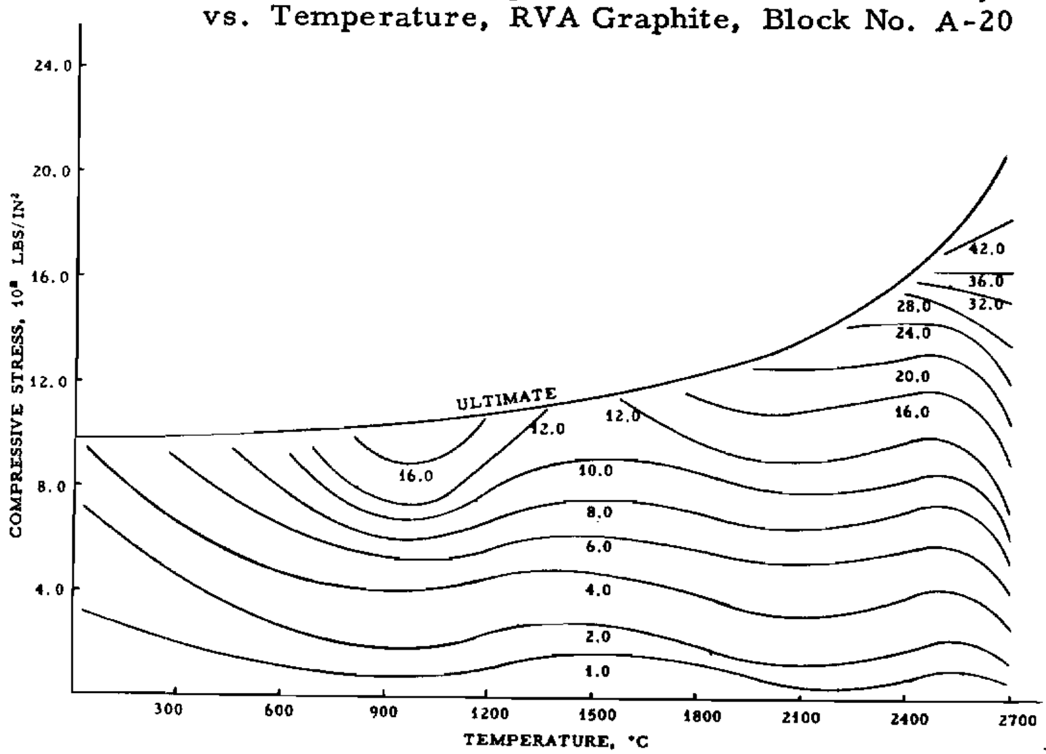
L-792

Figure 364. With-Grain Compressive Strain Contour Plot, Stress vs. Temperature, RVA Graphite, Block No. A-20



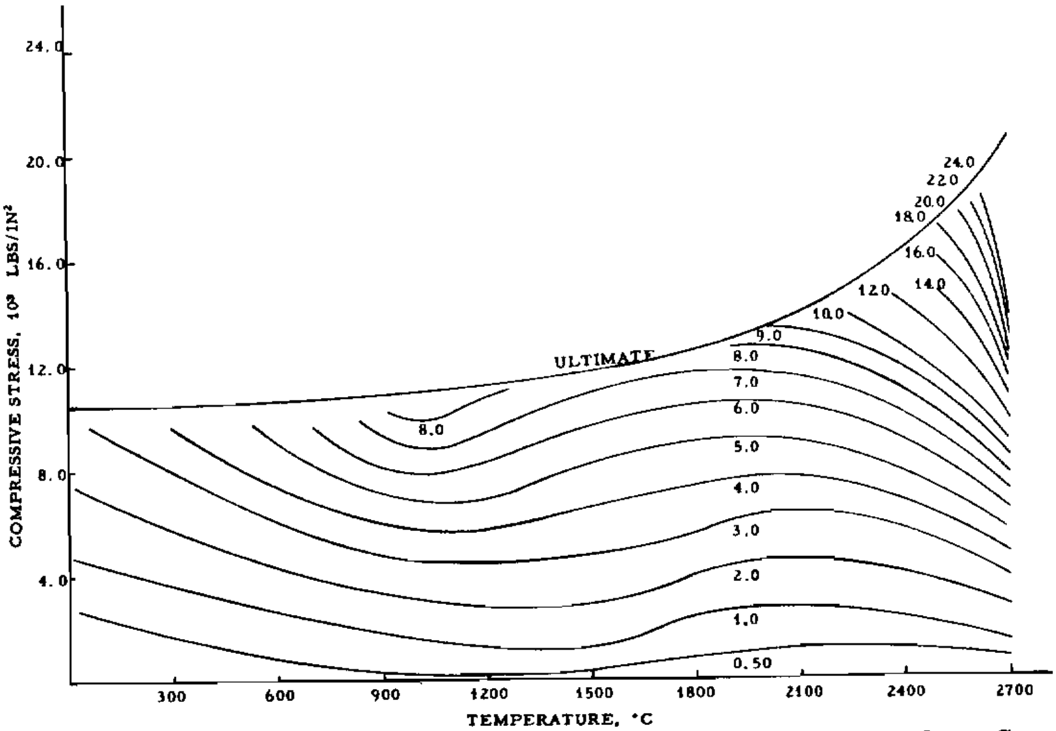
L-793

Figure 365. Across-Grain Compressive Strain Contour Plot, Stress vs. Temperature, RVA Graphite, Block No. A-20



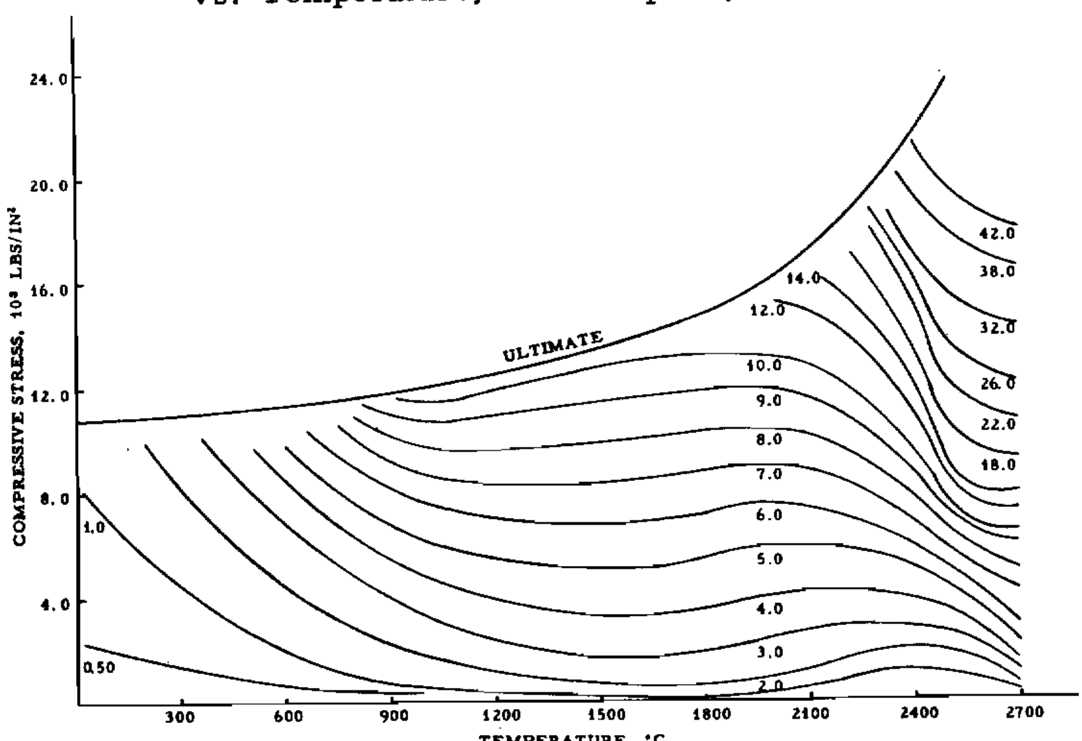
L-794

Figure 366. With-Grain Compressive Strain Contour Plot, Stress vs. Temperature, RVA Graphite, Block No. A-24



L-795

Figure 367. Across-Grain Compressive Strain Contour Plot, Stress vs. Temperature, RVA Graphite, Block No. A-24



L-796

Figure 368. With-Grain Compressive Strain Contour Plot, Stress vs. Temperature, RVC Graphite

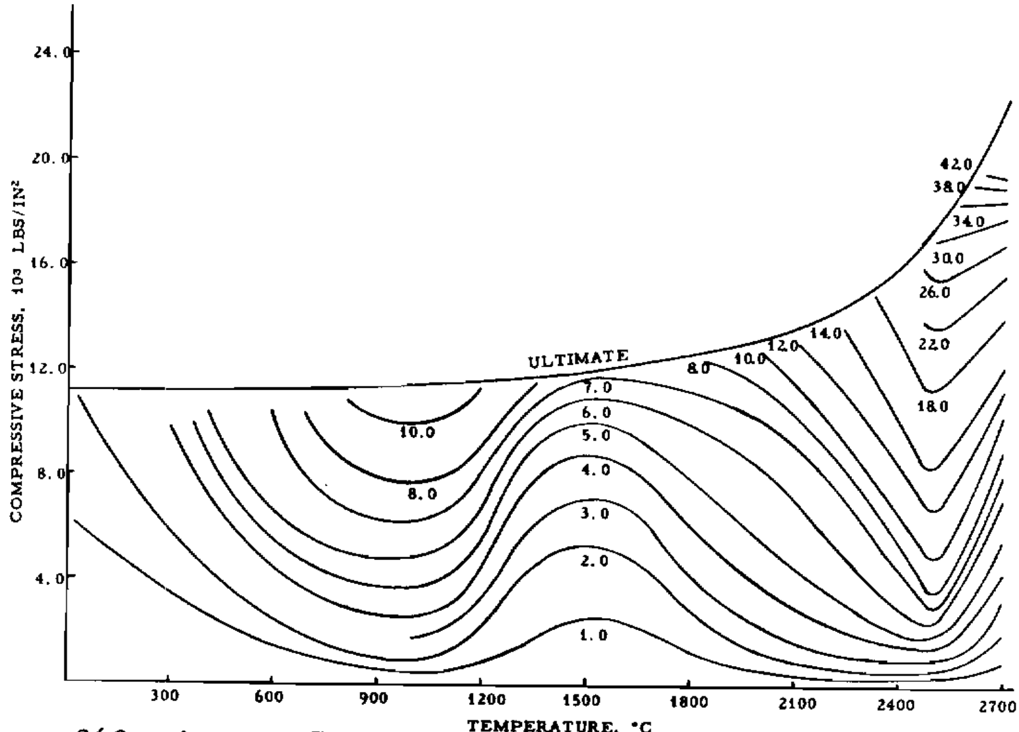


Figure 369. Across-Grain Compressive Strain Contour Plot, Stress vs. Temperature, RVC Graphite

L-797

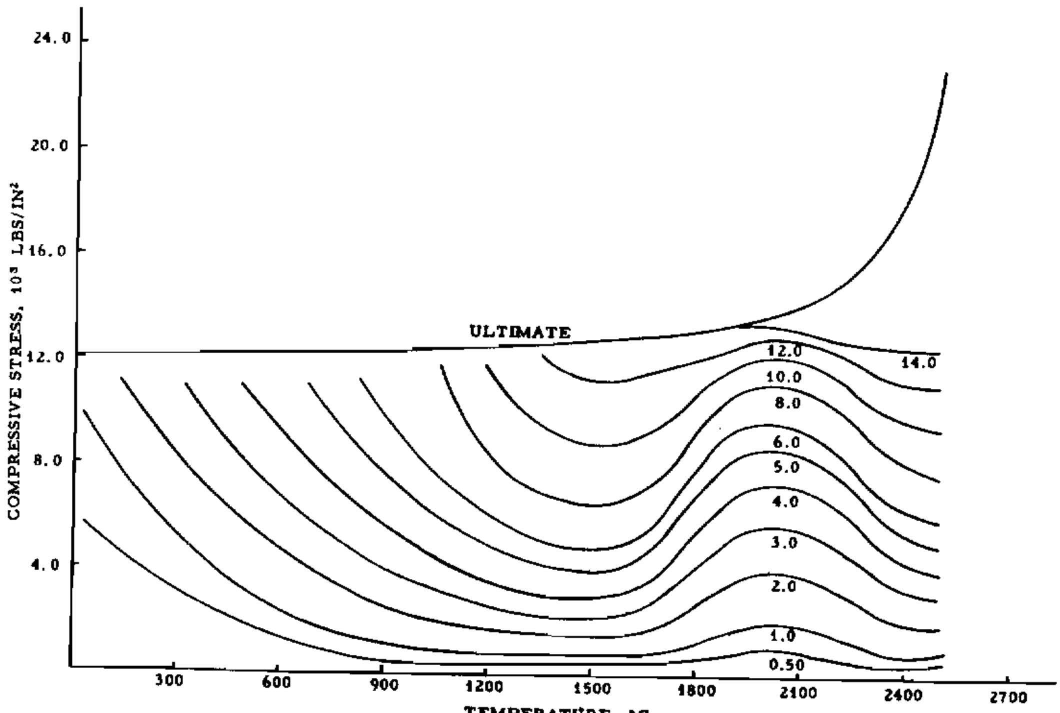
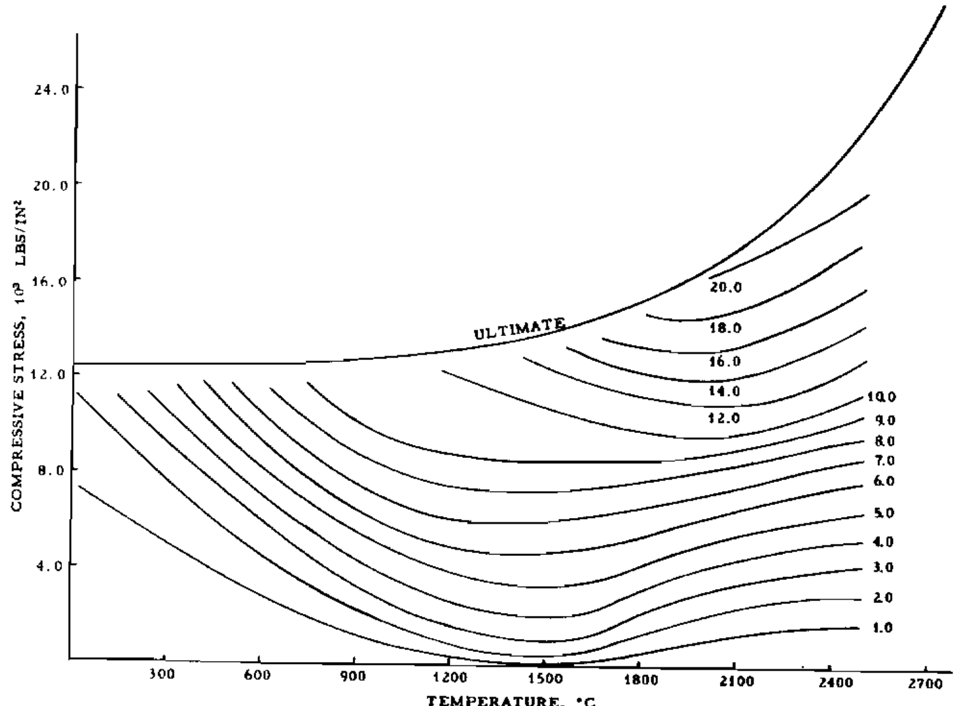


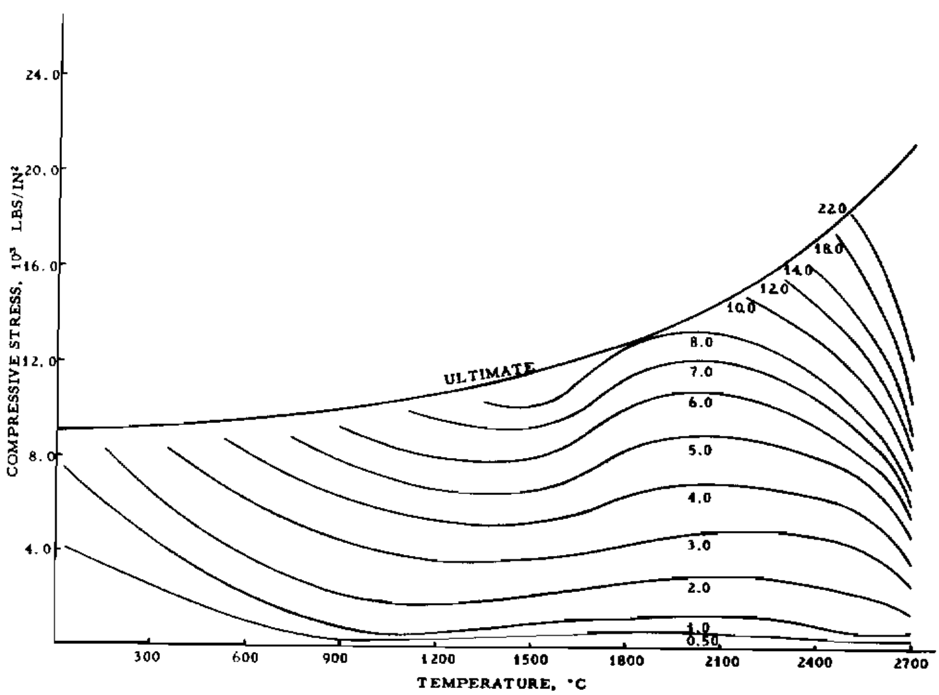
Figure 370. With-Grain Compressive Strain Contour Plot, Stress vs. Temperature, RVD Graphite

L-798



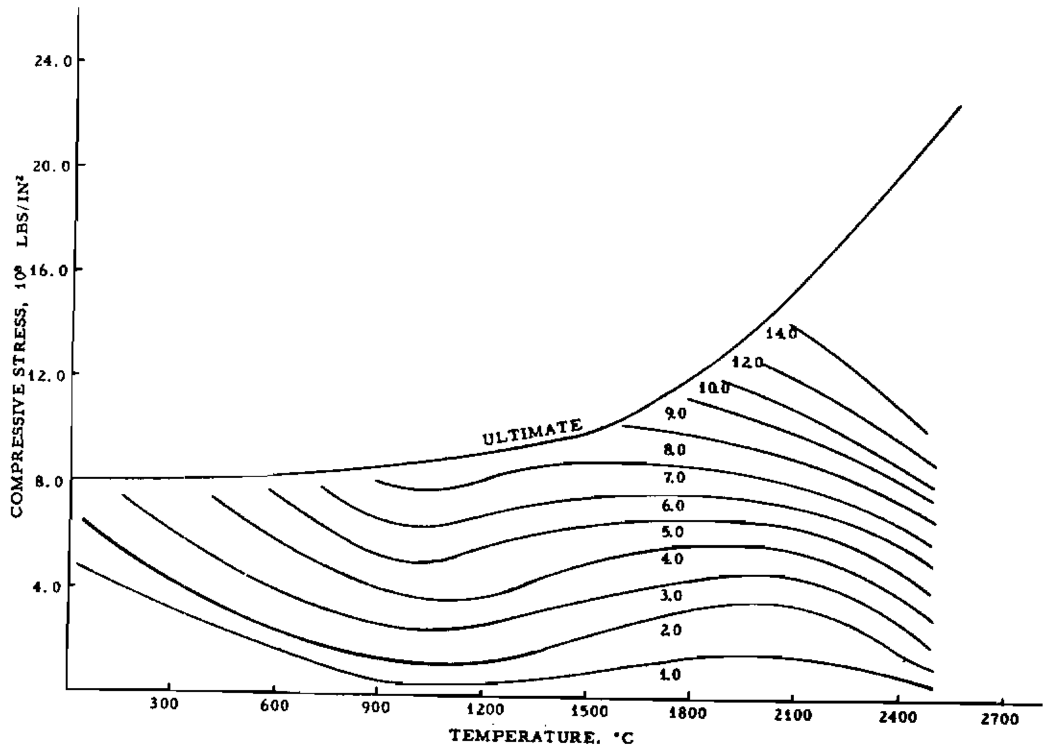
L-799

Figure 371. Across-Grain Compressive Strain Contour Plot, Stress vs. Temperature, RVD Graphite



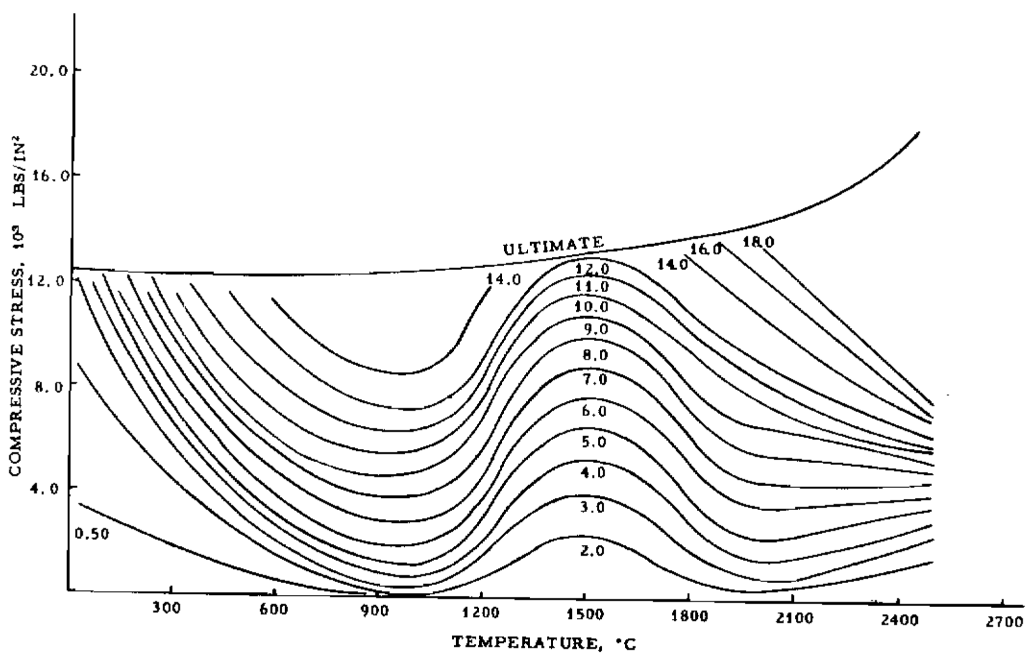
L-800

Figure 372. With-Grain Compressive Strain Contour Plot, Stress vs. Temperature, CFW Graphite



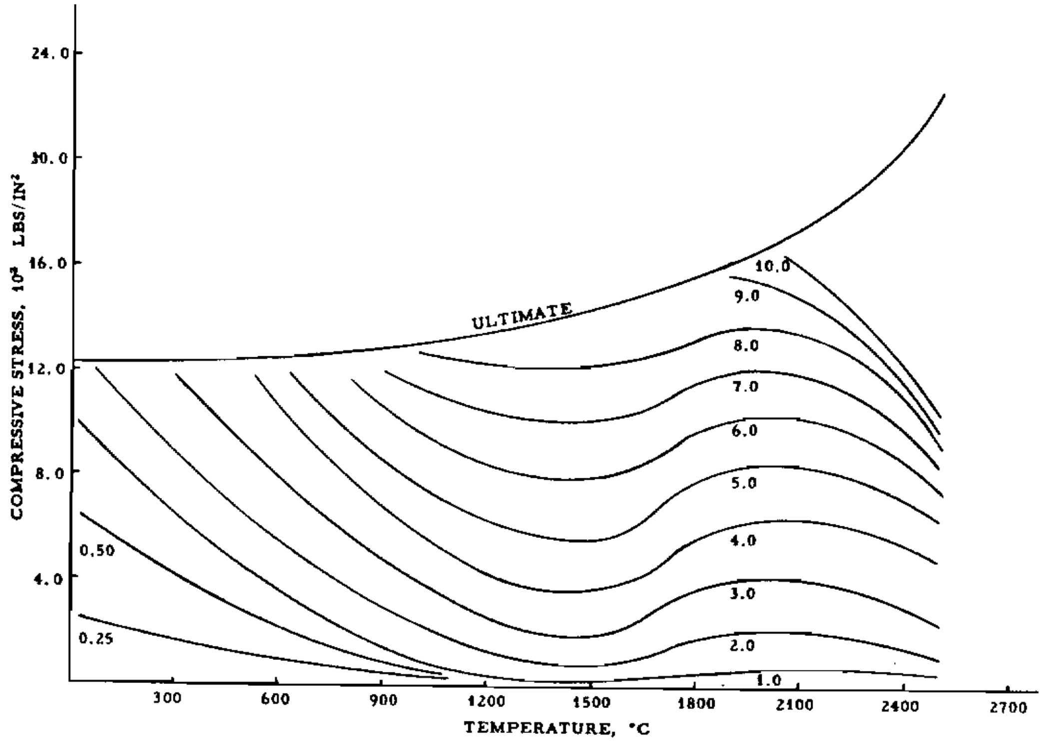
L-801

Figure 373. Across-Grain Compressive Strain Contour Plot, Stress vs. Temperature, CFW Graphite



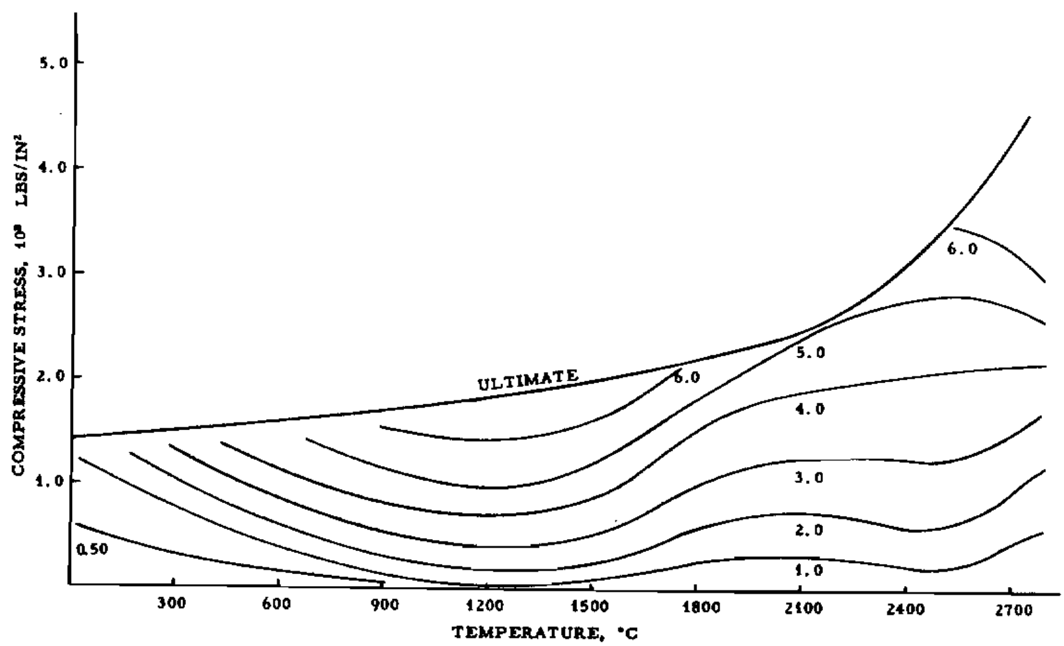
L-802

Figure 374. With-Grain Compressive Strain Contour Plot, Stress vs. Temperature, CFZ Graphite



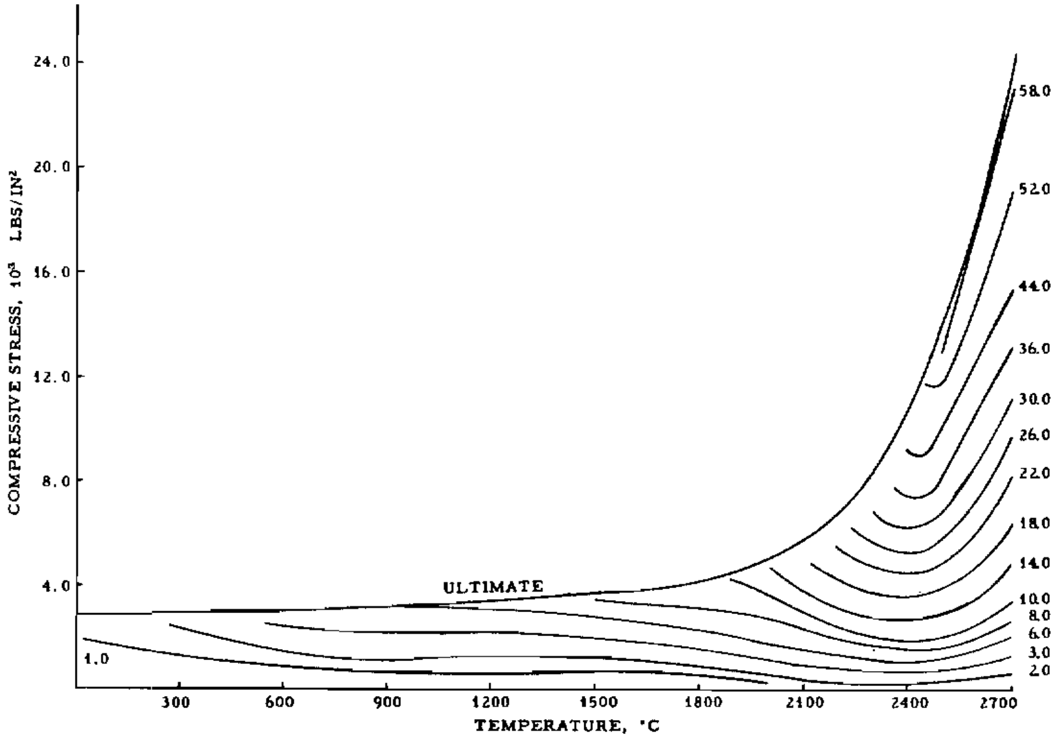
L-803

Figure 375. Across-Grain Compressive Strain Contour Plot, Stress vs. Temperature, CFZ Graphite



L-804

Figure 376. With-Grain Compressive Strain Contour Plot, Stress vs. Temperature, PT-0114



L-759

Figure 377. Across-Grain Compressive Strain Contour Plot, Stress vs. Temperature, PT-0114 Graphite

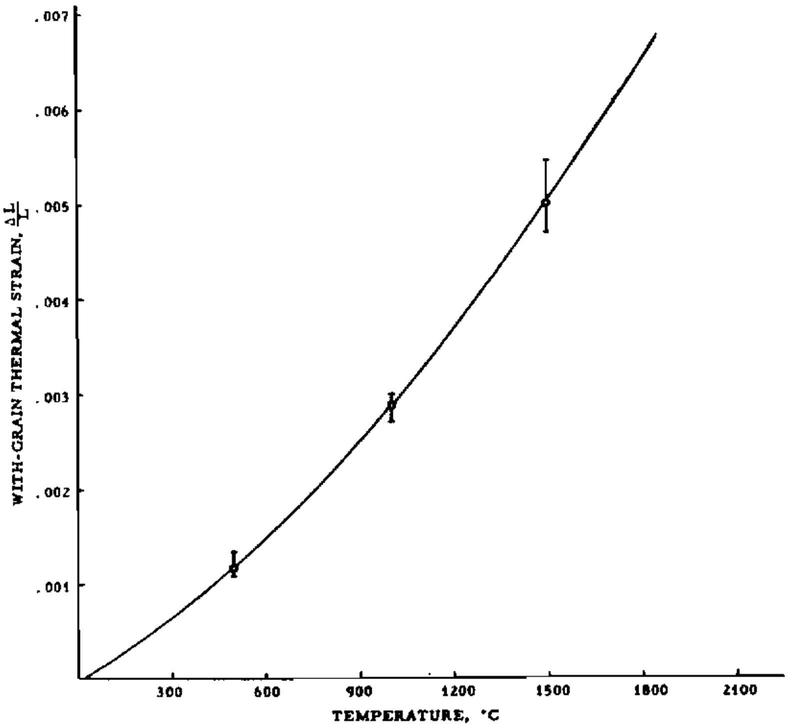
APPENDIX II

A GRAPHIC METHOD OF ESTIMATING THERMAL-SHOCK RESISTANCE OF GRAPHITE

The maximum temperature differential, ΔT_f, that can be withstood without fracture by a specific grade of graphite can be estimated graphically. As an example, consider RVA graphite in a with-grain direction. The thermal strain, $\frac{\Delta L}{L}$ (strain per unit length), versus temperature curve in Figure 378 is constructed from the thermal expansion data in Table 46, Section 3.8. The tensile strain-at-fracture versus temperature curve in Figure 379 is constructed from data taken from the stress-strain curves in Figures 122, 123, 128, 129, 134 and 135 in Section 3.8. If RVA graphite fractures in tension as a result of thermal stresses parallel to the grain direction it will occur when the thermal strain is equal to the tensile strain-at-failure. Assume that an infinite flat plate of RVA graphite at 1500°C is suddenly cooled. When Figure 378 is superimposed upon Figure 379 so that the thermal strain at 1500°C coincides with the tensile strain-at-failure at 1500°C, the thermal strain curve intersects the abscissa of the tensile strain-at-failure versus temperature plot at 940°C as illustrated in Figure 380. Under the assumed conditions the maximum temperature differential, ΔT_f, that can be withstood without fracture, is the difference between 1500°C and 940°C; i.e., $\Delta T_f = 560°C$.

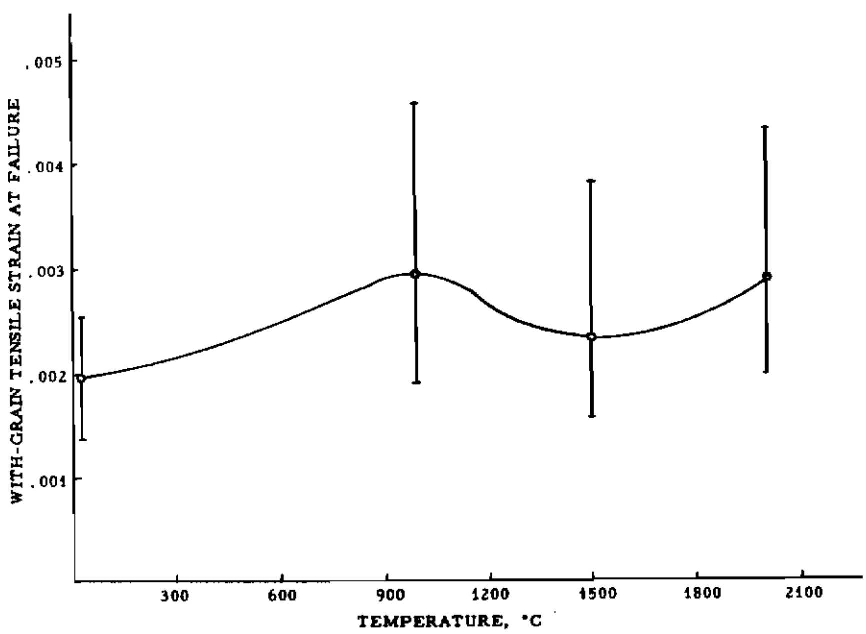
When the thermal stresses are across-grain, ΔT_f is determined in a similar manner by superimposing Figure 381 upon Figure 382 as illustrated in Figure 383. In this case, $\Delta T_f = 455°C$. The thermal-shock resistance of RVA graphite is, therefore, greater in the with-grain than in the across-grain direction.

Thermal-shock resistance depends upon the shape as well as thermal and mechanical properties of the material. Shape must therefore be taken into account when designing a graphite item which is to undergo large and rapid temperature changes.



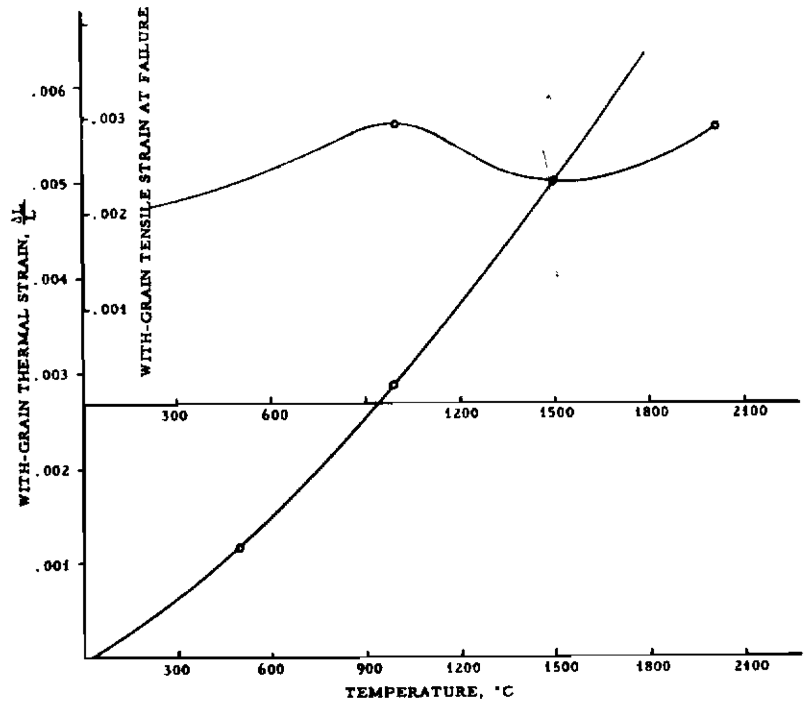
L-805

Figure 378. With-Grain Thermal Strain vs. Temperature, RVA Graphite, 33-Inch Diameter by 42-Inch Length



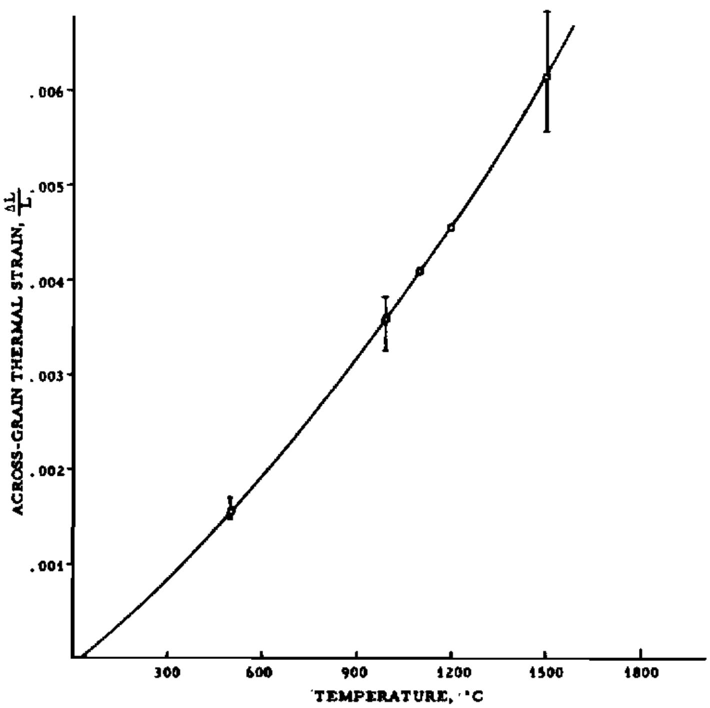
L-806

Figure 379. With-Grain Tensile Strain at Failure vs. Temperature, RVA Graphite, 33-Inch Diameter by 42-Inch Length



L-808

Figure 380. With-Grain Thermal Strain Curve Superimposed Upon With-Grain Tensile Strain at Failure Curve, RVA Graphite



L-807

Figure 381. Across-Grain Thermal Strain vs. Temperature, RVA Graphite, 33-Inch Diameter by 42-Inch Length

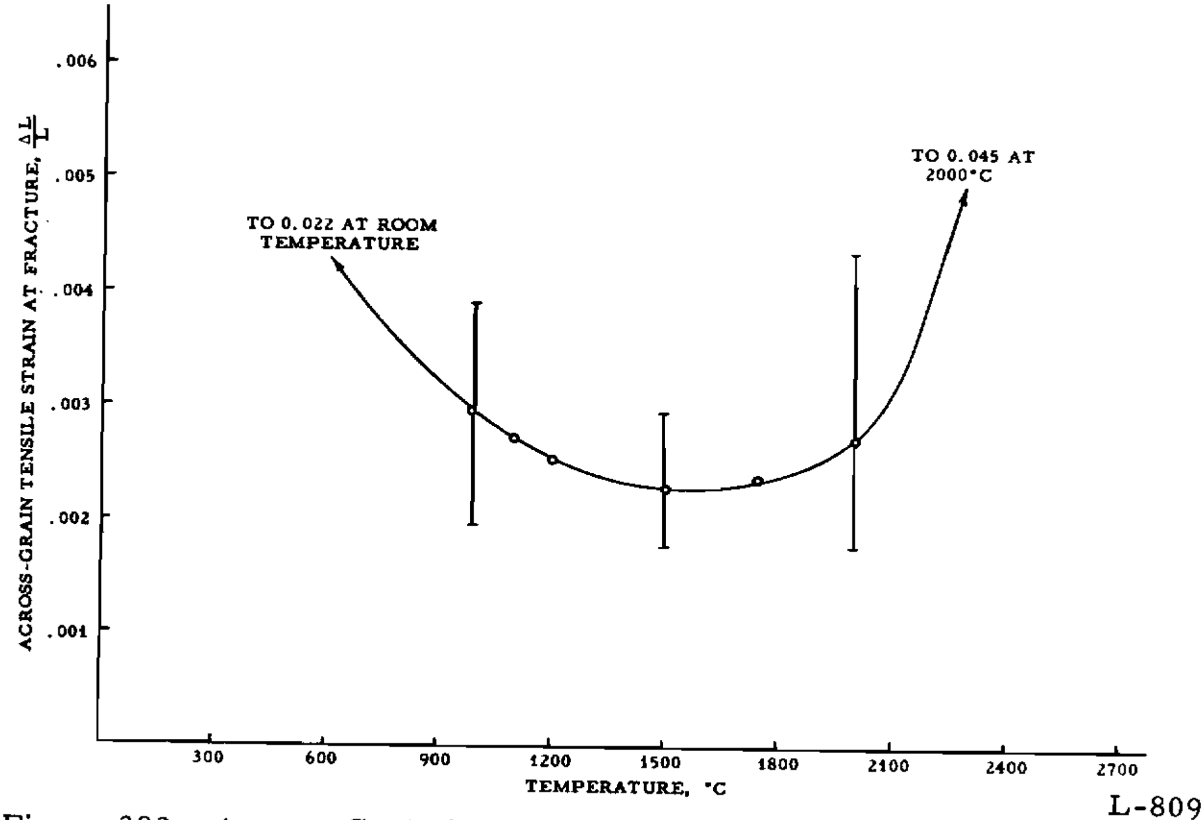


Figure 382. Across-Grain Tensile Strain at Fracture vs. Temperature, RVA Graphite, 33-Inch Diameter by 42-Inch Length

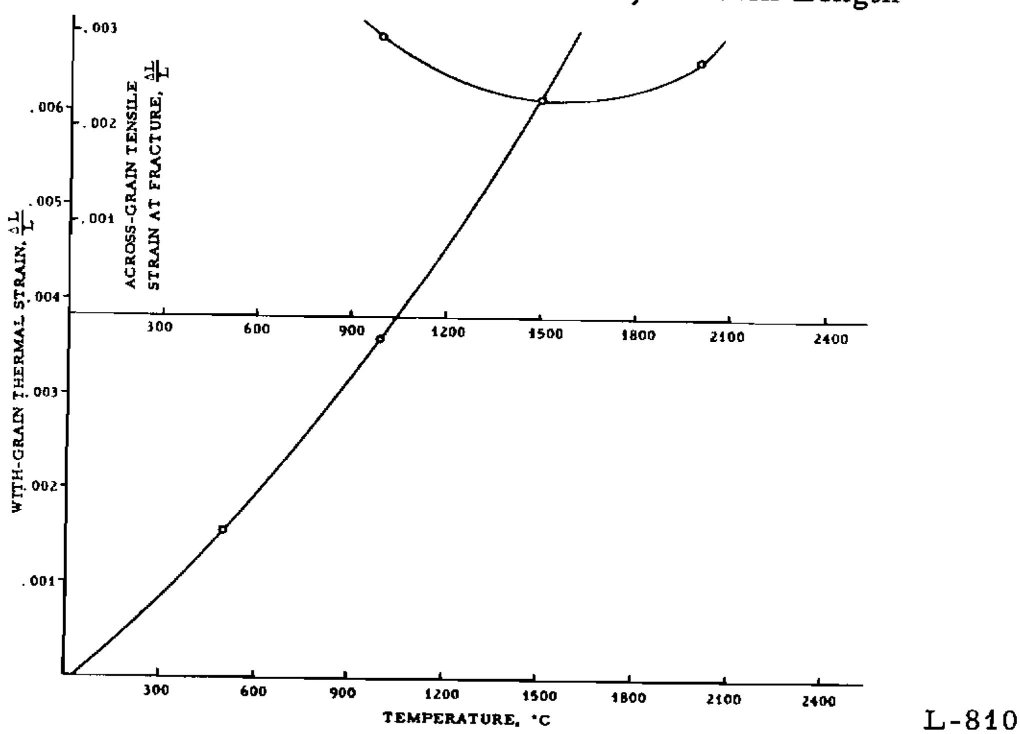


Figure 383. Across-Grain Thermal Strain Curve Superimposed Upon Across-Grain Tensile Strain at Failure Curve, RVA Graphite

APPENDIX III

FREQUENCY POLYGONS AND NORMAL DISTRIBUTION CURVES

When a property has been measured on a large number of samples of the same graphite grade, it is not only desirable to know the average and standard deviation but also to have some knowledge of the distribution of the data and how it deviates from a normal (Gaussian) distribution. The equation of a normal distribution curve is [27]

$$f(X) = \frac{n}{\sigma\sqrt{2\pi}} \exp\left[-(X_i - \bar{X})^2/2\sigma^2 \right] \quad (1)$$

where X_i = value of property measured on the i th sample

$\bar{X}$ = average value of property

σ = standard deviation

n = total number of samples

Once the average and standard deviation has been computed for a set of data it is possible to calculate a normal frequency distribution curve for that data by substituting the actual values of X_i, $\bar{X}$, n, and σ into Equation 1. By superimposing the normal distribution curve upon the actual frequency distribution (frequency polygon) it is possible to tell at a glance where and how the data deviates from a normal distribution. It is not feasible to plot frequency polygons and calculate and plot normal distribution curves for several sets of data unless it is done by a high-speed electronic computer.

The statistics, frequency polygons, and normal distribution curves presented in this appendix have been calculated and printed by an I. B. M. 7094 computer, the charts photographically reduced 30 per cent in size and figure numbers and captions added. The actual frequency polygons are formed by stars (*) and the normal distribution curves by zeros.

The computer prints four digit numbers along the abscissa. The decimal point, which is always printed between the first and second digits, counting from left to right, is not always in the correct location. The computer, therefore, prints a statement directly below the numbers which gives the correct location of the decimal point. For example, in Figure 384 the statement in ". . . . X is the cell midpoint times ten to the plus 0", indicating that the decimal is correctly located as printed; in Figure 414 it reads ". . . . X is the cell midpoint times ten to the plus 3", indicating that the decimal point should be moved three places to the right of the location shown in the figure.

A series of letters, S S X S S, is printed at the top of each figure by the computer. The location of X is such that a line through X perpendicular to the abscissa will intersect the abscissa at the average value; i.e., at 1.940 in Figure 384. The average bulk density of ZTA graphite is 1.940 g/cc (Table 3, Section 3.2.1.). Similarly, lines through the second and third S perpendicular to the abscissa intersect the abscissa at minus 1σ and plus 1σ, respectively. Lines through the first and fourth S perpendicular to the abscissa intersect the abscissa at minus 2σ and plus 2σ, respectively.

In the upper left hand corner of each figure the computer has printed the number of samples, the average value, the maximum and minimum values, the standard deviation, the skewness and the kurtosis. Skewness is the departure of a frequency distribution from symmetry and is measured by the third mean moment μ_3 of the distribution divided by $\mu_2{}^{3/2}$, where μ_2 is the second mean moment.[28] Kurtosis is a property intended to express the relative peakedness of a distribution, and is the ratio $\mu_4/\mu_2{}^2$, where μ_4 is the fourth moment of the distribution.[29] Although kurtosis is a statistic of questionable significance it has been included as a point of minor interest.

The deviation of a number from the average value is represented by $X_i - \overline{X}$. The arithmetic means of the various powers of $X_i - \overline{X}$ are called the moments of the distribution.[30] Thus

$$\text{1st moment} = \mu_1 = \frac{\Sigma(X_i - \overline{X})}{n}$$

$$\text{2nd moment} = \mu_2 = \frac{\Sigma(X_i - \overline{X})^2}{n} = \sigma^2$$

$$\text{3rd moment} = \mu_3 = \frac{\Sigma(X_i - \overline{X})^3}{n}$$

$$\text{4th moment} = \mu_4 = \frac{\Sigma(X_i - \overline{X})^4}{n}$$

therefore

$$\text{skewness} = \frac{\Sigma(X_i - \overline{X})^3}{n\sigma^3} \tag{2}$$

$$\text{kurtosis} = \frac{\Sigma(X_i - \overline{X})^4}{n\sigma^4} \tag{3}$$

The skewness and kurtosis printed on each of the figures were computed by means of Equation 2 and 3, respectively.

Frequency polygons and normal distribution curves are presented for only those graphite grades for which three or more blocks have been sampled. This limits the curves to 14-inch and $8\frac{1}{2}$-inch diameter ZTA and 33-inch diameter RVA graphite. Distribution data for the following room-temperature properties are presented in this appendix.

Bulk Density

Specific Resistance

Young's Modulus of Elasticity

Flexural Strength

Compressive Strength

Apparent Shear Strength (RVA graphite only)

In addition to frequency polygons and normal distribution curves for the combined data from three or more blocks, polygons and curves are presented for individual blocks whenever the number of samples is twenty or greater. When the number of samples is small the deviation of the frequency polygon from the normal distribution curve can be large. This should be kept in mind when examining the figures in this appendix.

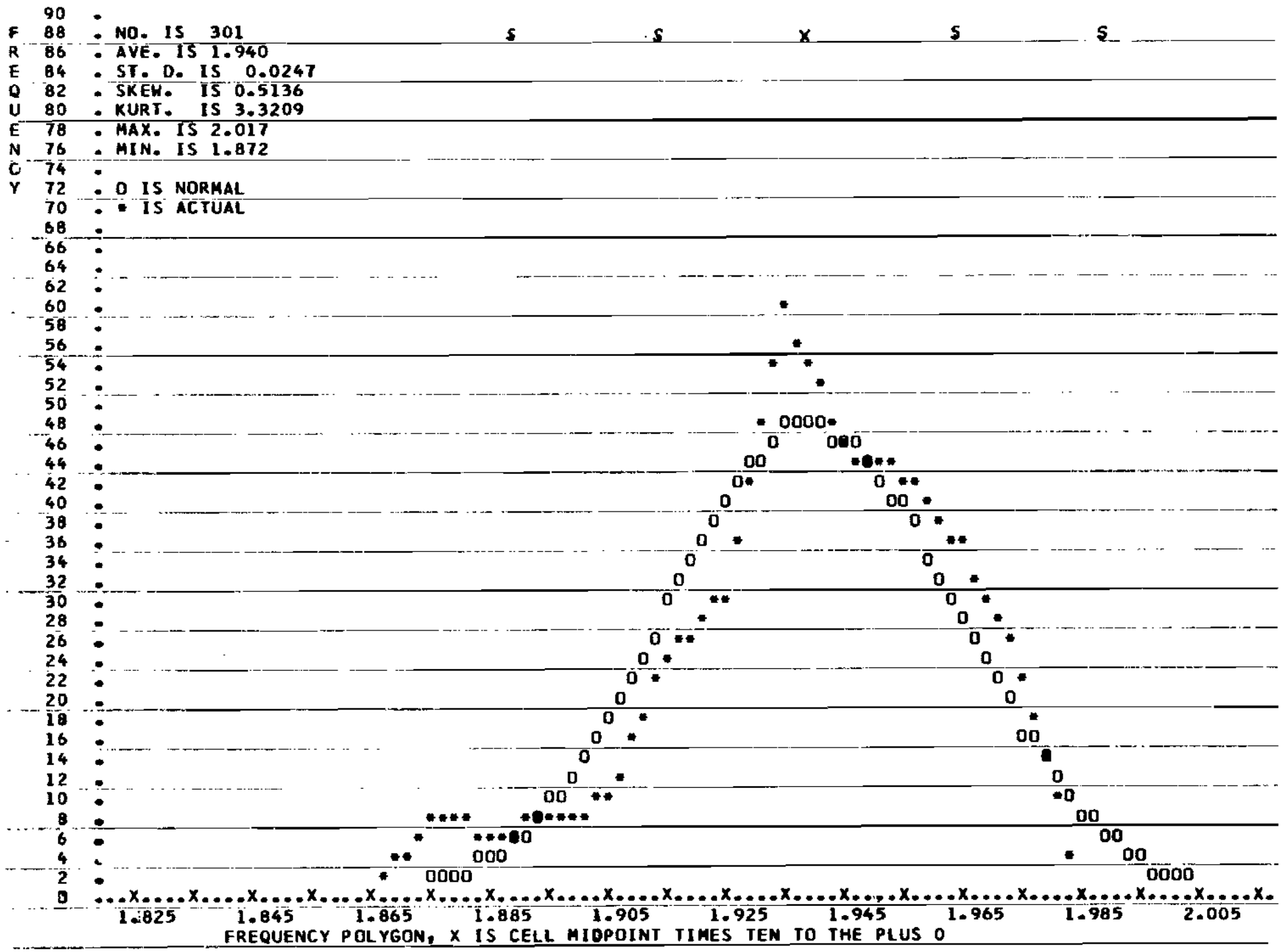


Figure 384. Frequency Distribution of Bulk Density Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Blocks No. 20, 23, 111, 153, and 159 Combined

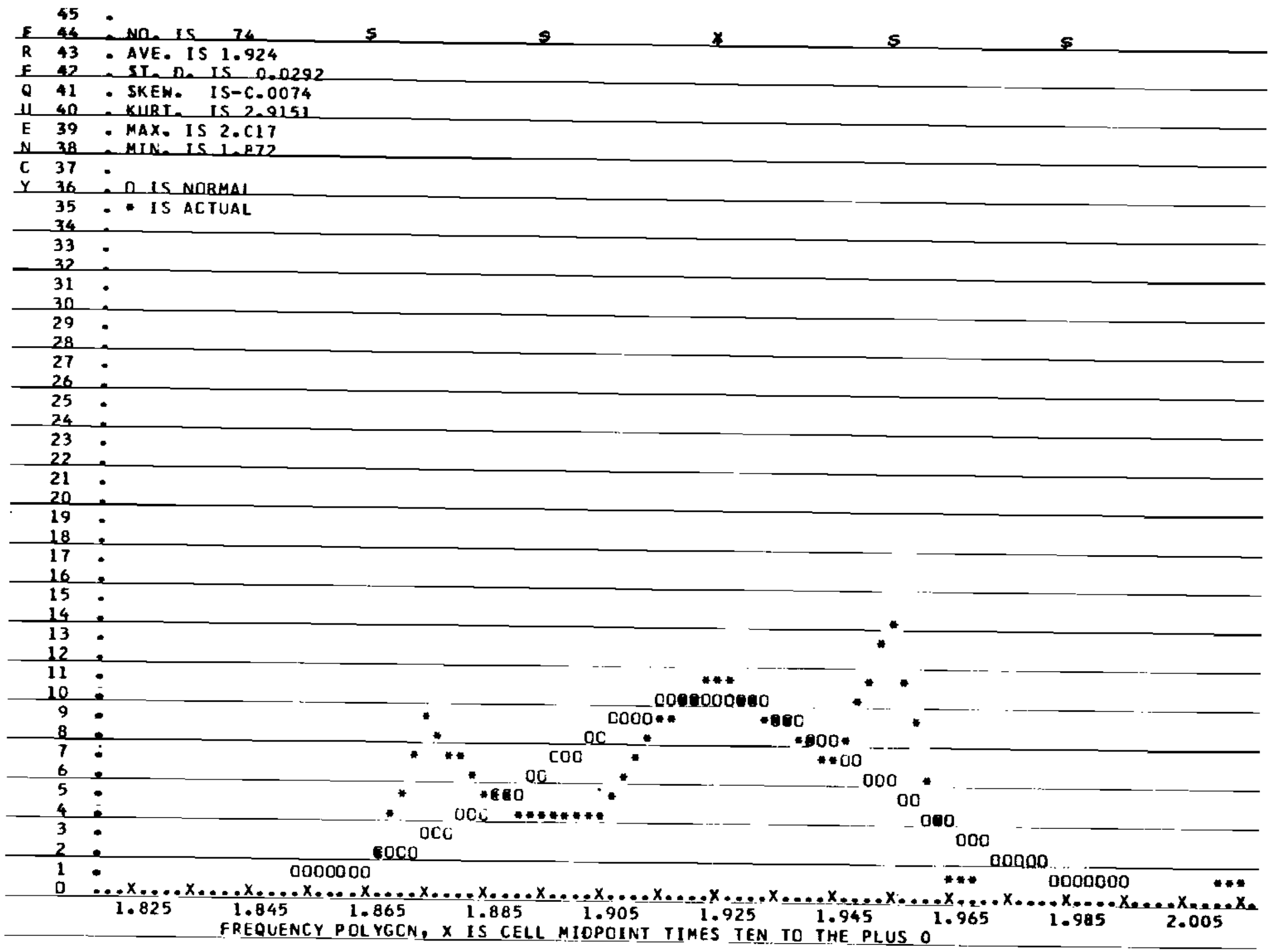


Figure 385. Frequency Distribution of Bulk Density Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 20

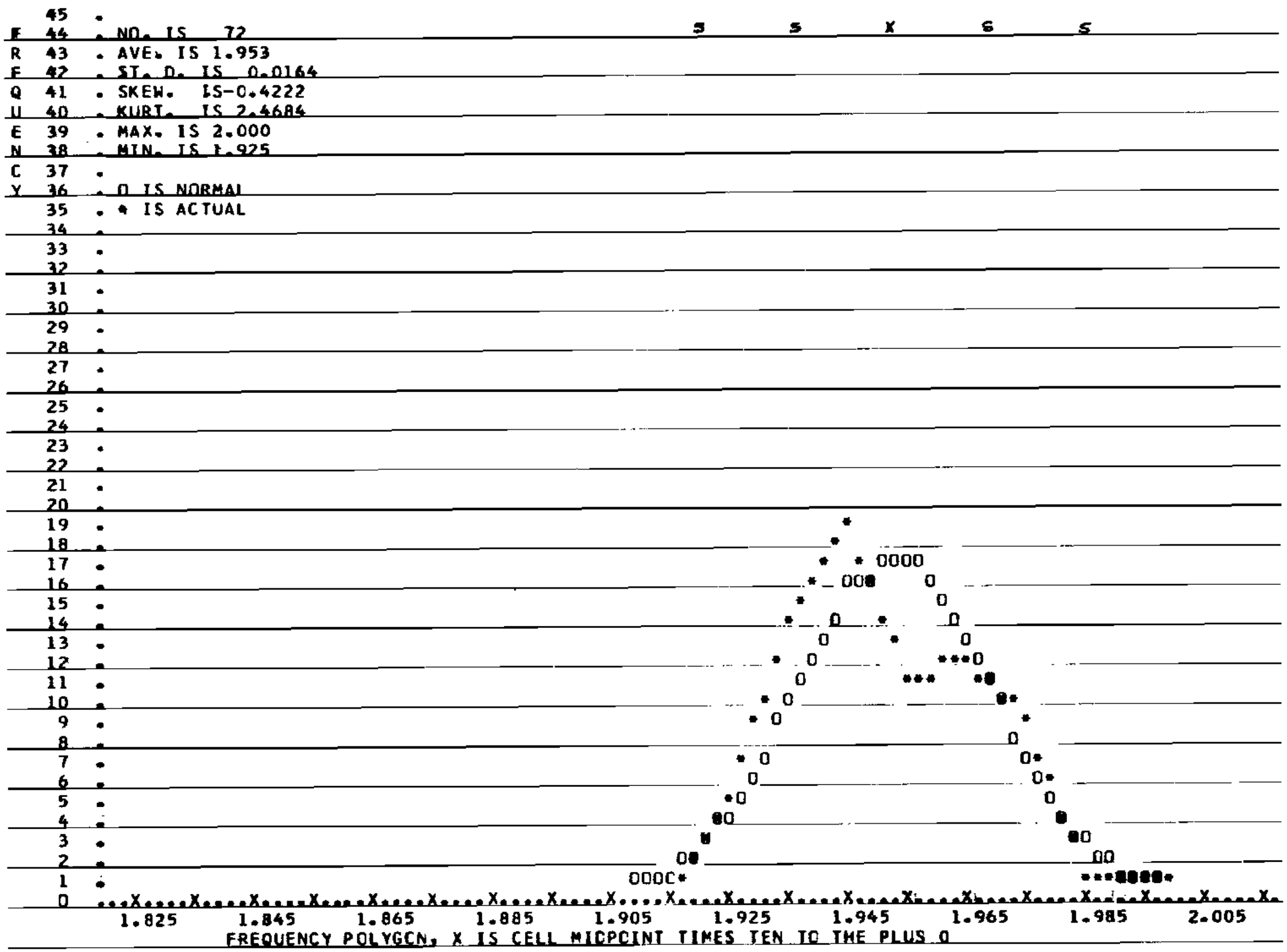


Figure 386. Frequency Distribution of Bulk Density Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 23

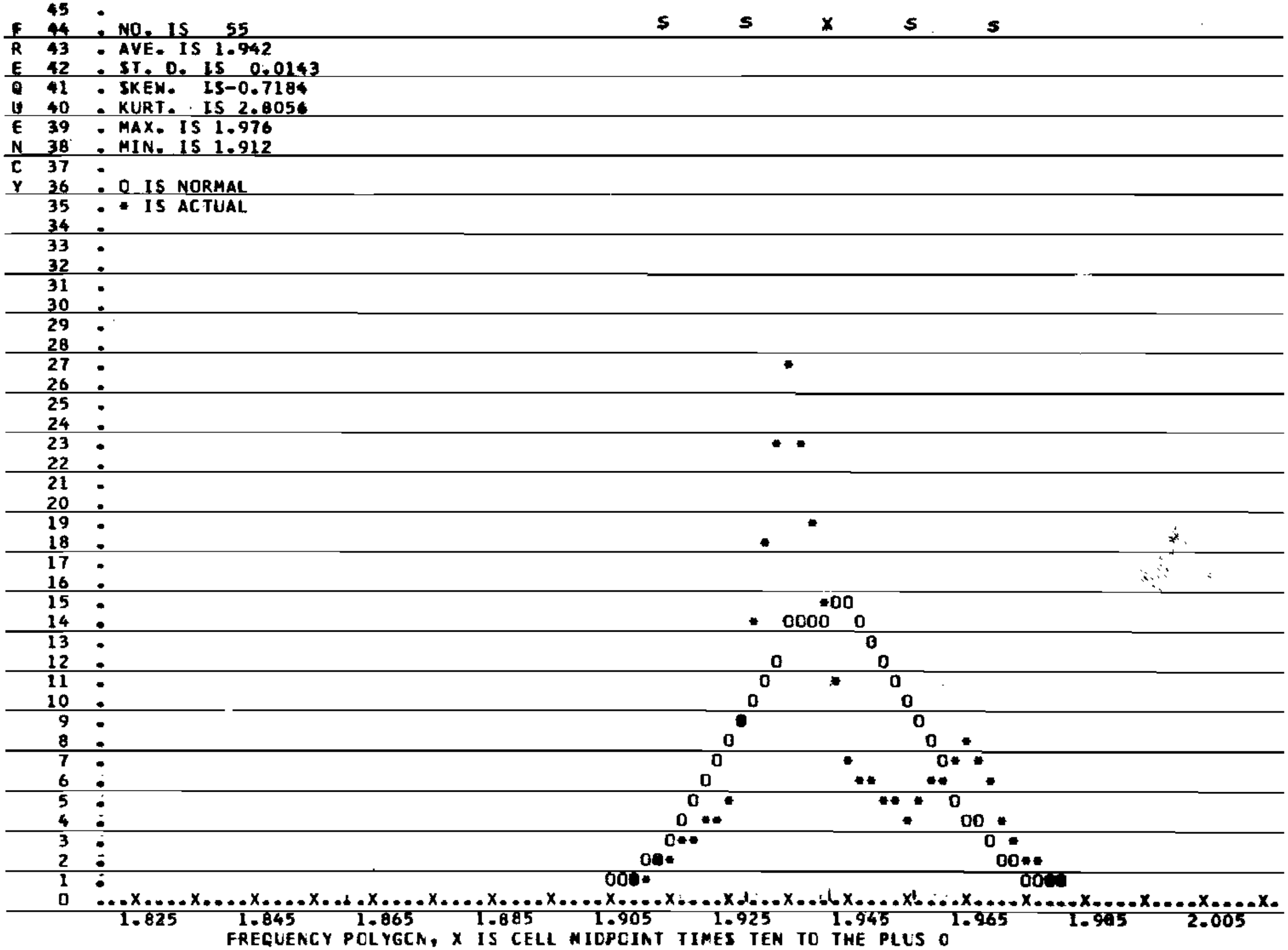


Figure 387. Frequency Distribution of Bulk Density Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 111

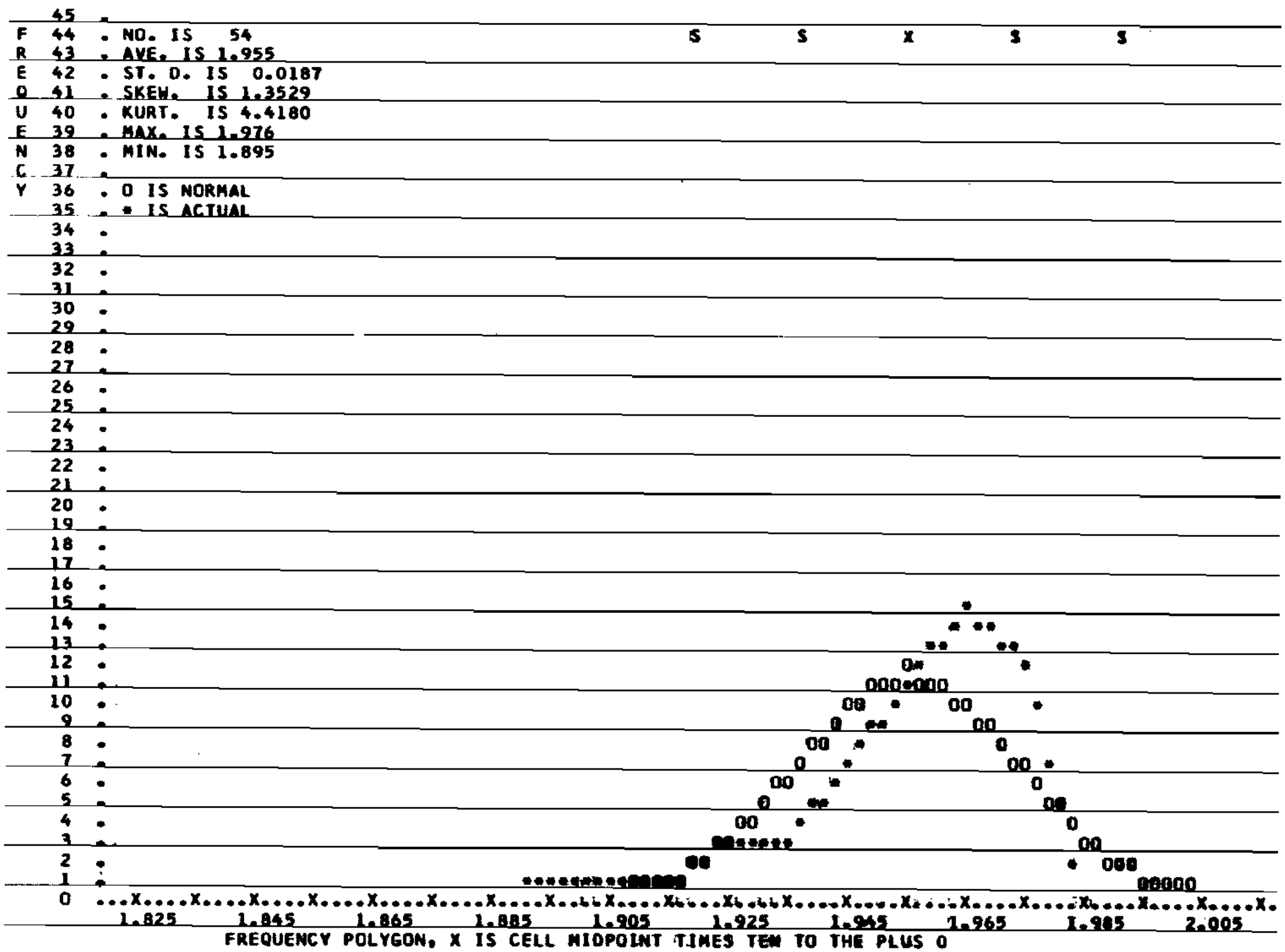


Figure 388. Frequency Distribution of Bulk Density Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 153

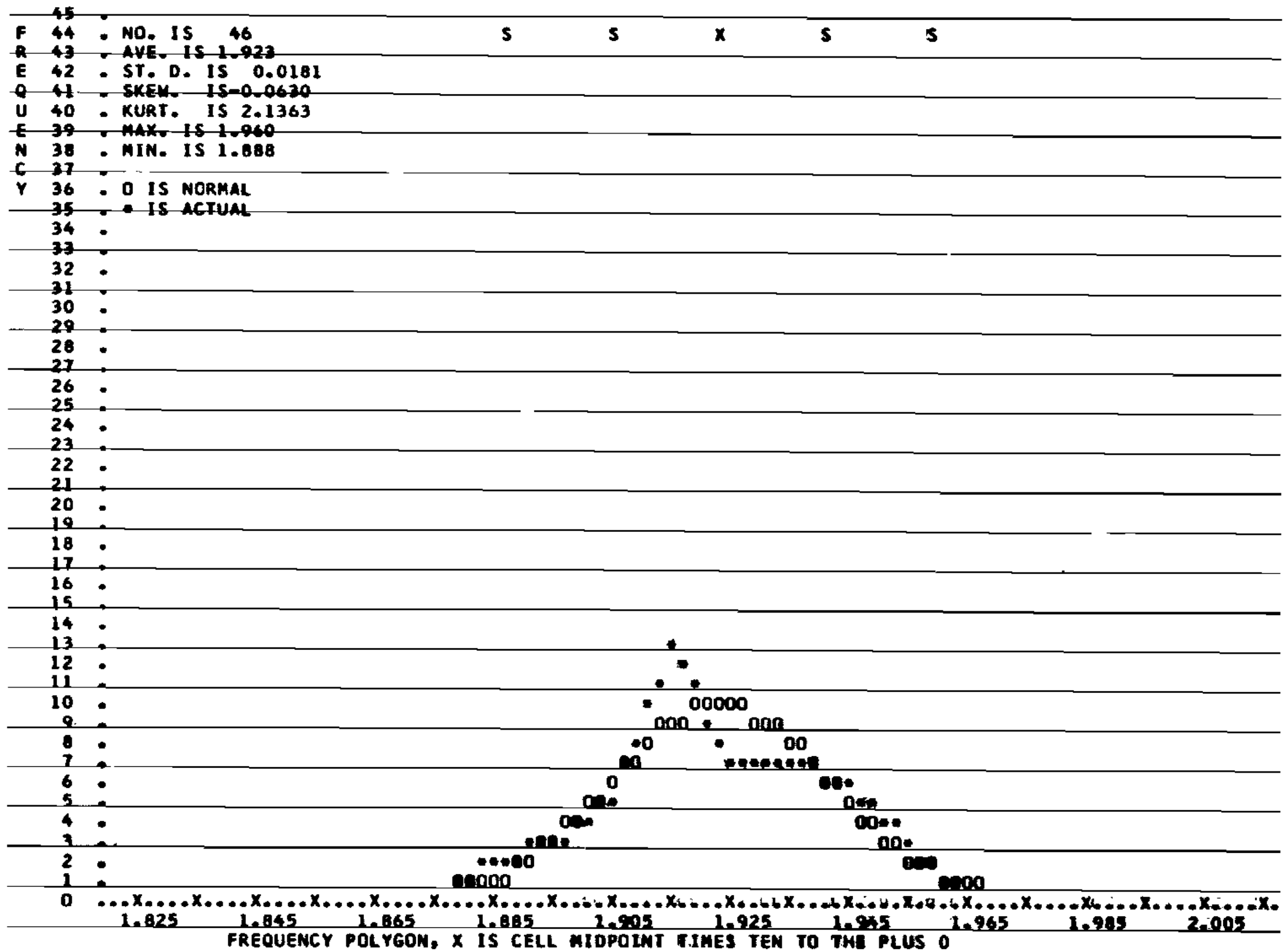


Figure 389. Frequency Distribution of Bulk Density Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 159

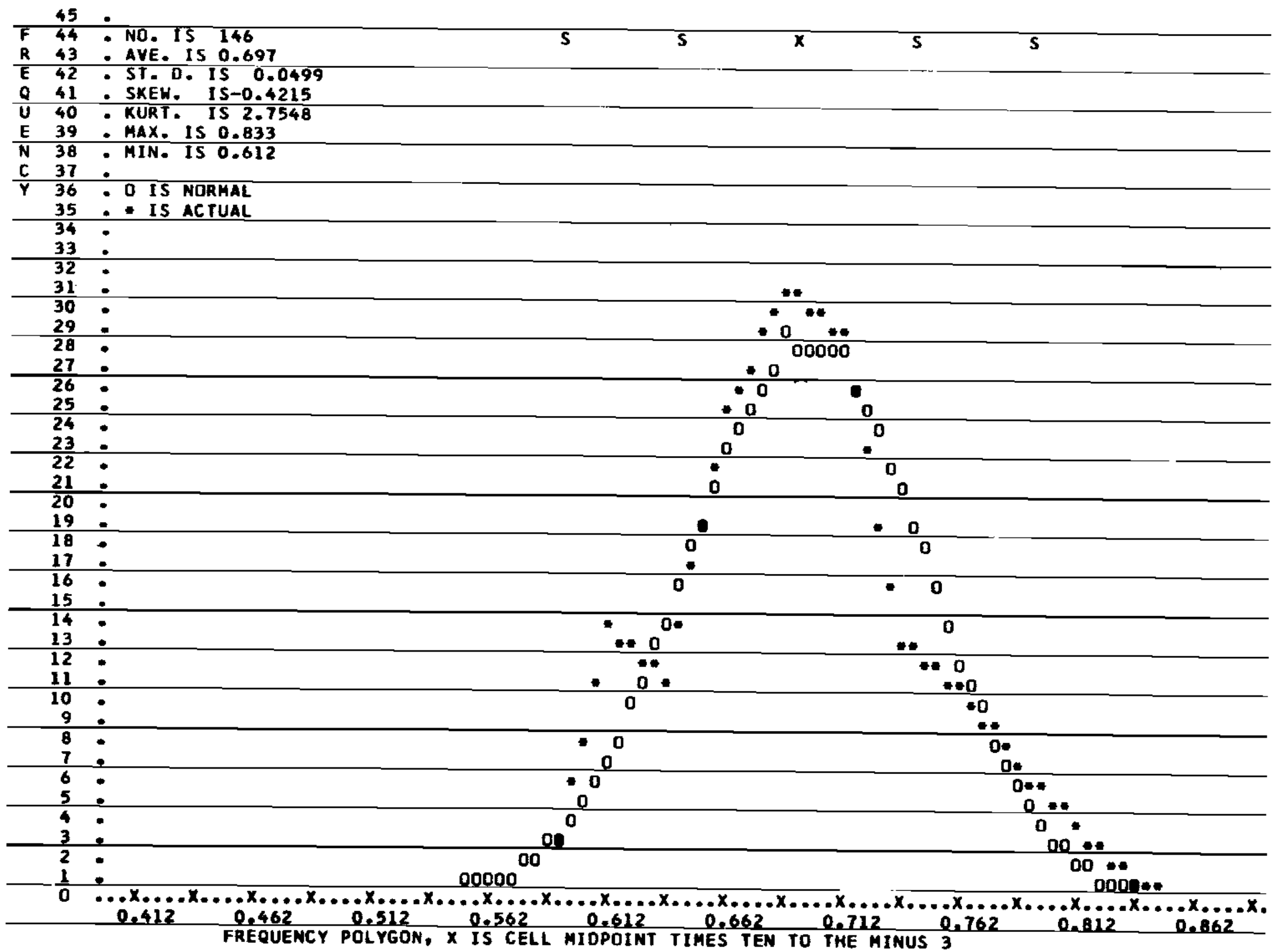


Figure 390. Frequency Distribution of With-Grain Specific Resistance Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Blocks No. 20, 23, 111, 153, and 159 Combined

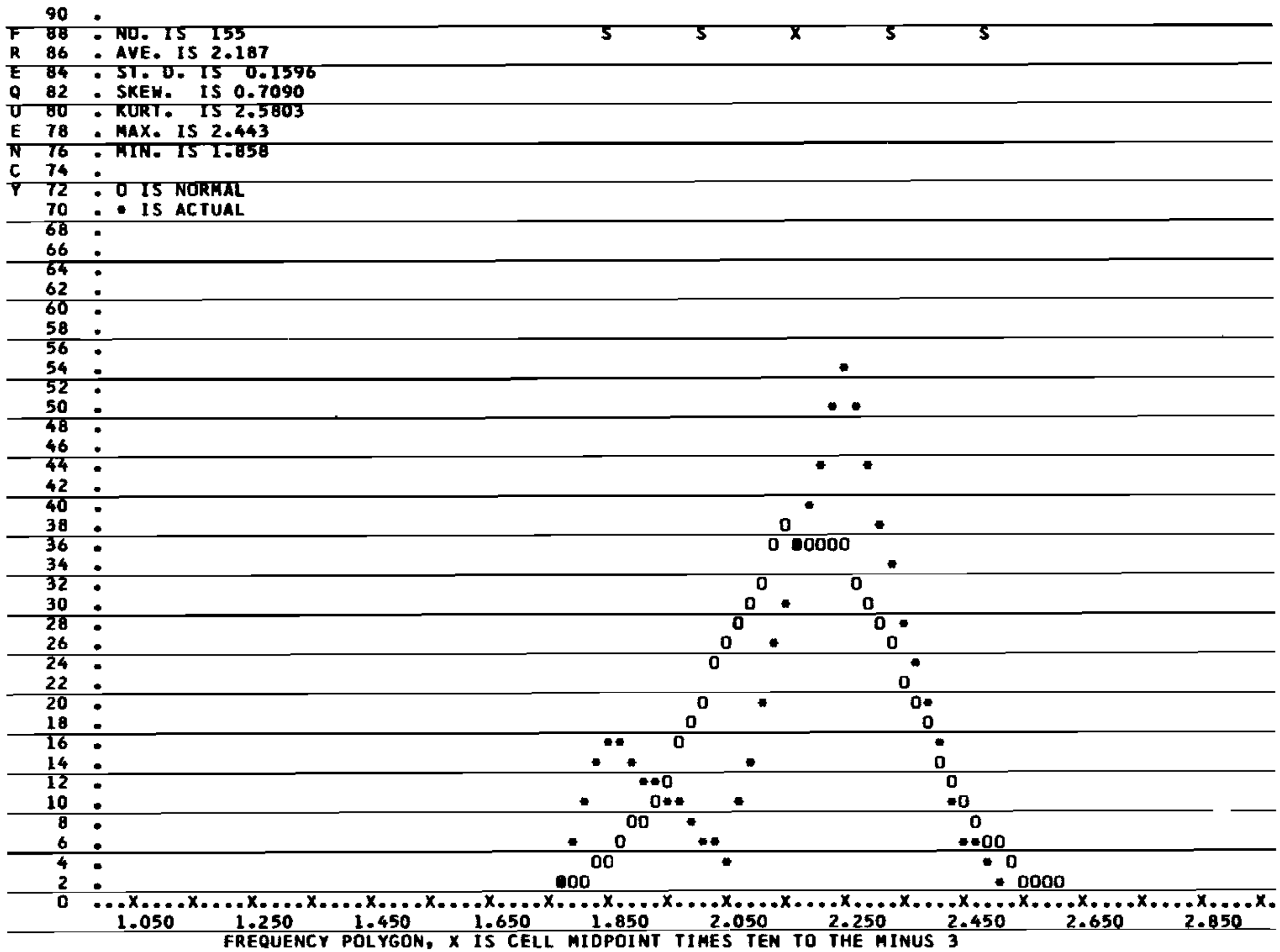


Figure 391. Frequency Distribution of Across-Grain Specific Resistance Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Blocks No. 20, 23, 111, 153, and 159 Combined

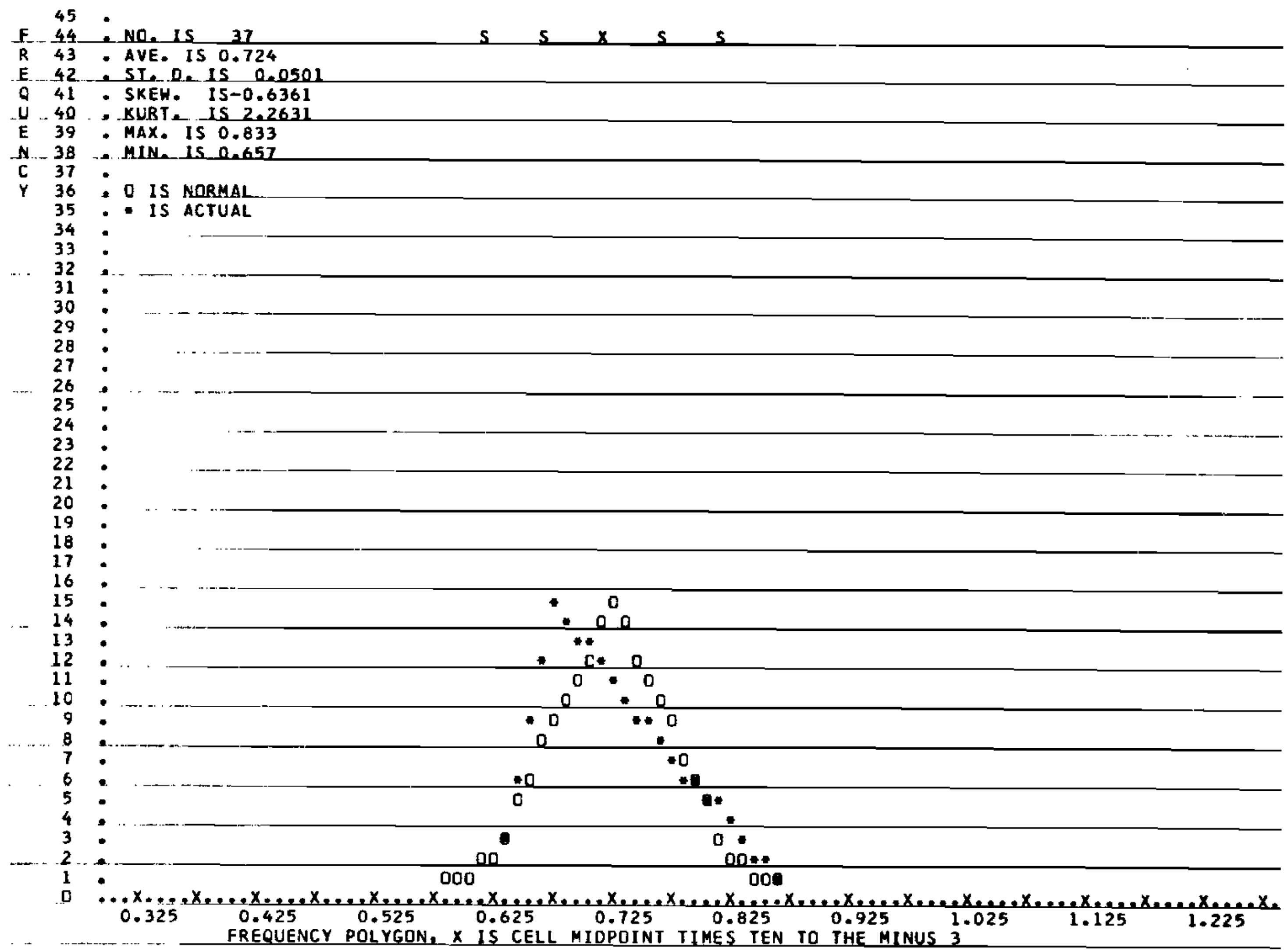


Figure 392. Frequency Distribution of With-Grain Specific Resistance Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 20

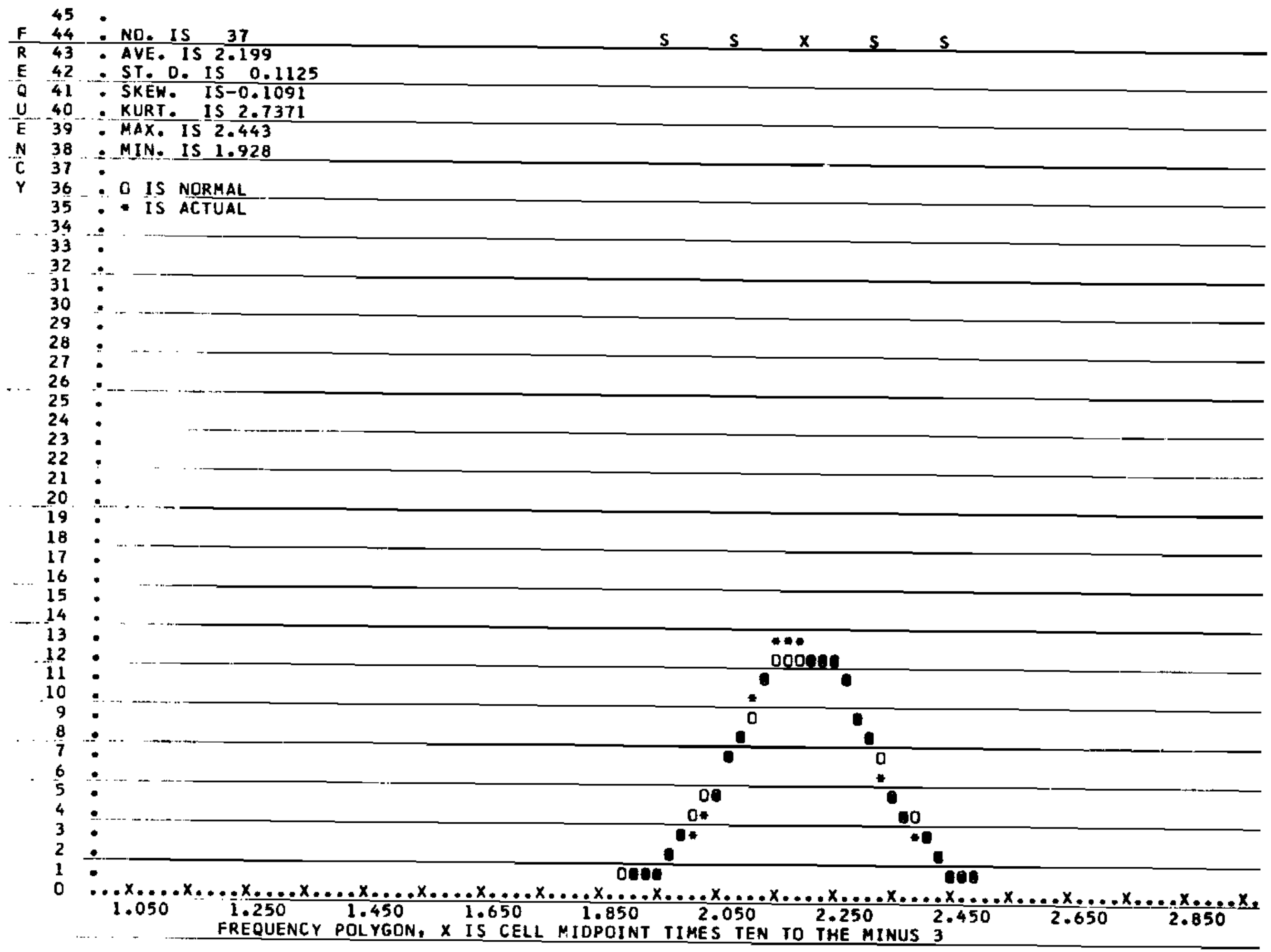


Figure 393. Frequency Distribution of Across-Grain Specific Resistance Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 20

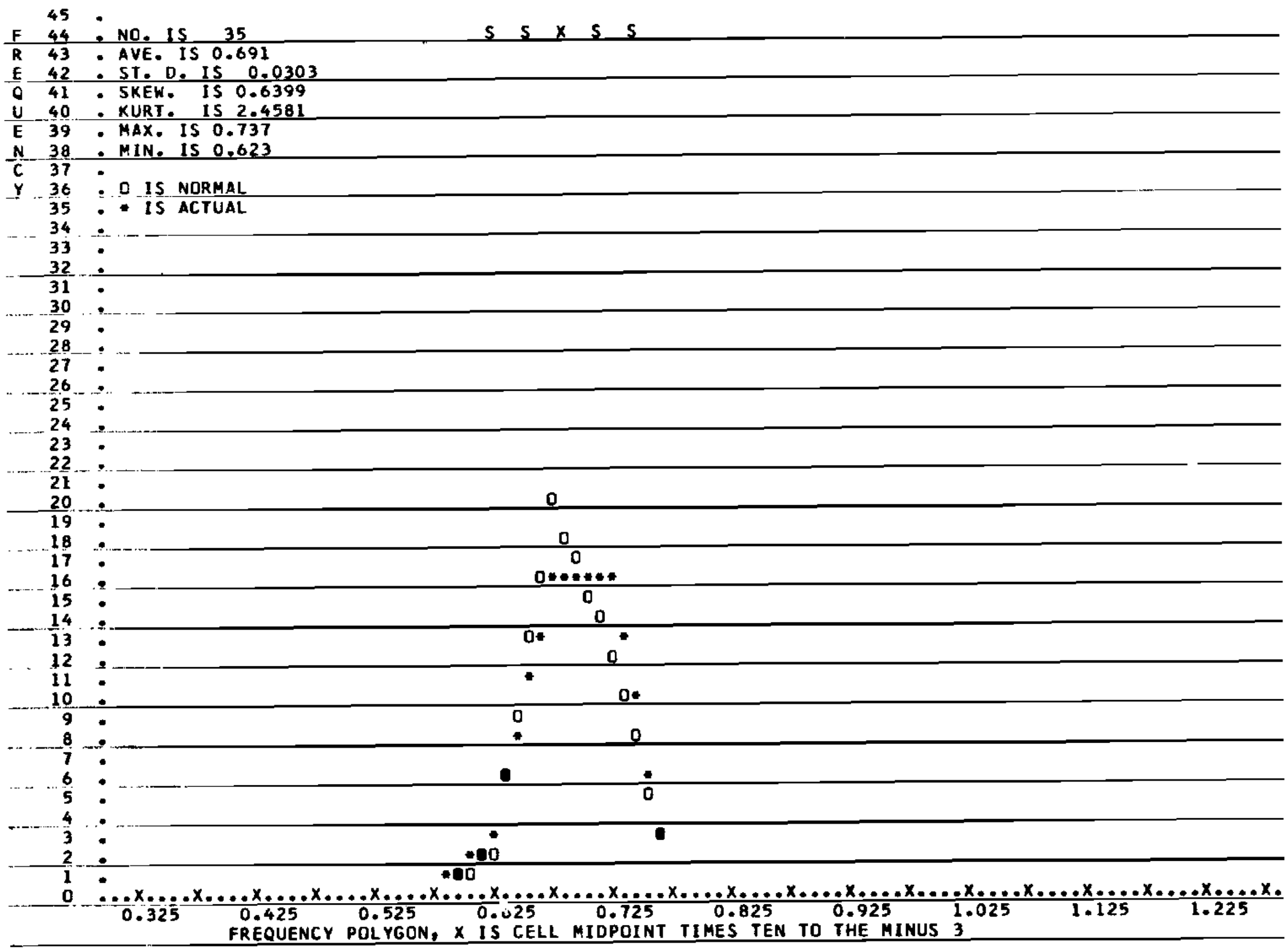


Figure 394. Frequency Distribution of With-Grain Specific Resistance Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 23

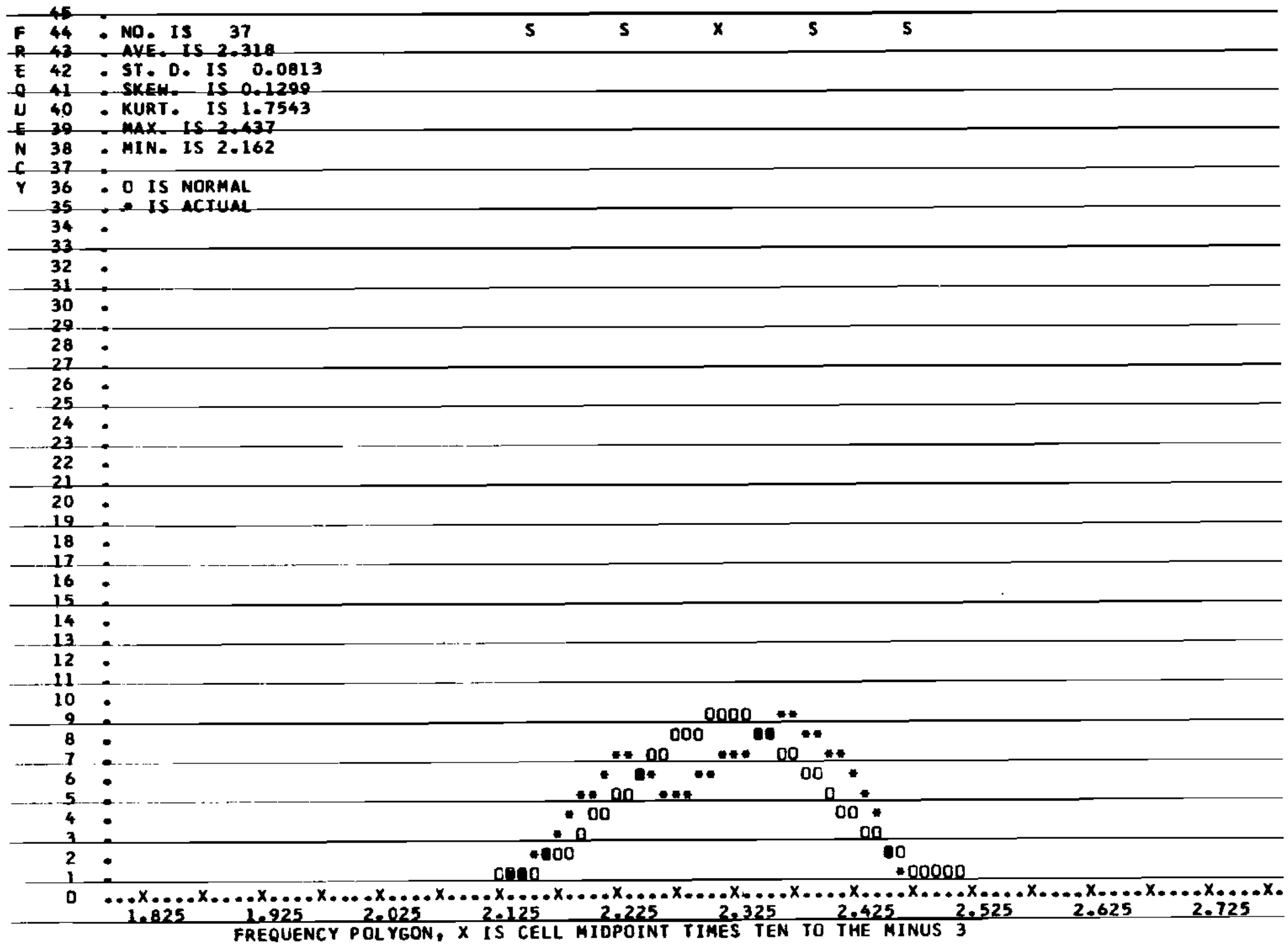


Figure 395. Frequency Distribution of Across-Grain Specific Resistance Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 23

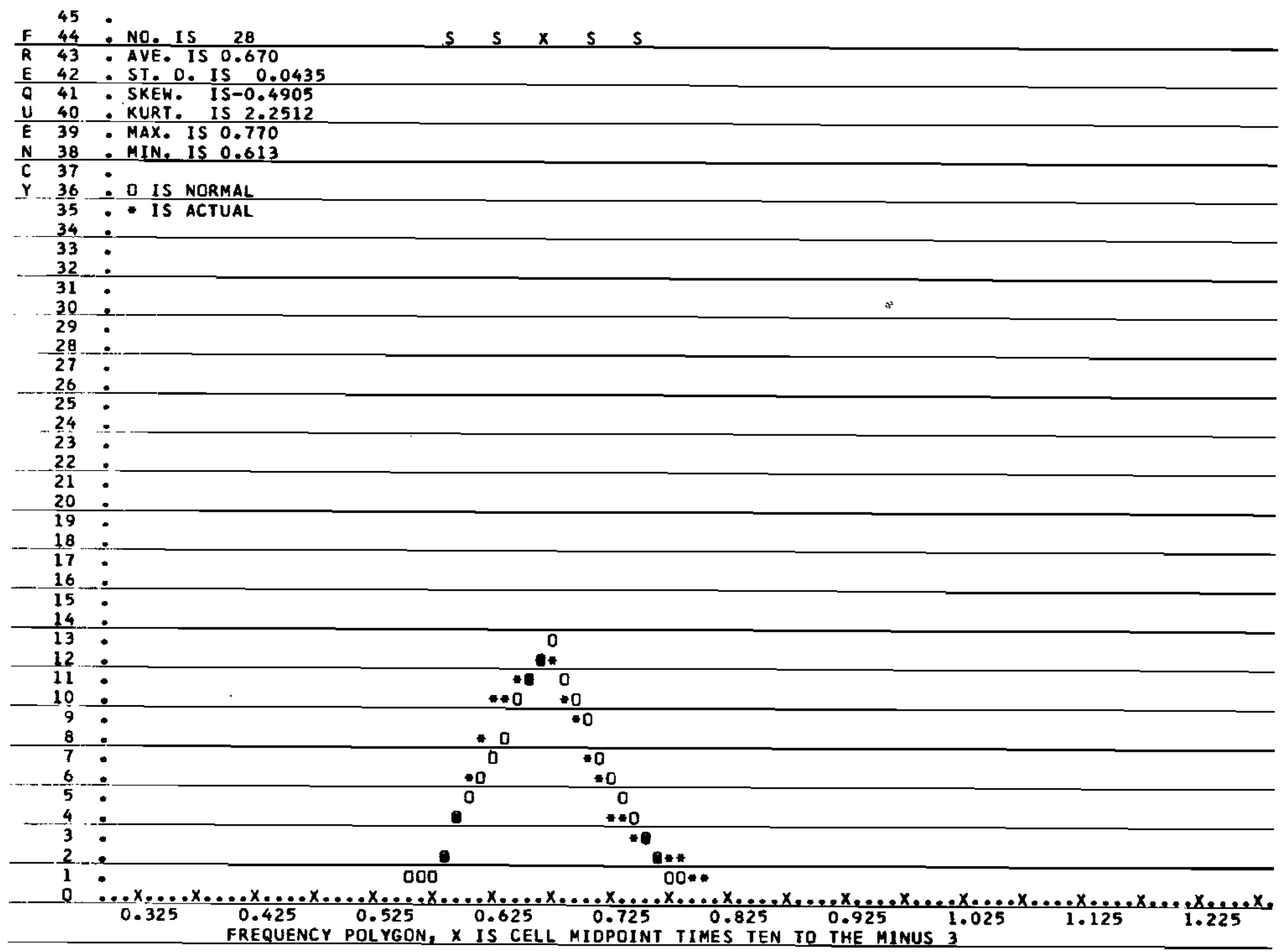


Figure 396. Frequency Distribution of With-Grain Specific Resistance Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 111

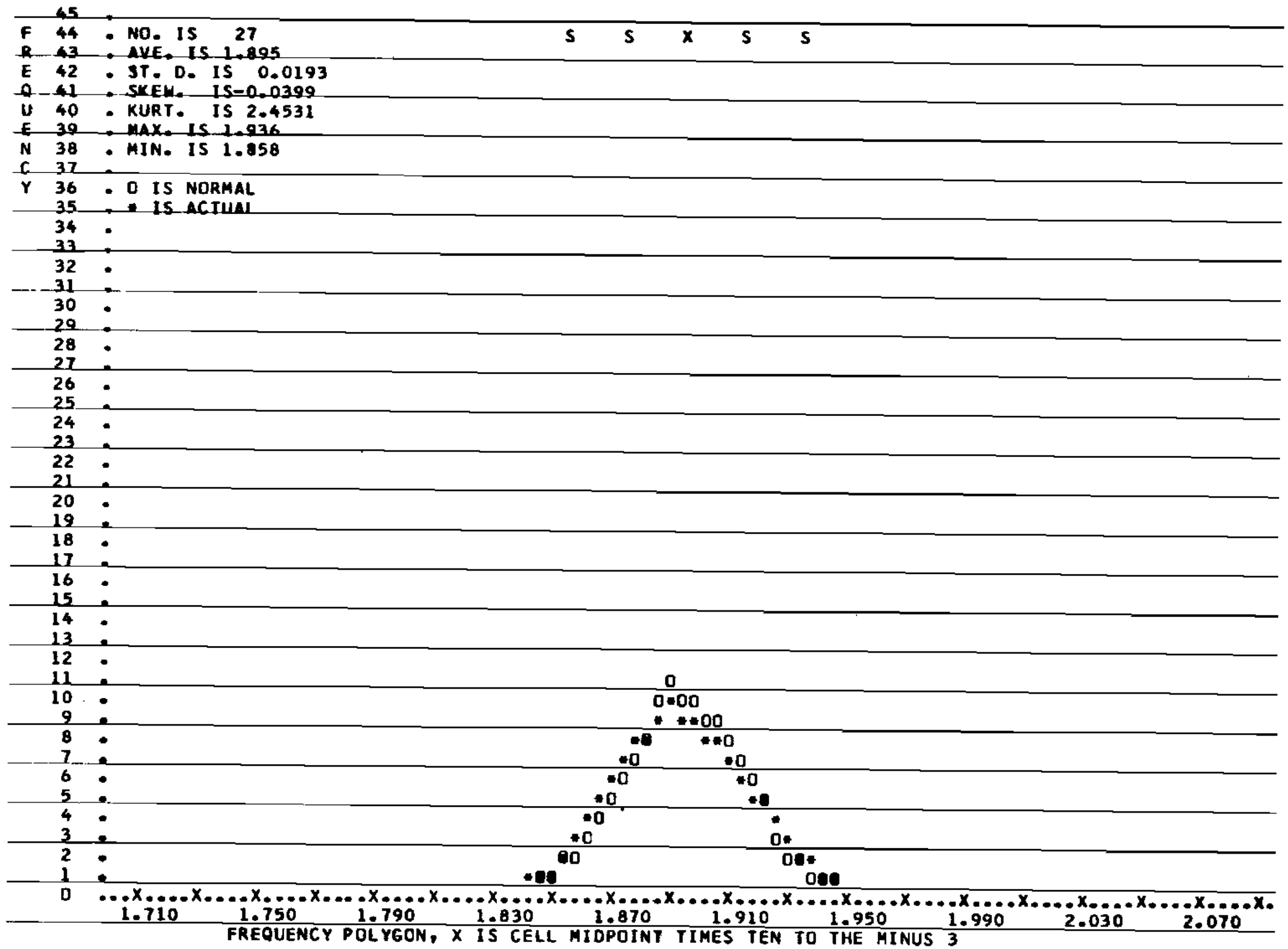


Figure 397. Frequency Distribution of Across-Grain Specific Resistance Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 111

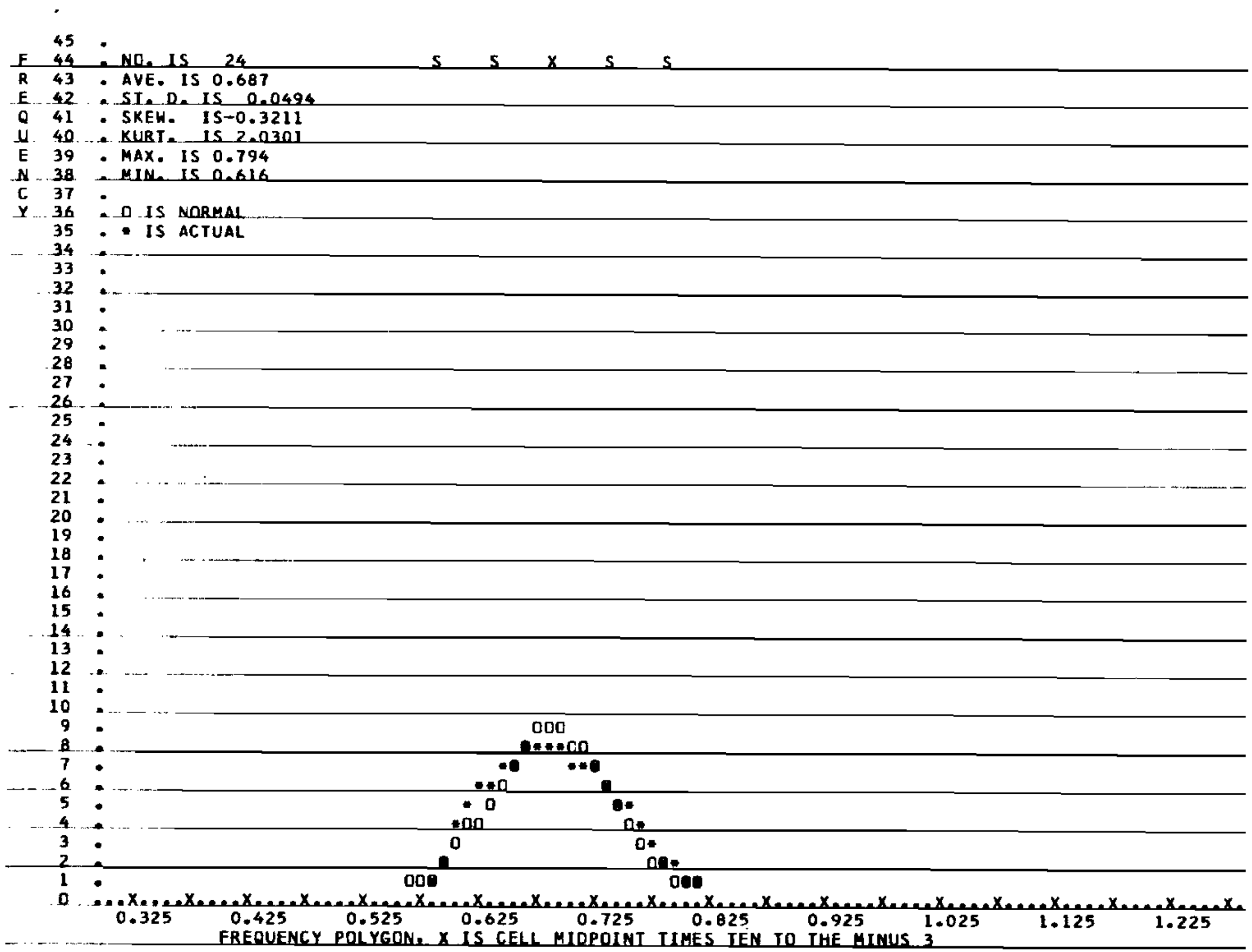


Figure 398. Frequency Distribution of With-Grain Specific Resistance Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 153

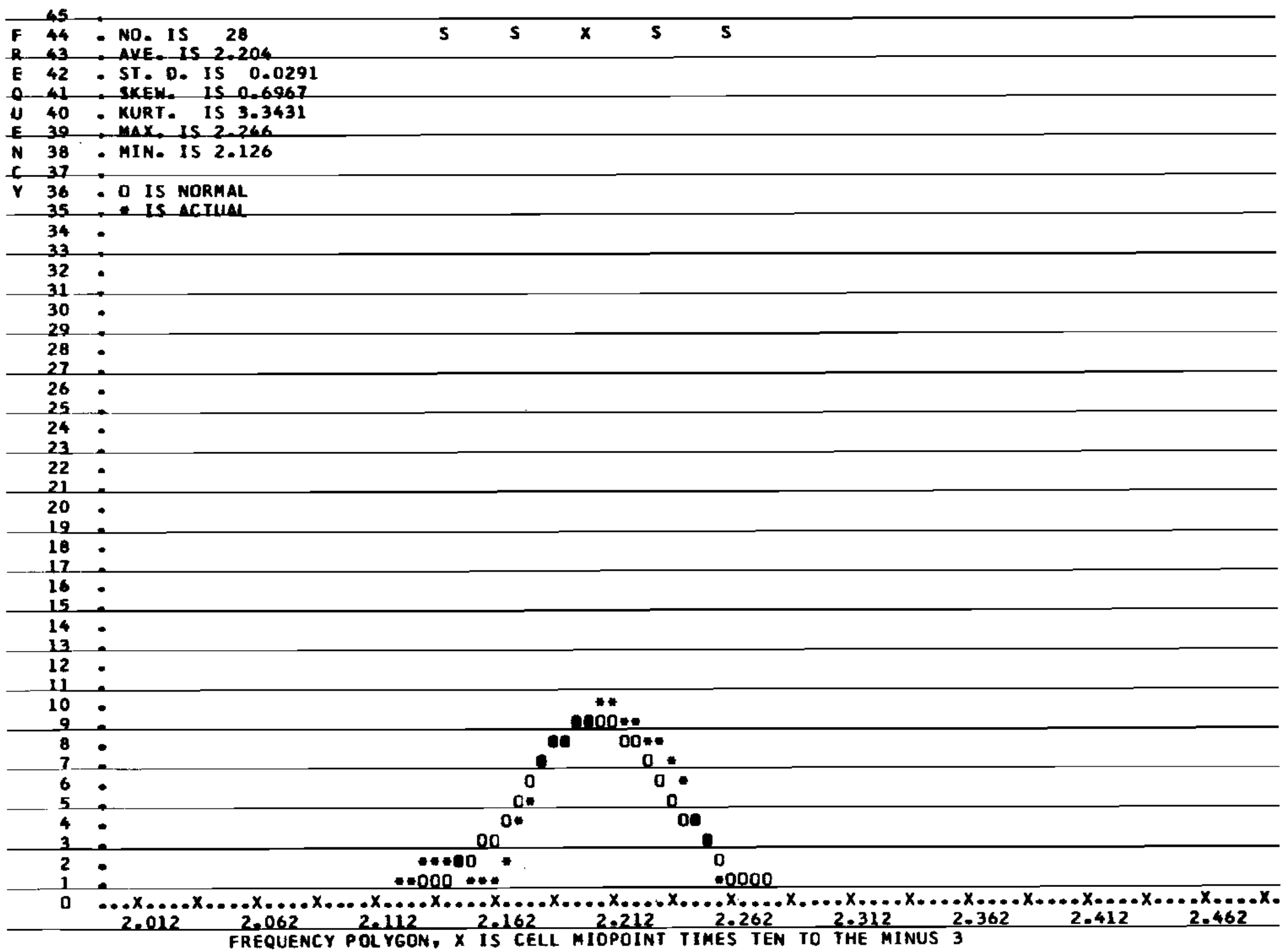


Figure 399. Frequency Distribution of Across-Grain Specific Resistance Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 153

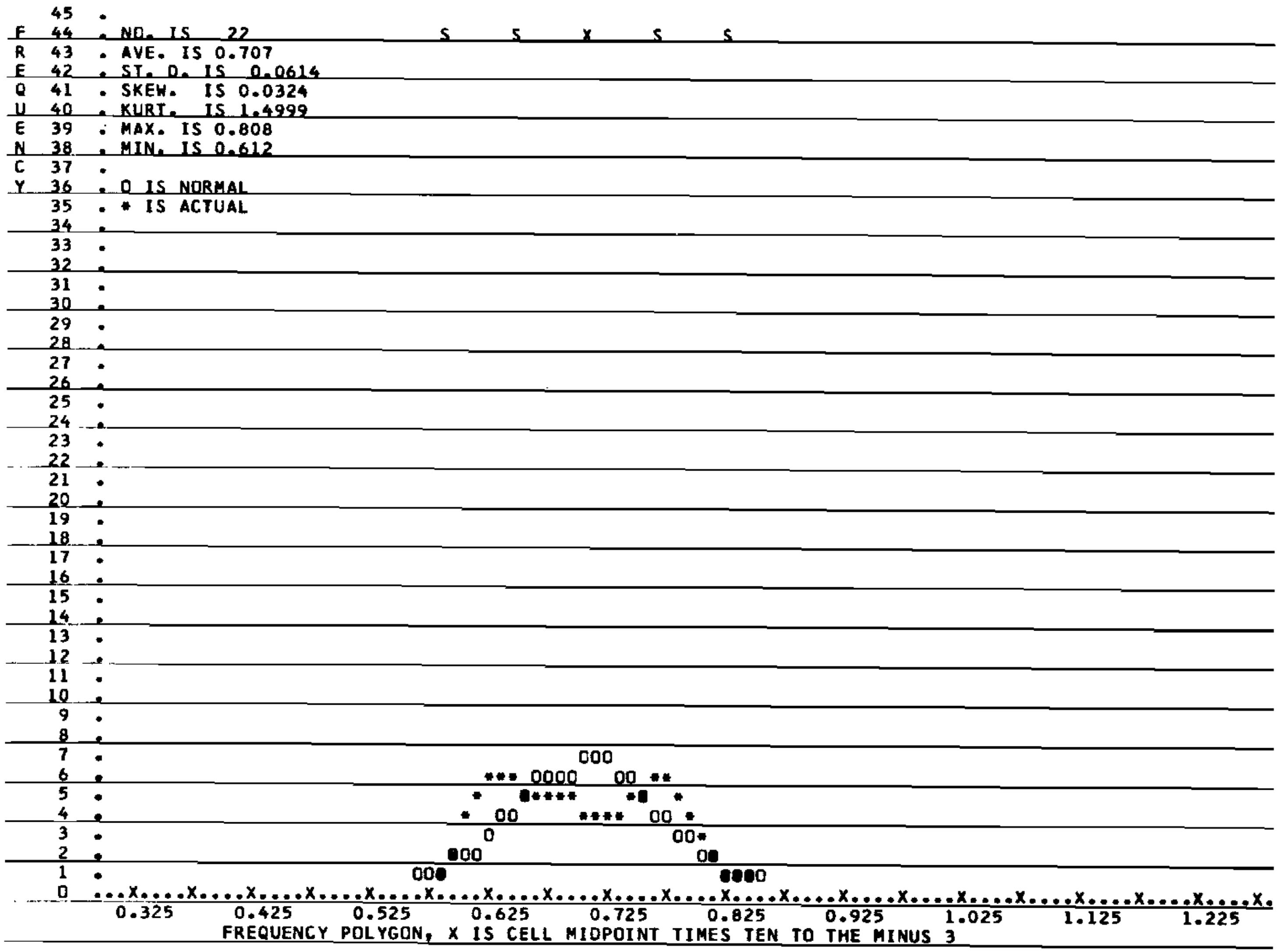


Figure 400. Frequency Distribution of With-Grain Specific Resistance Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 159

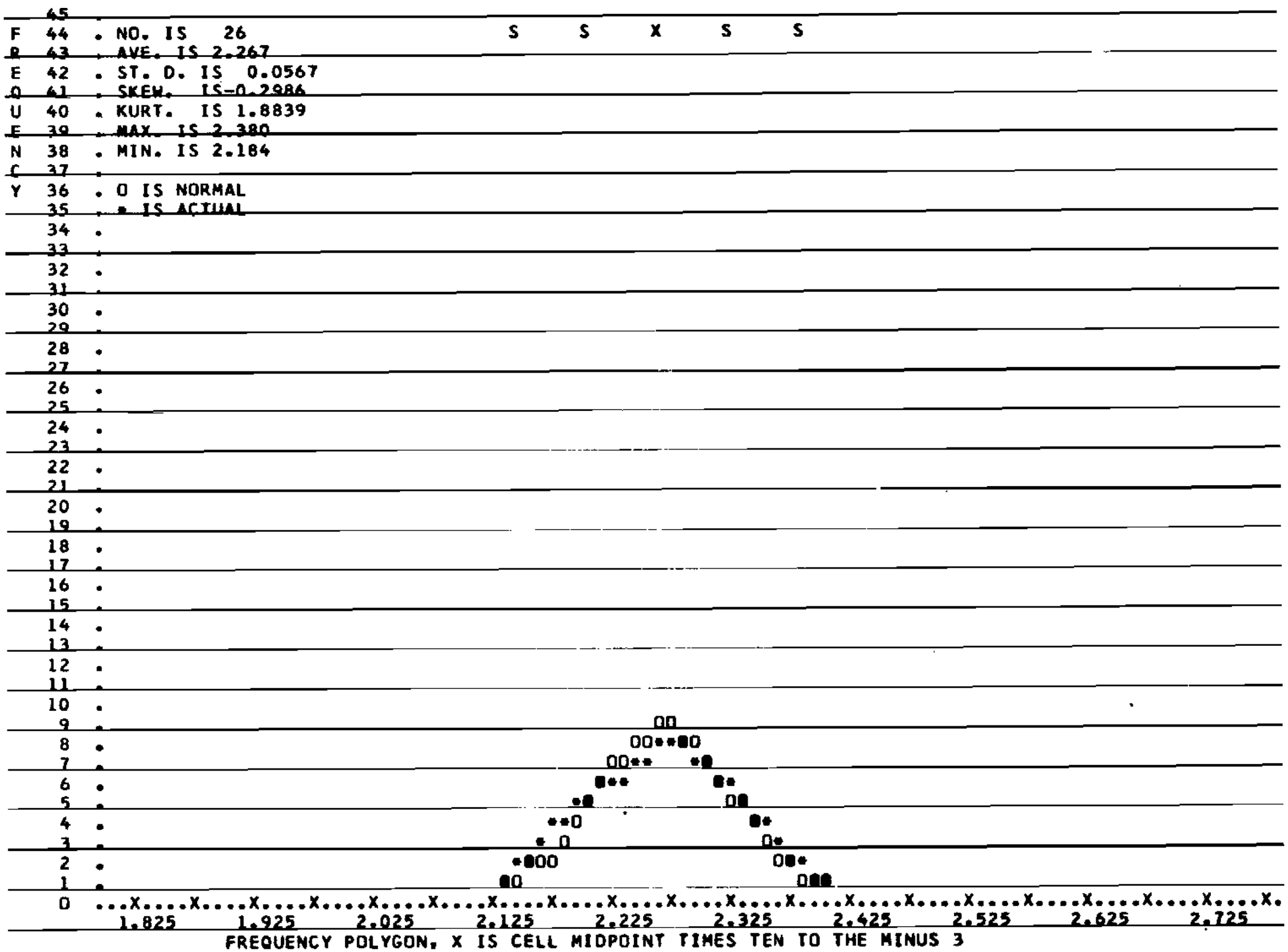


Figure 401. Frequency Distribution of Across-Grain Specific Resistance Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 159

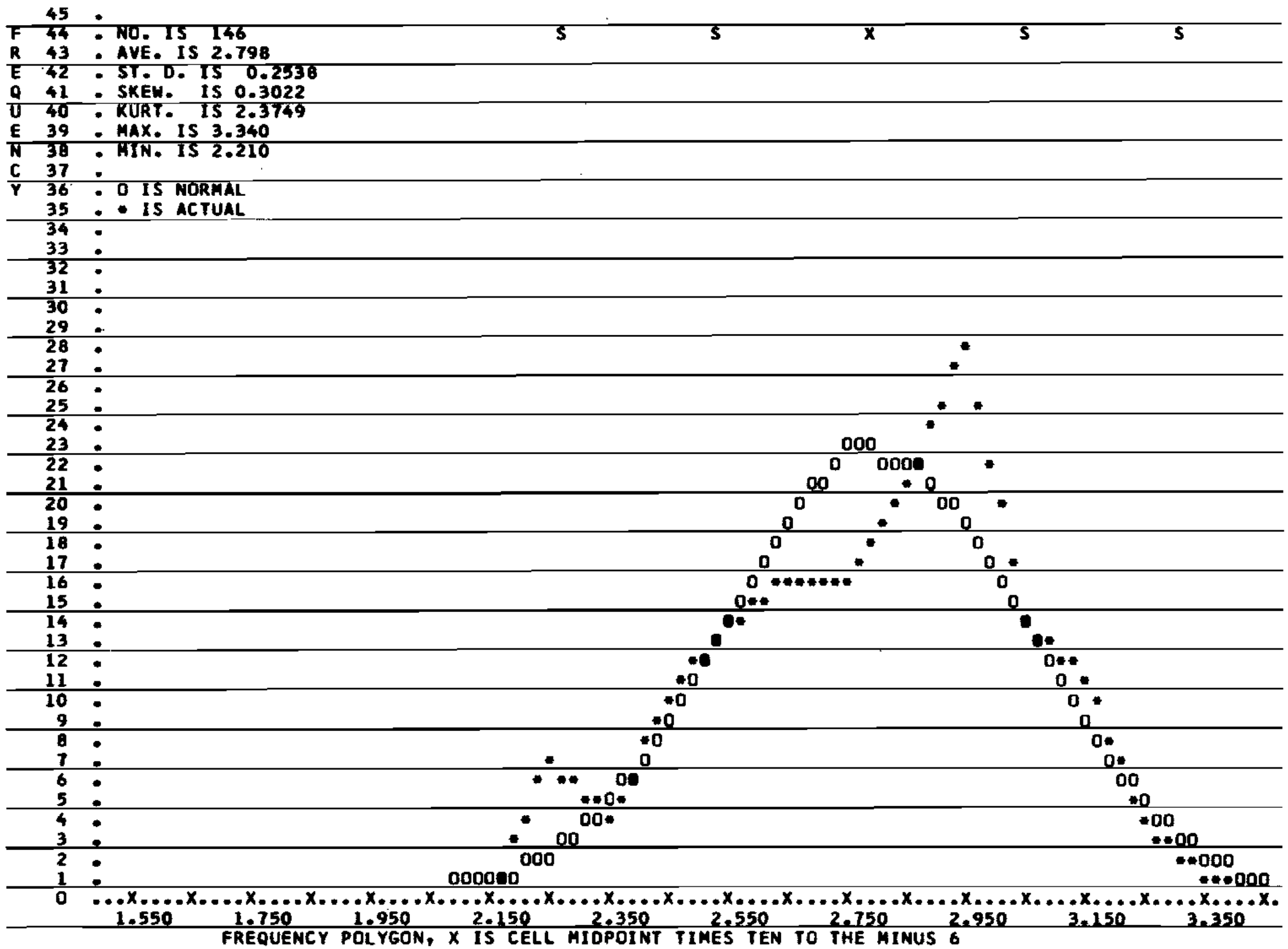


Figure 402. Frequency Distribution of With-Grain Young's Modulus of Elasticity Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Blocks No. 20, 23, 111, 153 and 159 Combined

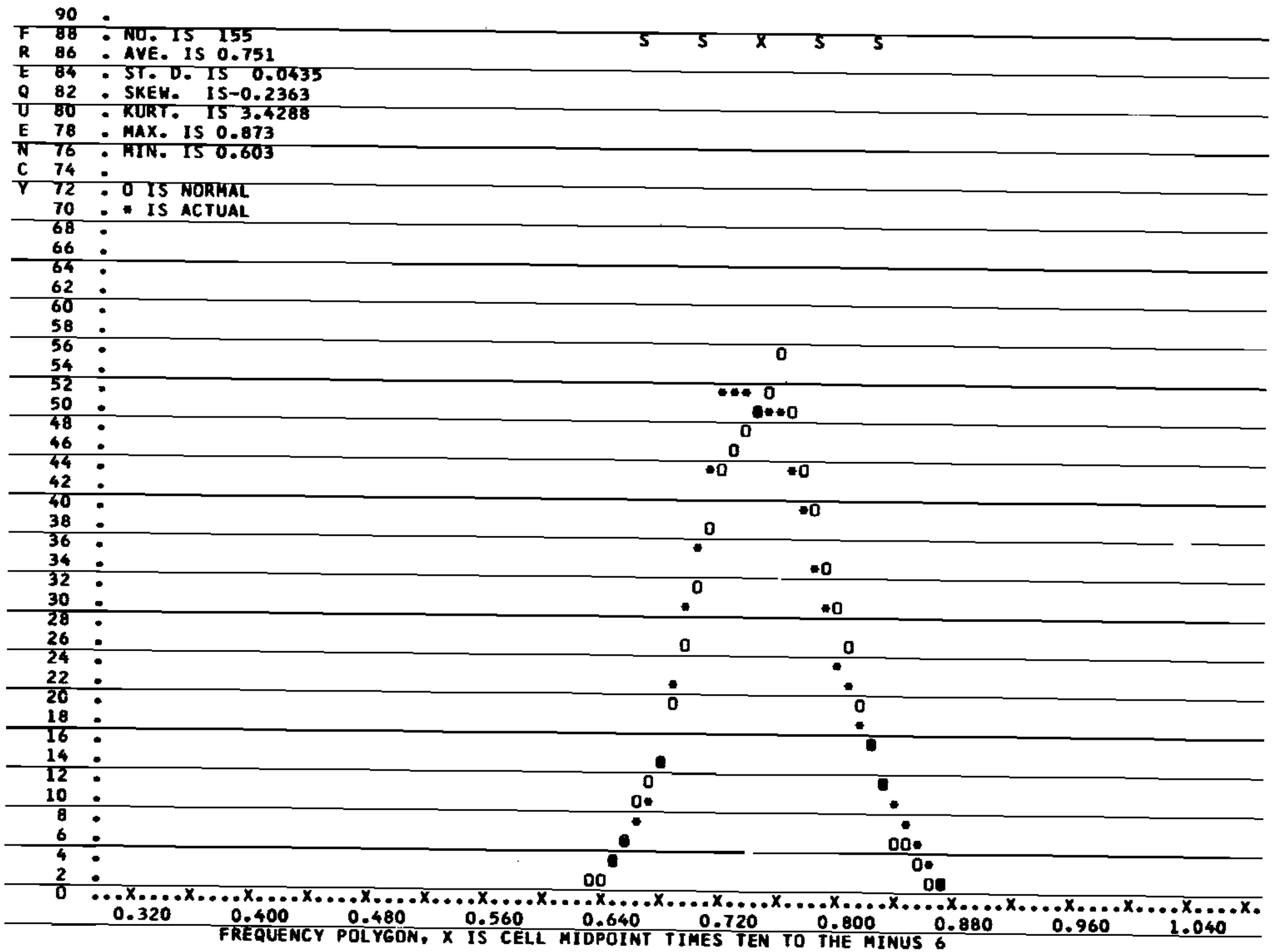


Figure 403. Frequency Distribution of Across-Grain Young's Modulus of Elasticity Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Blocks No. 20, 23, 111, 153 and 159 Combined

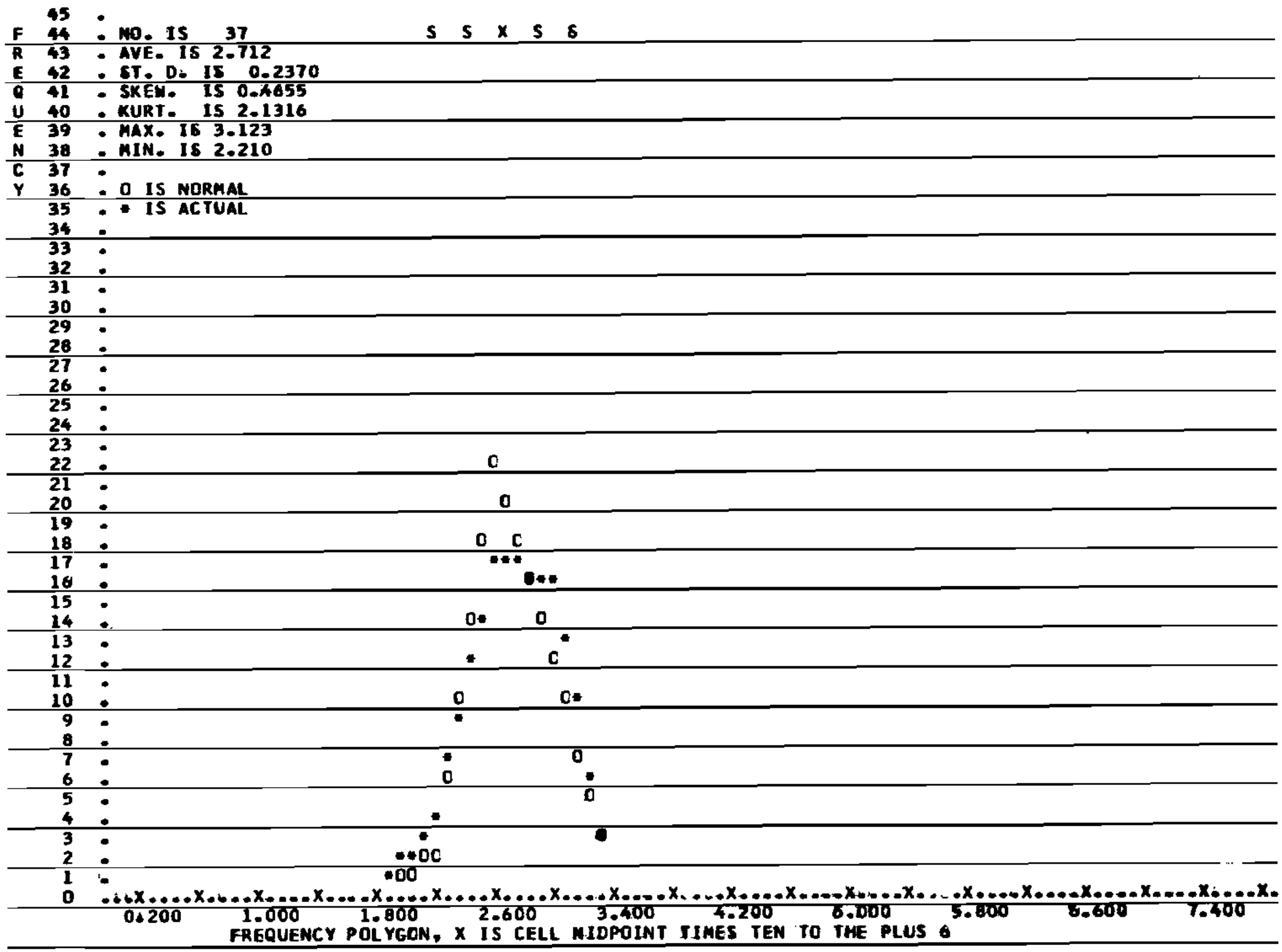


Figure 404. Frequency Distribution of With-Grain Young's Modulus of Elasticity Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 20

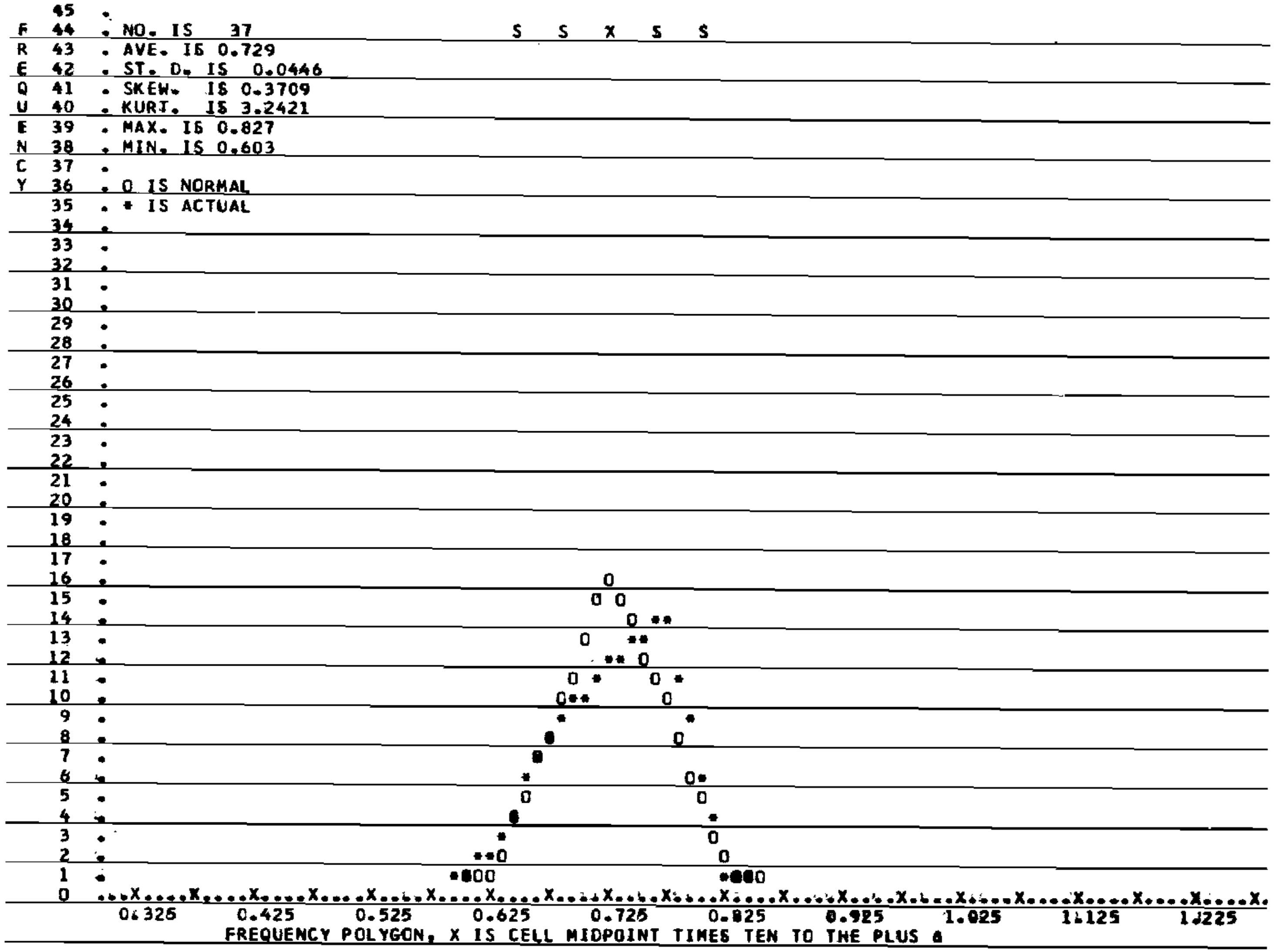


Figure 405. Frequency Distribution of Across-Grain Young's Modulus of Elasticity Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 20.

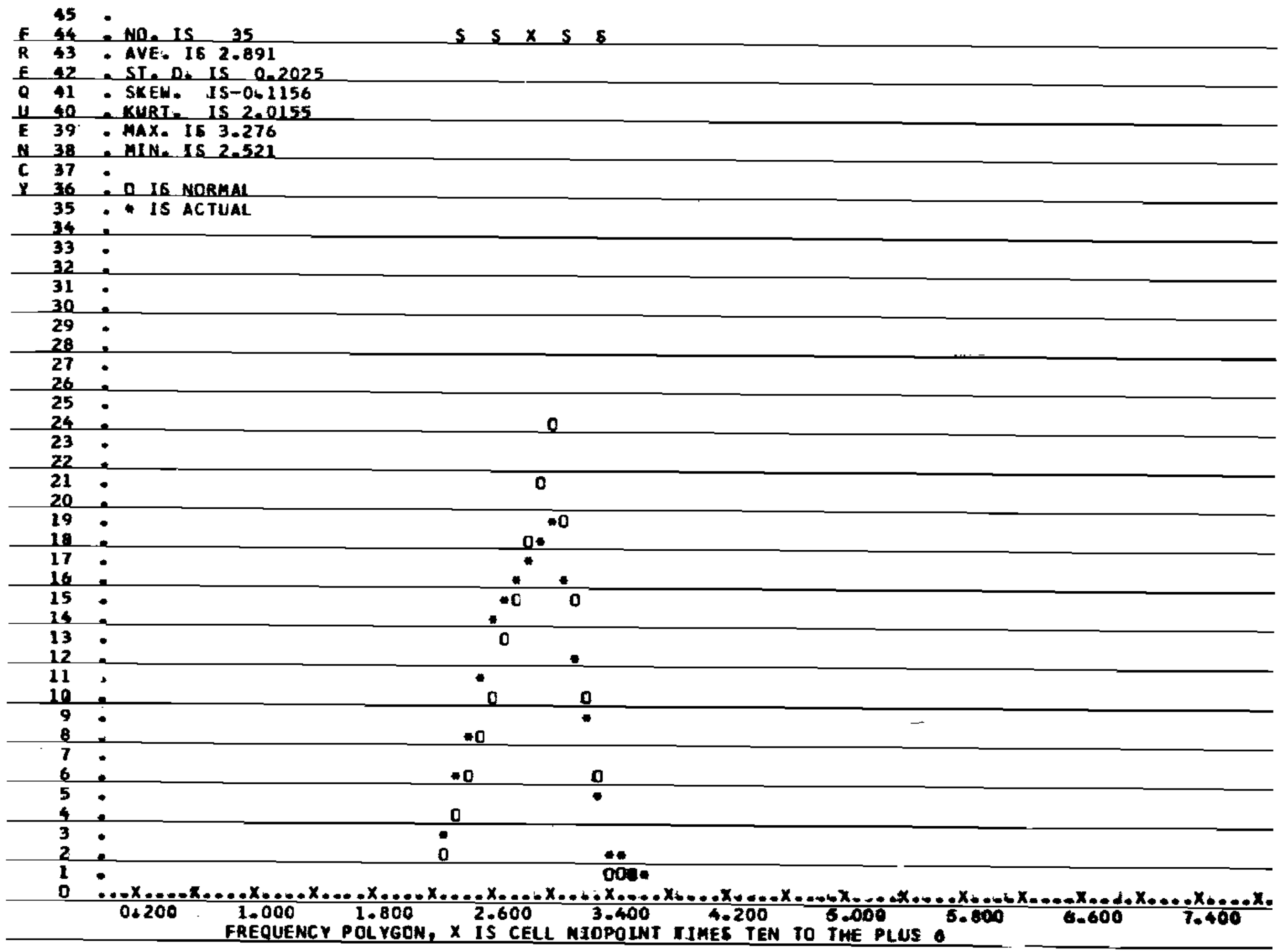


Figure 406. Frequency Distribution of With-Grain Young's Modulus of Elasticity Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 23

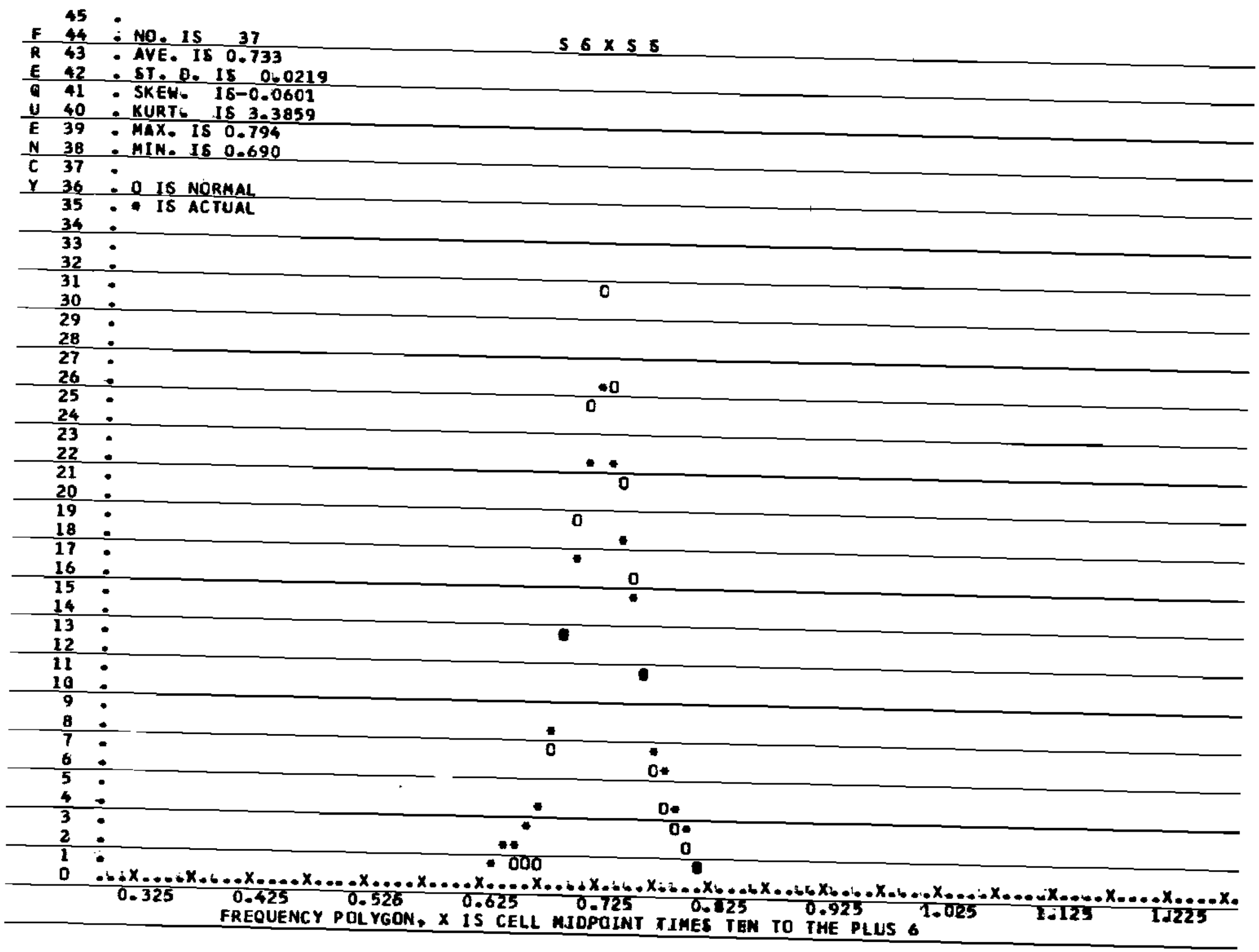


Figure 407. Frequency Distribution of Across-Grain Young's Modulus of Elasticity Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 23

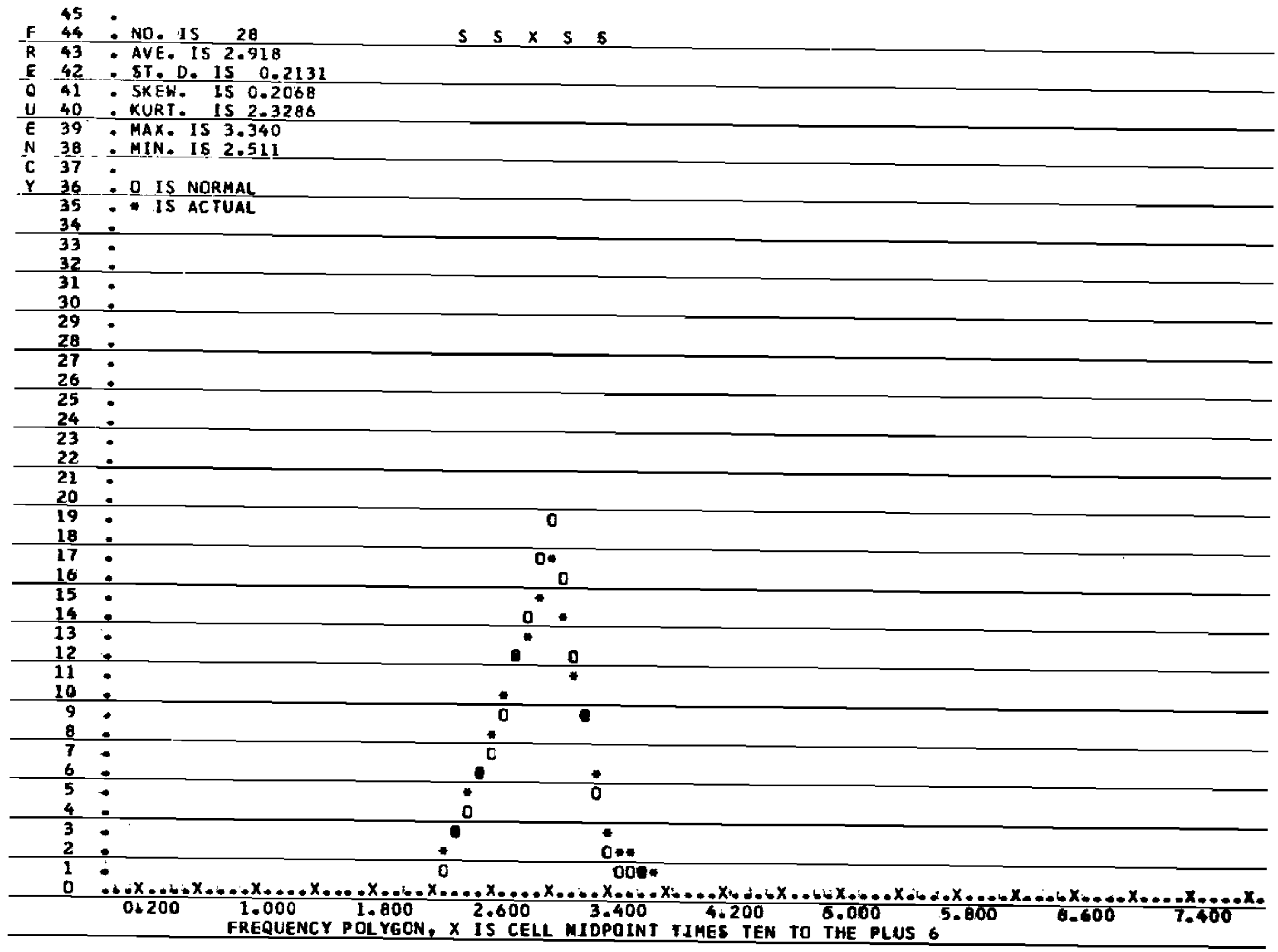


Figure 408. Frequency Distribution of With-Grain Young's Modulus of Elasticity Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 111

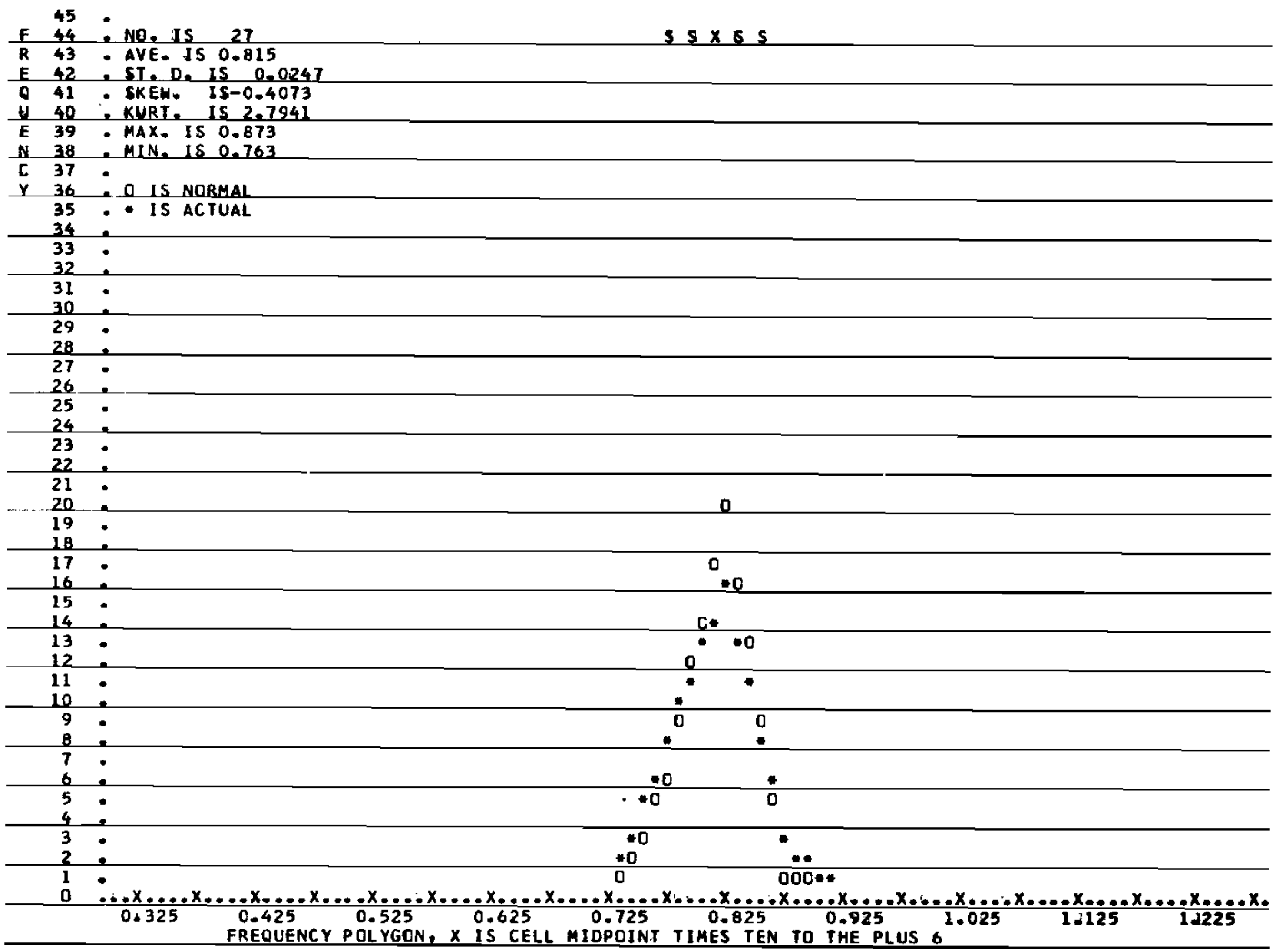


Figure 409. Frequency Distribution of Across-Grain Young's Modulus of Elasticity Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 111

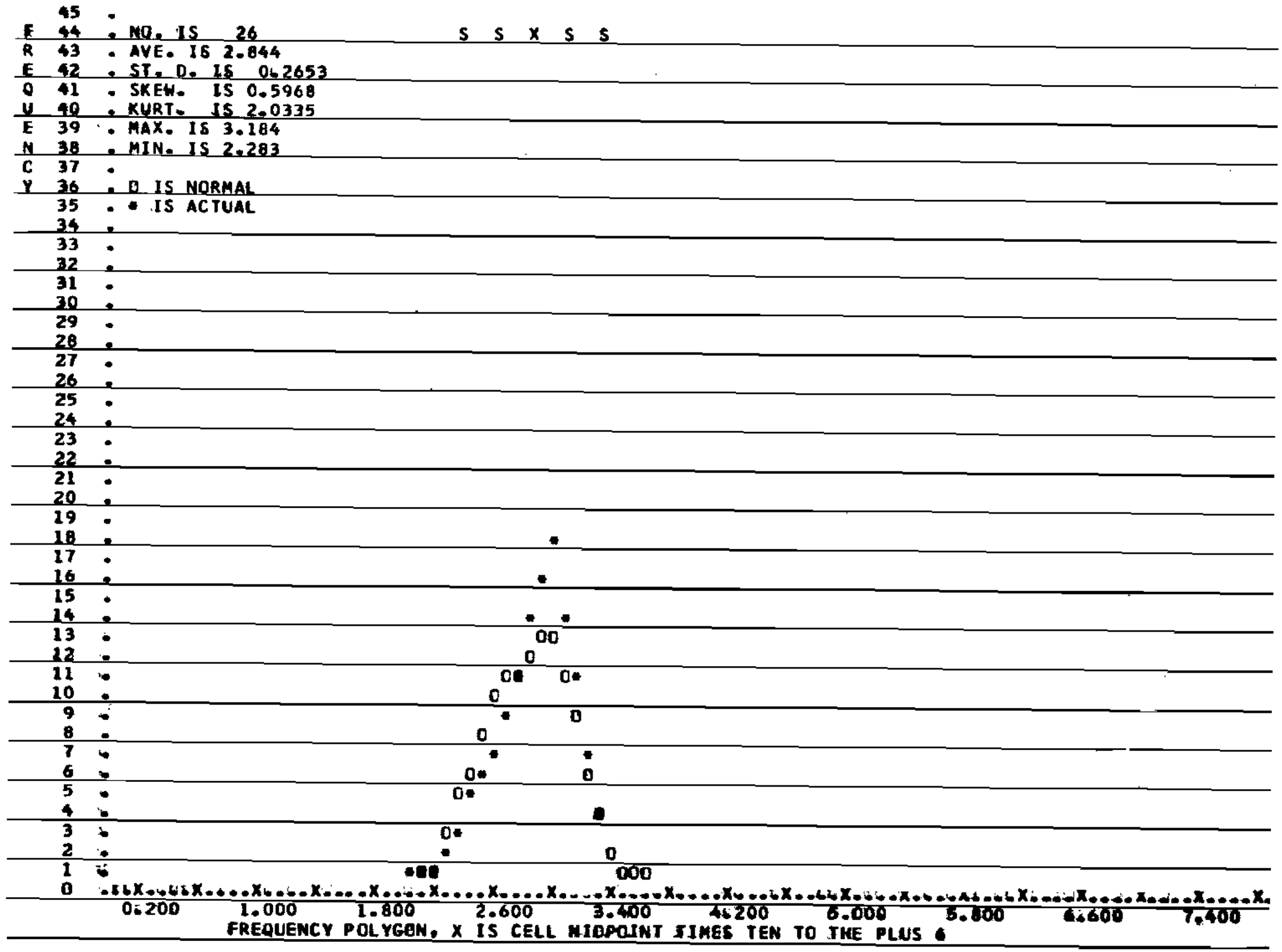


Figure 410. Frequency Distribution of With-Grain Young's Modulus of Elasticity Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 153

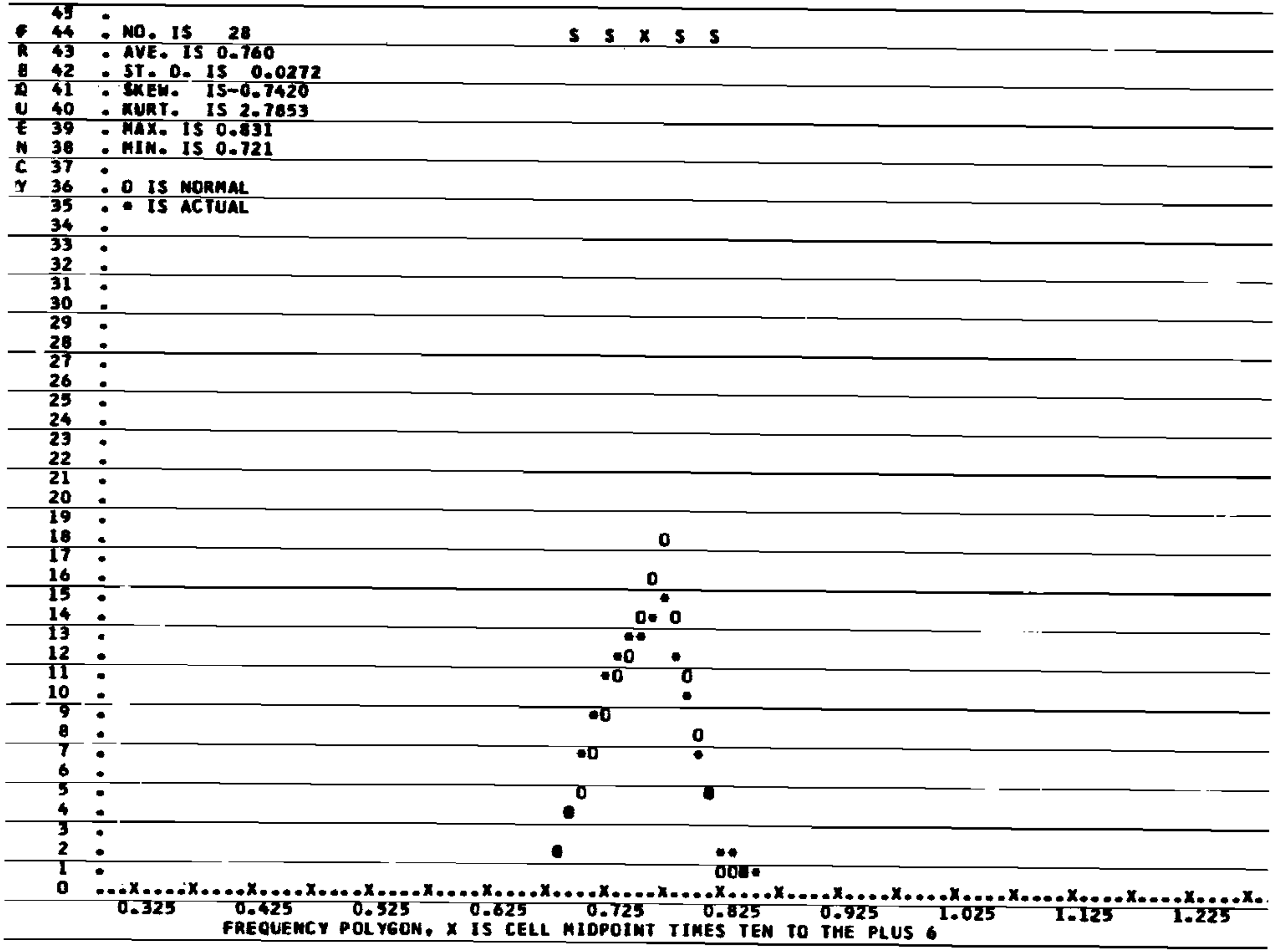


Figure 411. Frequency Distribution of Across-Grain Young's Modulus of Elasticity Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 153

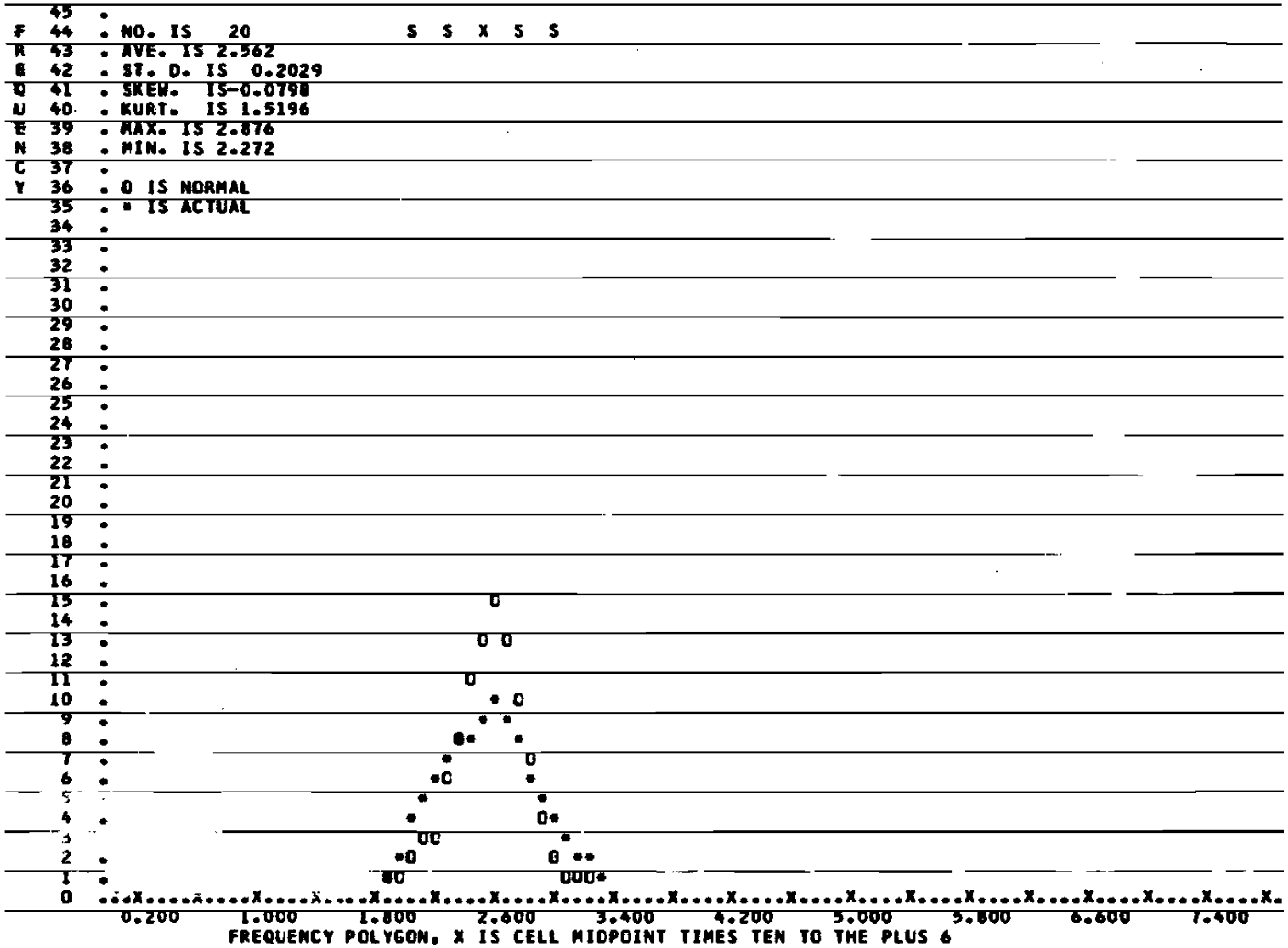


Figure 412. Frequency Distribution of With-Grain Young's Modulus of Elasticity Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 159

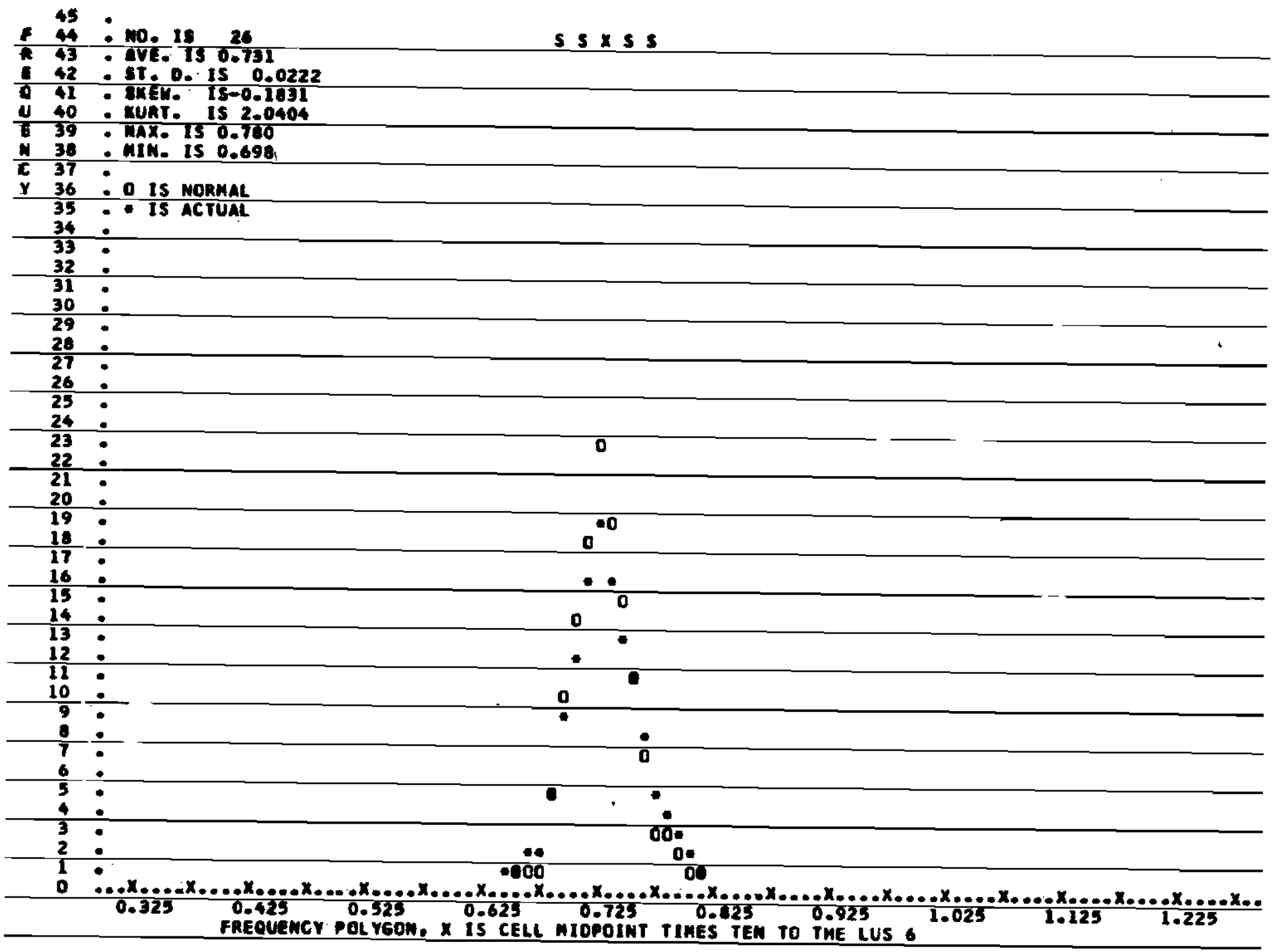


Figure 413. Frequency Distribution of Across-Grain Young's Modulus of Elasticity Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 159

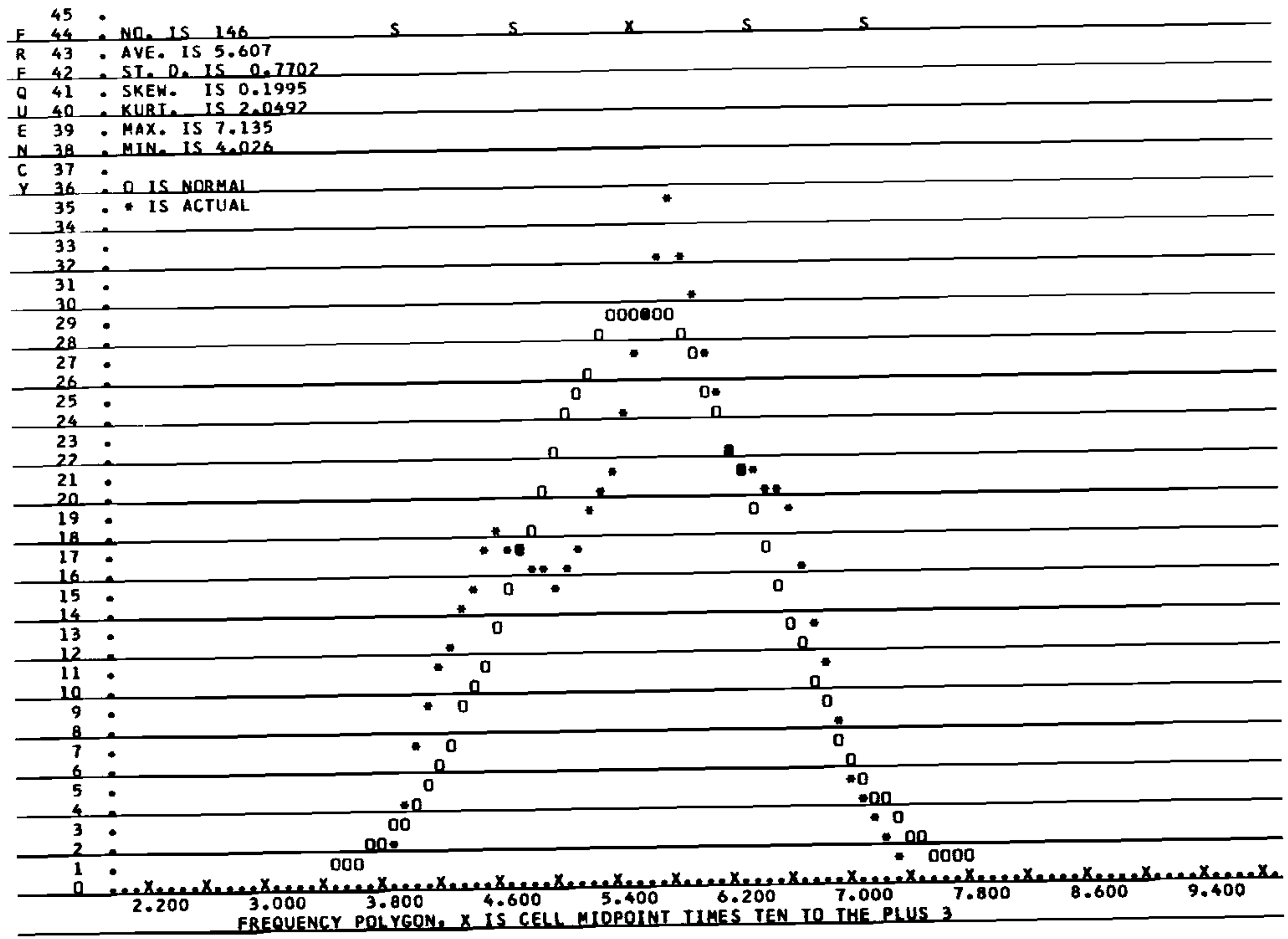


Figure 414. Frequency Distribution of With-Grain Flexural Strength Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Blocks No. 20, 23, 111, 153 and 159 Combined

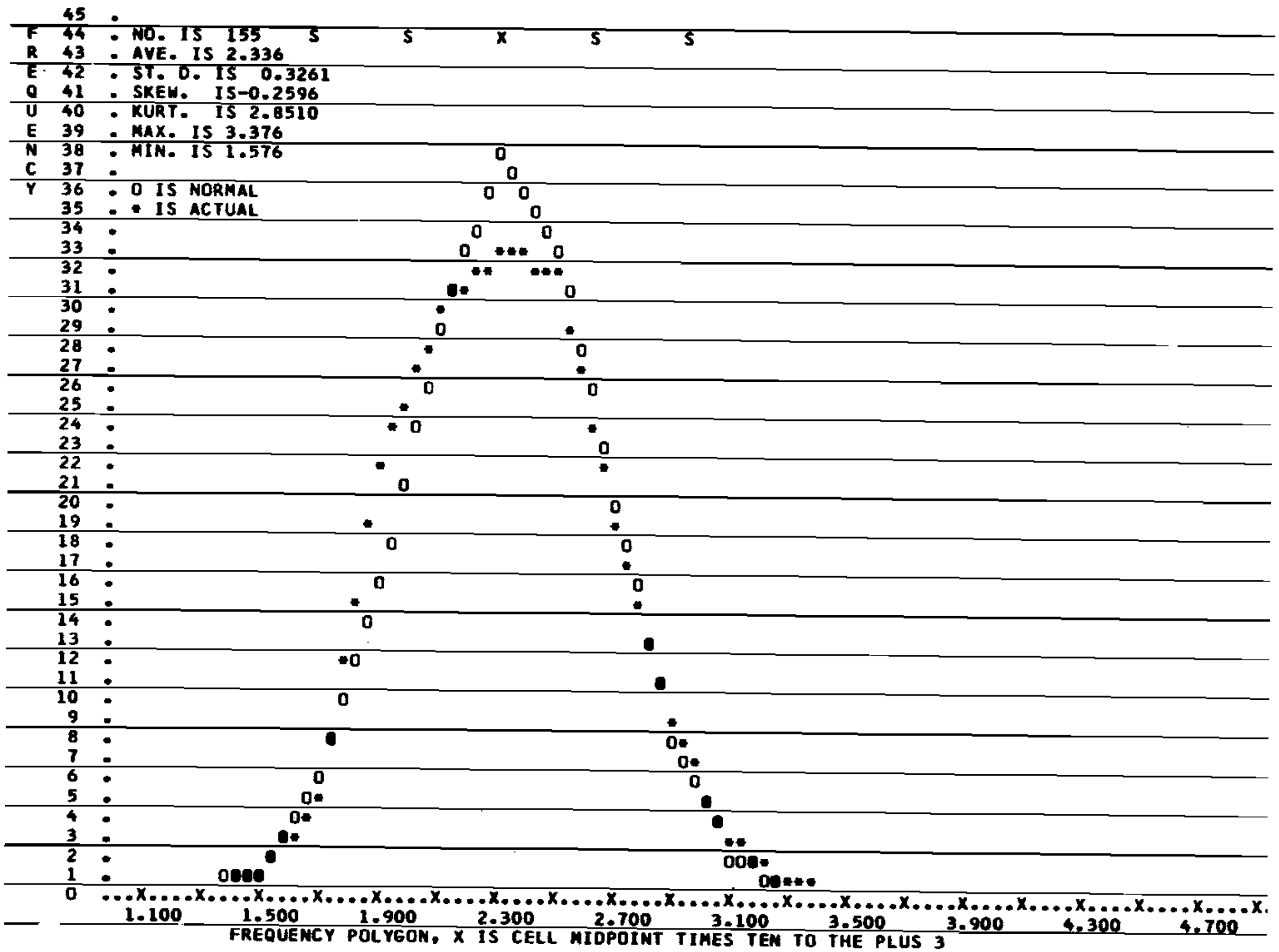


Figure 415. Frequency Distribution of Across-Grain Flexural Strength Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Blocks No. 20, 23, 111, 153 and 159 Combined

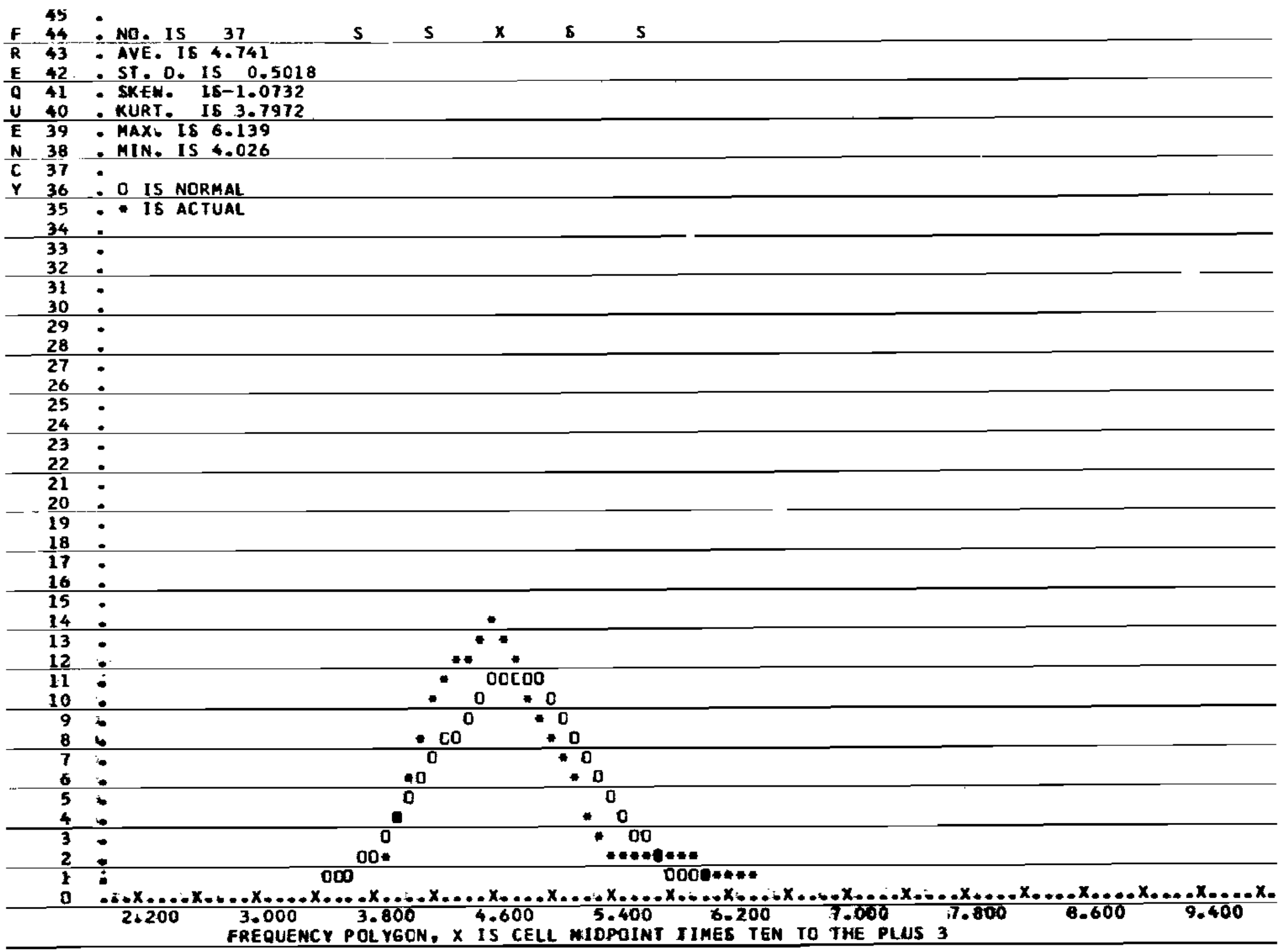


Figure 416. Frequency Distribution of With-Grain Flexural Strength Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 20

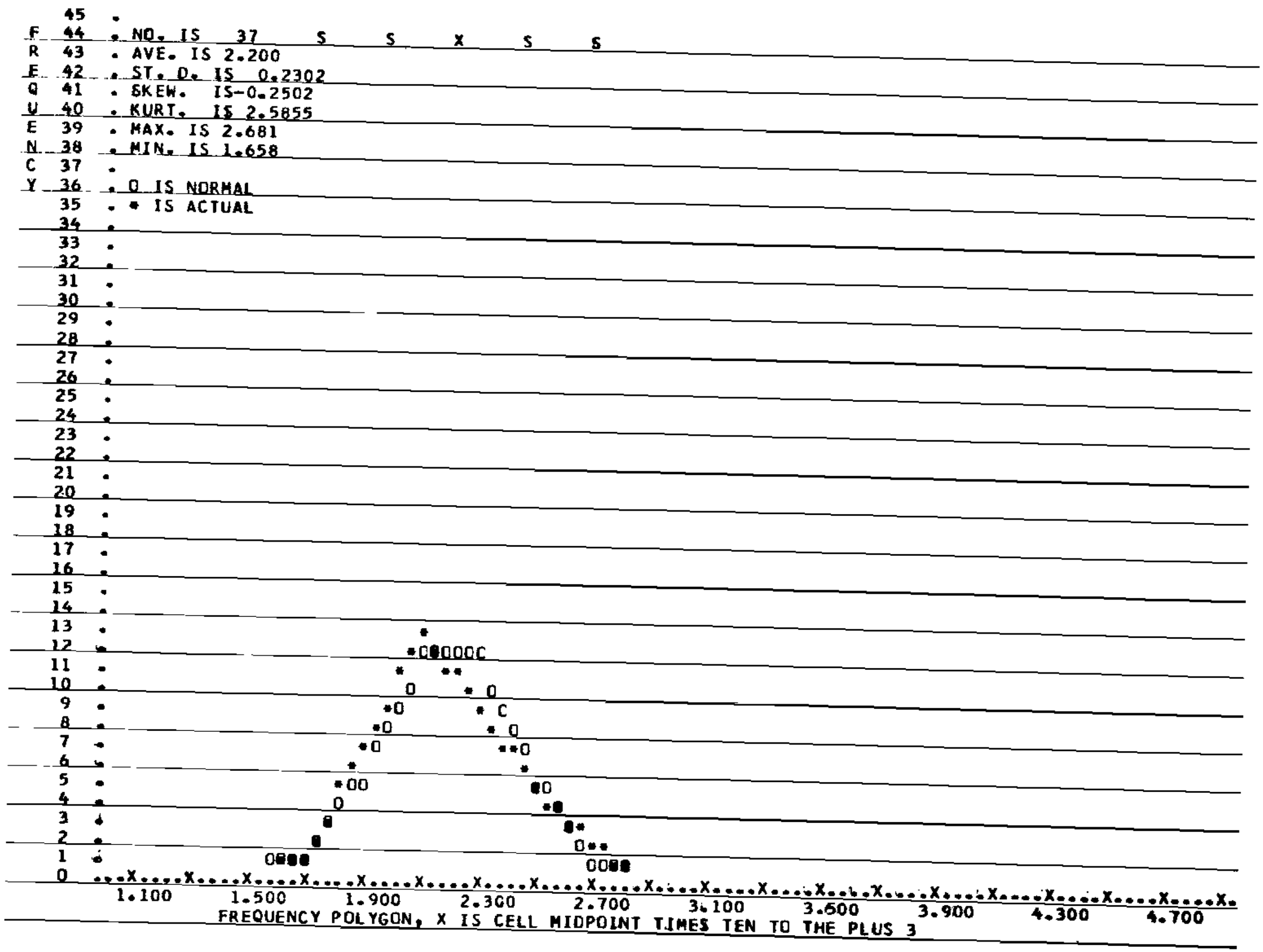


Figure 417. Frequency Distribution of Across-Grain Flexural Strength Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 20

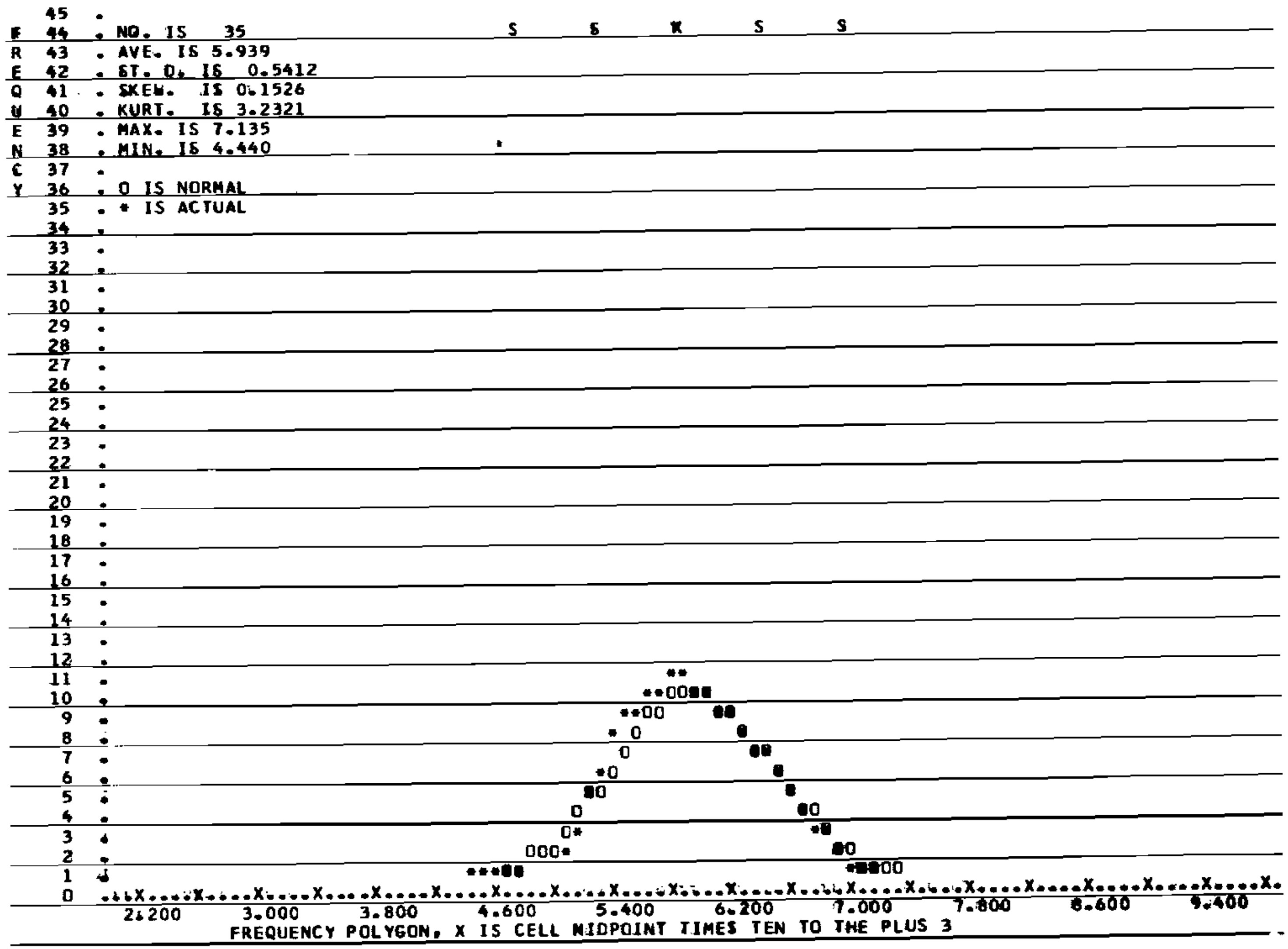


Figure 418. Frequency Distribution of With-Grain Flexural Strength Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 23

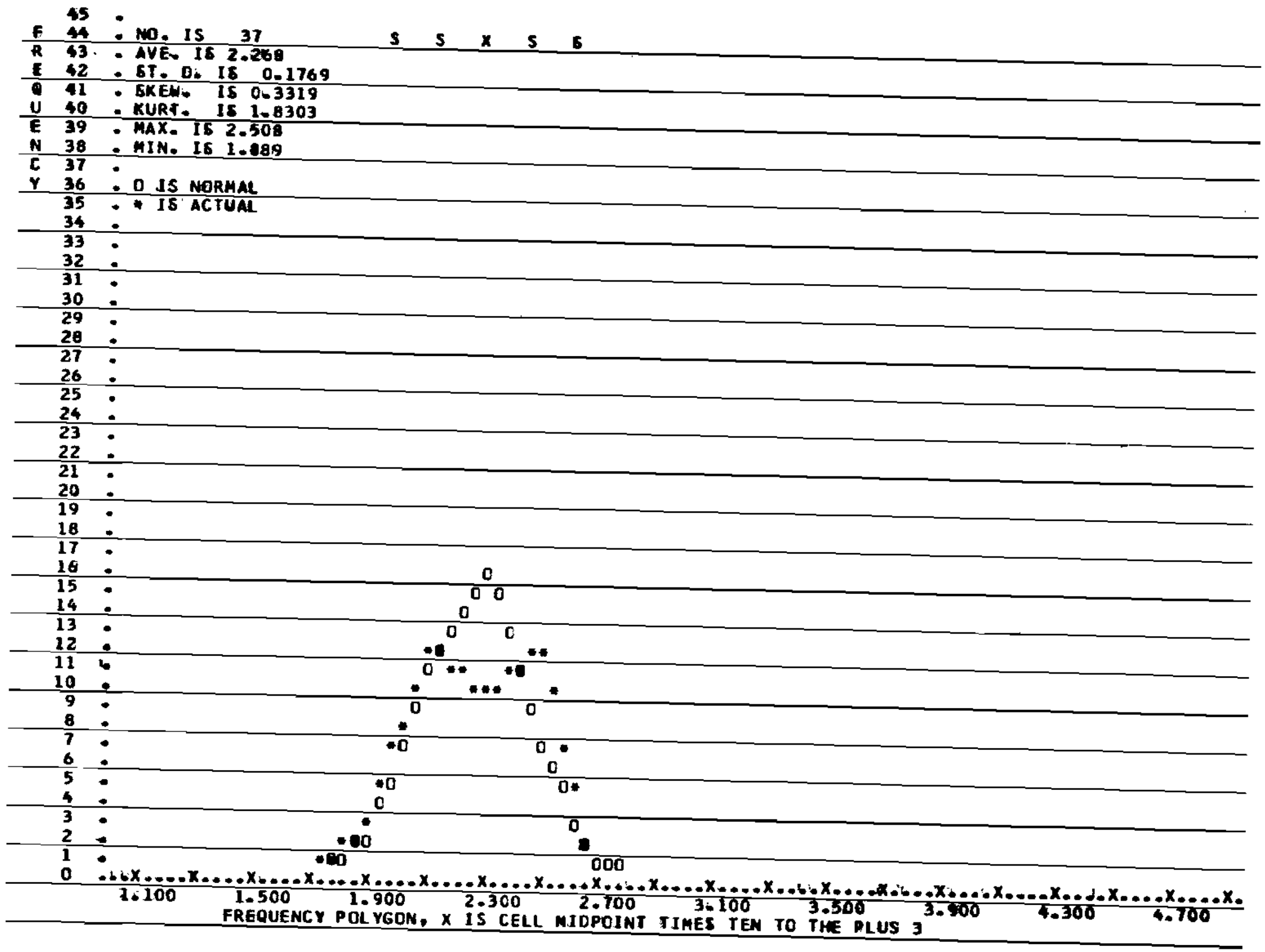


Figure 419. Frequency Distribution of Across-Grain Flexural Strength Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 23

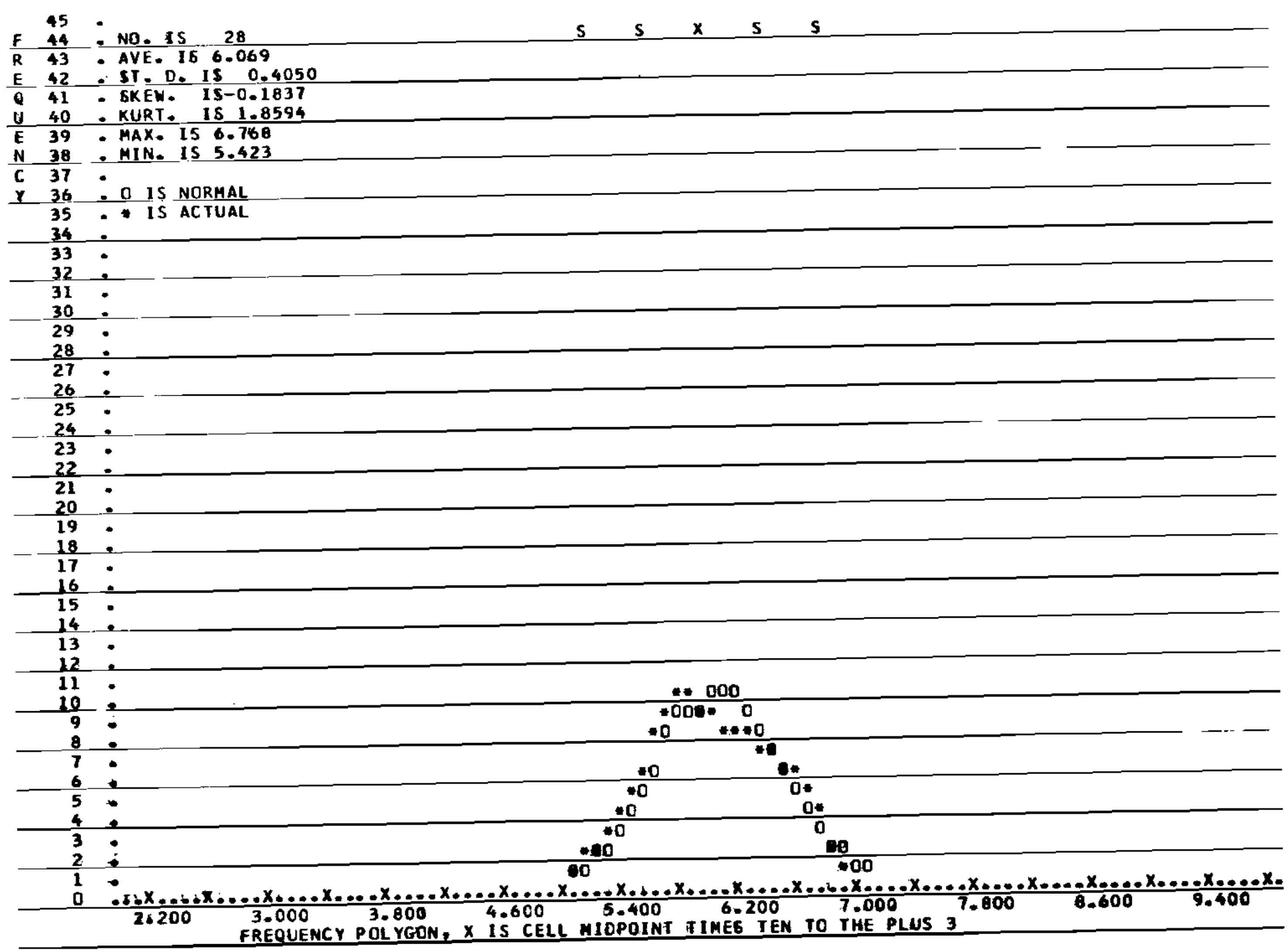


Figure 420. Frequency Distribution of With-Grain Flexural Strength Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 111

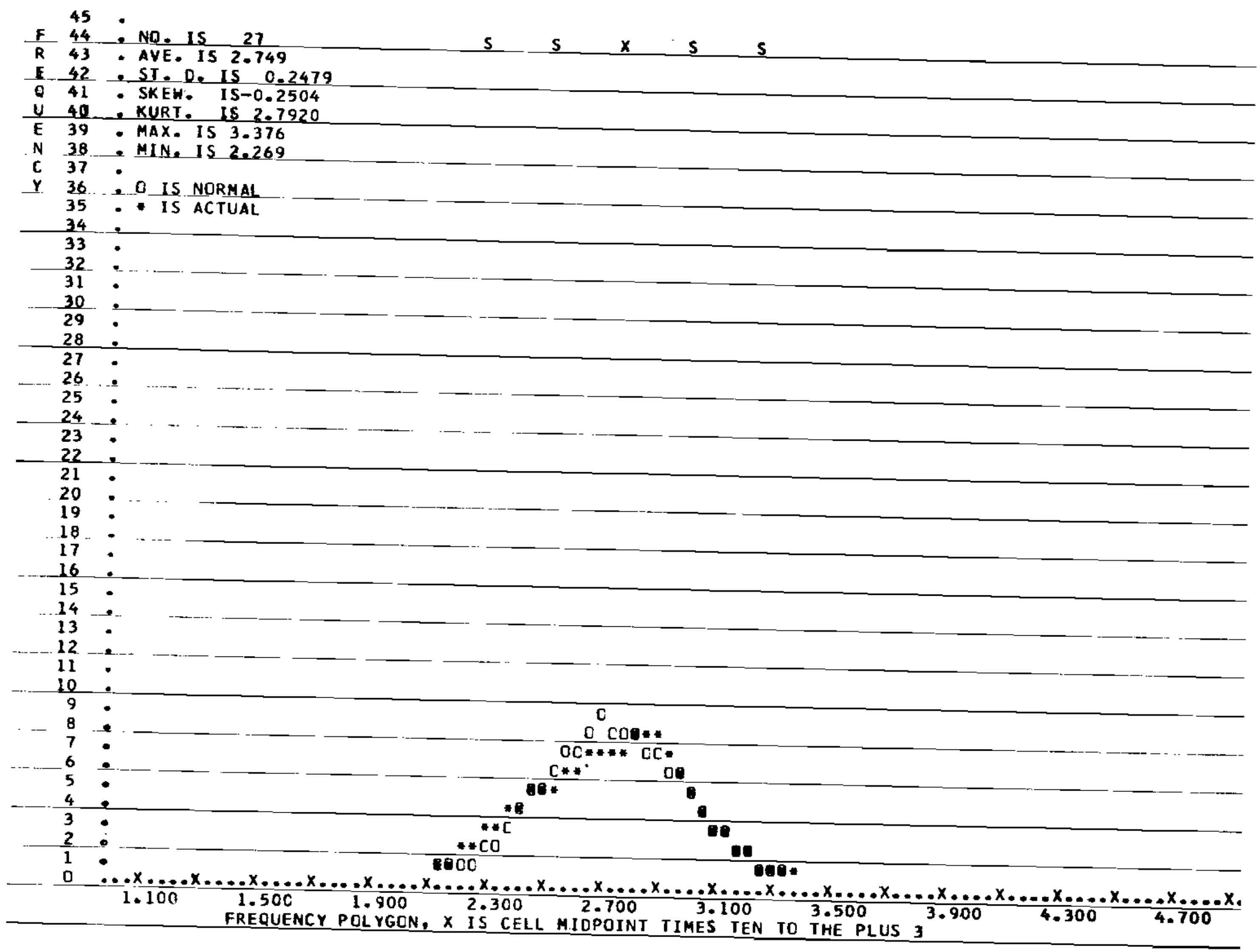


Figure 421. Frequency Distribution of Across-Grain Flexural Strength Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 111

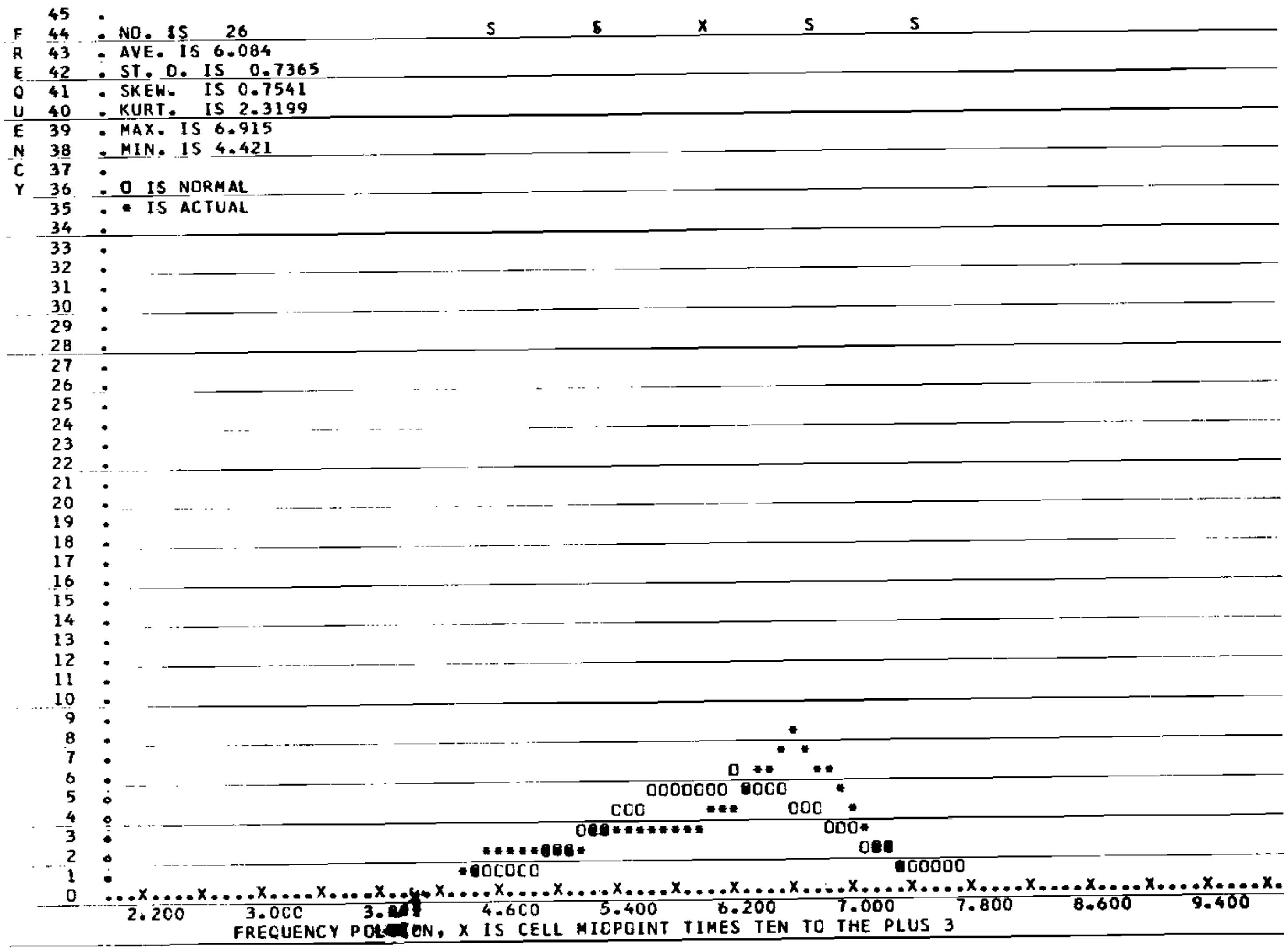


Figure 422. Frequency Distribution of With-Grain Flexural Strength Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 153

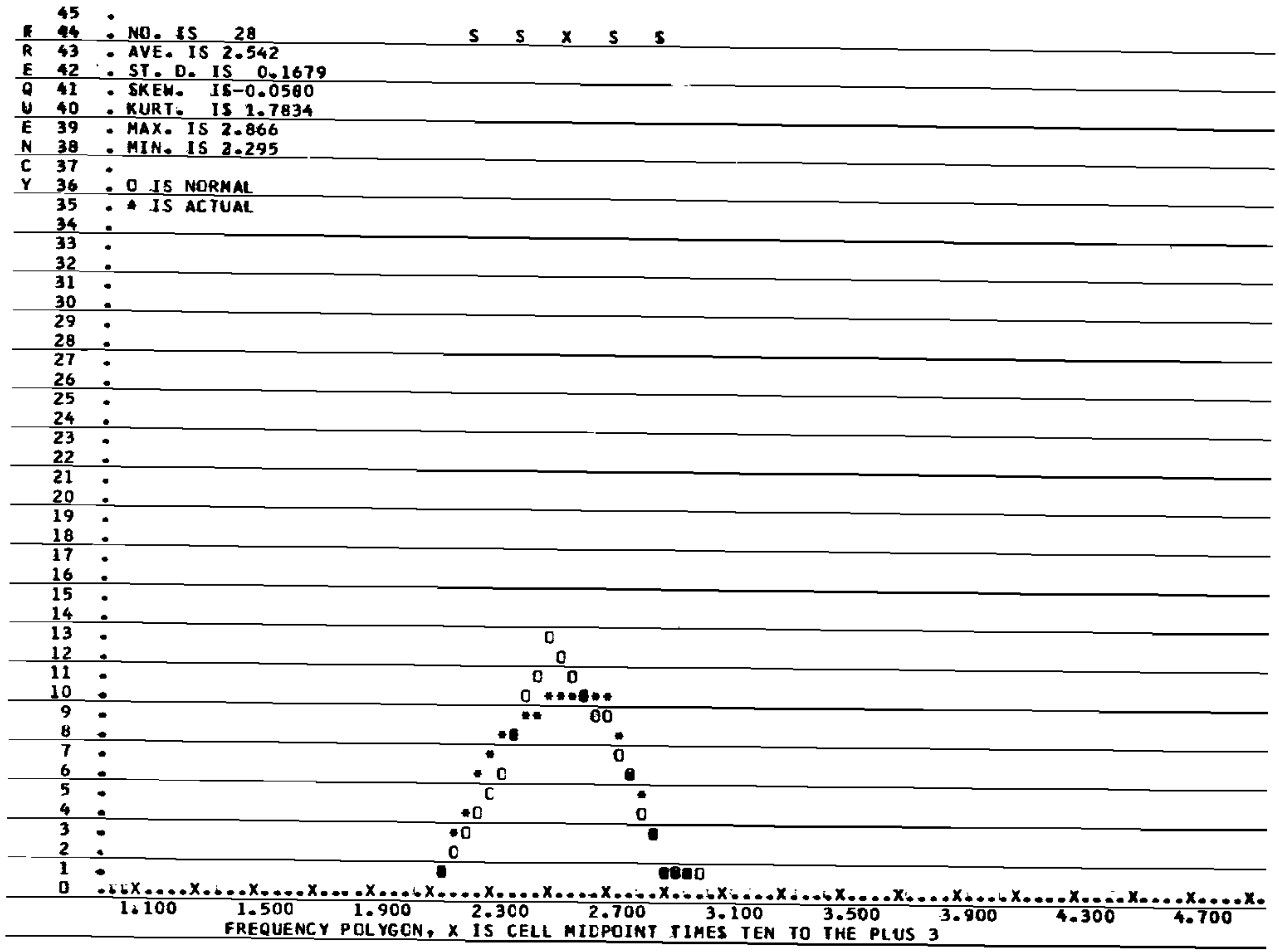


Figure 423. Frequency Distribution of Across-Grain Flexural Strength Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 153

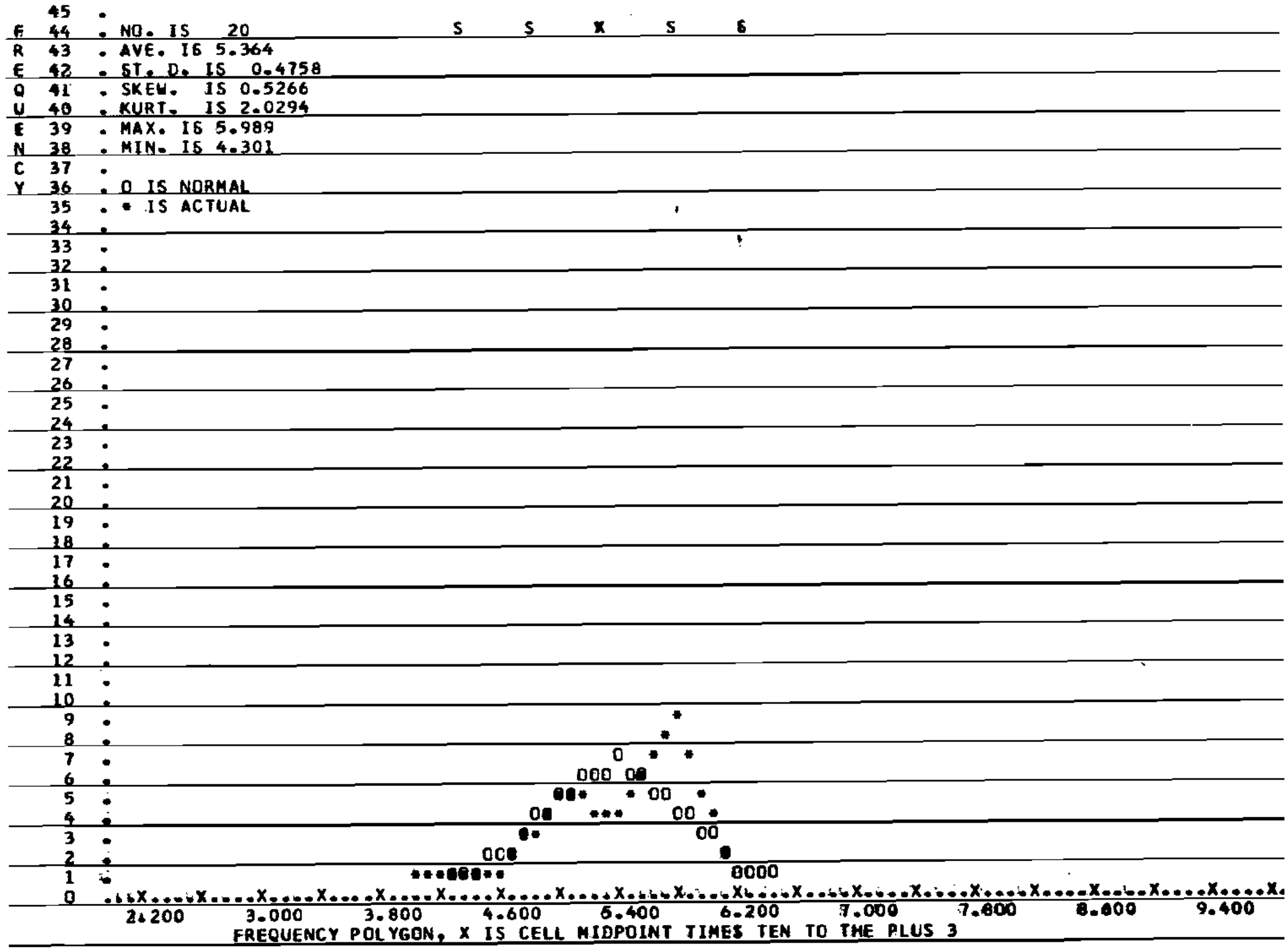


Figure 424. Frequency Distribution of With-Grain Flexural Strength Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 159

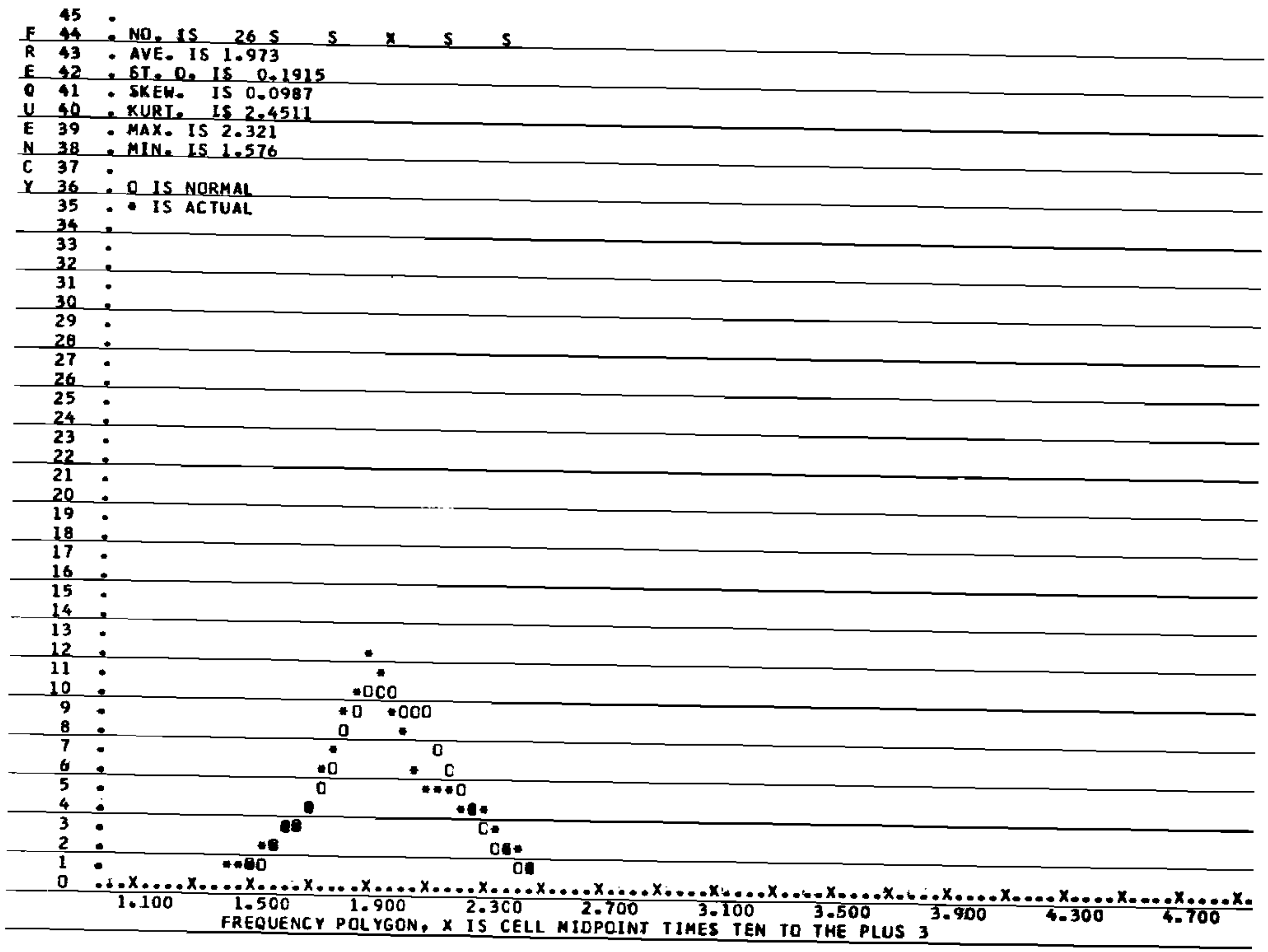


Figure 425. Frequency Distribution of Across-Grain Flexural Strength Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 159

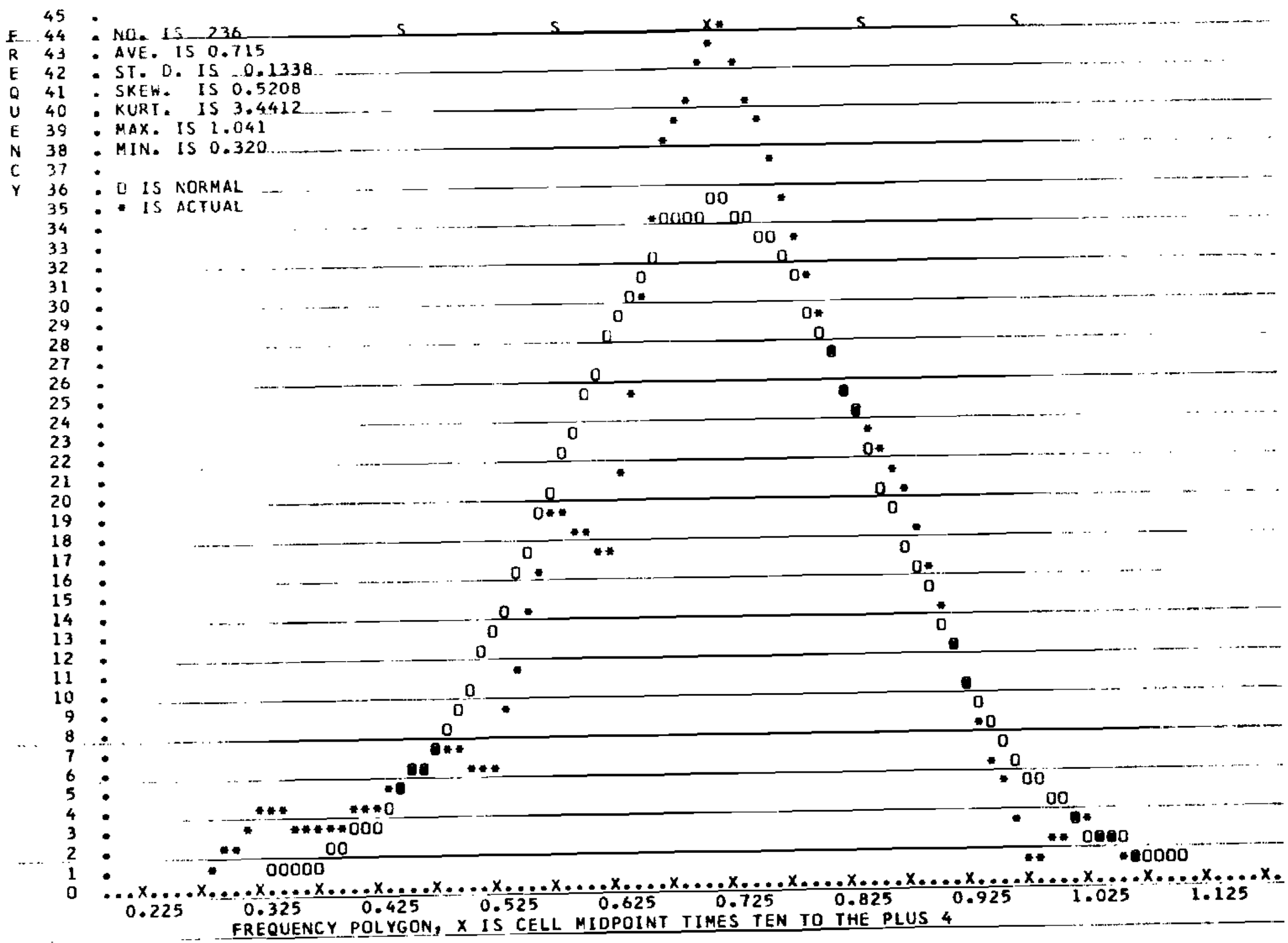


Figure 426. Frequency Distribution of With-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Blocks No. 20, 23, 111, 153 and 159 Combined

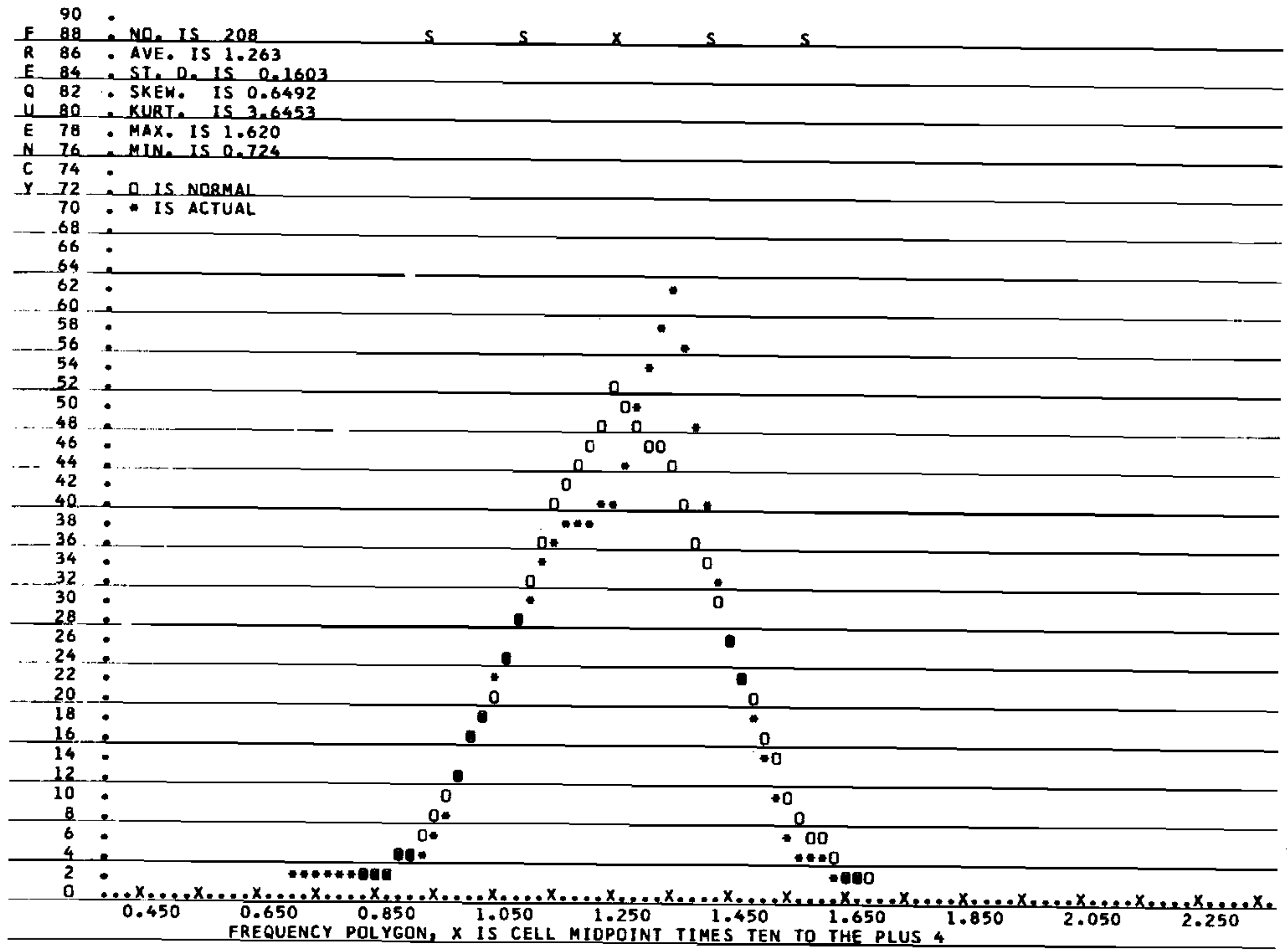


Figure 427. Frequency Distribution of Across-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Blocks No. 20, 23, 111, 153 and 159 Combined

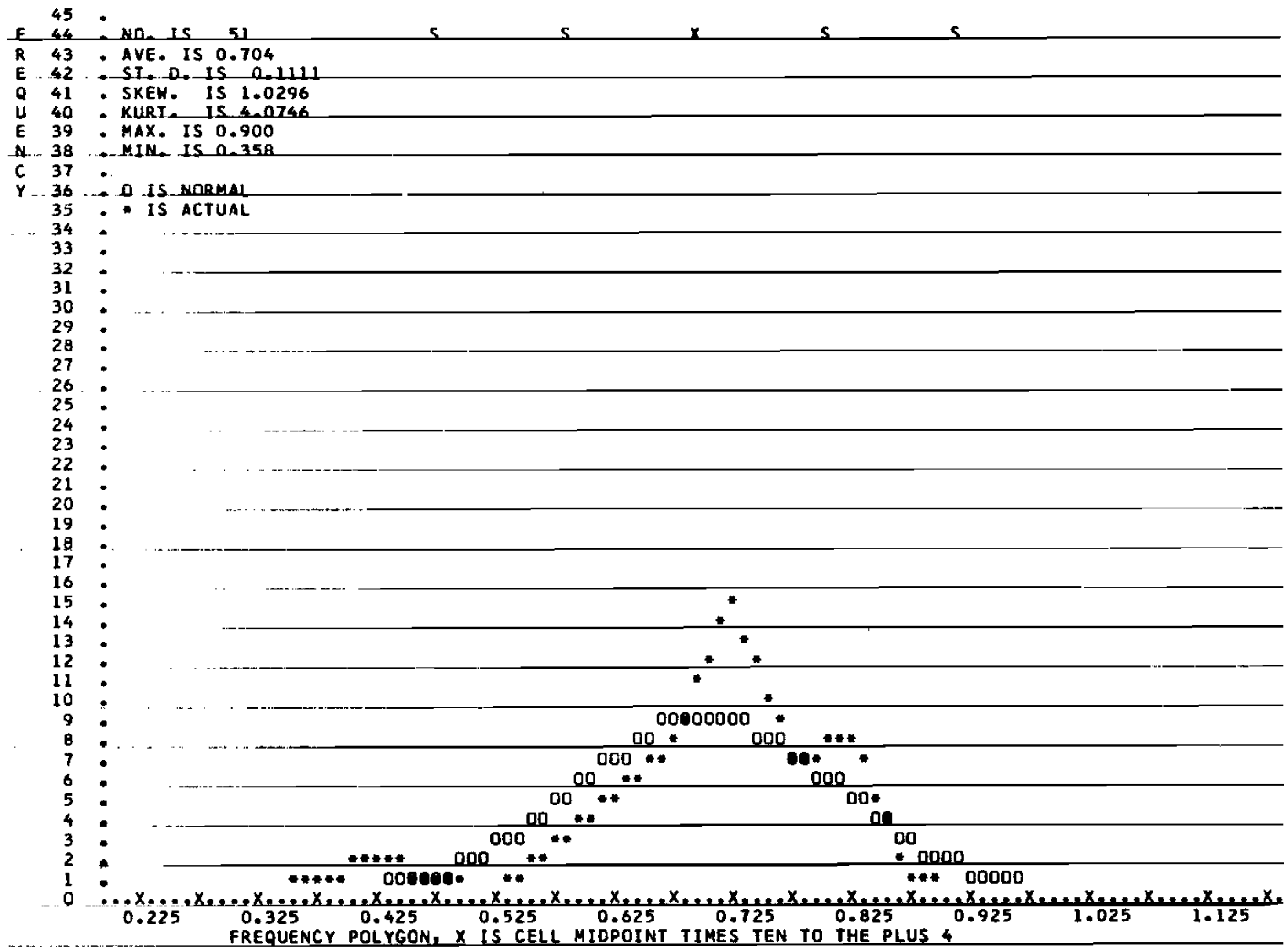


Figure 428. Frequency Distribution of With-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 20

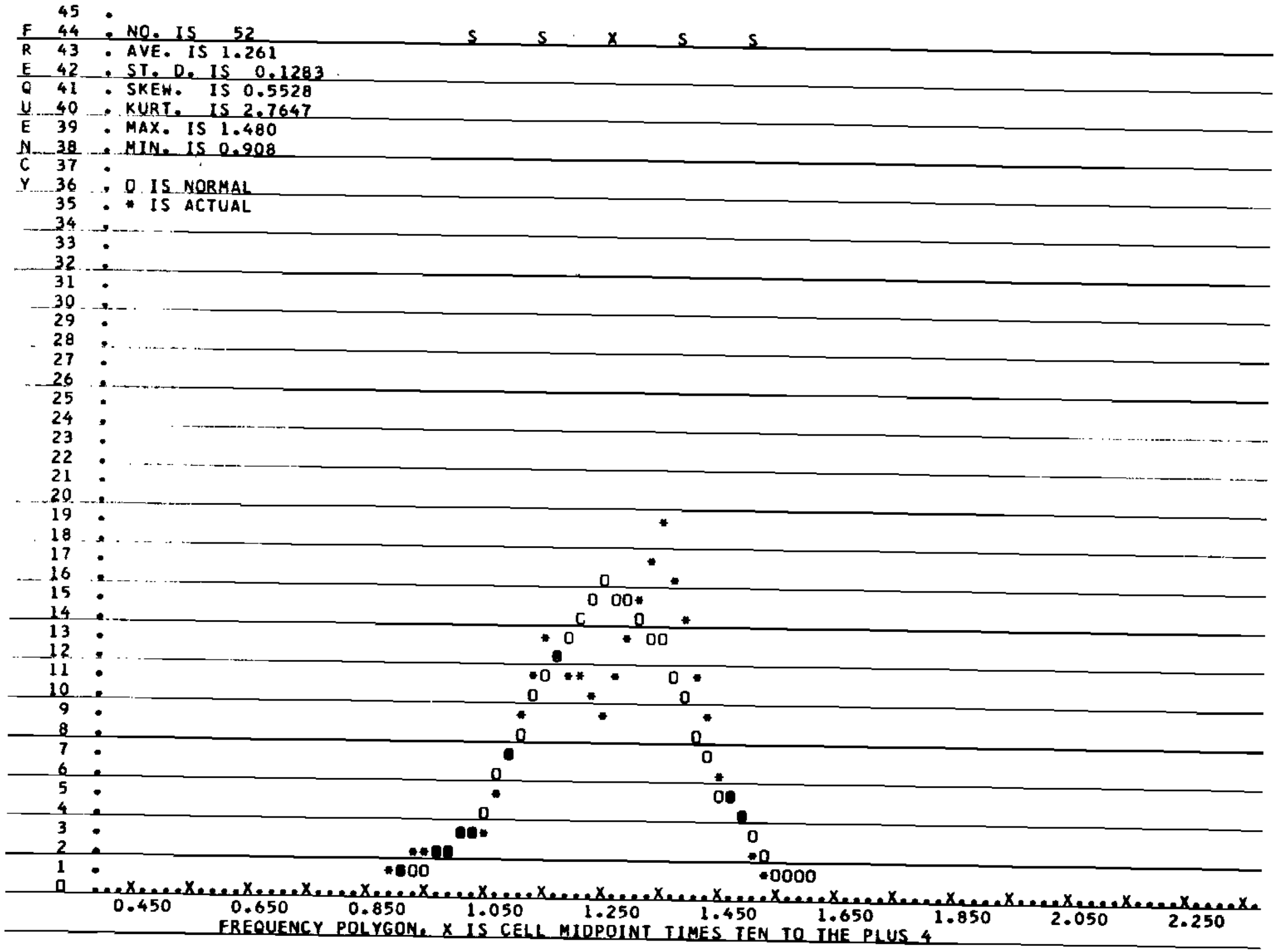


Figure 429. Frequency Distribution of Across-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 20

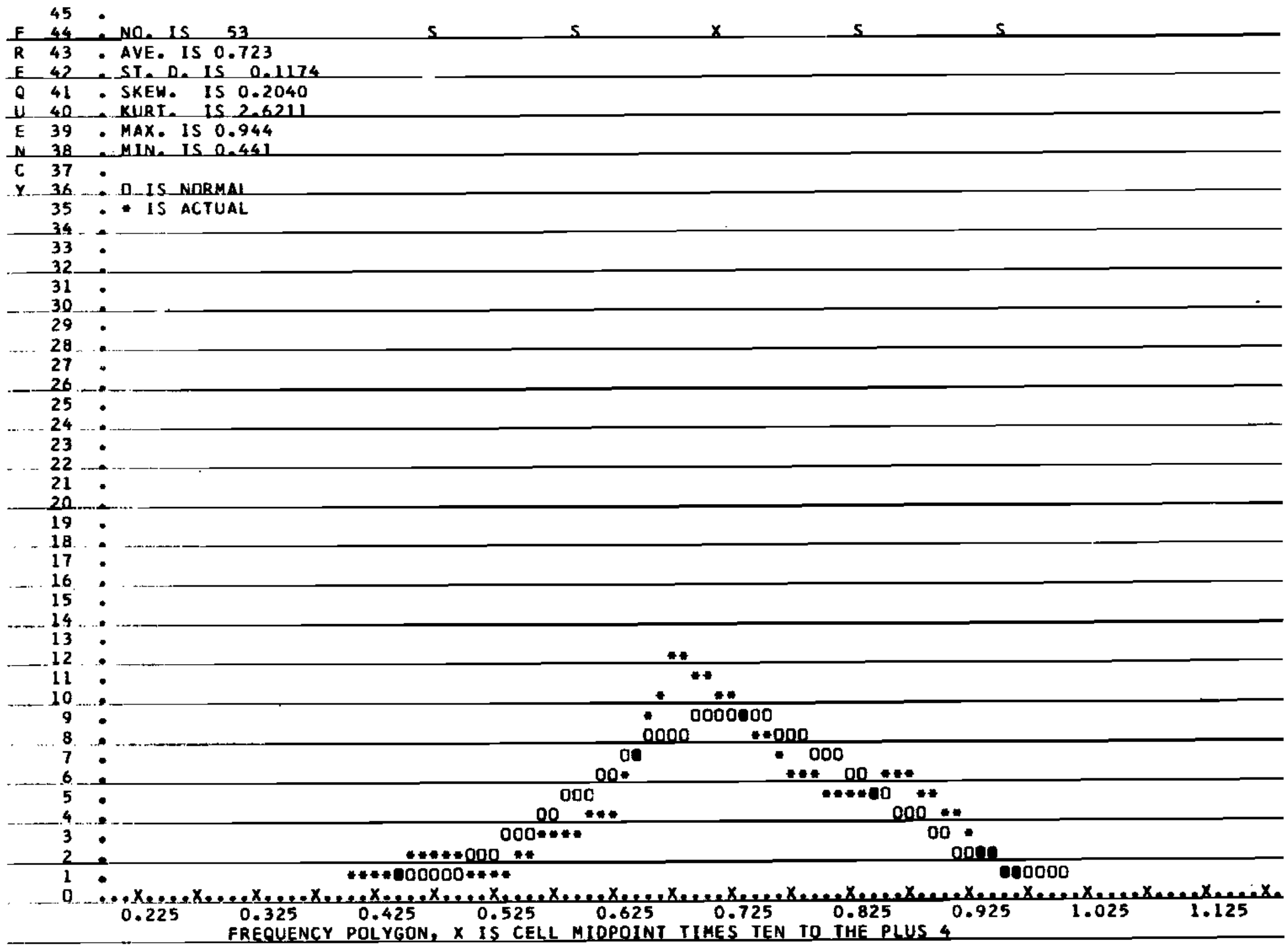


Figure 430. Frequency Distribution of With-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 23

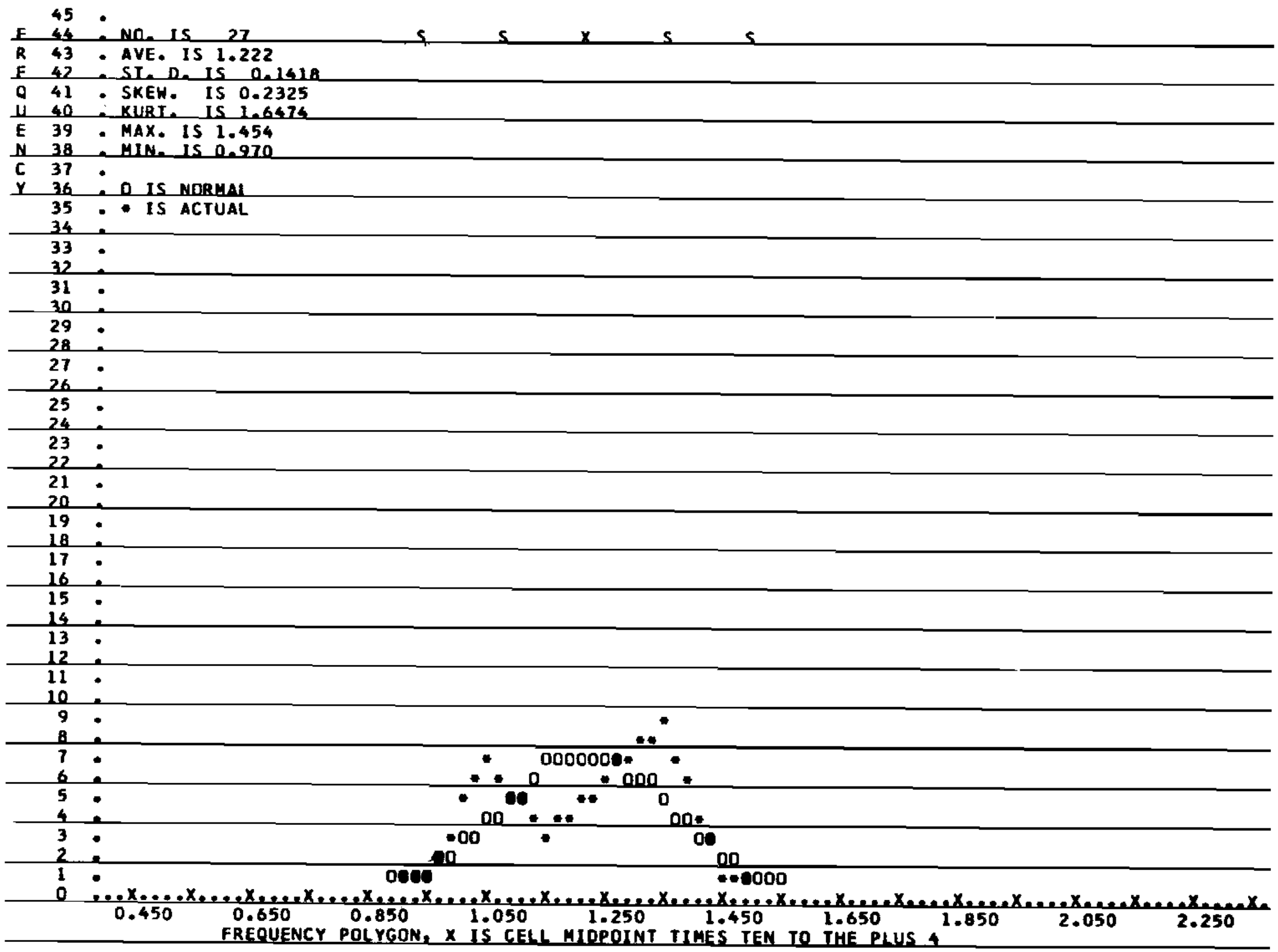


Figure 431. Frequency Distribution of Across-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 23

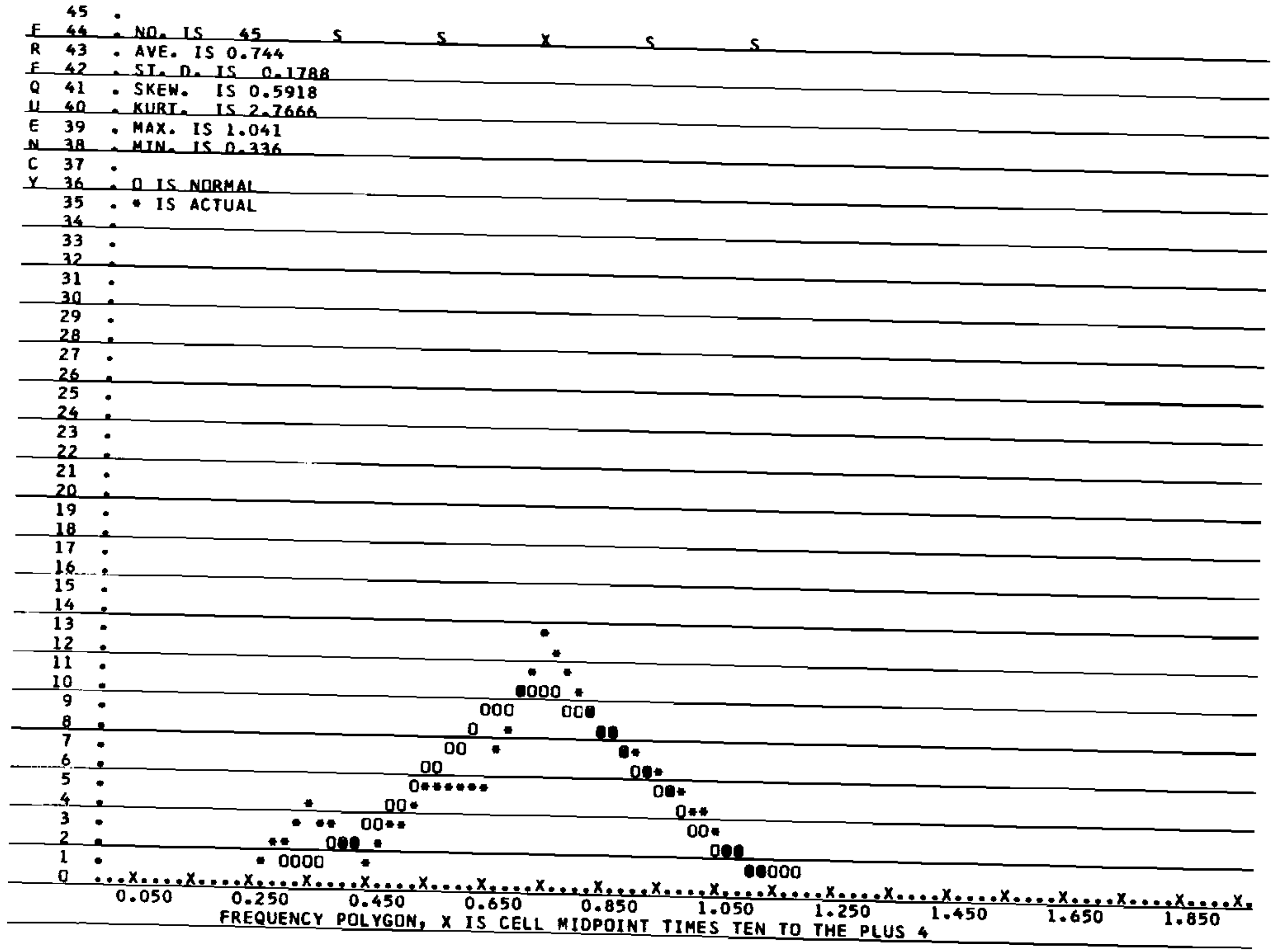


Figure 432. Frequency Distribution of With-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 111

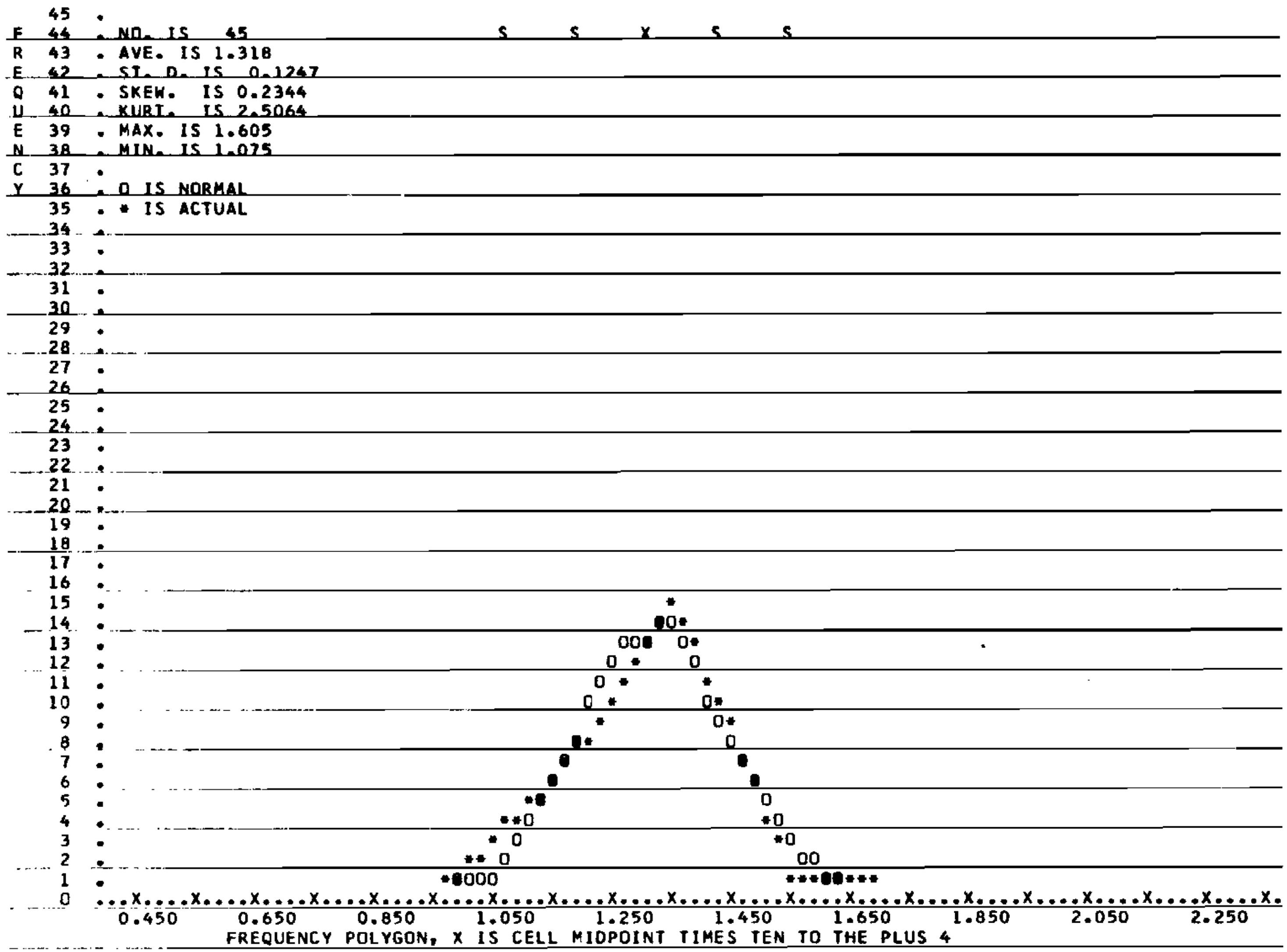


Figure 433. Frequency Distribution of Across-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 111

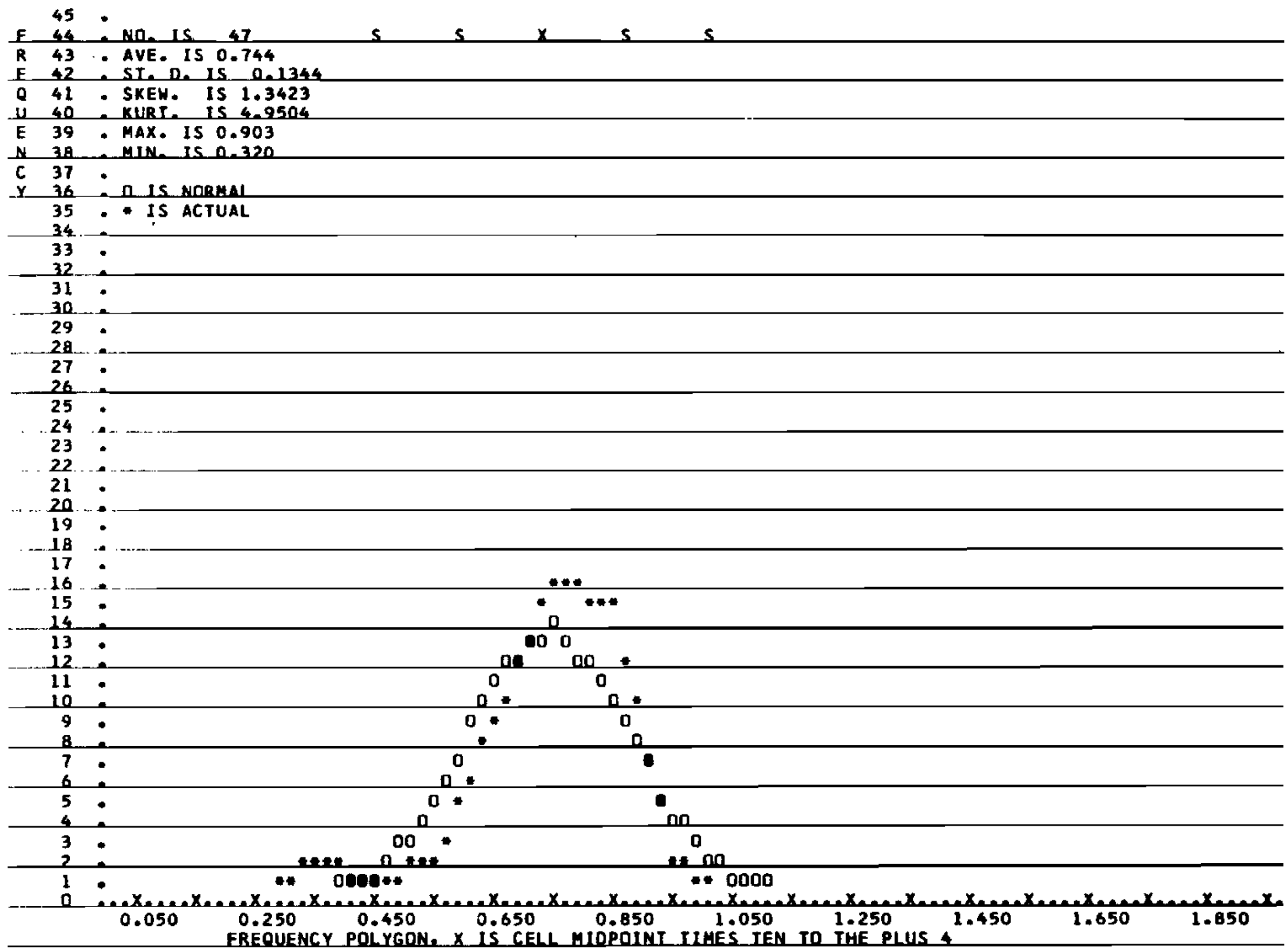


Figure 434. Frequency Distribution of With-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 153

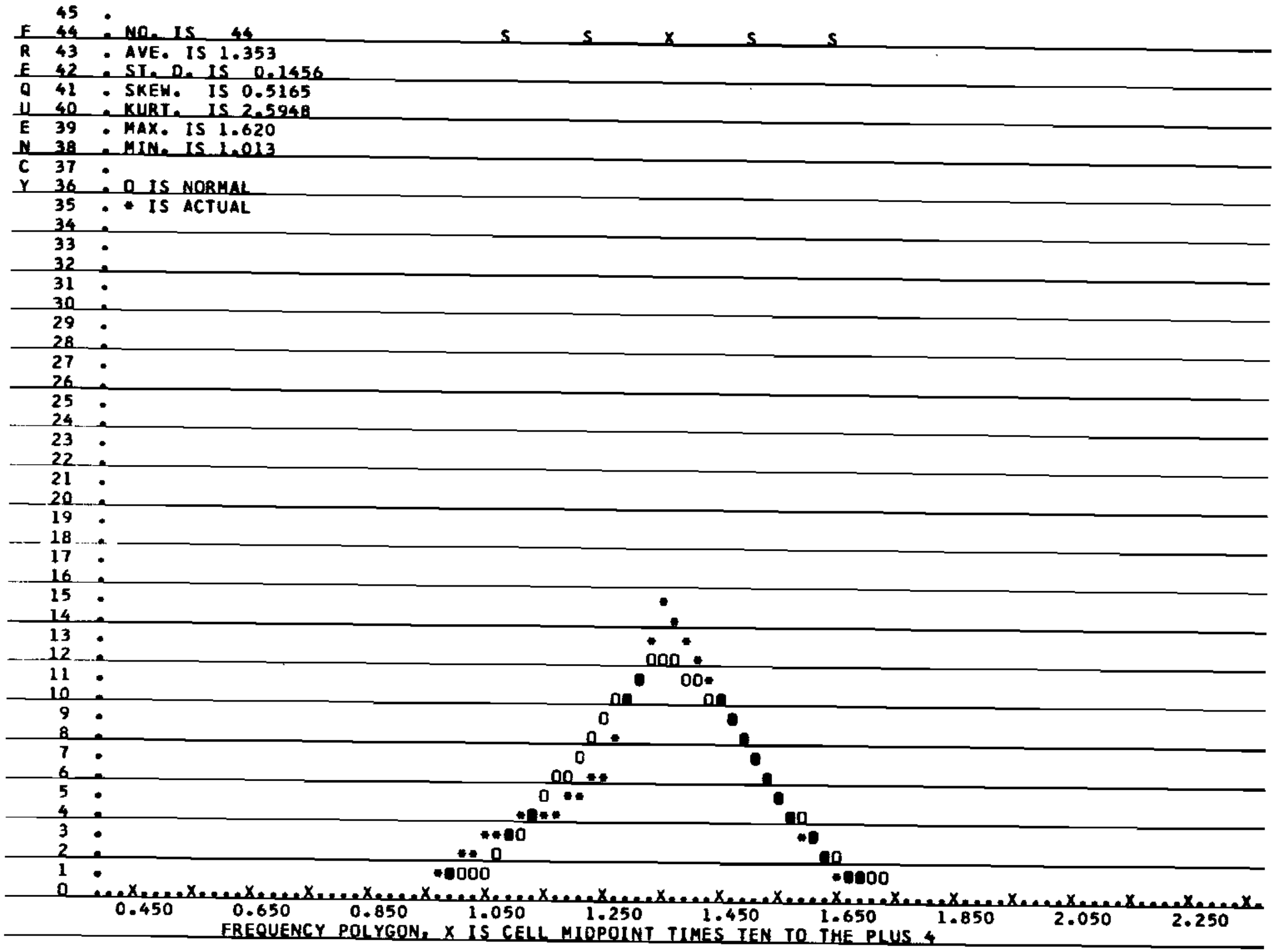


Figure 435. Frequency Distribution of Across-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 153

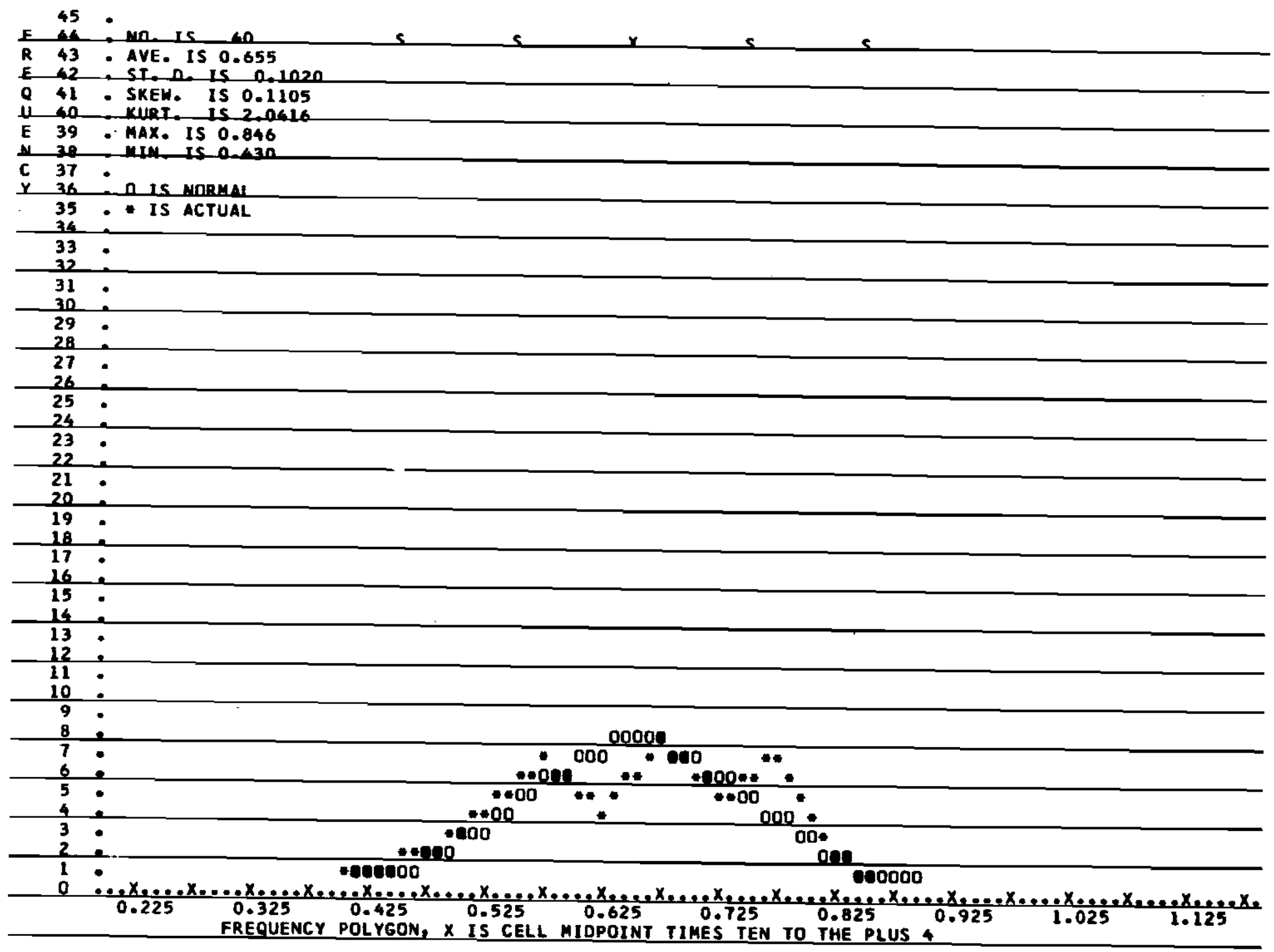


Figure 436. Frequency Distribution of With-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 159

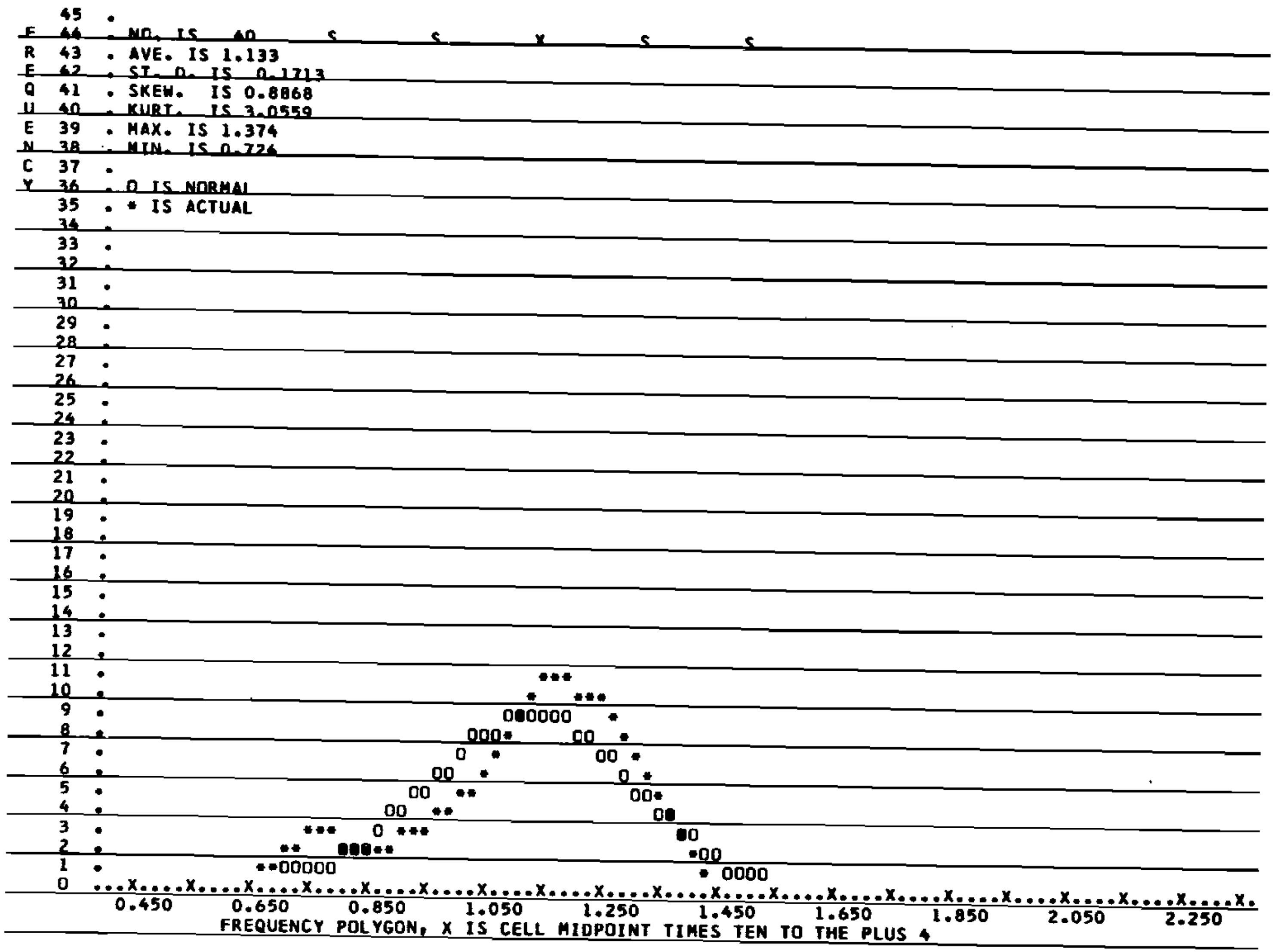


Figure 437. Frequency Distribution of Across-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Block No. 159

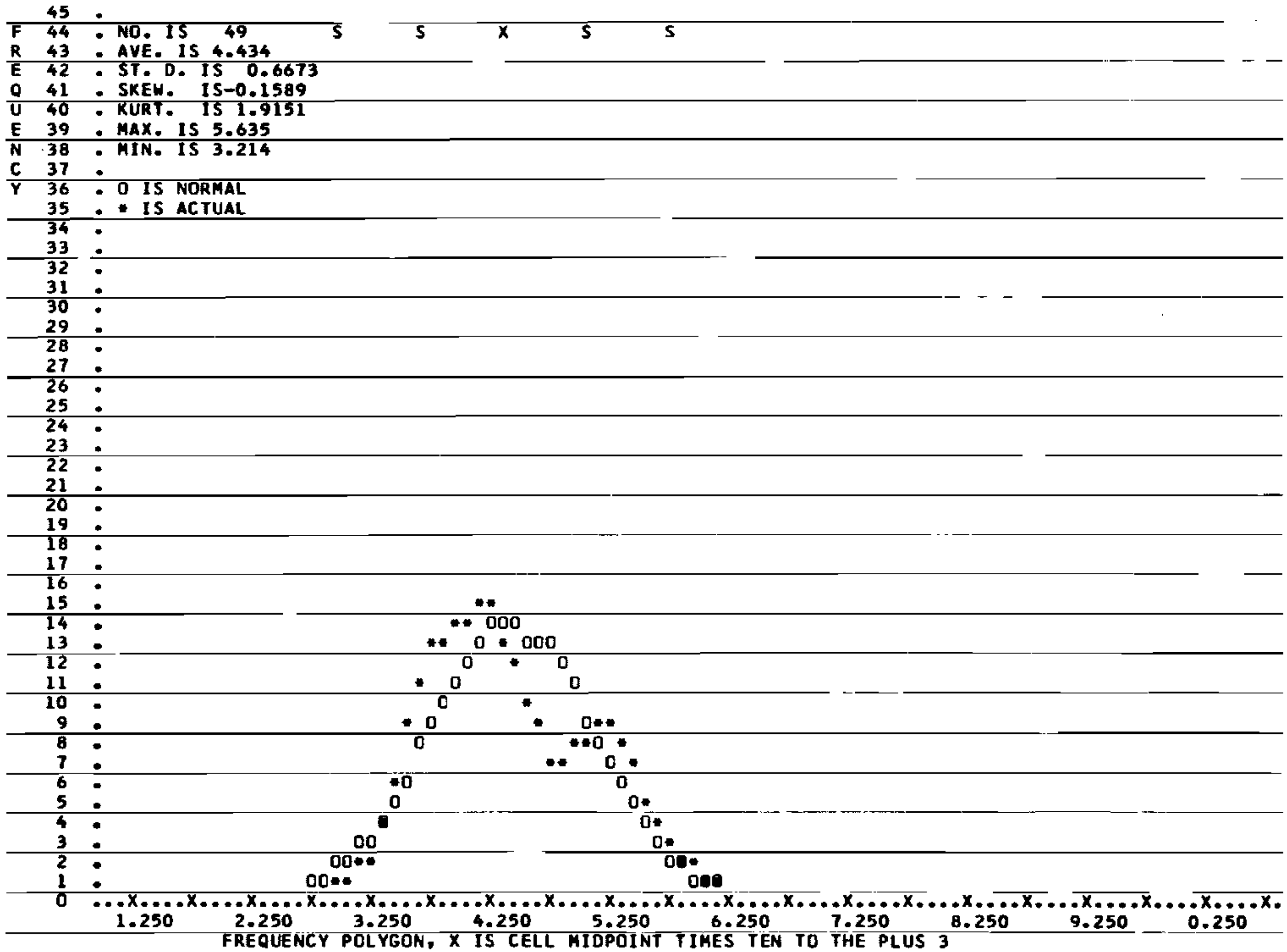


Figure 438. Frequency Distribution of With-Grain Tensile Strength Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Blocks No. 20, 23, 111, 153 and 159 Combined.

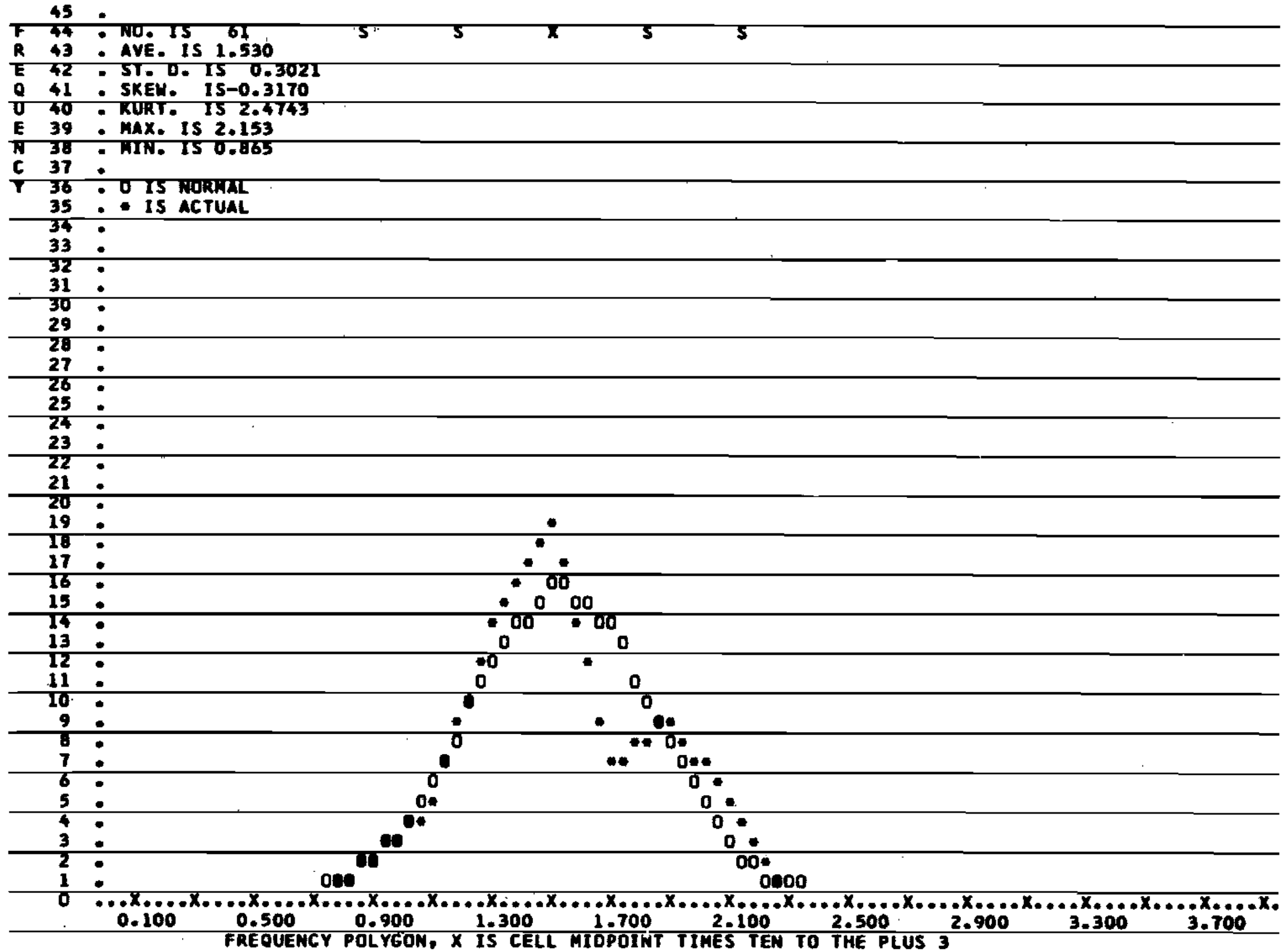


Figure 439. Frequency Distribution of Across-Grain Tensile Strength Data, ZTA Graphite, 14-Inch Diameter x 10-Inch Length, Blocks No. 20, 23, 111, 153 and 159 Combined

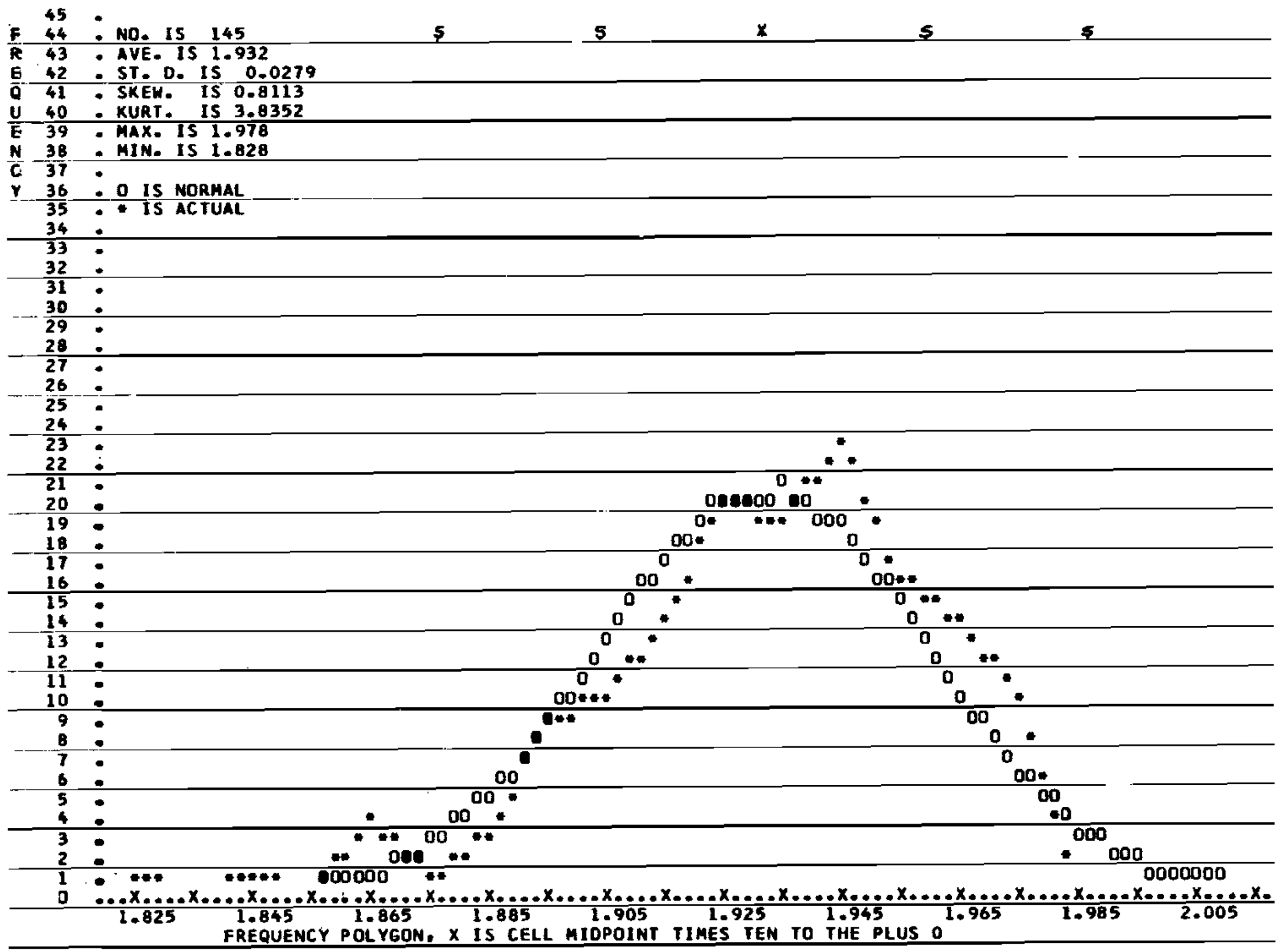


Figure 440. Frequency Distribution of Bulk Density Data, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Blocks No. H-363, K-366, N-367 and M-373 Combined

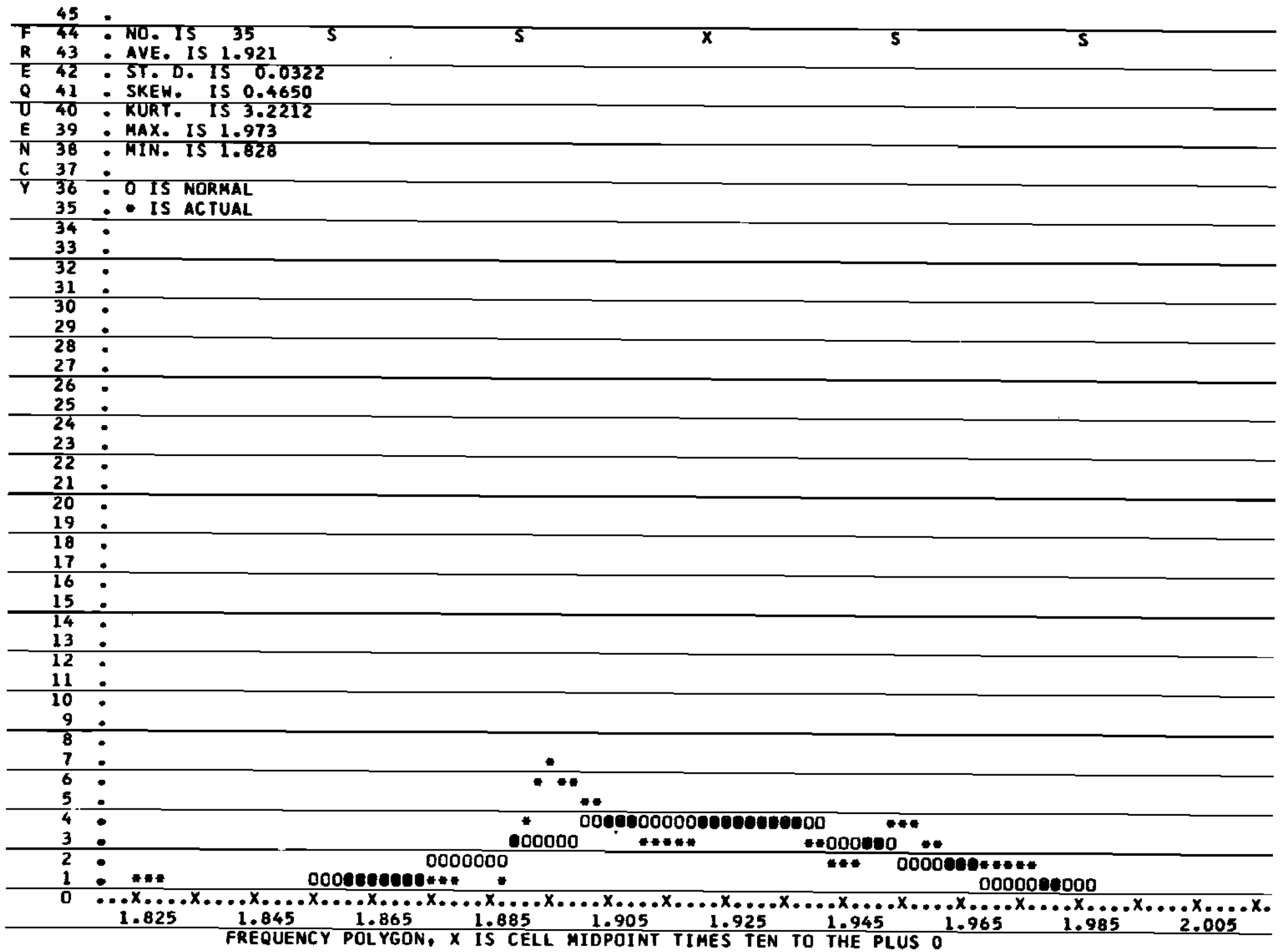


Figure 441. Frequency Distribution of Bulk Density Data, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Block No. H-363

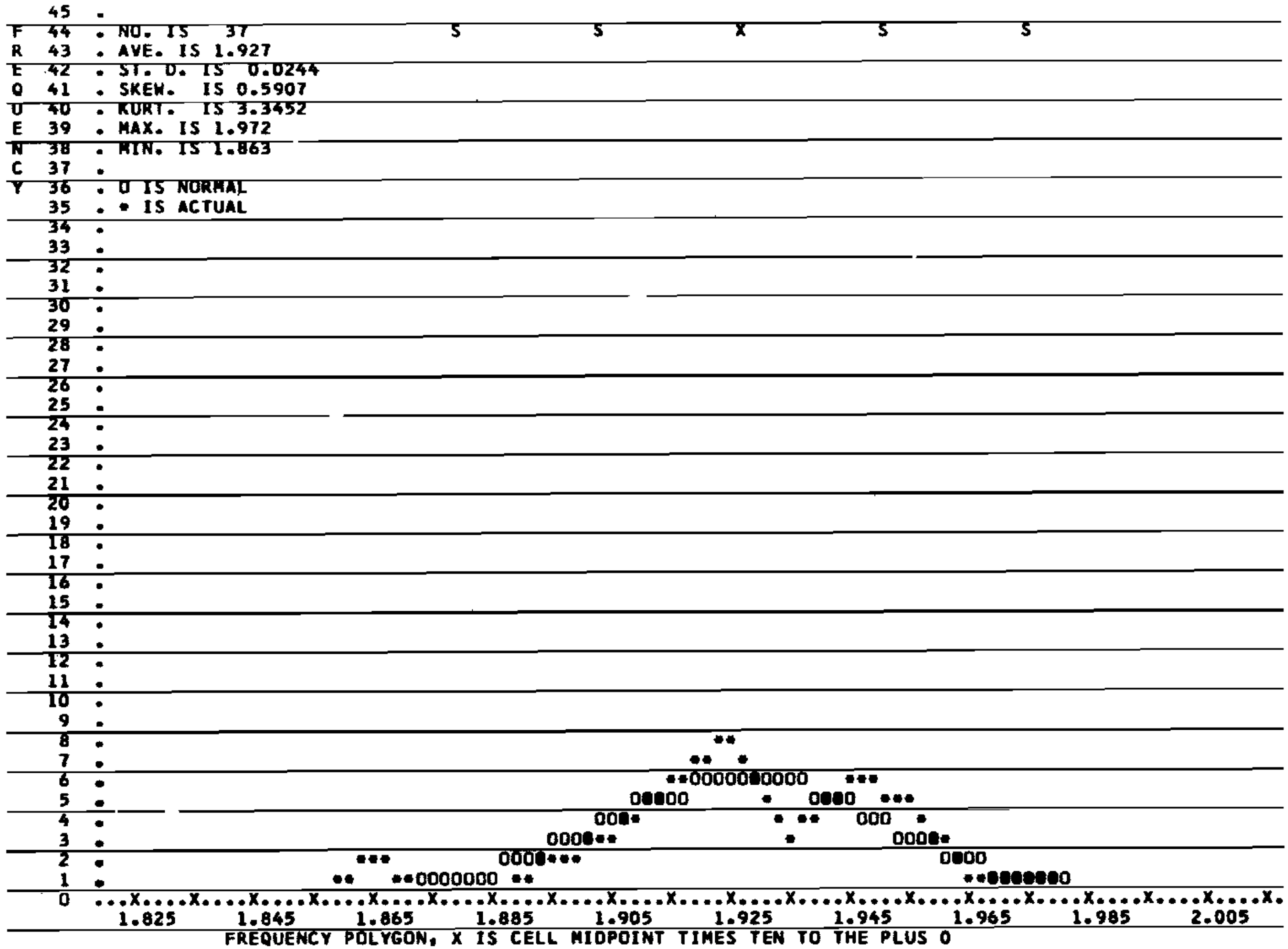


Figure 442. Frequency Distribution of Bulk Density Data, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Block No. K-366

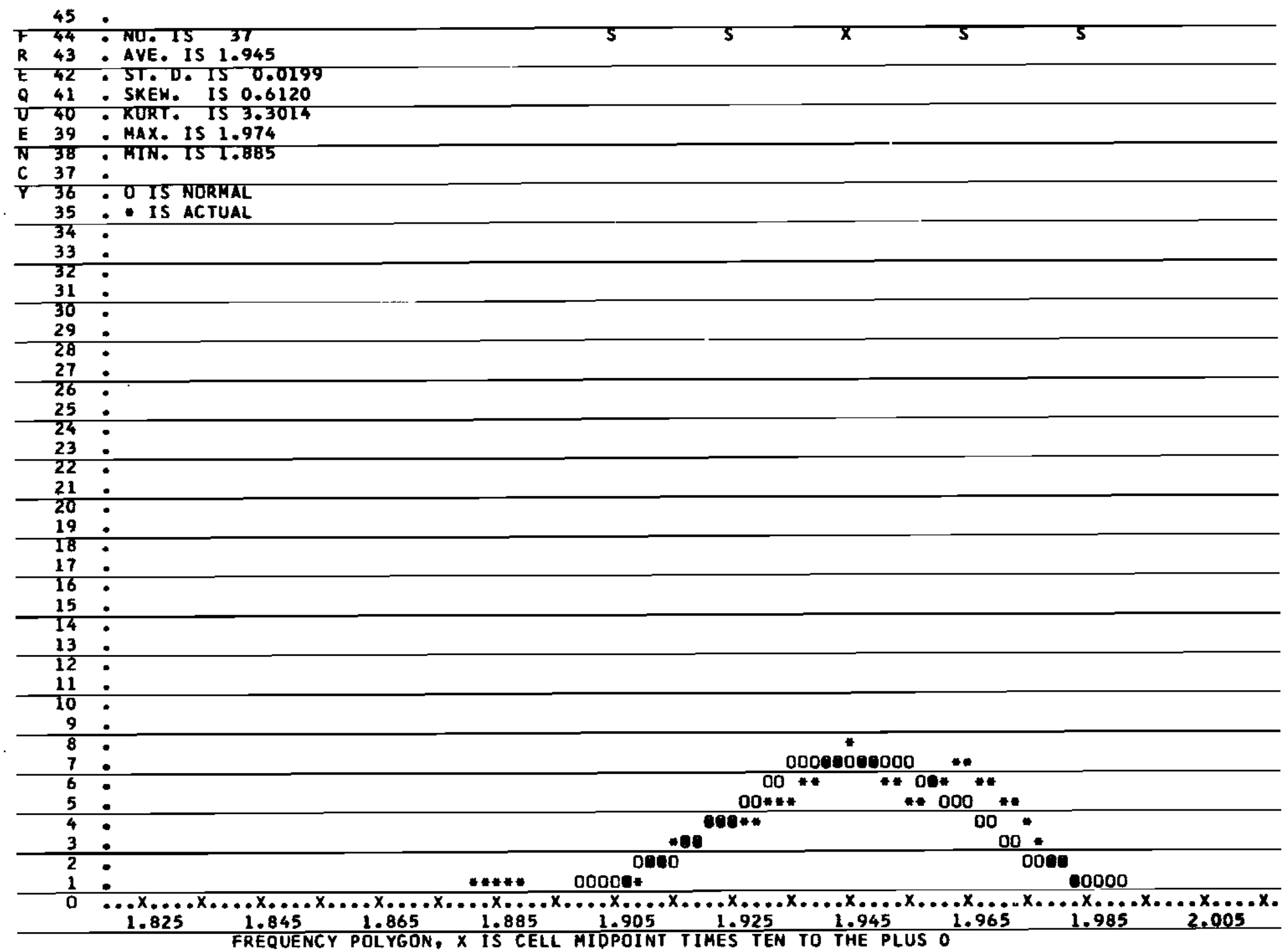


Figure 443. Frequency Distribution of Bulk Density Data, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Block No. N-367

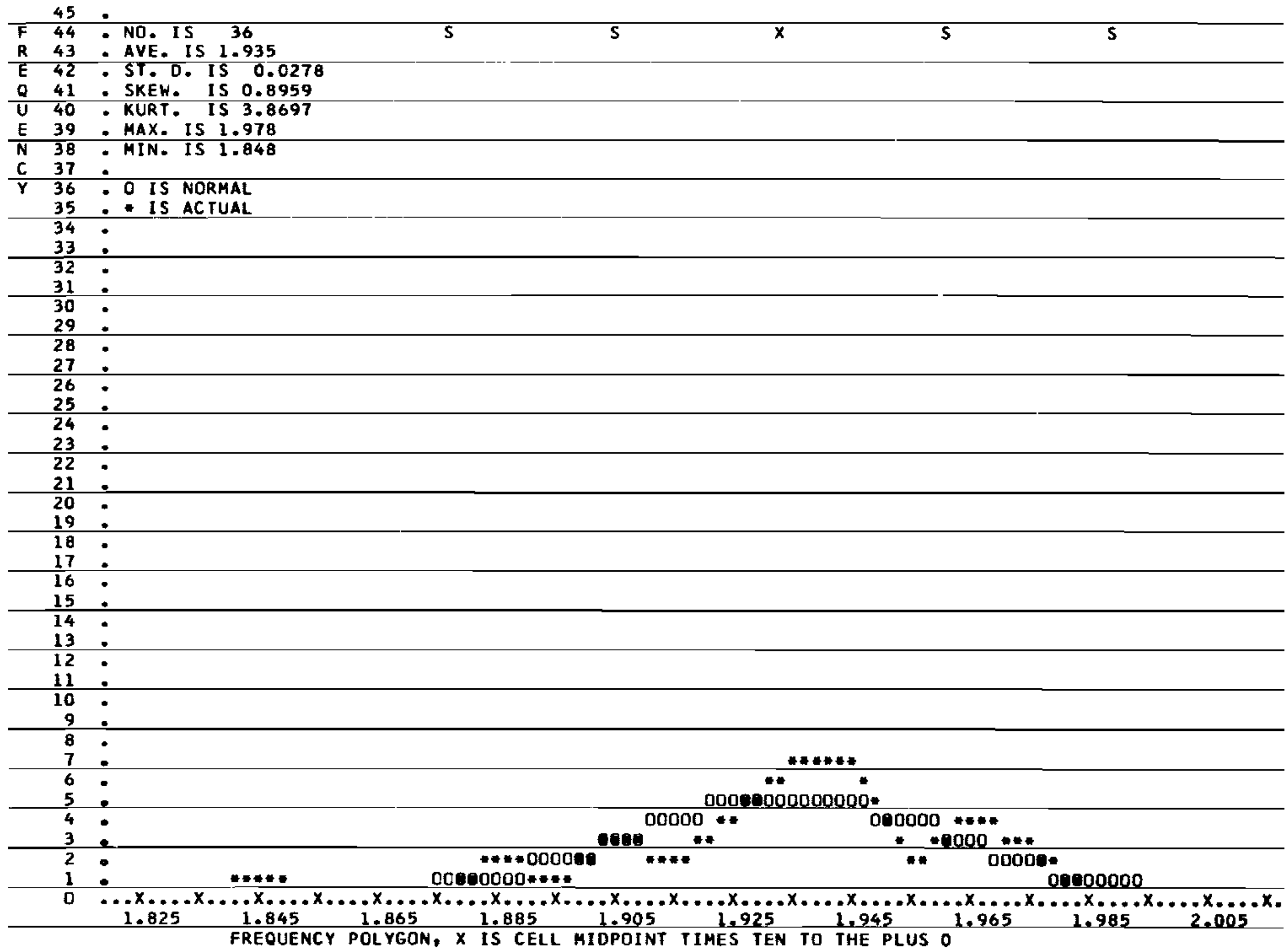


Figure 444. Frequency Distribution of Bulk Density Data, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Block No. M-373

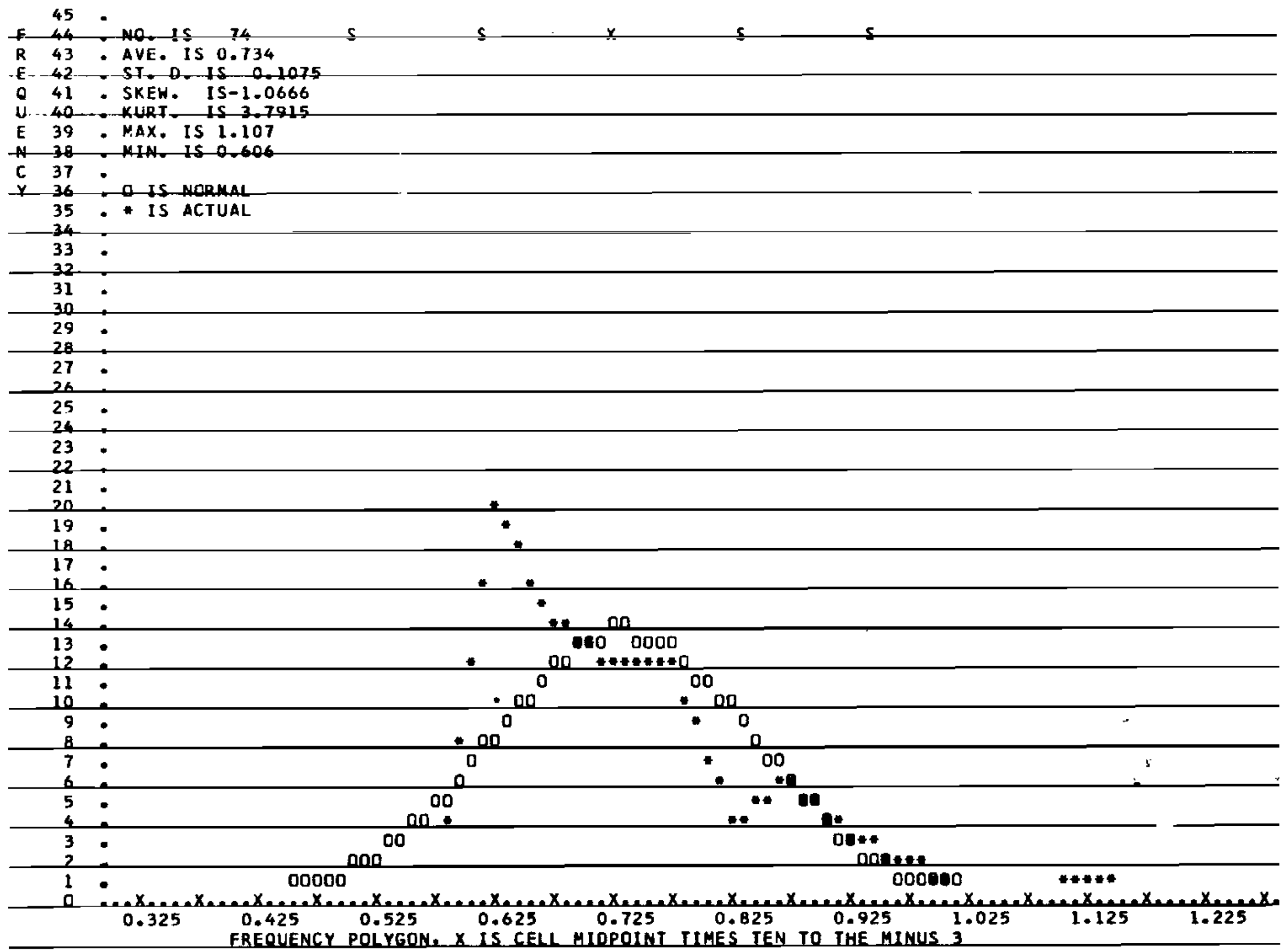


Figure 445. Frequency Distribution of With-Grain Specific Resistance Data, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length Blocks No. H-363, K-366, N-367 and M-373 Combined

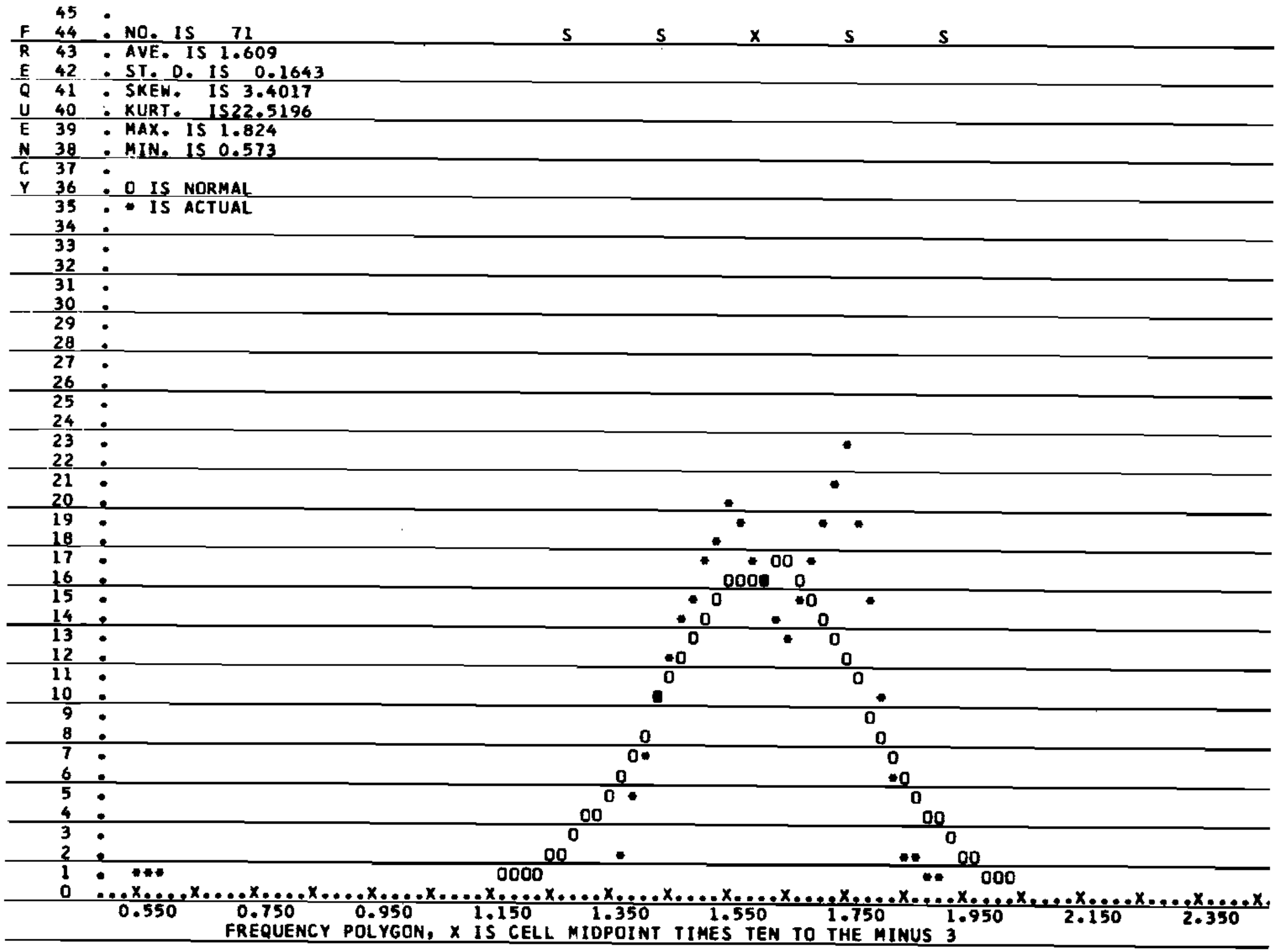


Figure 446. Frequency Distribution of Across-Grain Specific Resistance Data, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Blocks No. H-363, K-366, N-367 and M-373 Combined

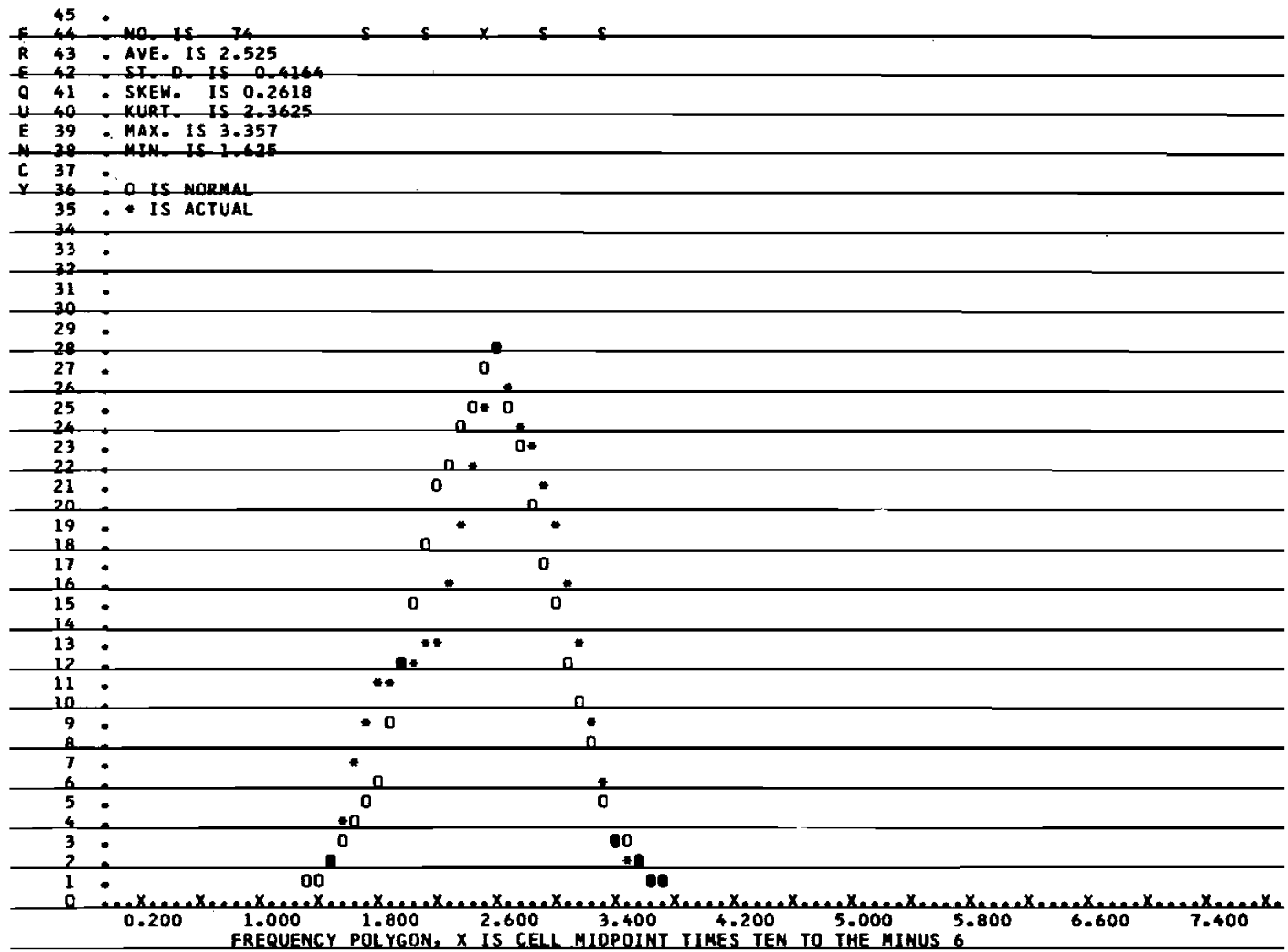


Figure 447. Frequency Distribution of With-Grain Young's Modulus of Elasticity Data, ZTA Graphite, $8\frac{1}{2}$ -Inch Diameter x 11-Inch Length, Blocks No. H-363, K-366, N-367 and M-373 Combined

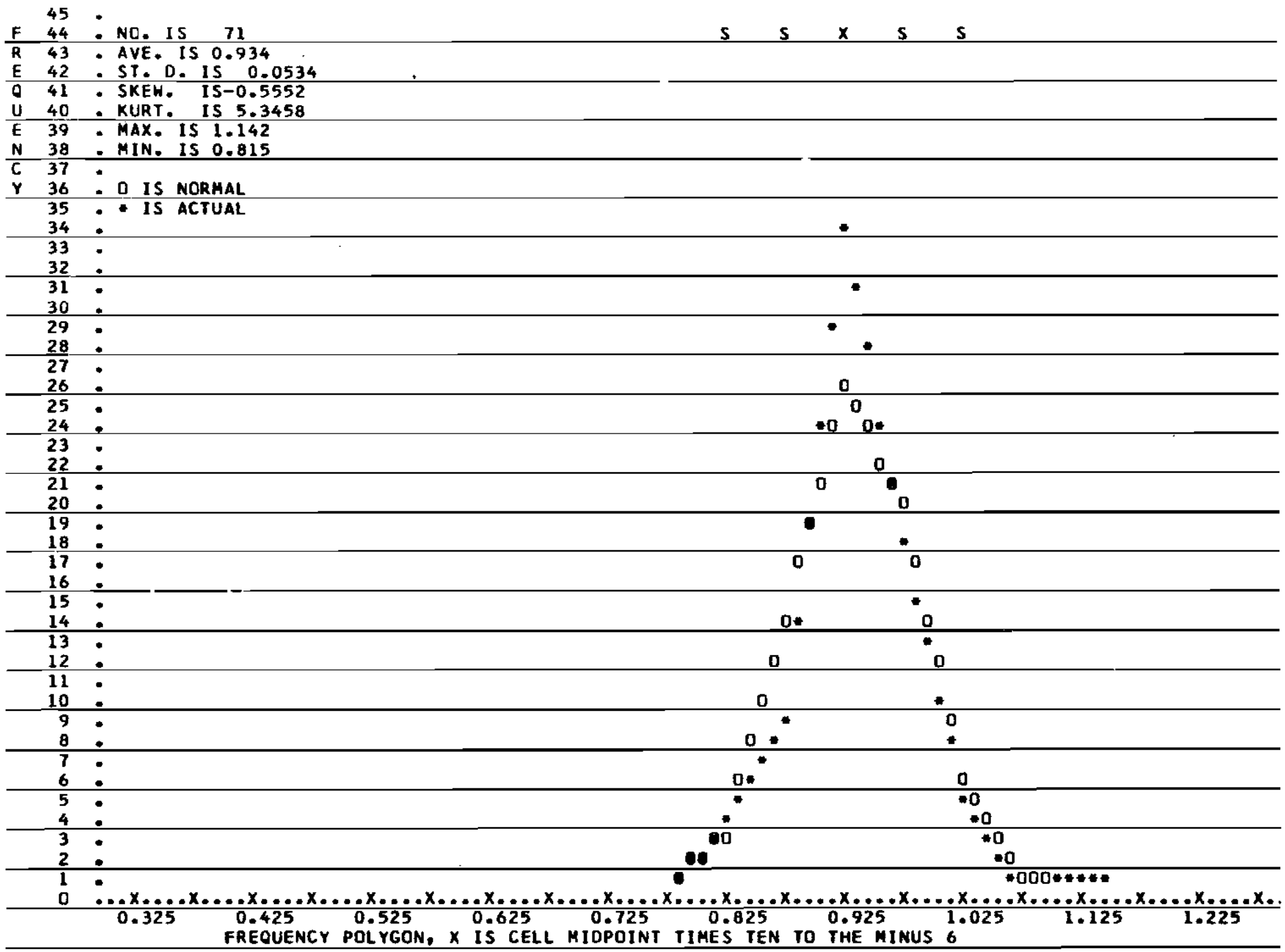


Figure 448. Frequency Distribution of Across-Grain Young's Modulus of Elasticity Data, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Blocks No. H-363, K-366, N-367 and M-373 Combined

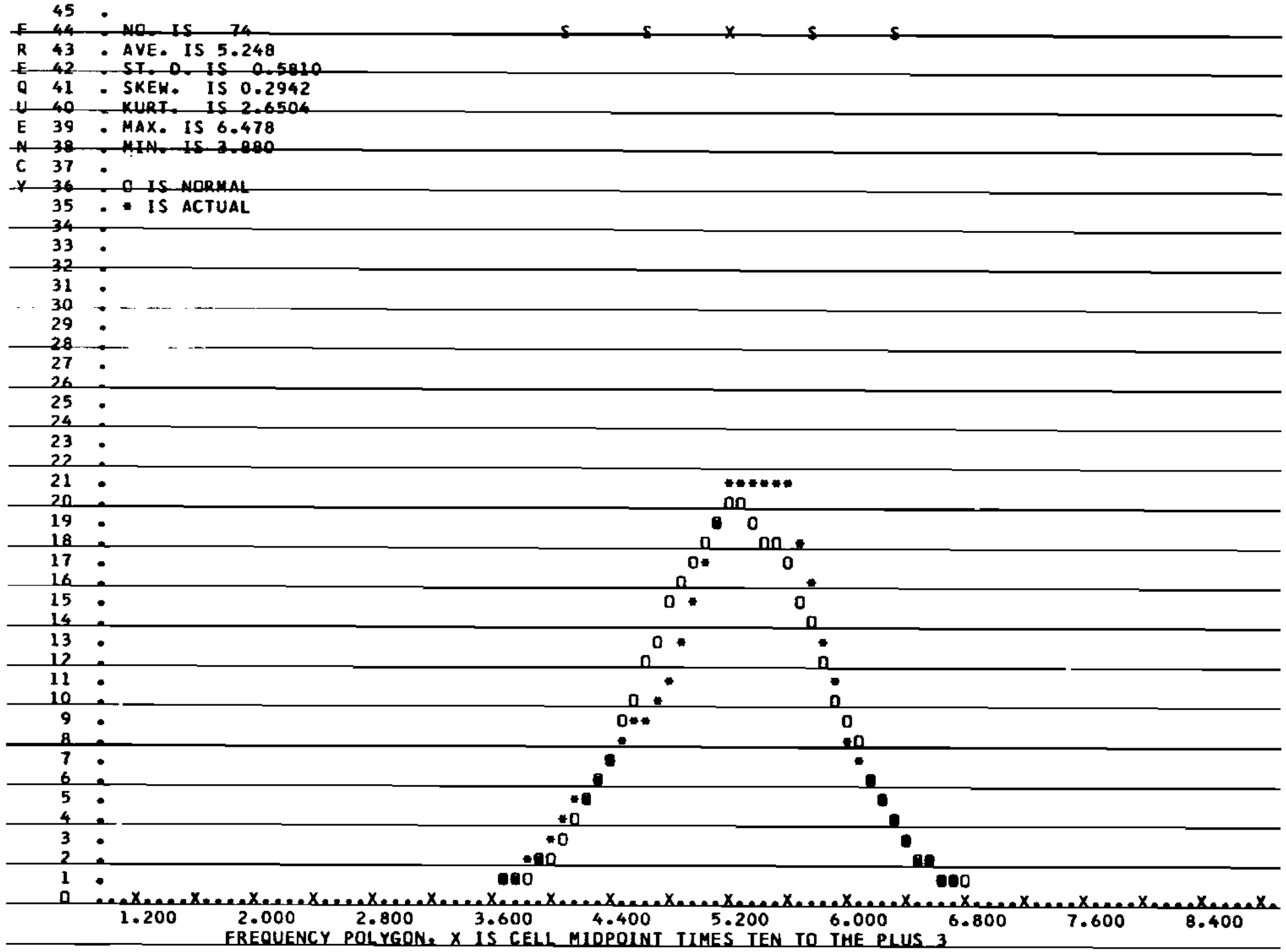


Figure 449. Frequency Distribution of With-Grain Flexural Strength Data, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Blocks No. H-363, K-366, N-367 and M-373 Combined

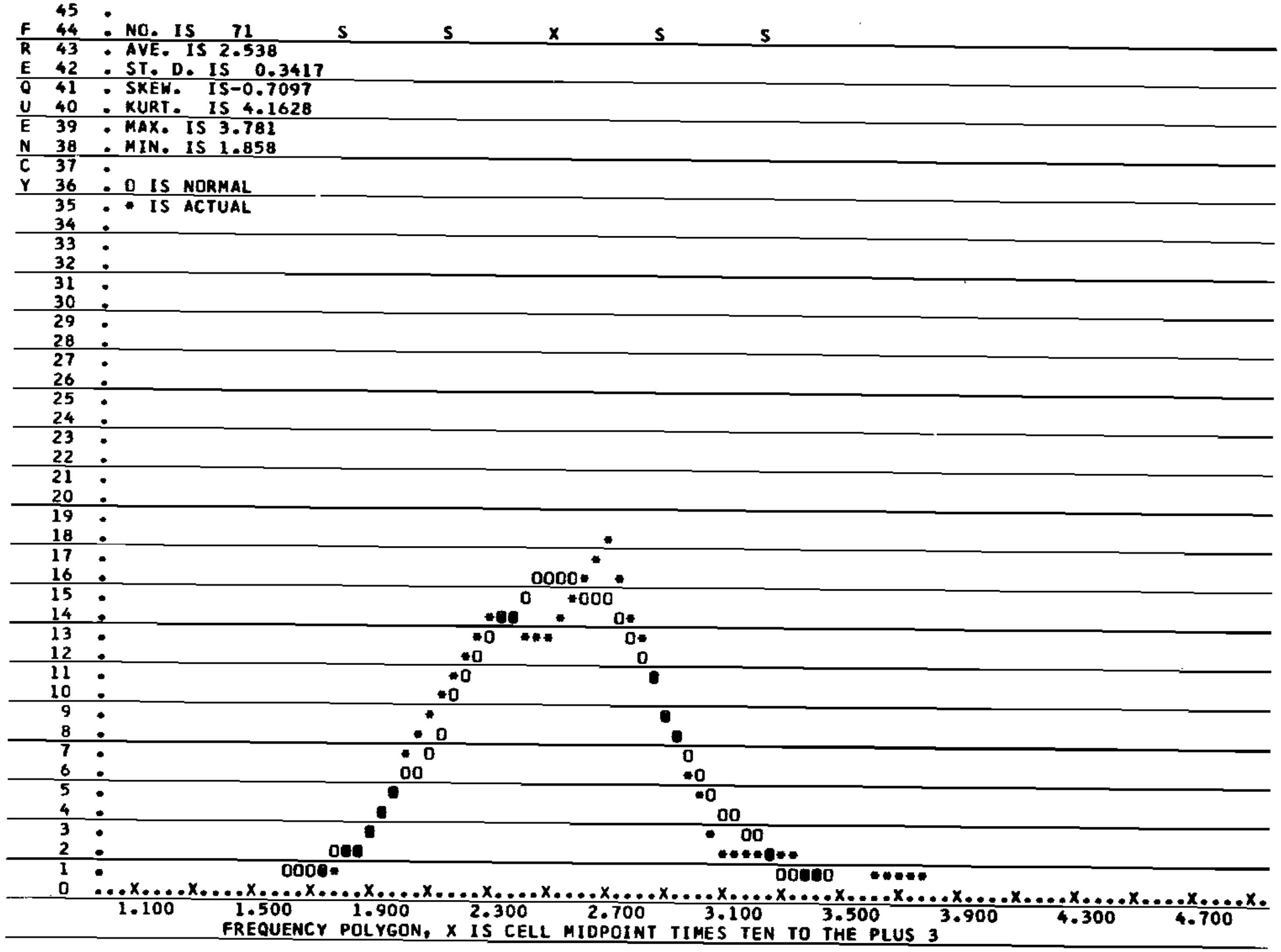


Figure 450. Frequency Distribution of Across-Grain Flexural Strength Data, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Blocks No. H-363, K-366, N-367 and M-373 Combined

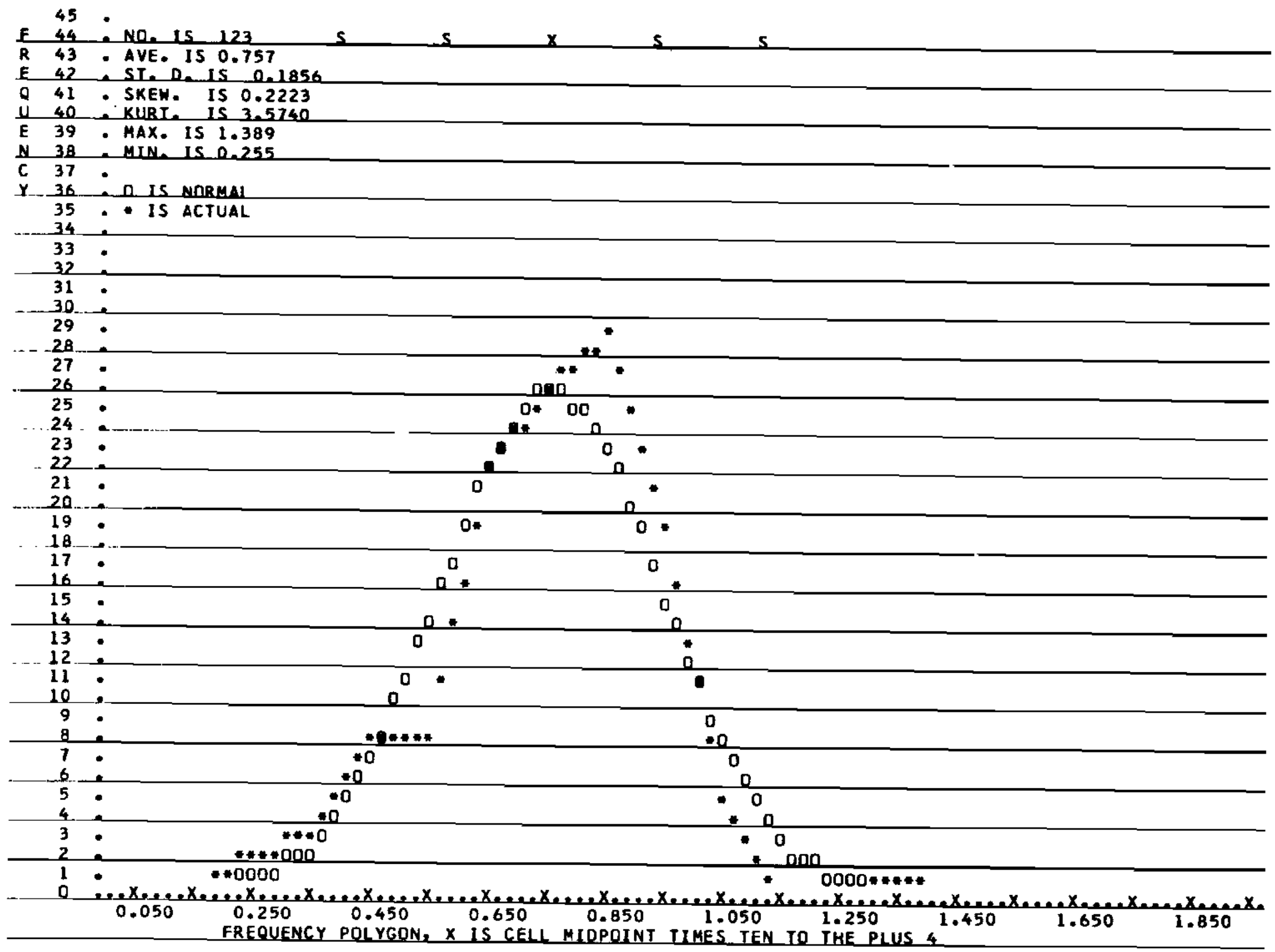


Figure 451. Frequency Distribution of With-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Blocks No. H-363, K-366, N-367 and M-373 Combined

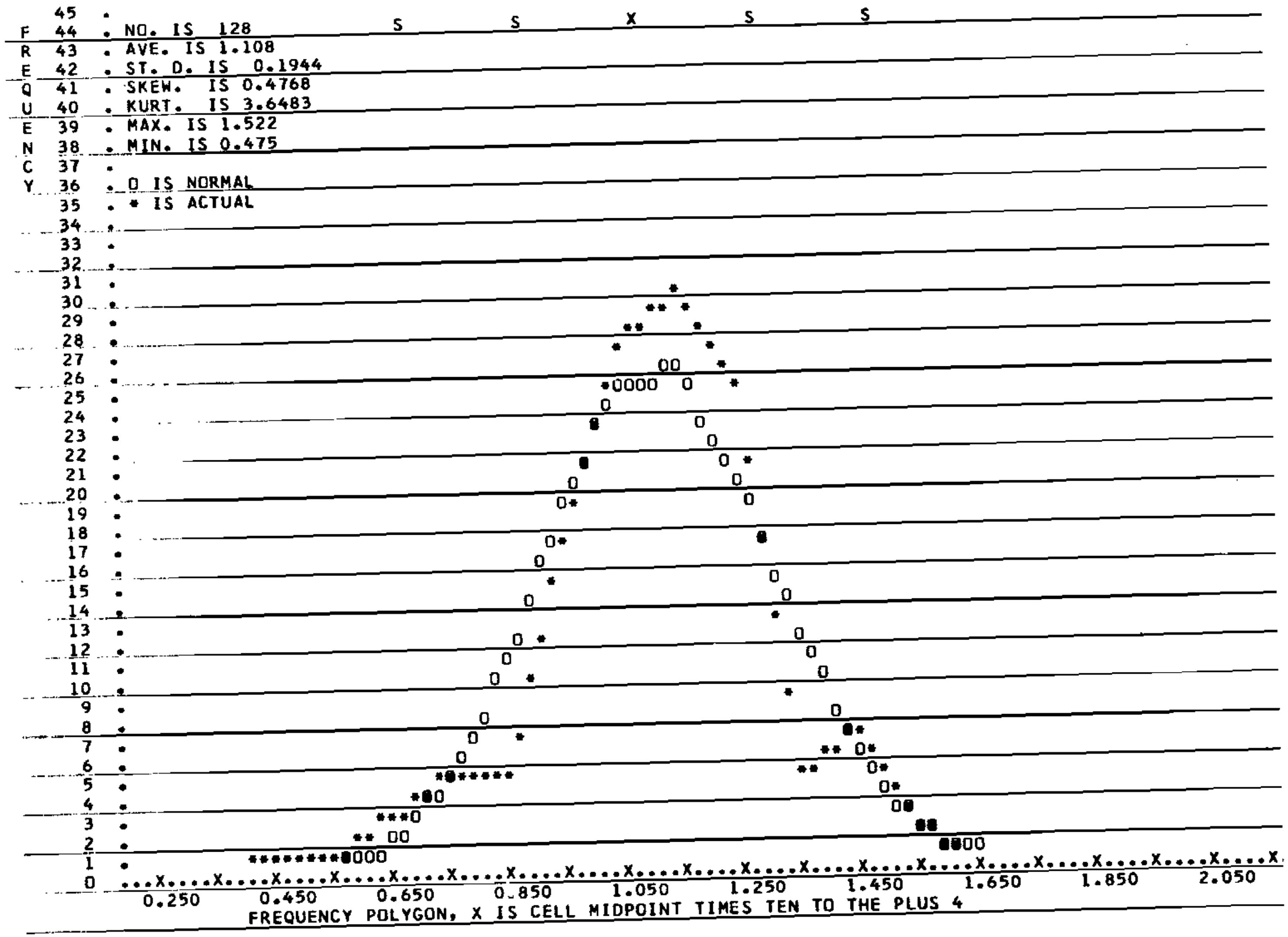


Figure 452. Frequency Distribution of Across-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Blocks No. H-363, K-366, N-367 and M-373 Combined

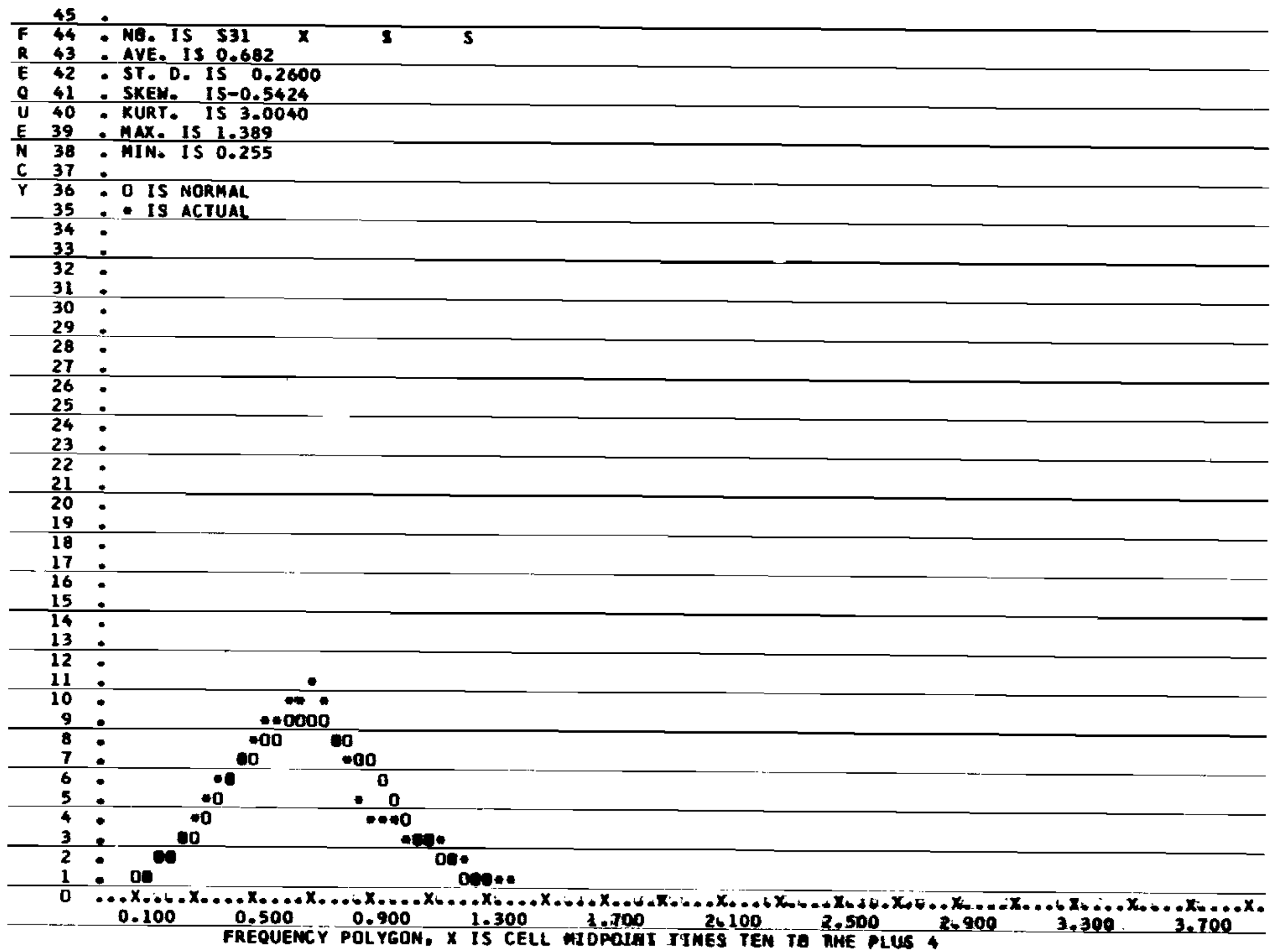


Figure 453. Frequency Distribution of With-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Block No. H-363

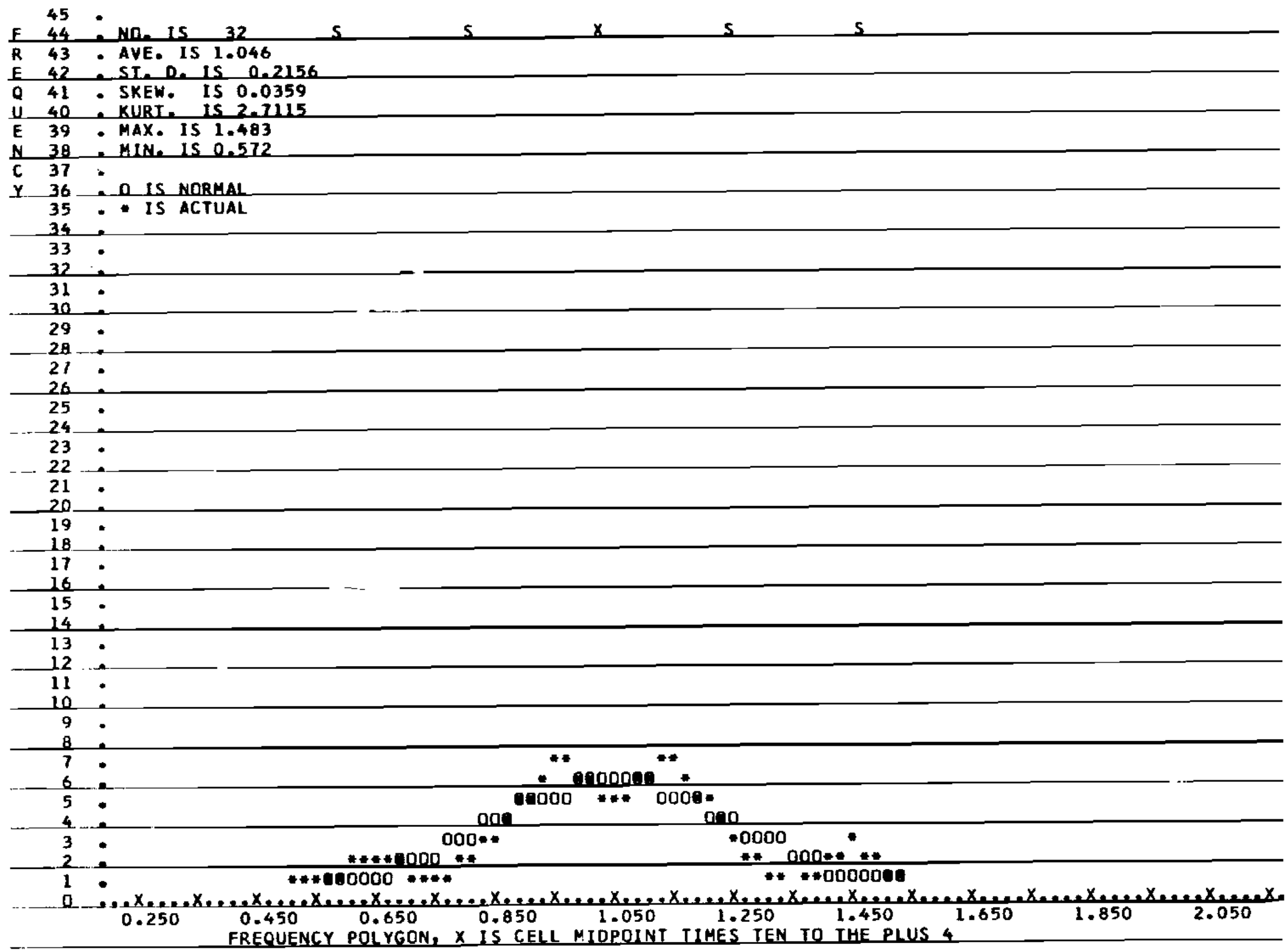


Figure 454. Frequency Distribution of Across-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Block No. H-363

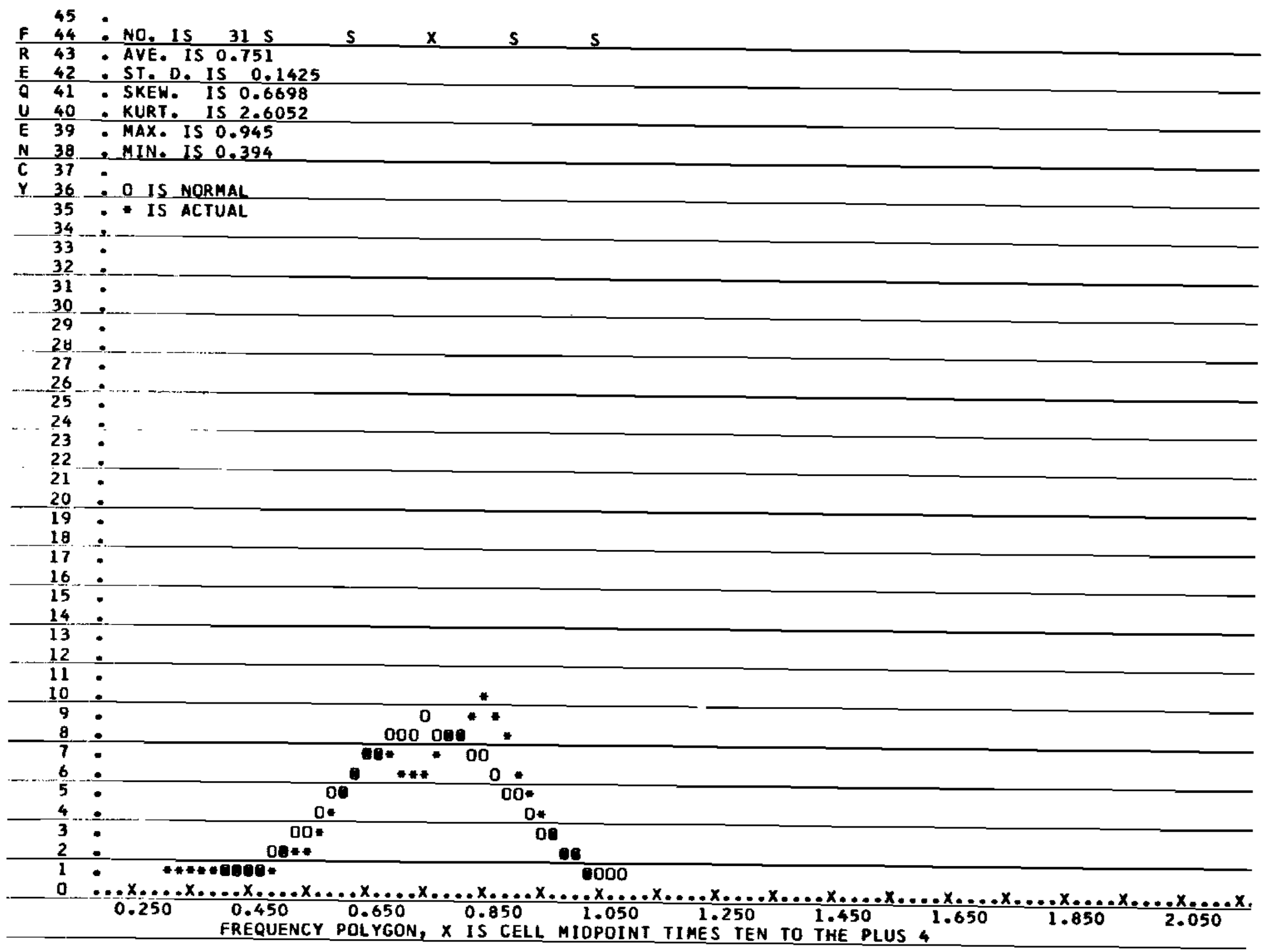


Figure 455. Frequency Distribution of With-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Block No. K-366

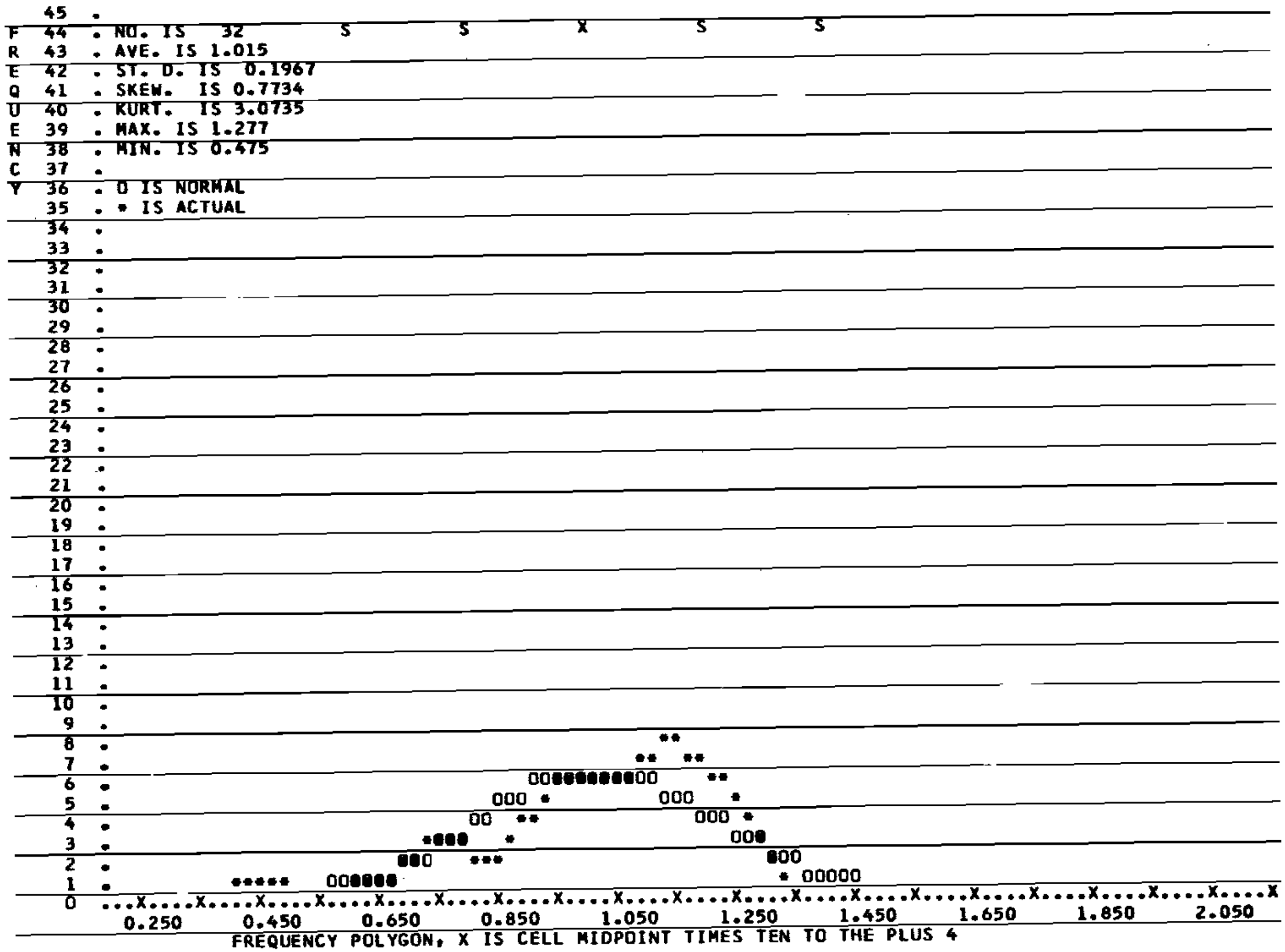


Figure 456. Frequency Distribution of Across-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, $8\frac{1}{2}$ -Inch Diameter x 11-Inch Length, Block No. K-366

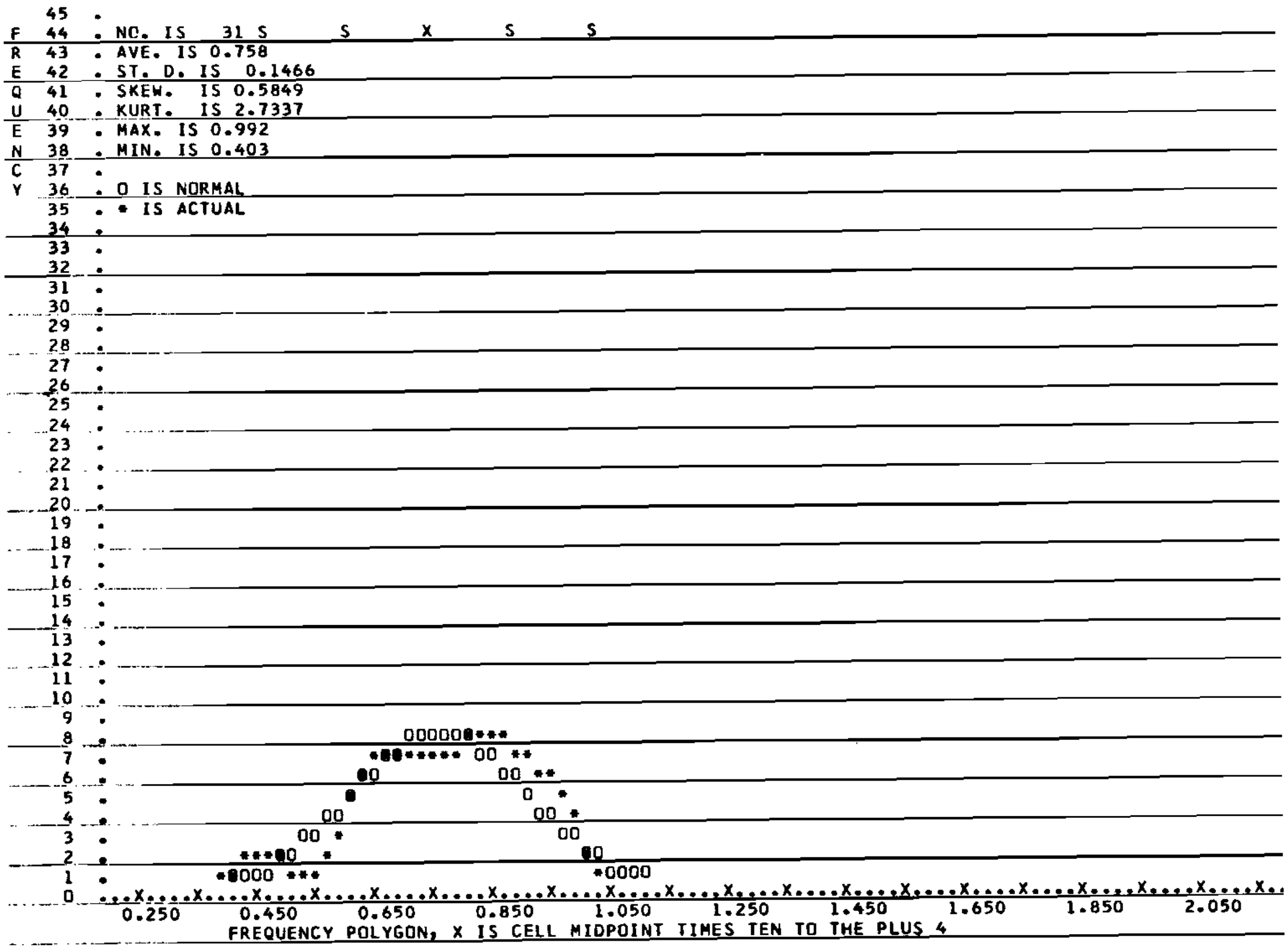


Figure 457. Frequency Distribution of With-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, $8\frac{1}{2}$ -Inch Diameter x 11-Inch Length, Block No. N-367

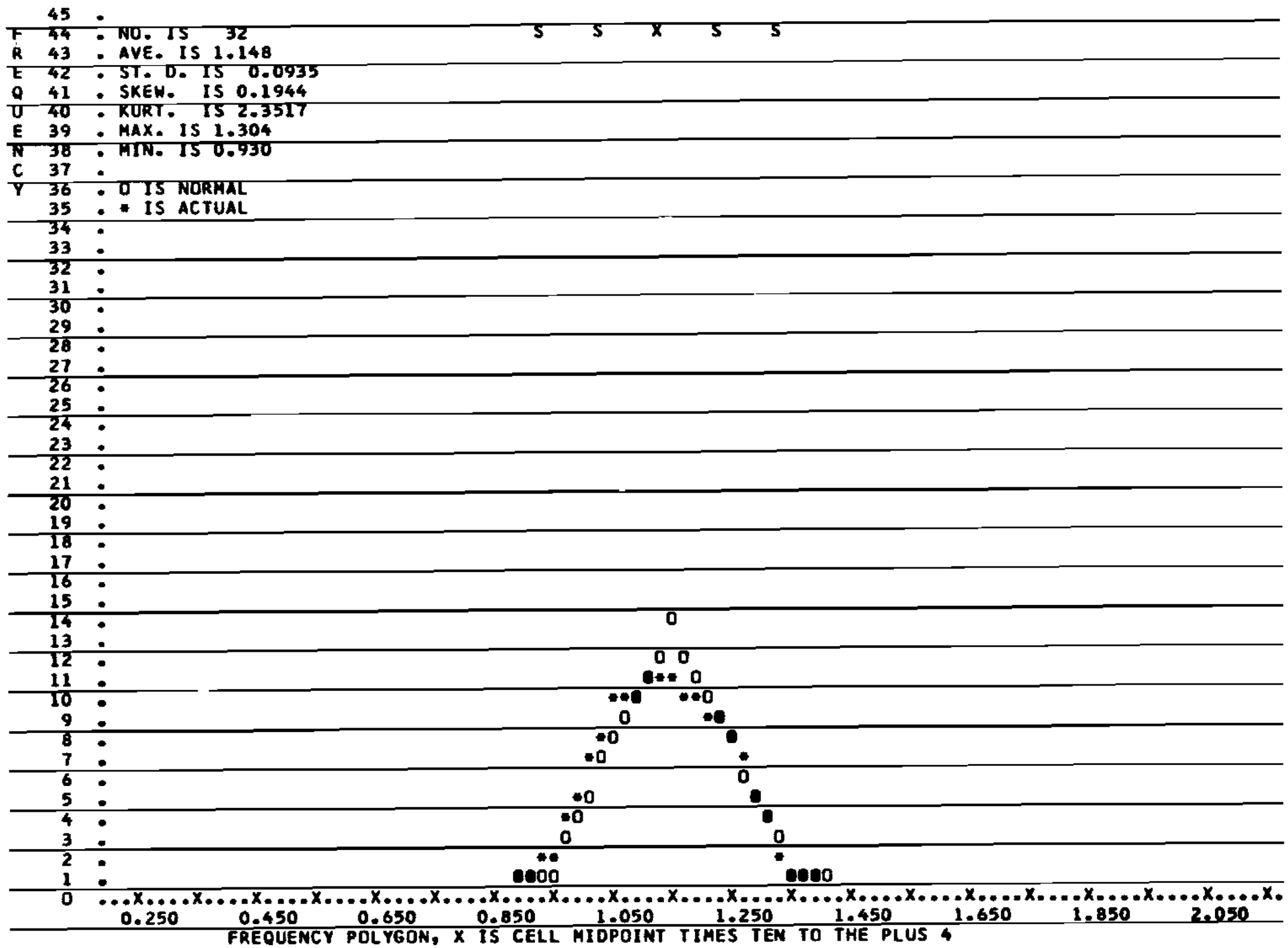


Figure 458. Frequency Distribution of Across-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Block No. N-367

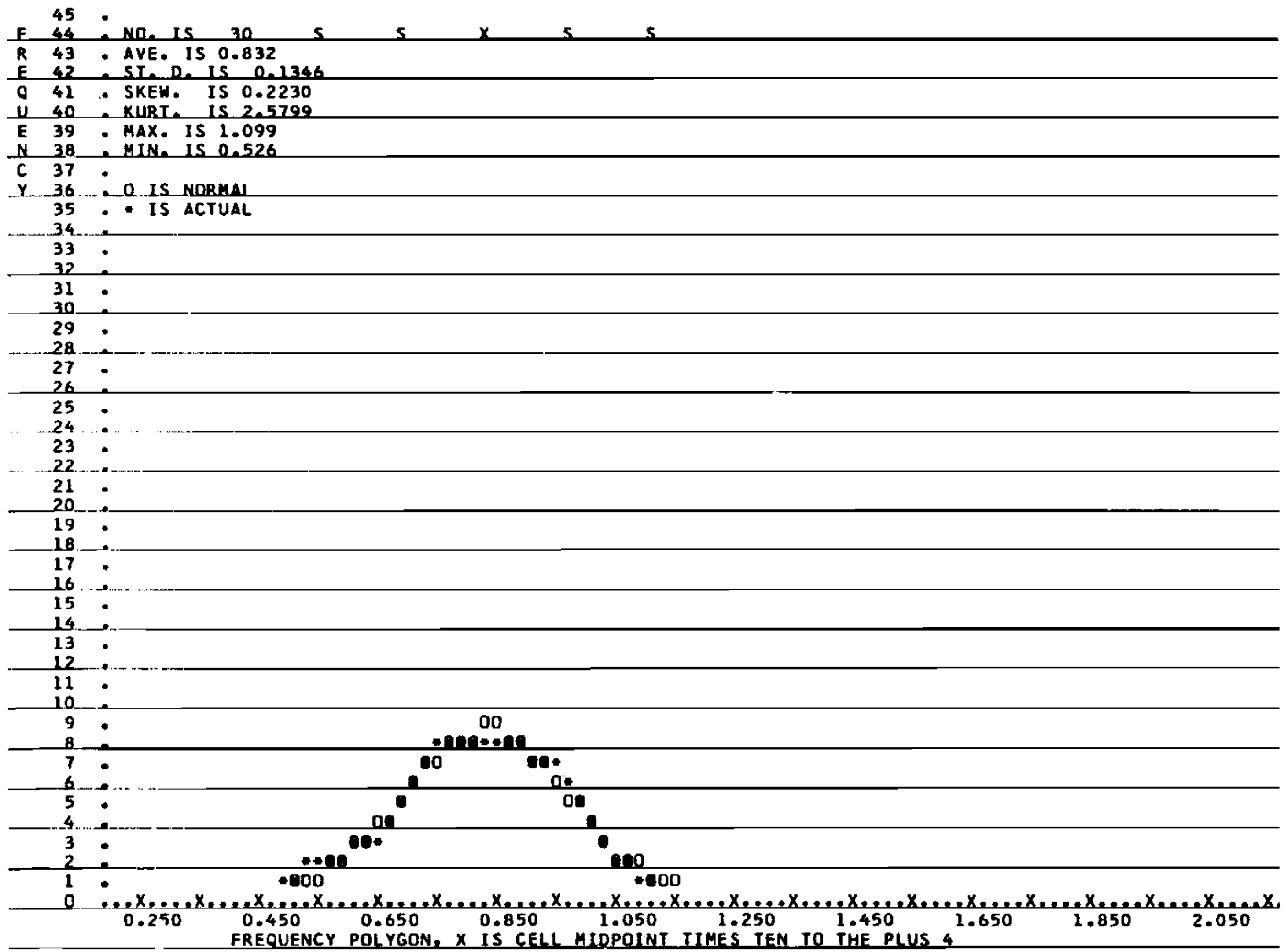


Figure 459. Frequency Distribution of With-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Block No. M-373

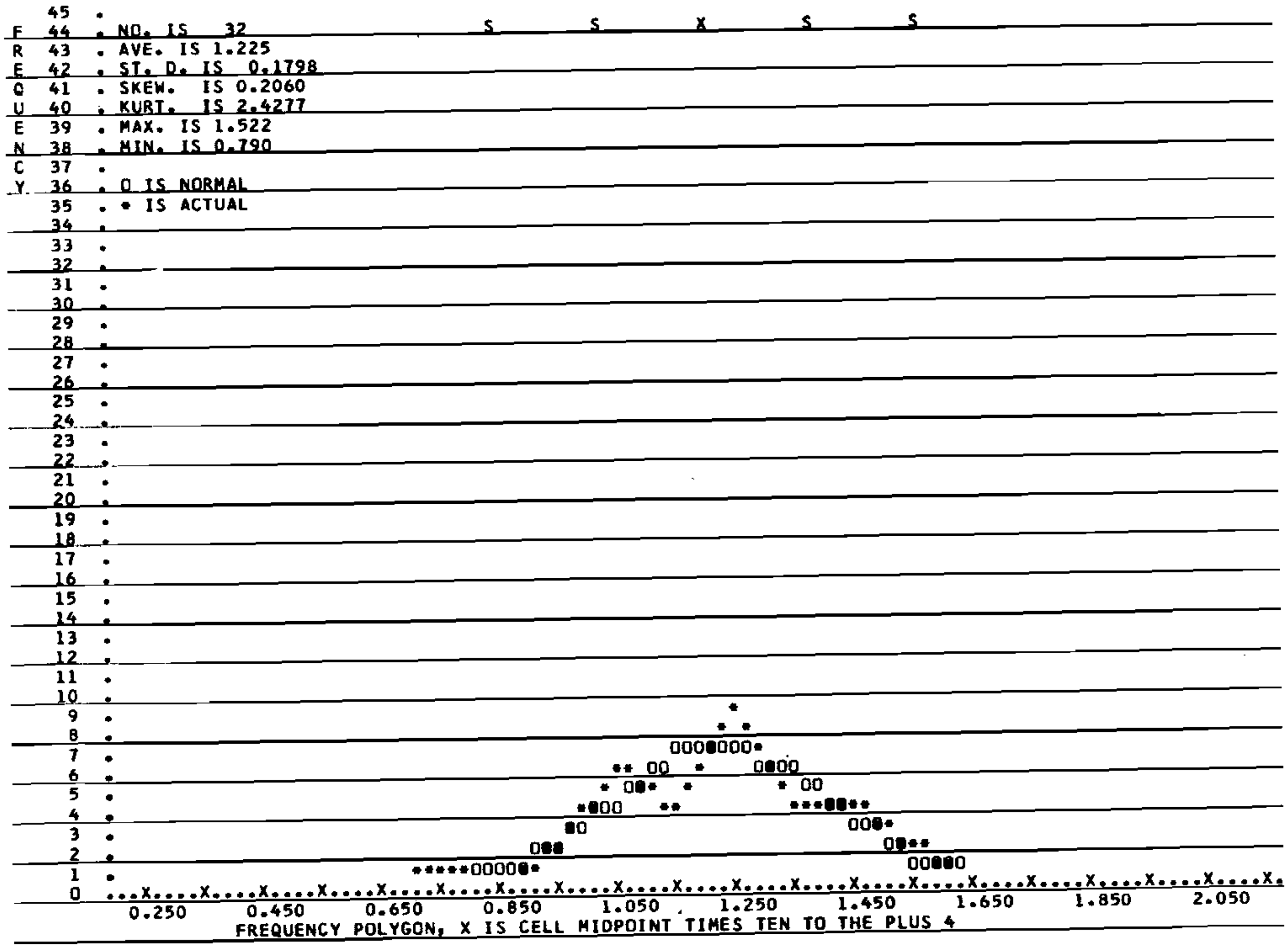


Figure 460. Frequency Distribution of Across-Grain Compressive Strength Data, Cubical Specimen, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Block No. M-373

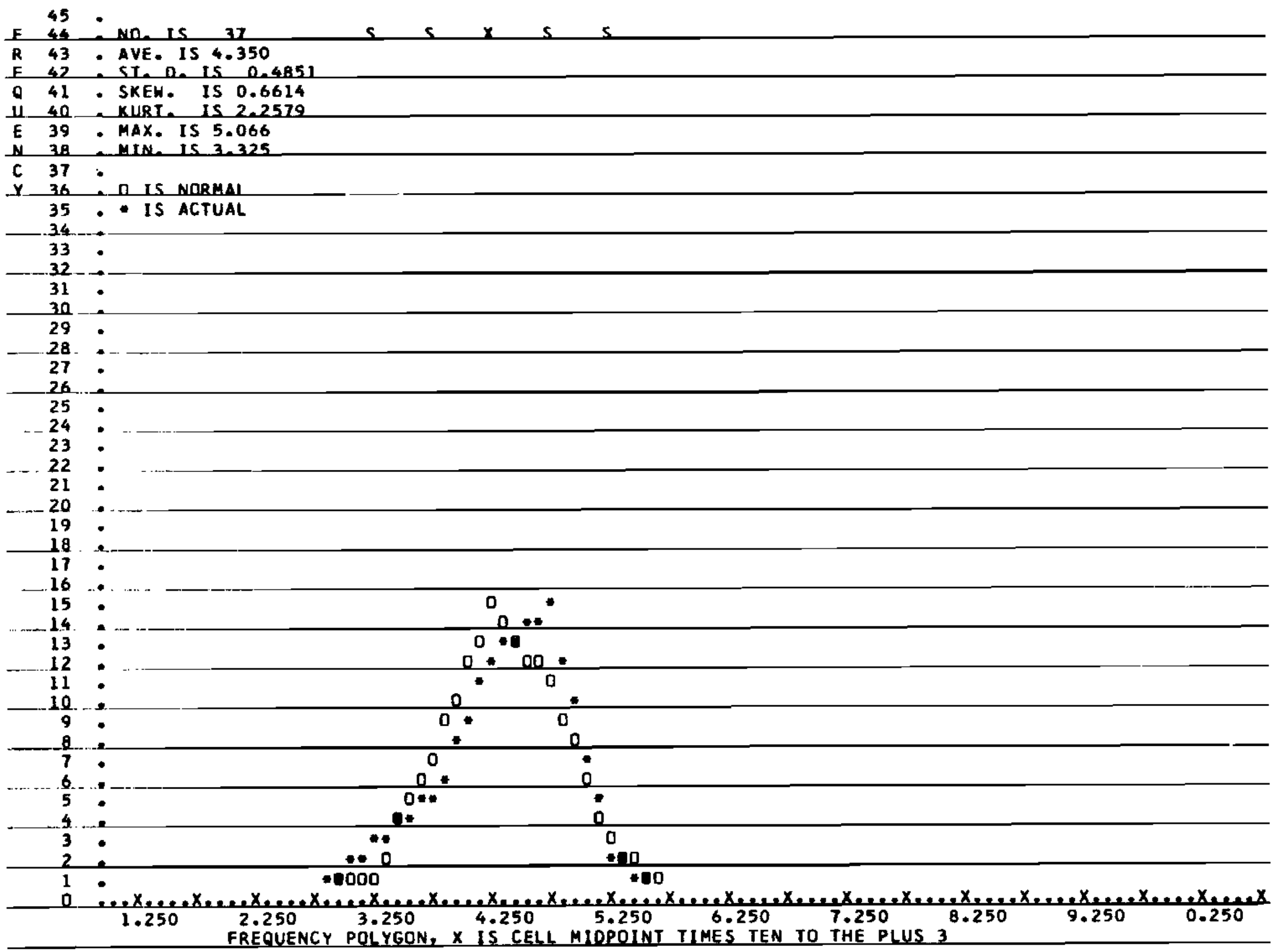


Figure 461. Frequency Distribution of With-Grain Tensile Strength Data, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Blocks No. H-363, K-366, N-367 and M-373 Combined

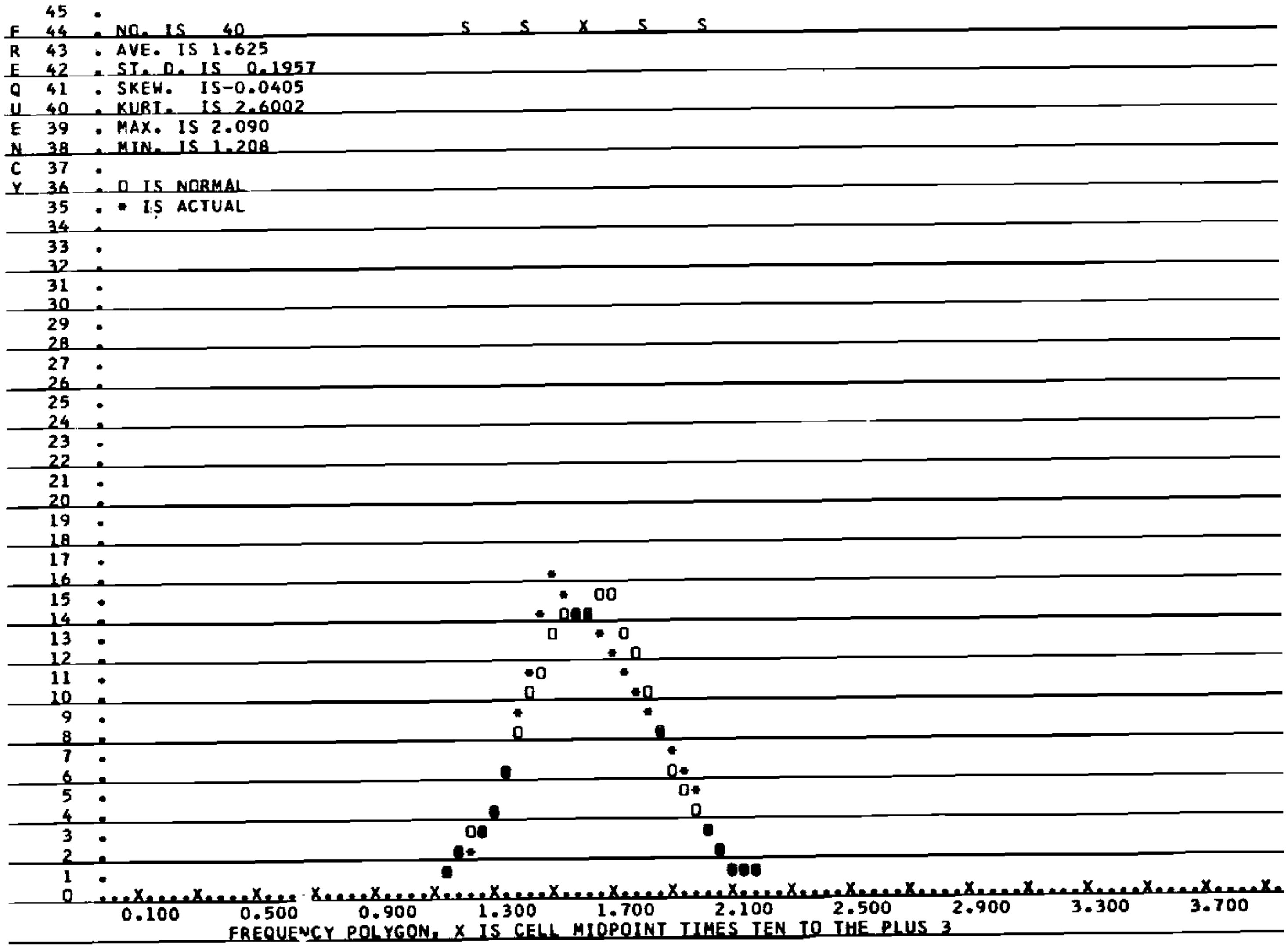


Figure 462. Frequency Distribution of Across-Grain Tensile Strength Data, ZTA Graphite, $8\frac{1}{2}$-Inch Diameter x 11-Inch Length, Blocks No. H-363, K-366, N-367 and M-373 Combined

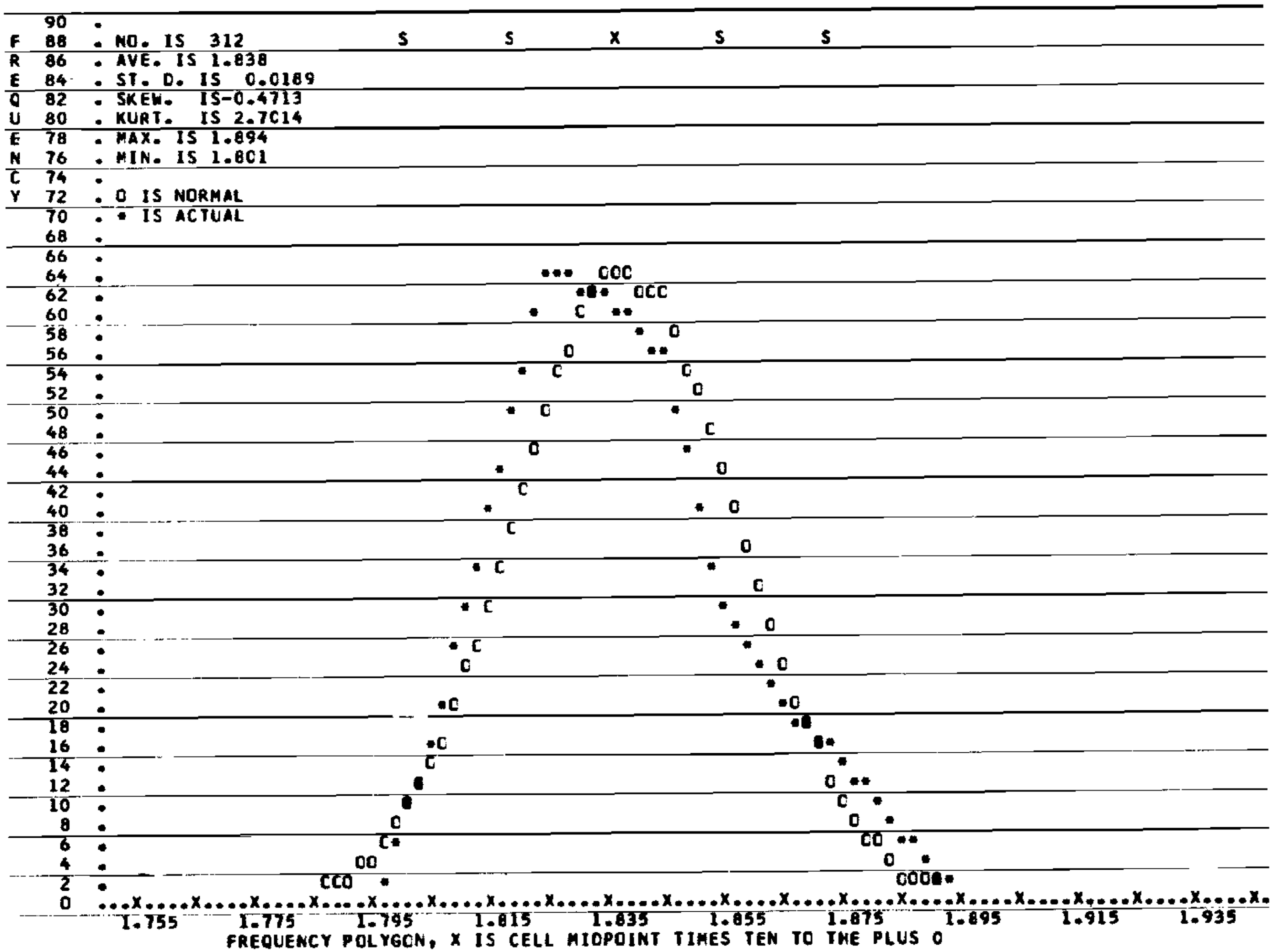


Figure 463. Frequency Distribution of Bulk Density Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Blocks No. A-19, A-20 and A-24 Combined

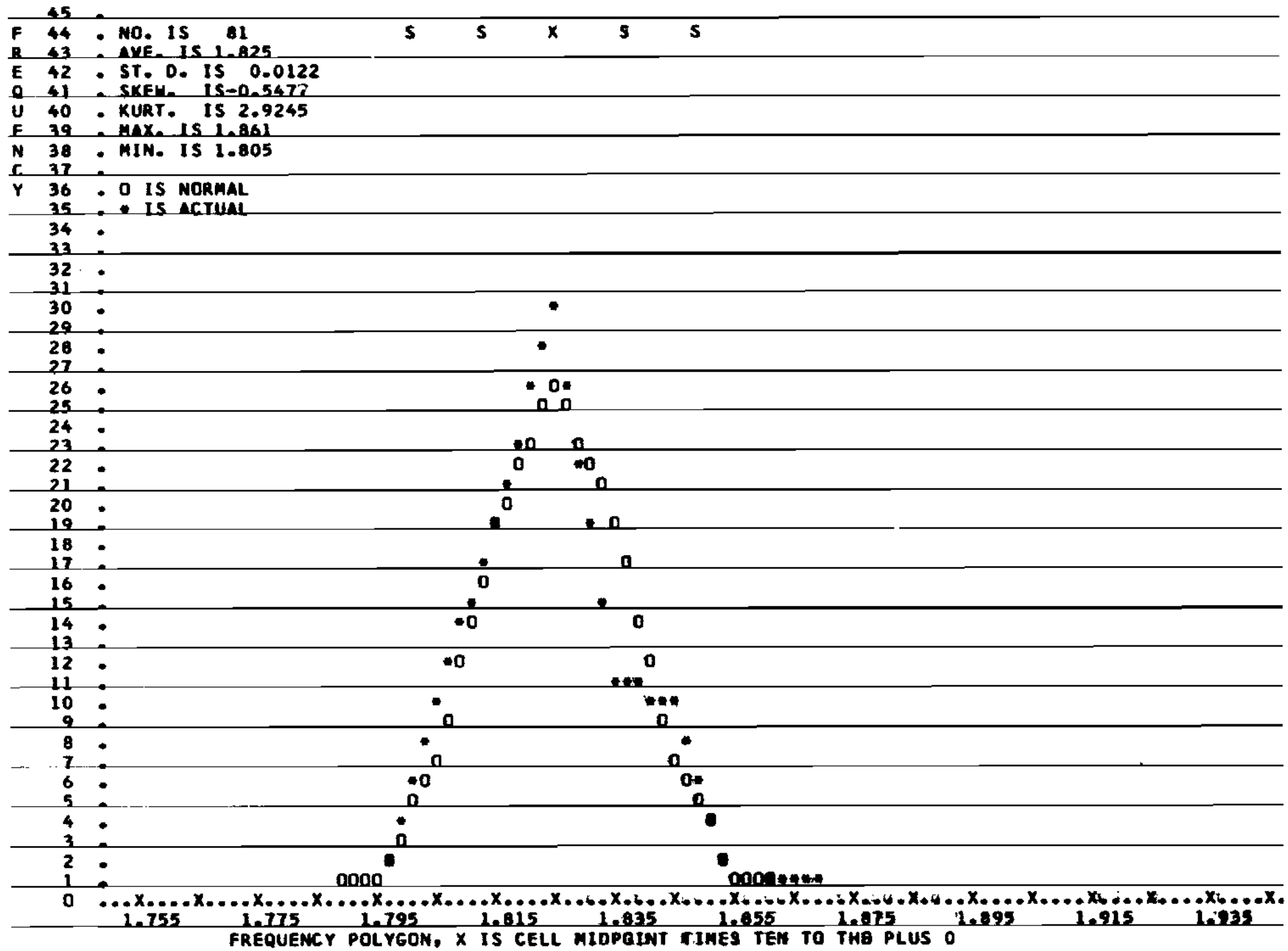


Figure 464. Frequency Distribution of Bulk Density Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-19

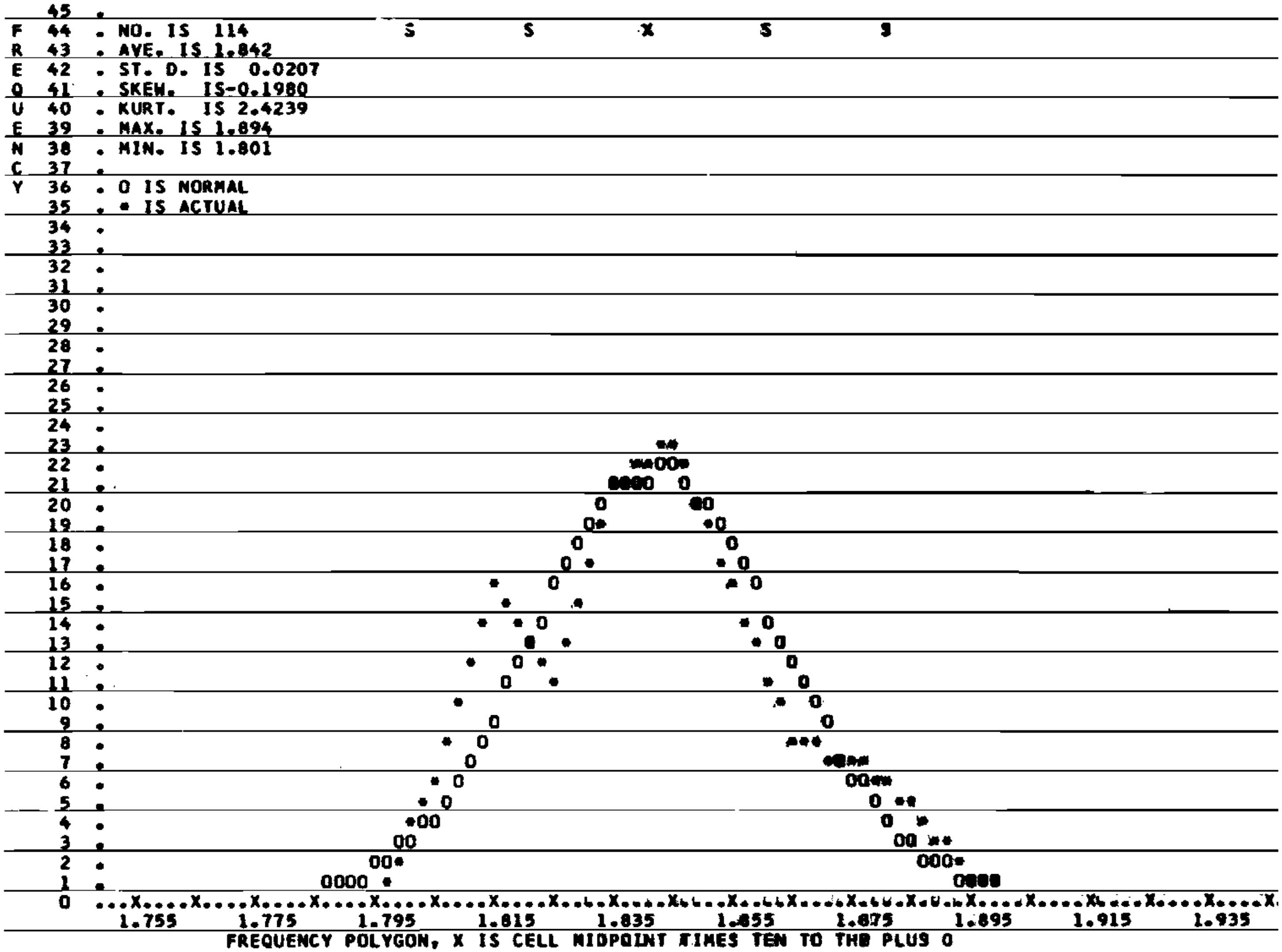


Figure 465. Frequency Distribution of Bulk Density Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-20

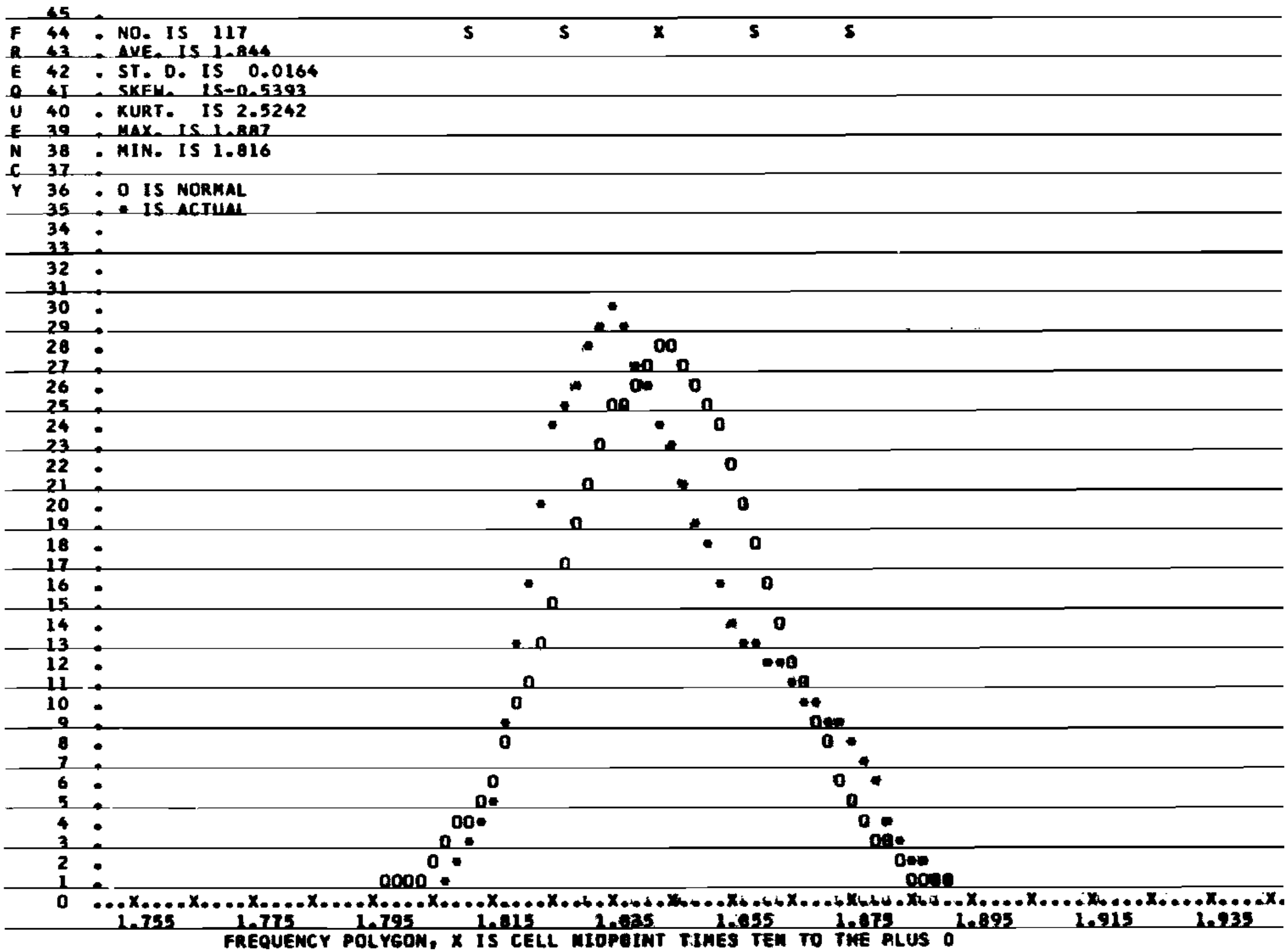


Figure 466. Frequency Distribution of Bulk Density Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-24.

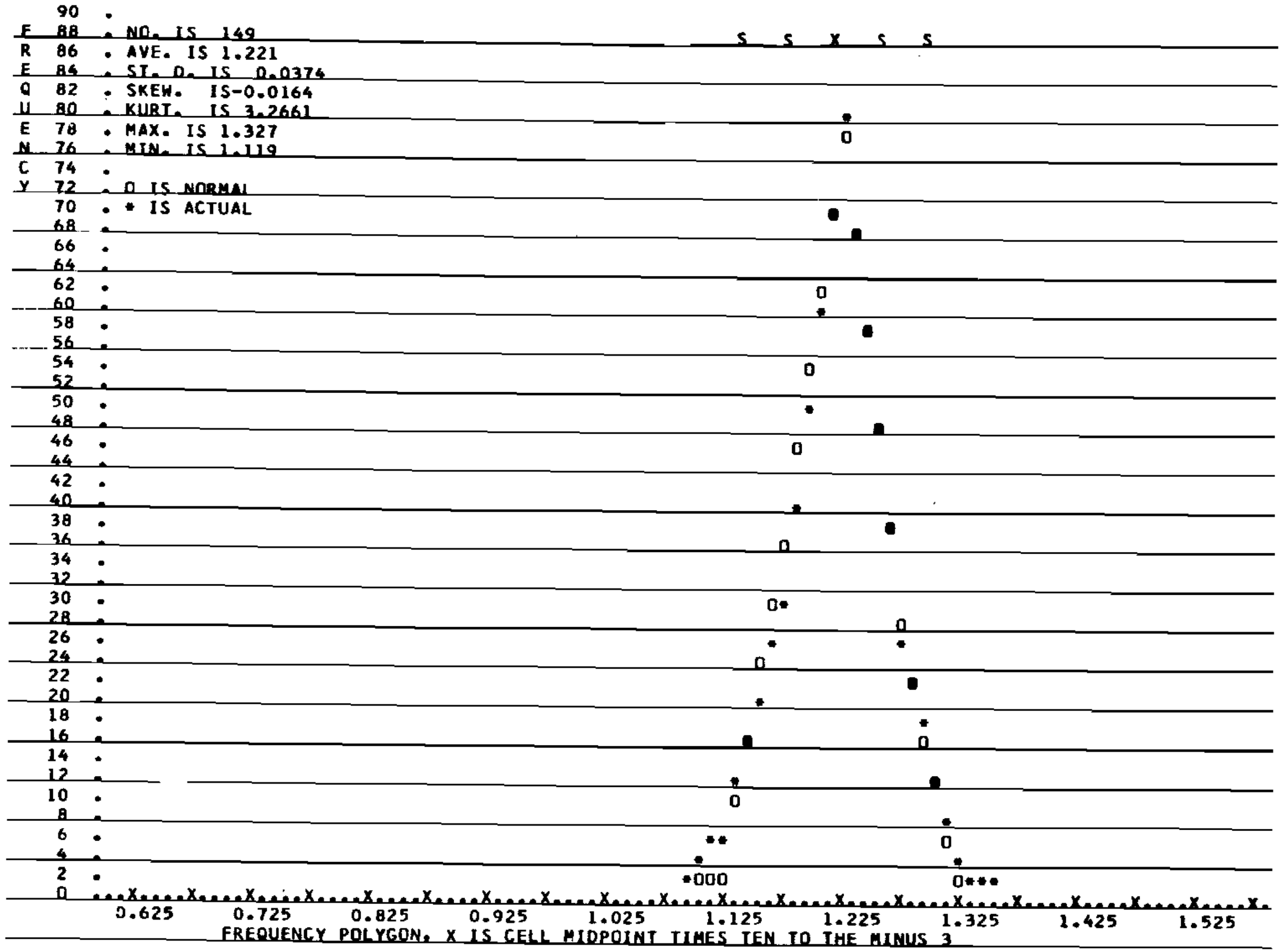


Figure 467. Frequency Distribution of With-Grain Specific Resistance Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Blocks No. A-19, A-20 and A-24 Combined.

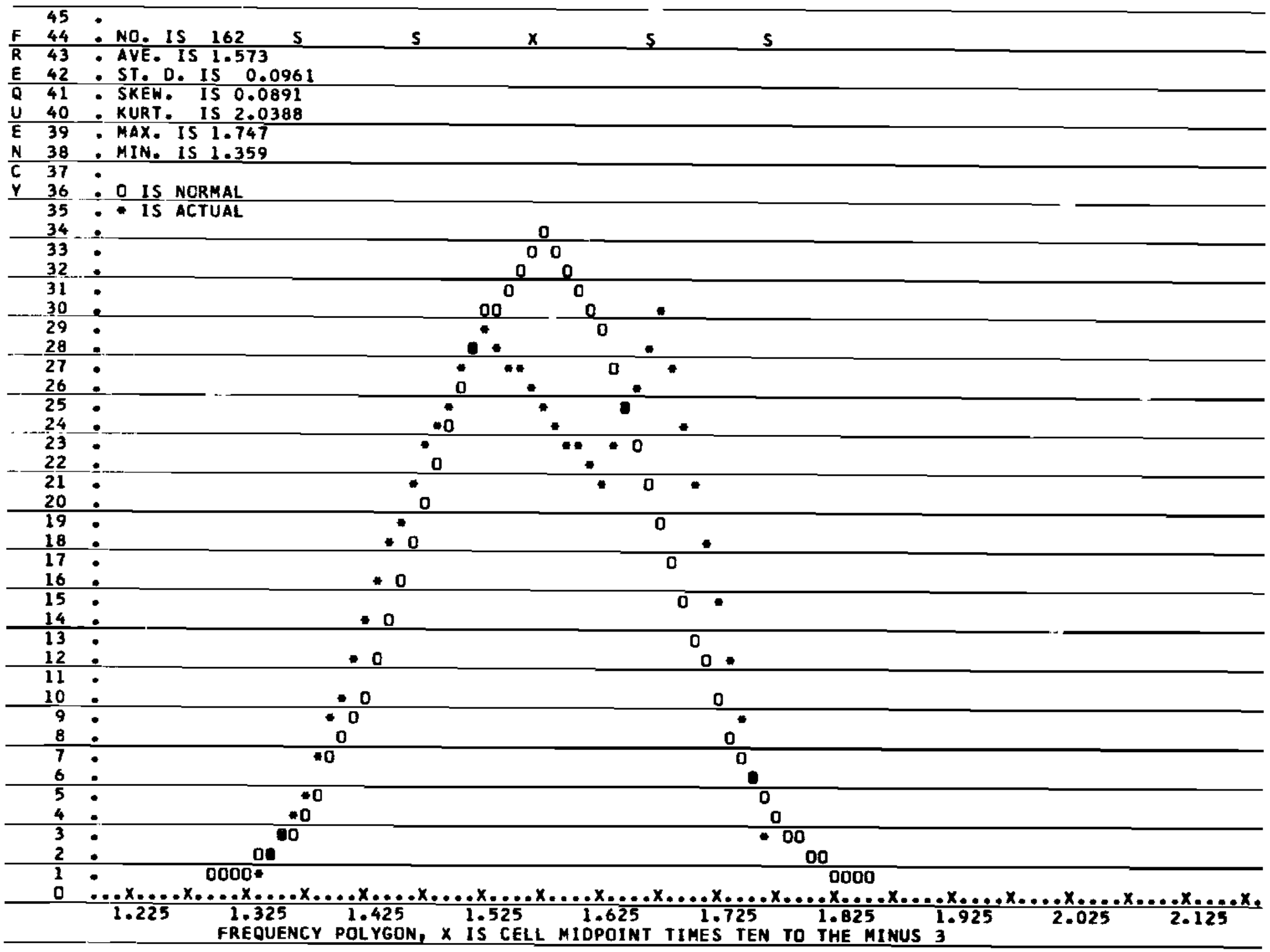


Figure 468. Frequency Distribution of Across-Grain Specific Resistance Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Blocks No. A-19, A-20 and A-24 Combined.

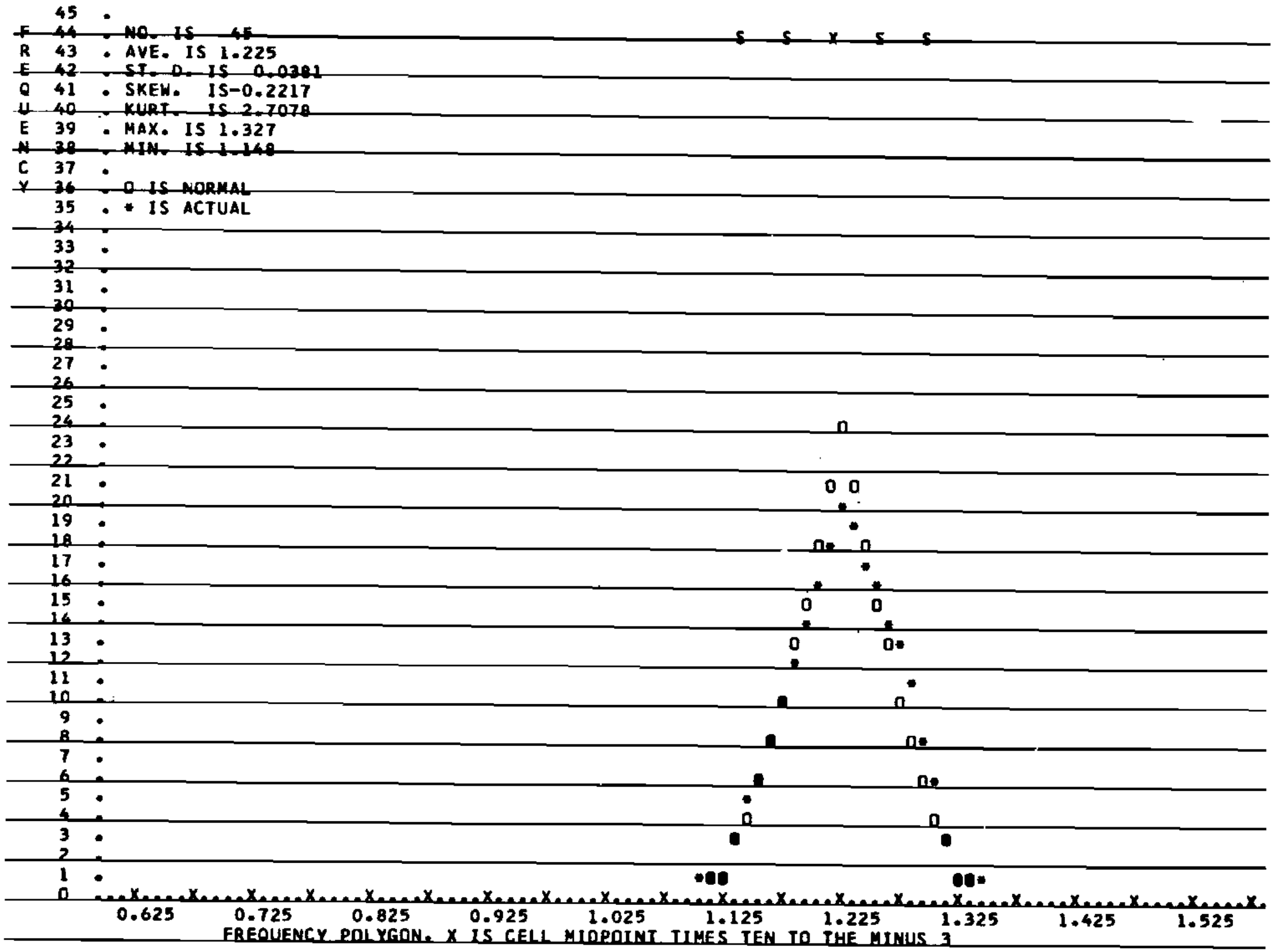


Figure 469. Frequency Distribution of With-Grain Specific Resistance Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-19

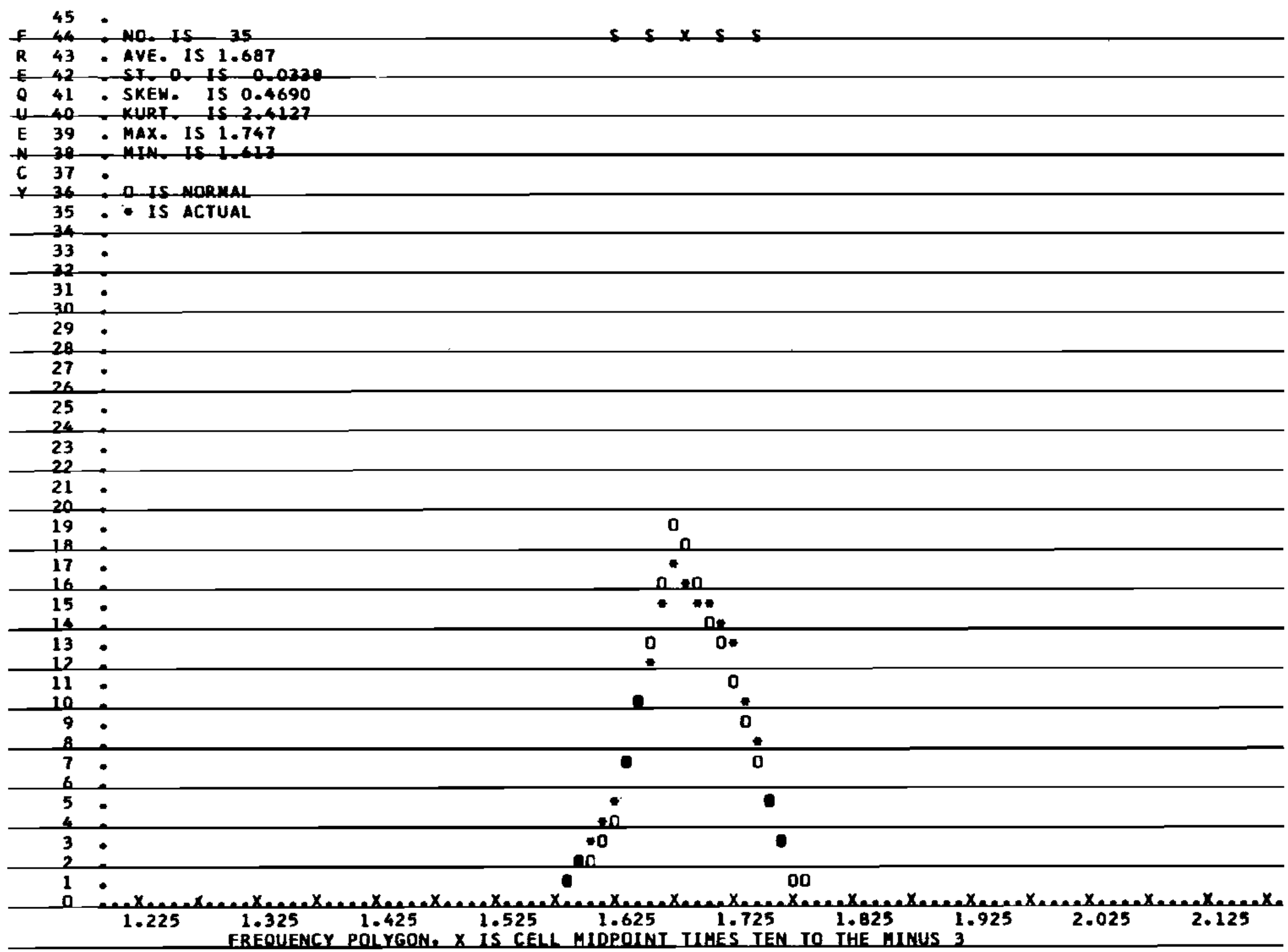


Figure 470. Frequency Distribution of Across-Grain Specific Resistance Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-19

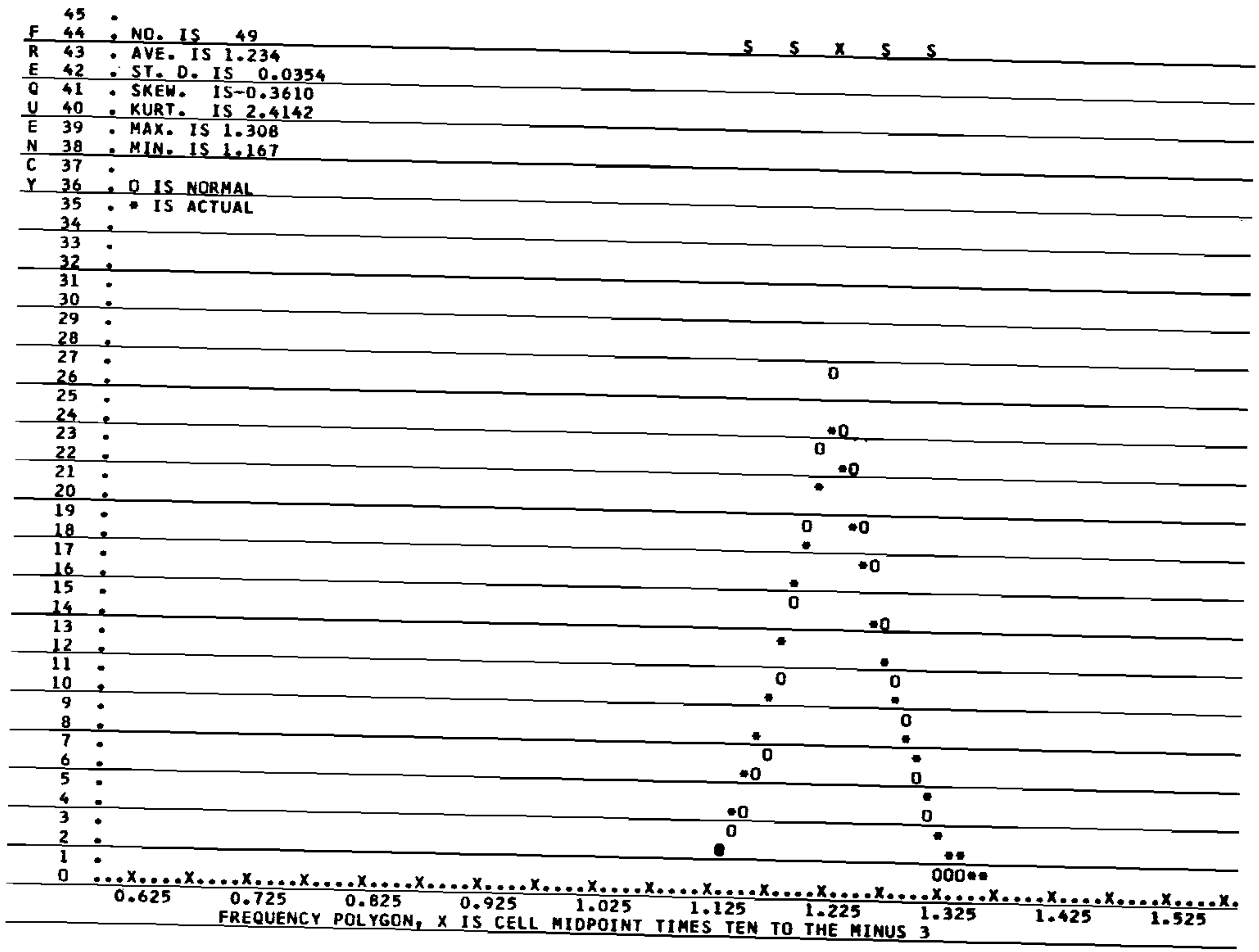


Figure 471. Frequency Distribution of With-Grain Specific Resistance Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-20

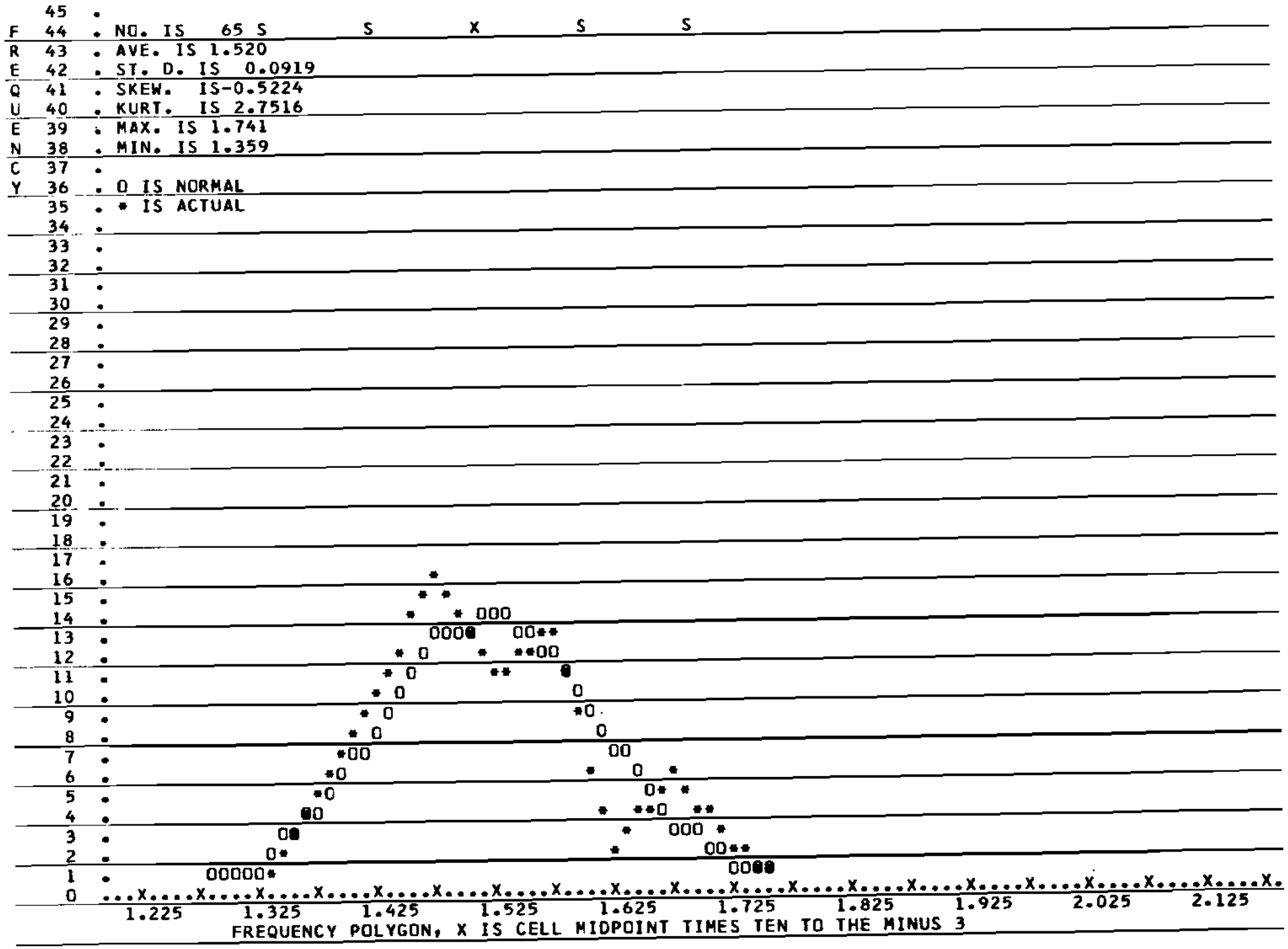


Figure 472. Frequency Distribution of Across-Grain Specific Resistance Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-20

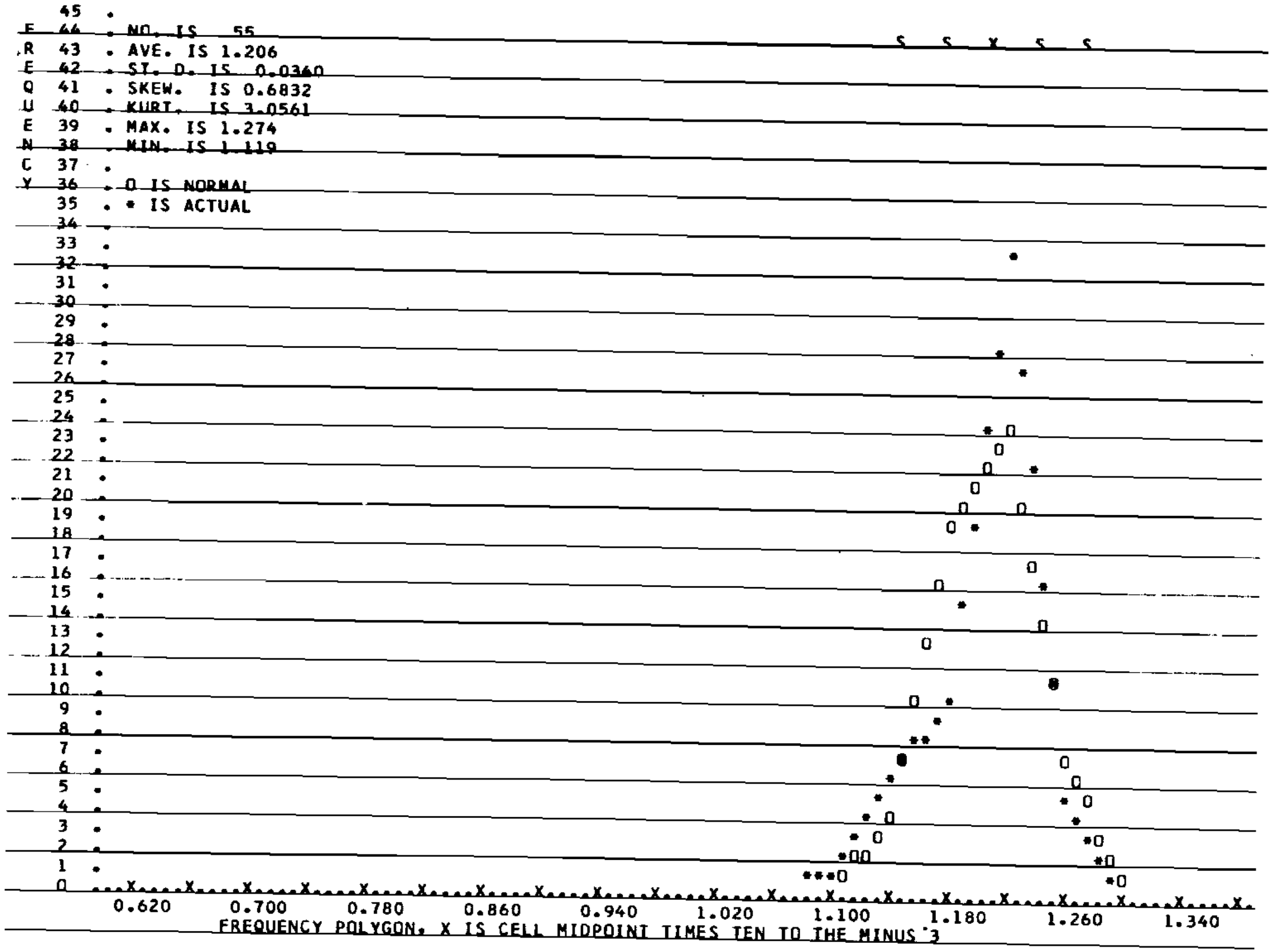


Figure 473. Frequency Distribution of With-Grain Specific Resistance Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-24

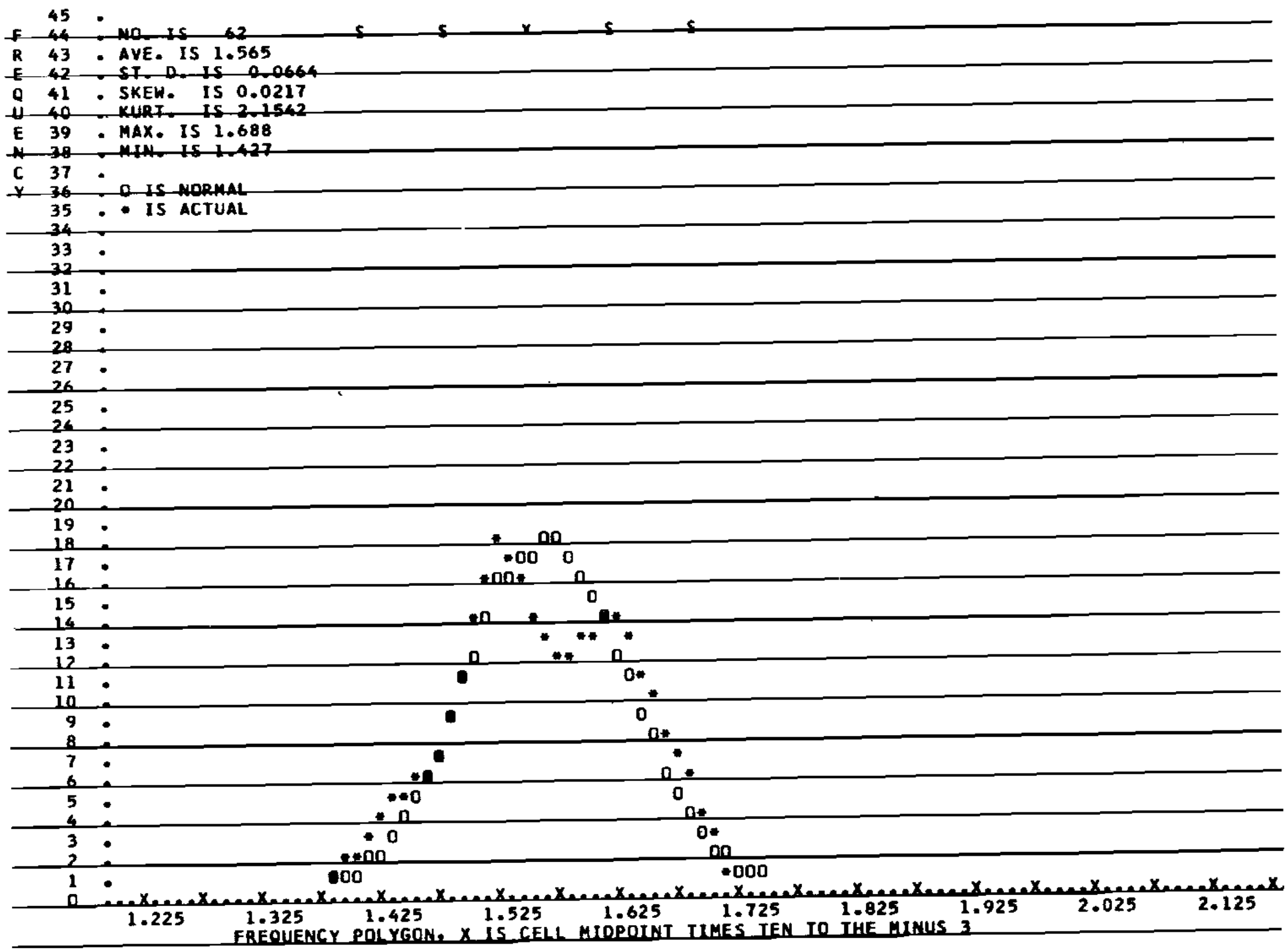


Figure 474. Frequency Distribution of Across-Grain Specific Resistance Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-24

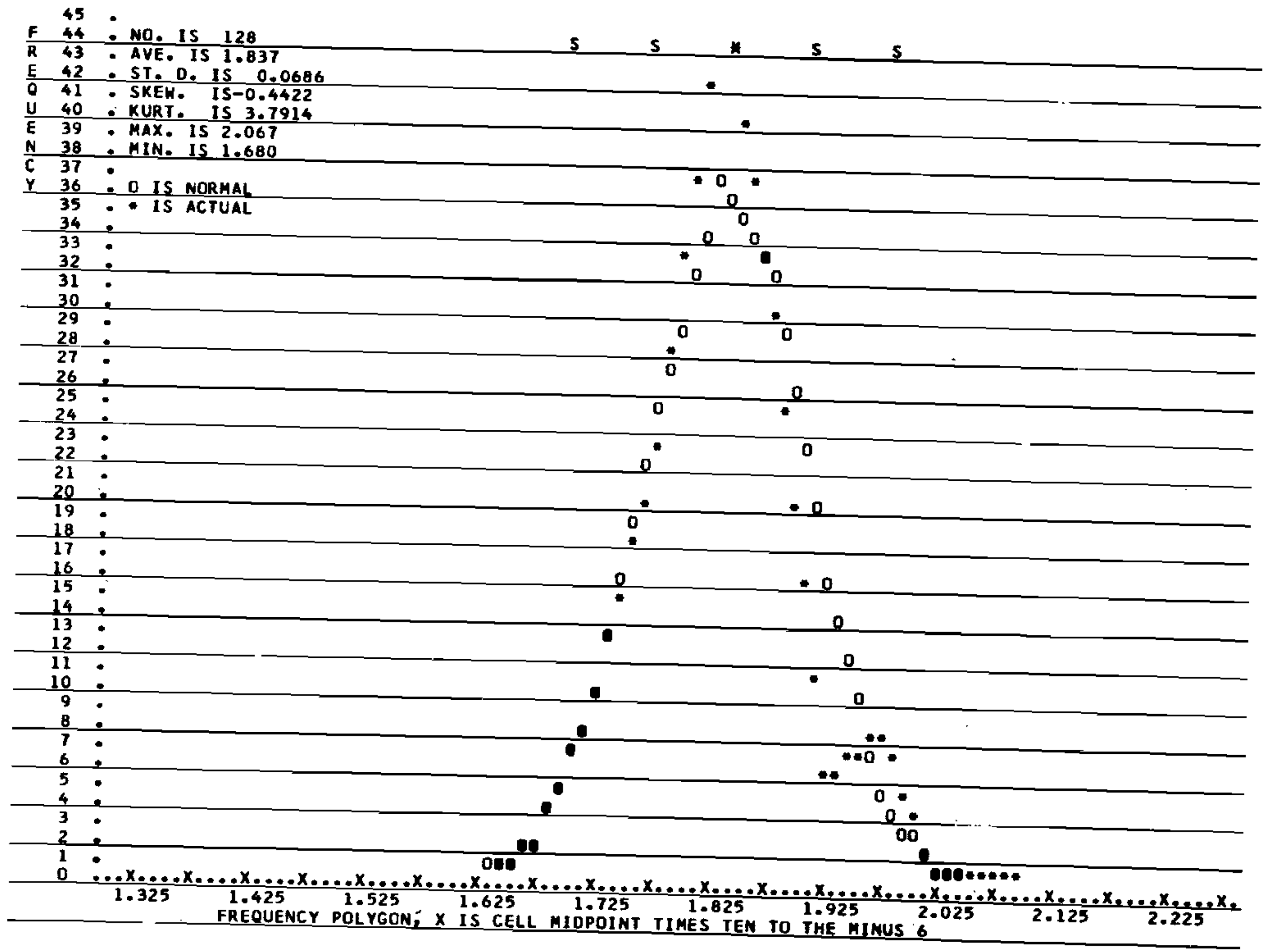


Figure 475. Frequency Distribution of With-Grain Young's Modulus of Elasticity Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Blocks No. A-19, A-20 and A-24 Combined

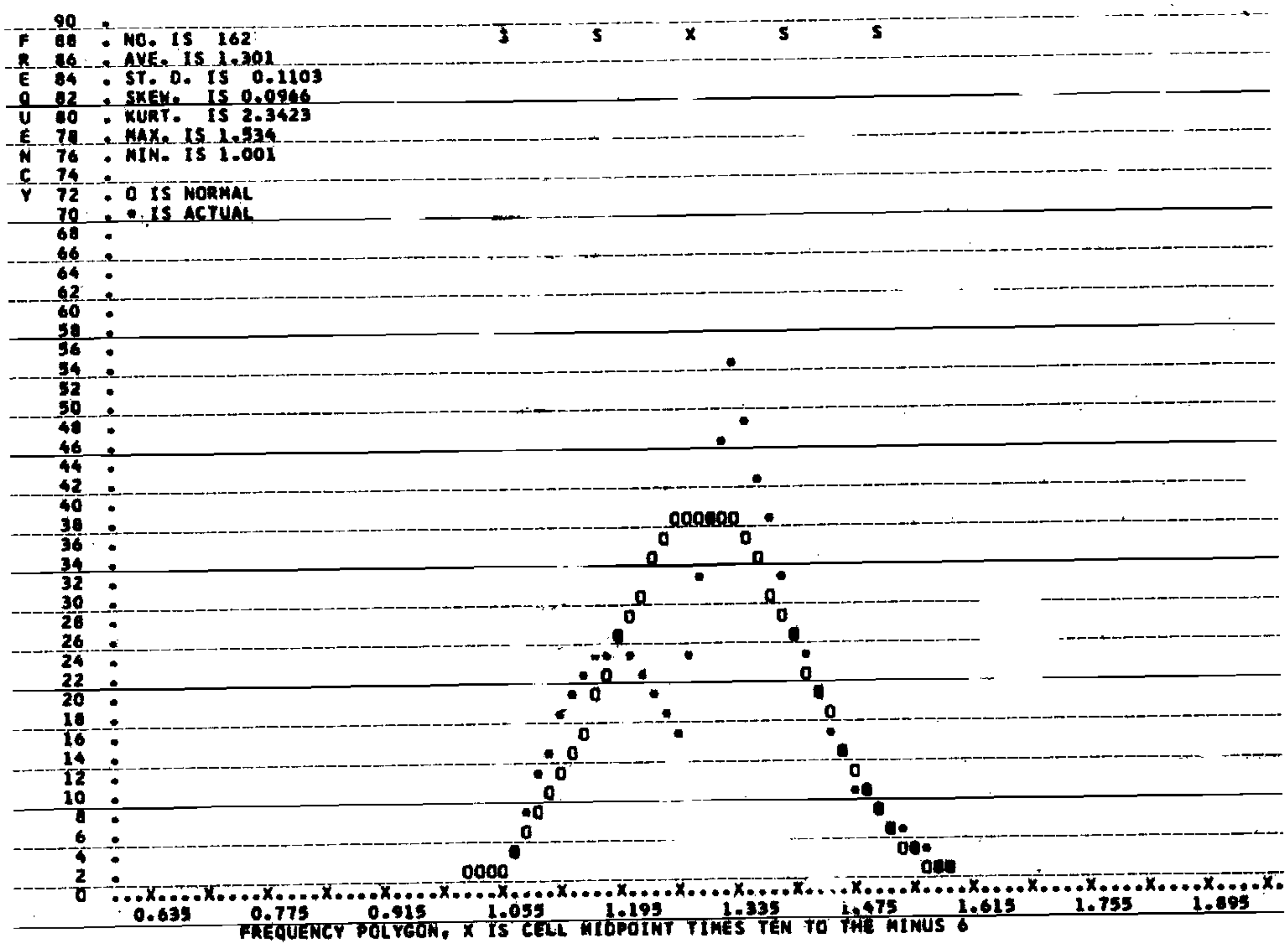


Figure 476. Frequency Distribution of Across-Grain Young's Modulus of Elasticity Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Blocks No. A-19, A-20 and A-24 Combined

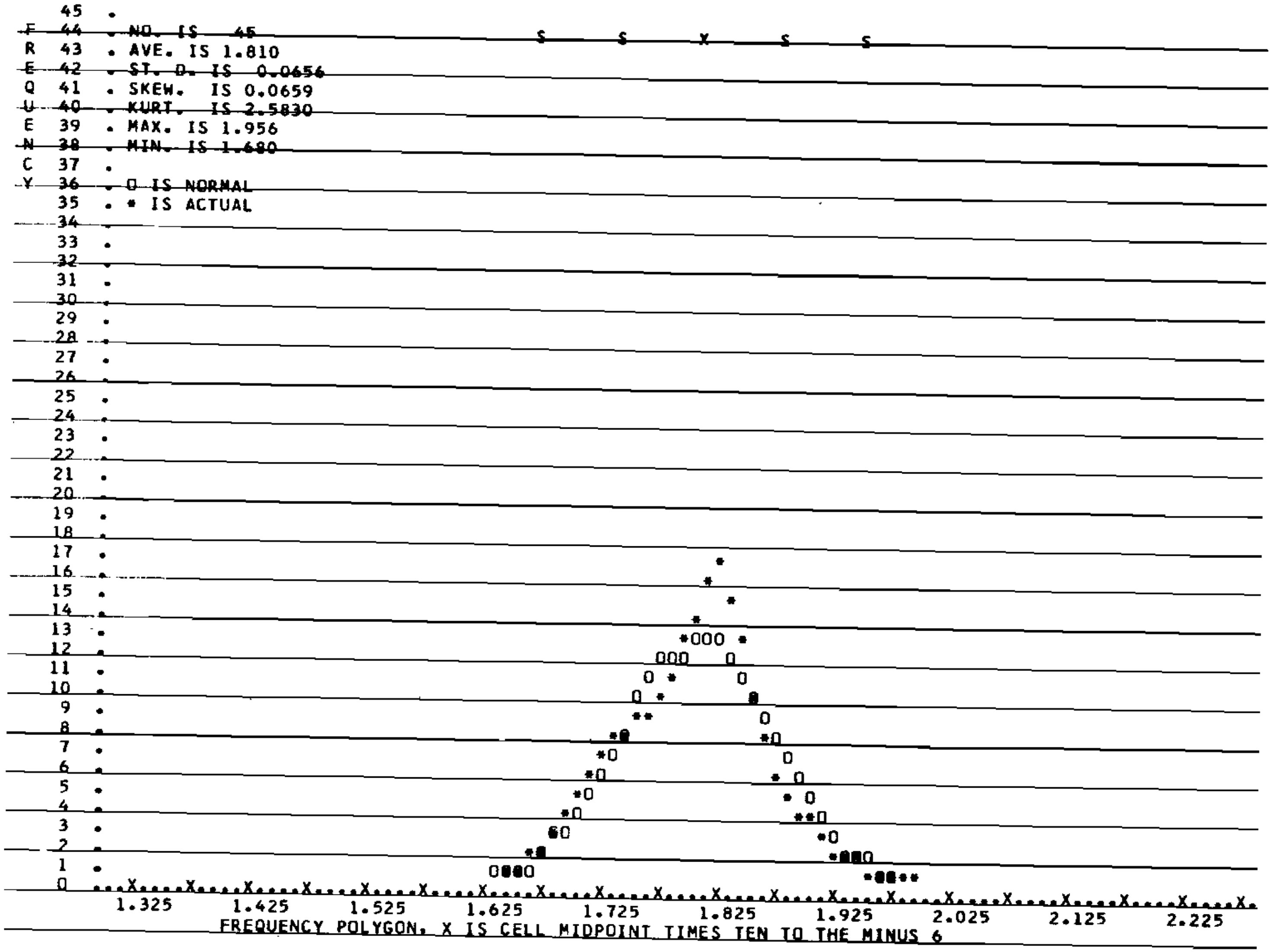


Figure 477. Frequency Distribution of With-Grain Young's Modulus of Elasticity Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-19

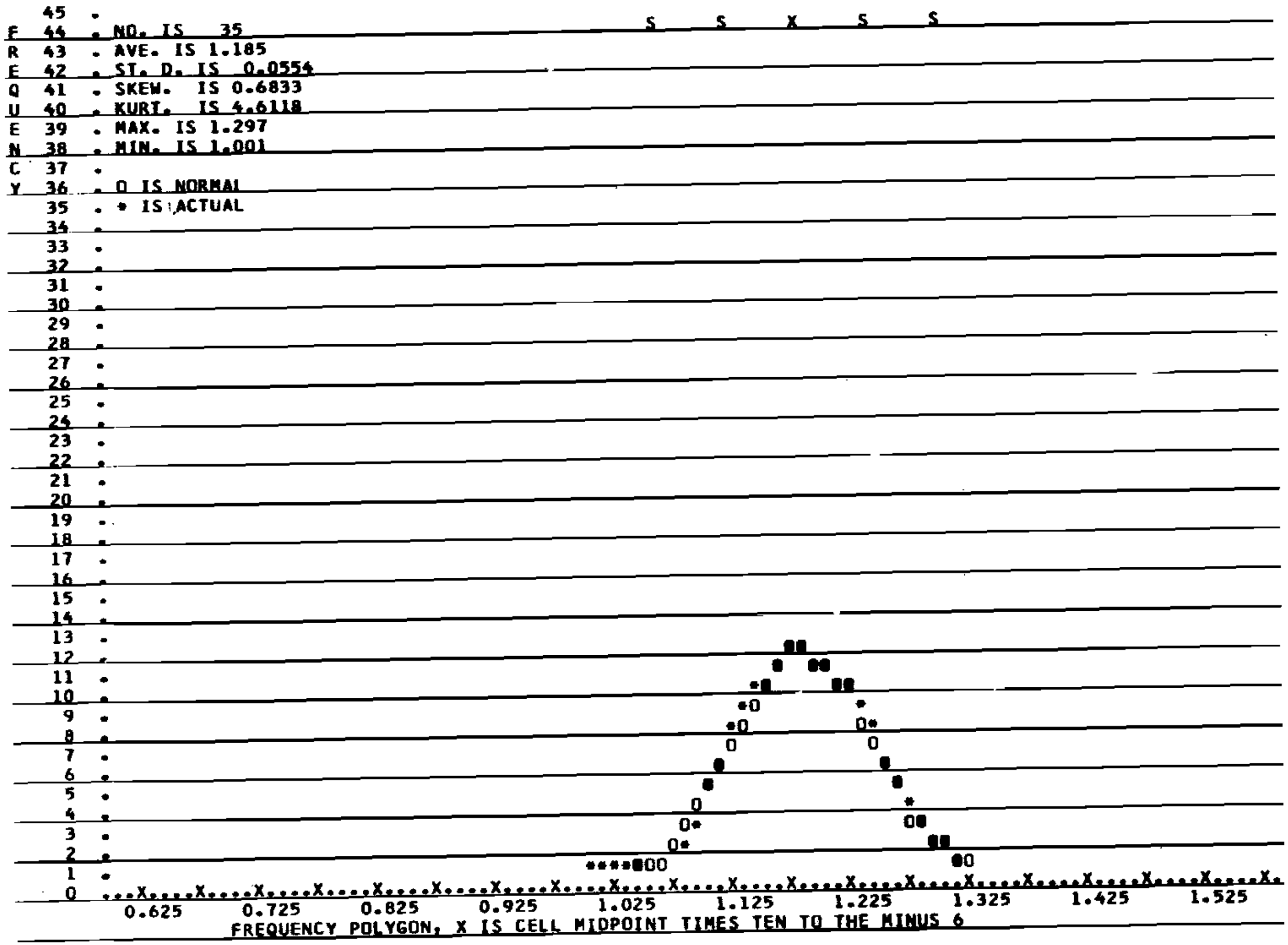


Figure 478. Frequency Distribution of Across-Grain Young's Modulus of Elasticity Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-19

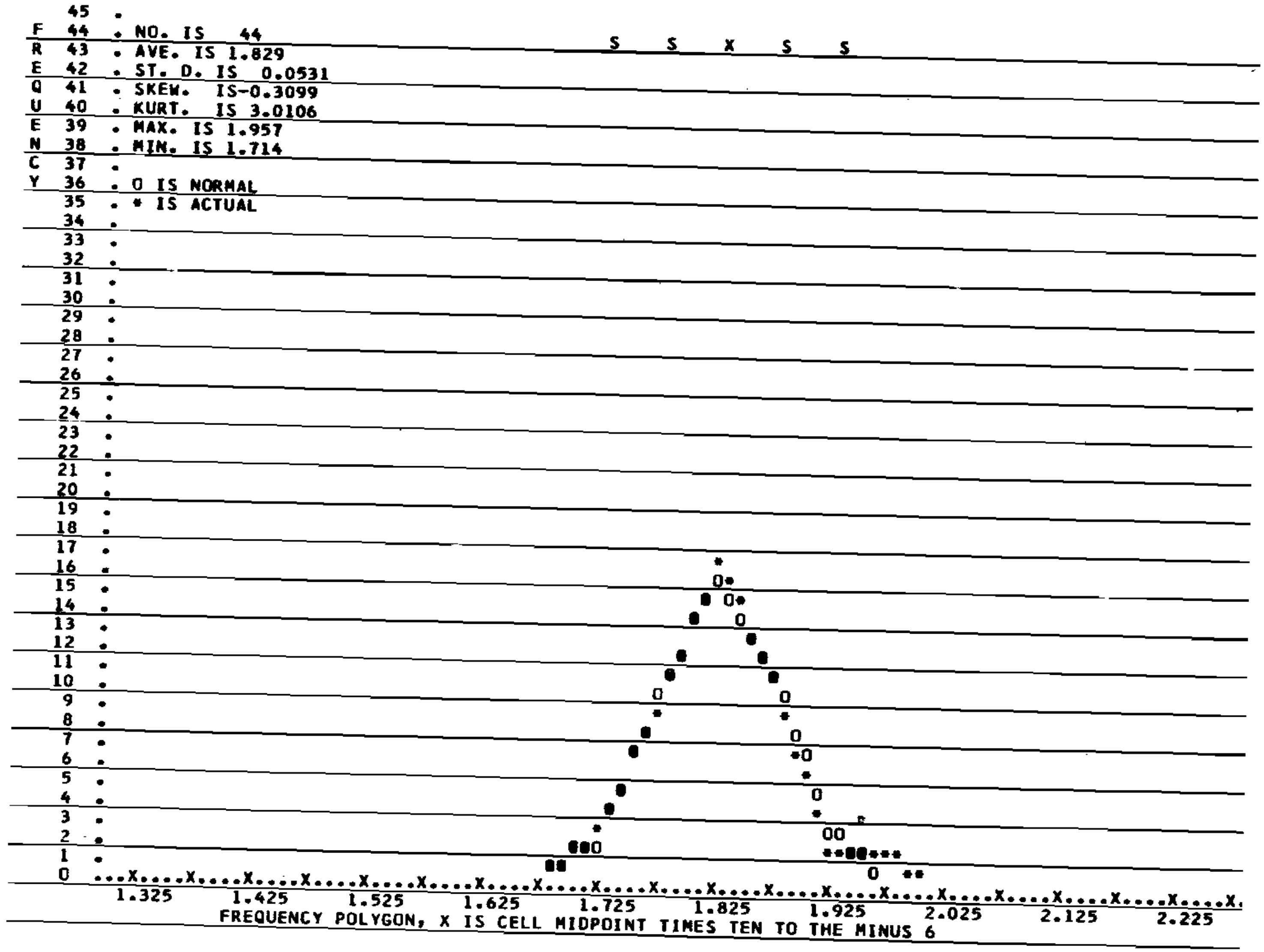


Figure 479. Frequency Distribution of With-Grain Young's Modulus of Elasticity Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-20

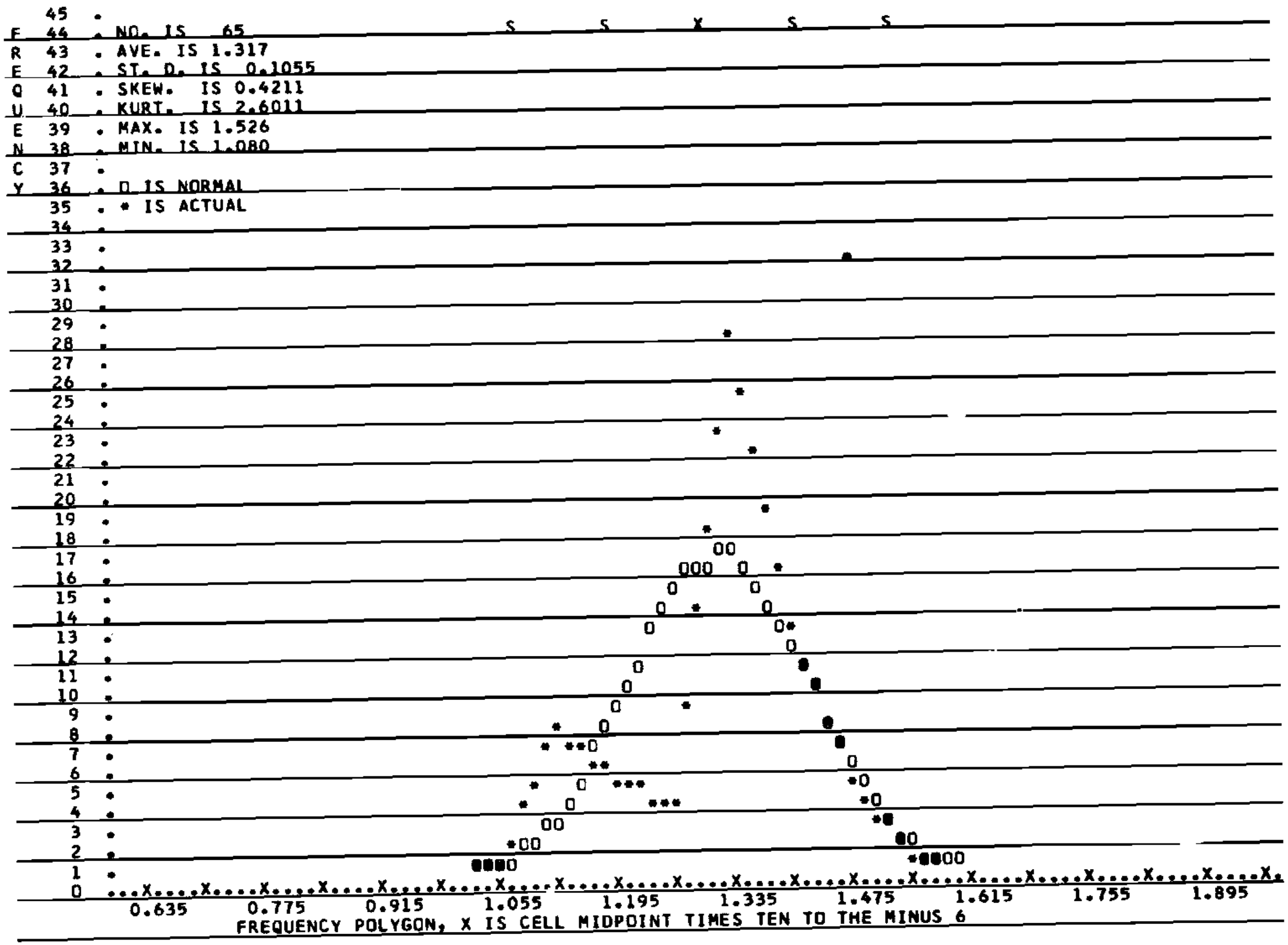


Figure 480. Frequency Distribution of Across-Grain Young's Modulus of Elasticity Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-20

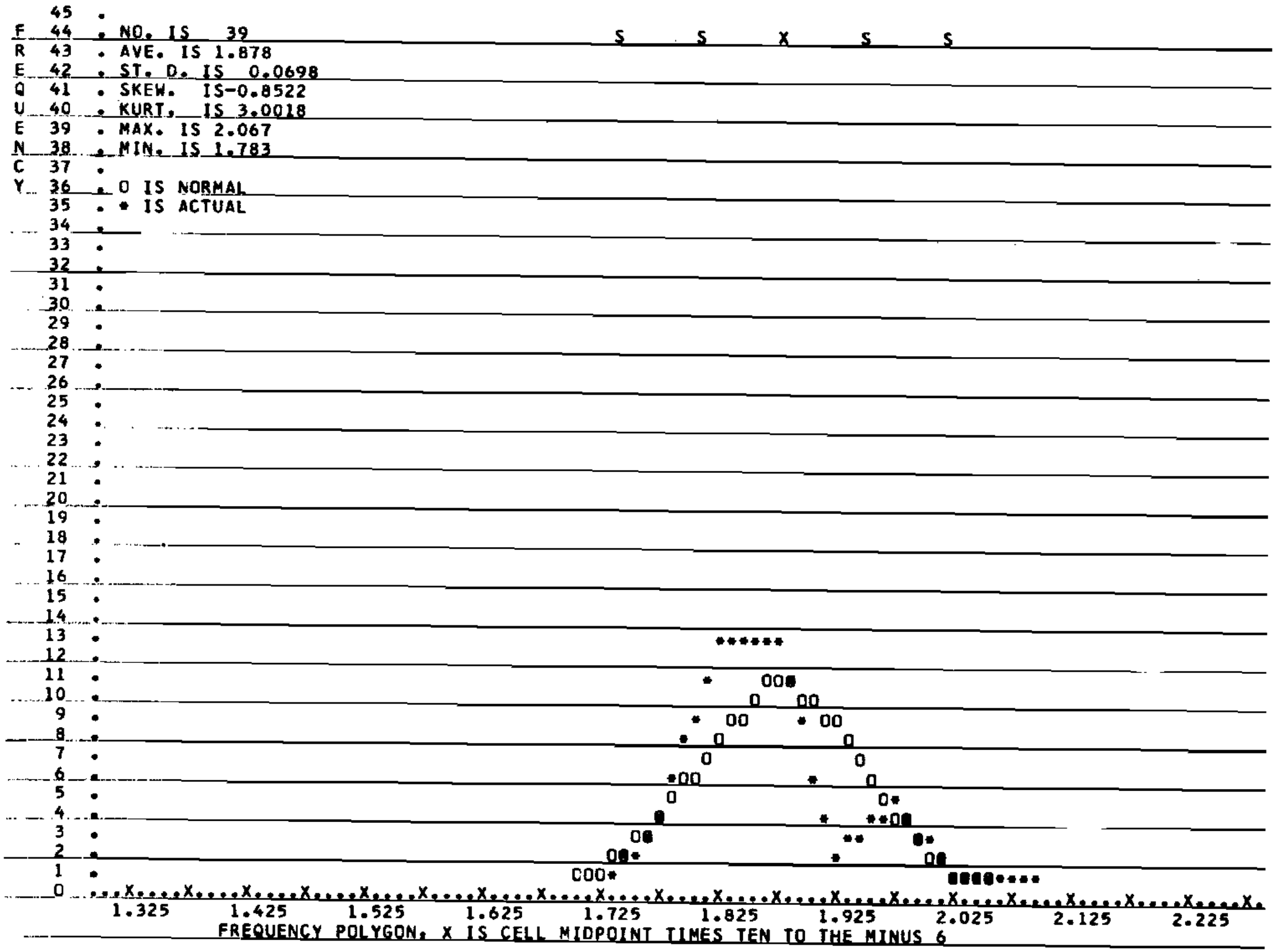


Figure 481. Frequency Distribution of With-Grain Young's Modulus of Elasticity Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-24

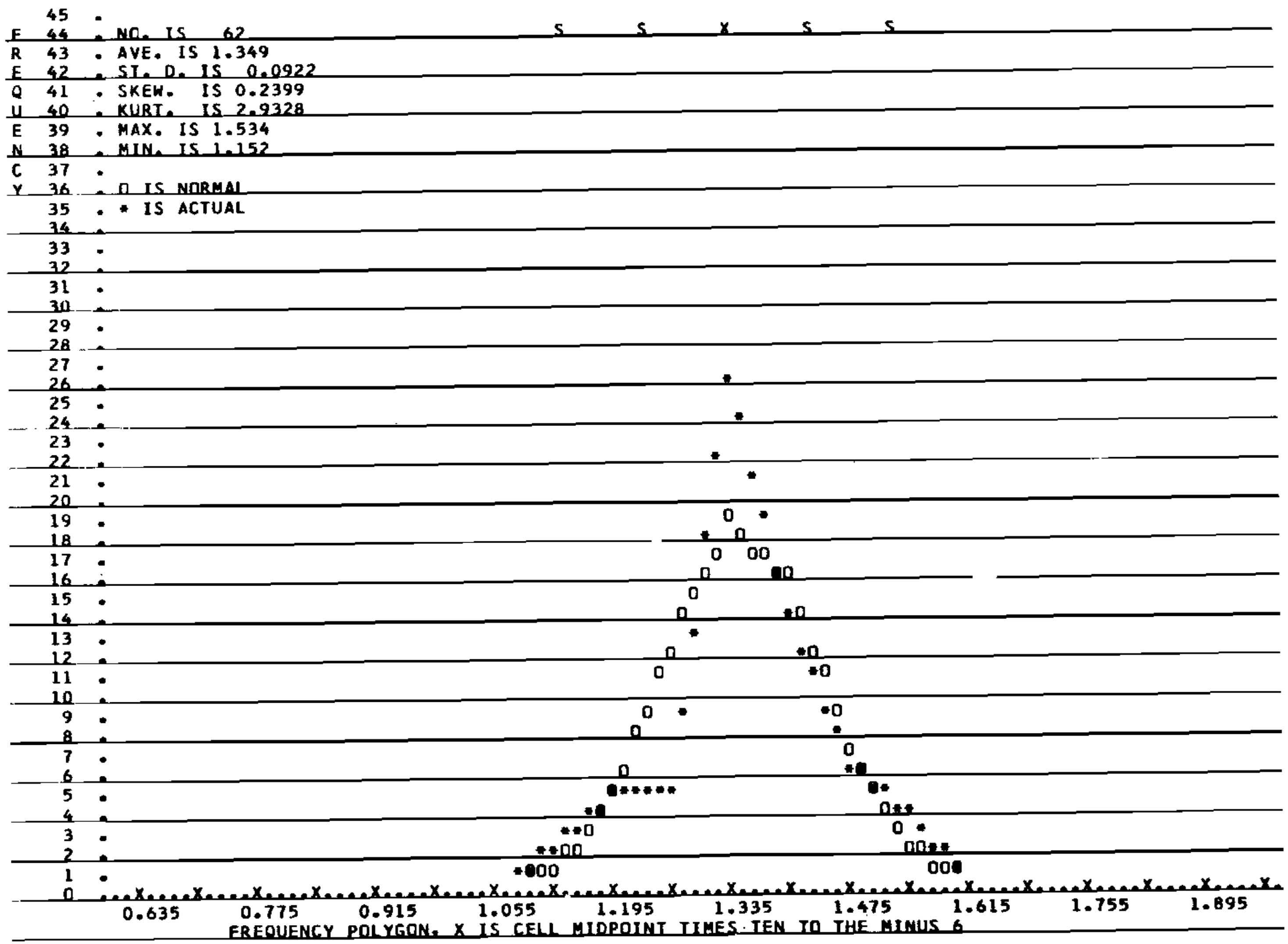


Figure 482. Frequency Distribution of Across-Grain Young's Modulus of Elasticity Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-24

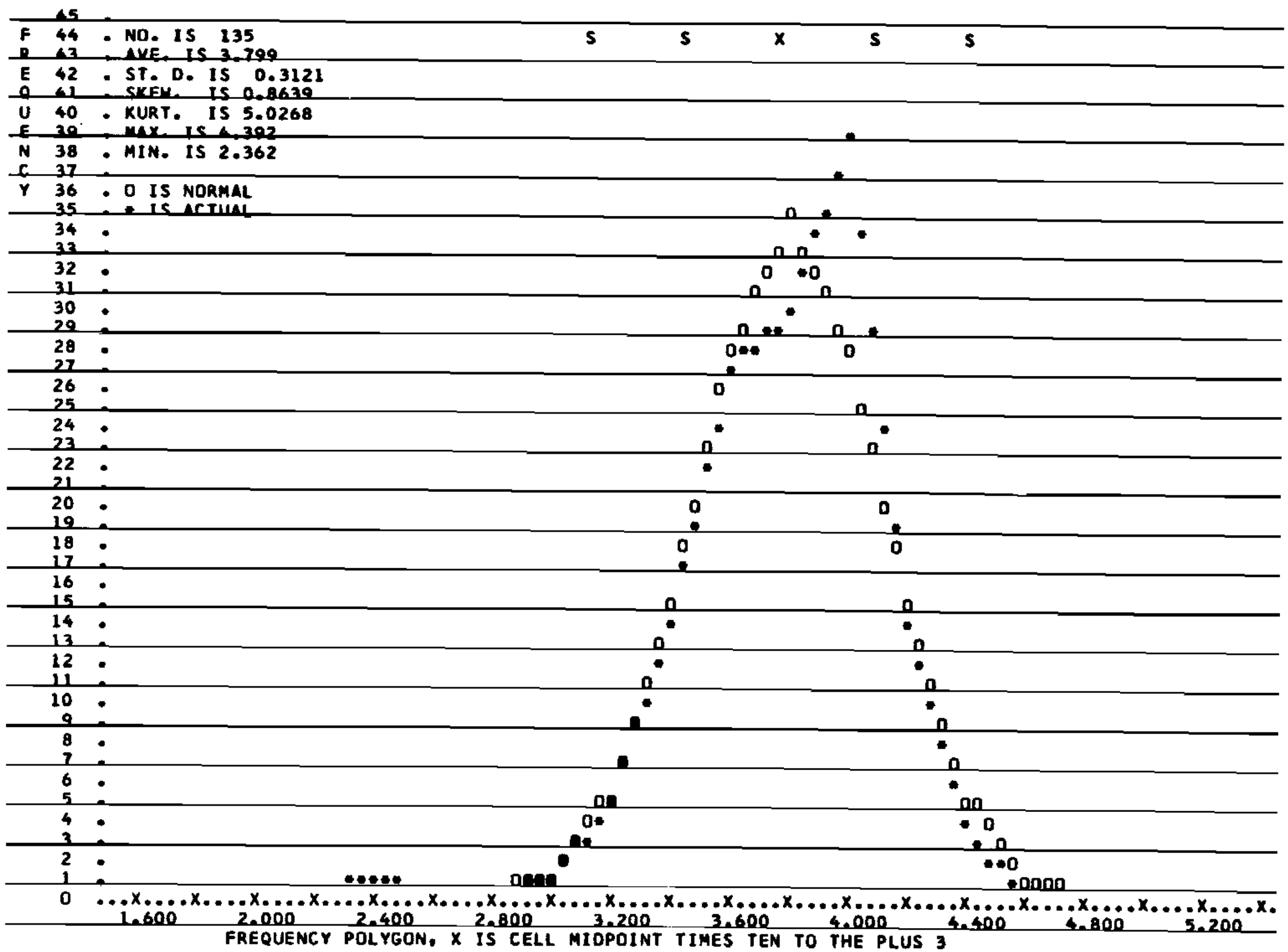


Figure 483. Frequency Distribution of With-Grain Flexural Strength Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Blocks No. A-19, A-20 and A-24 Combined

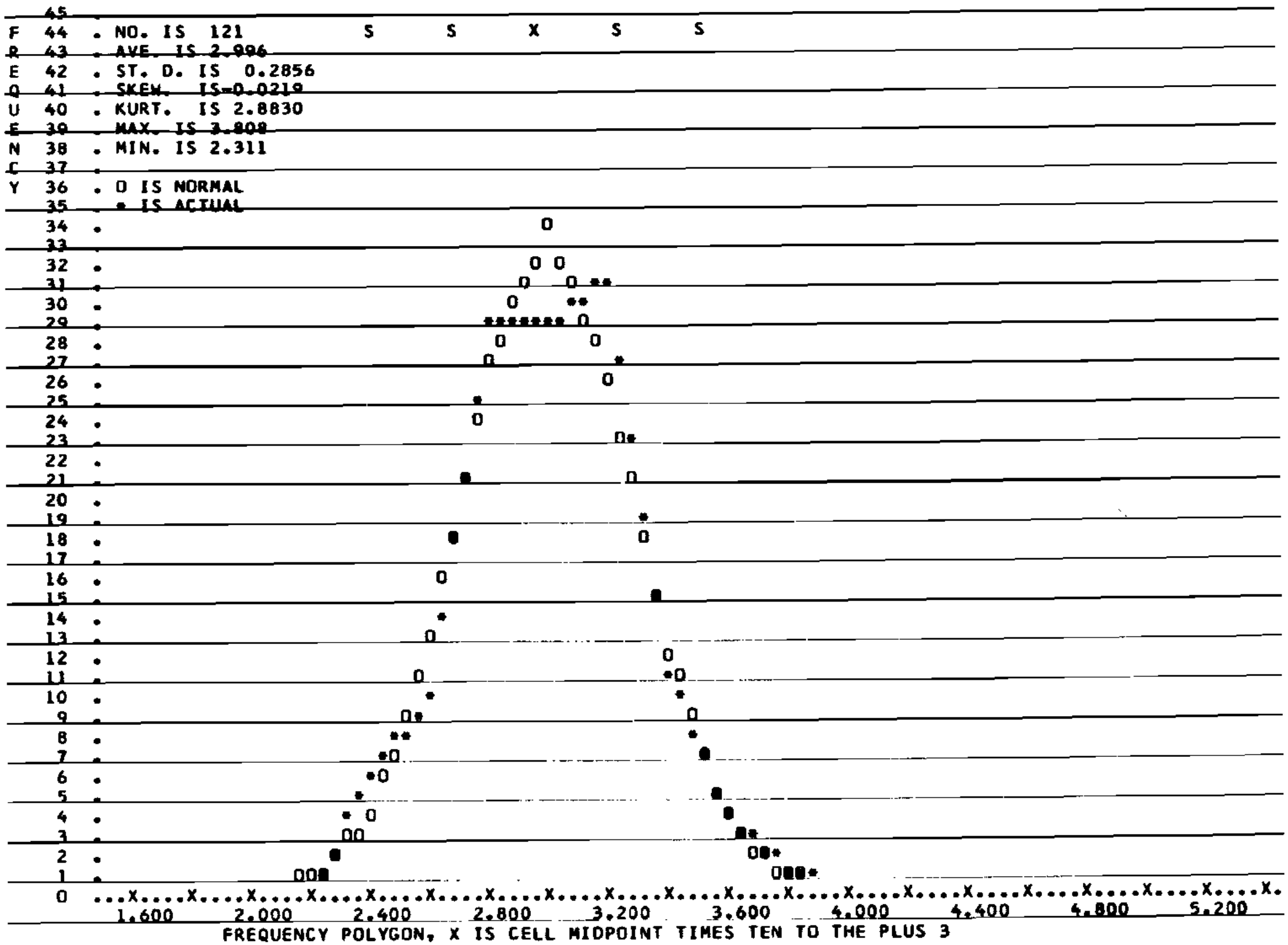


Figure 484. Frequency Distribution of Across-Grain Flexural Strength Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Blocks No. A-19, A-20 and A-24 Combined

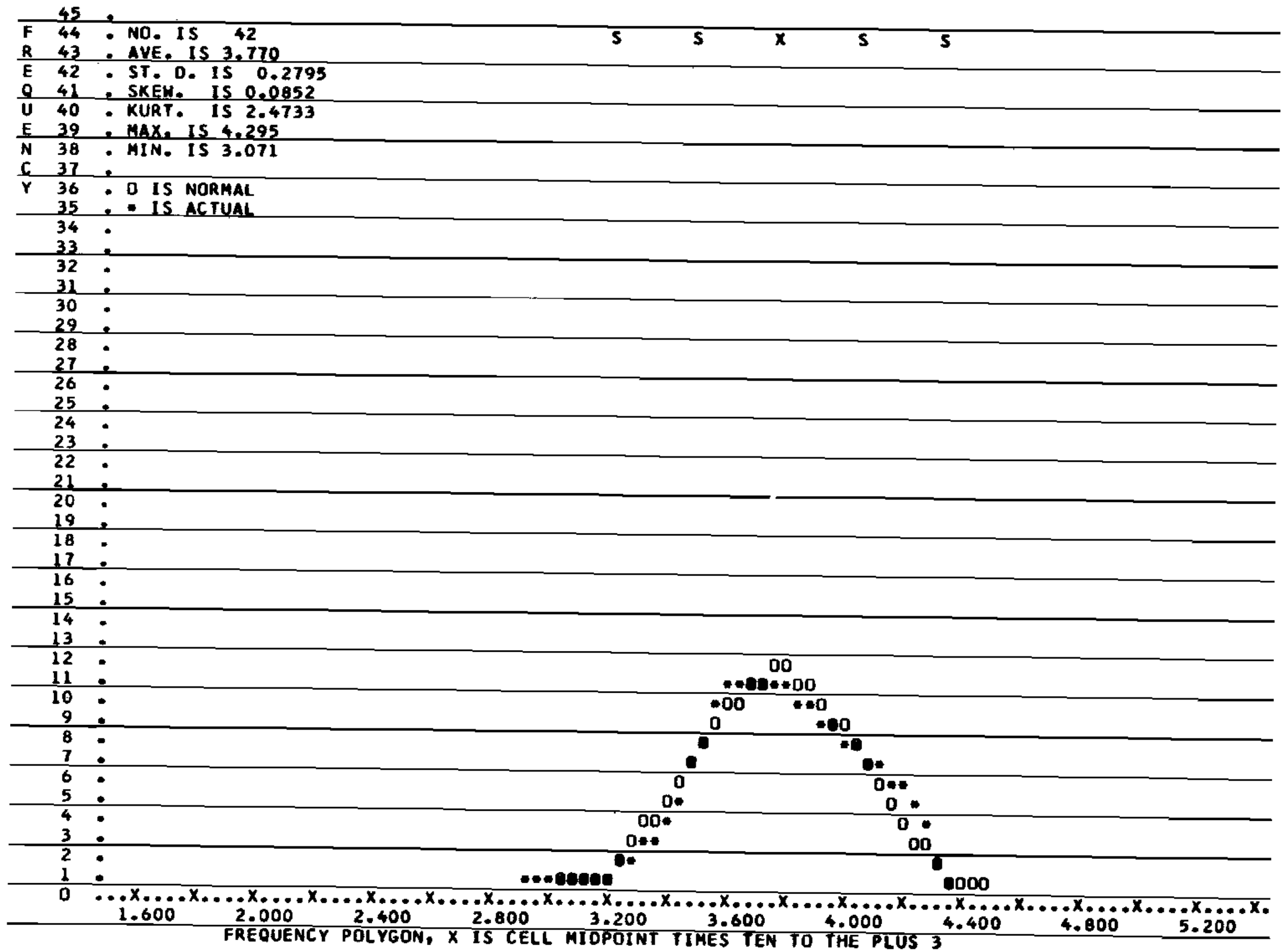


Figure 485. Frequency Distribution of With-Grain Flexural Strength Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-19

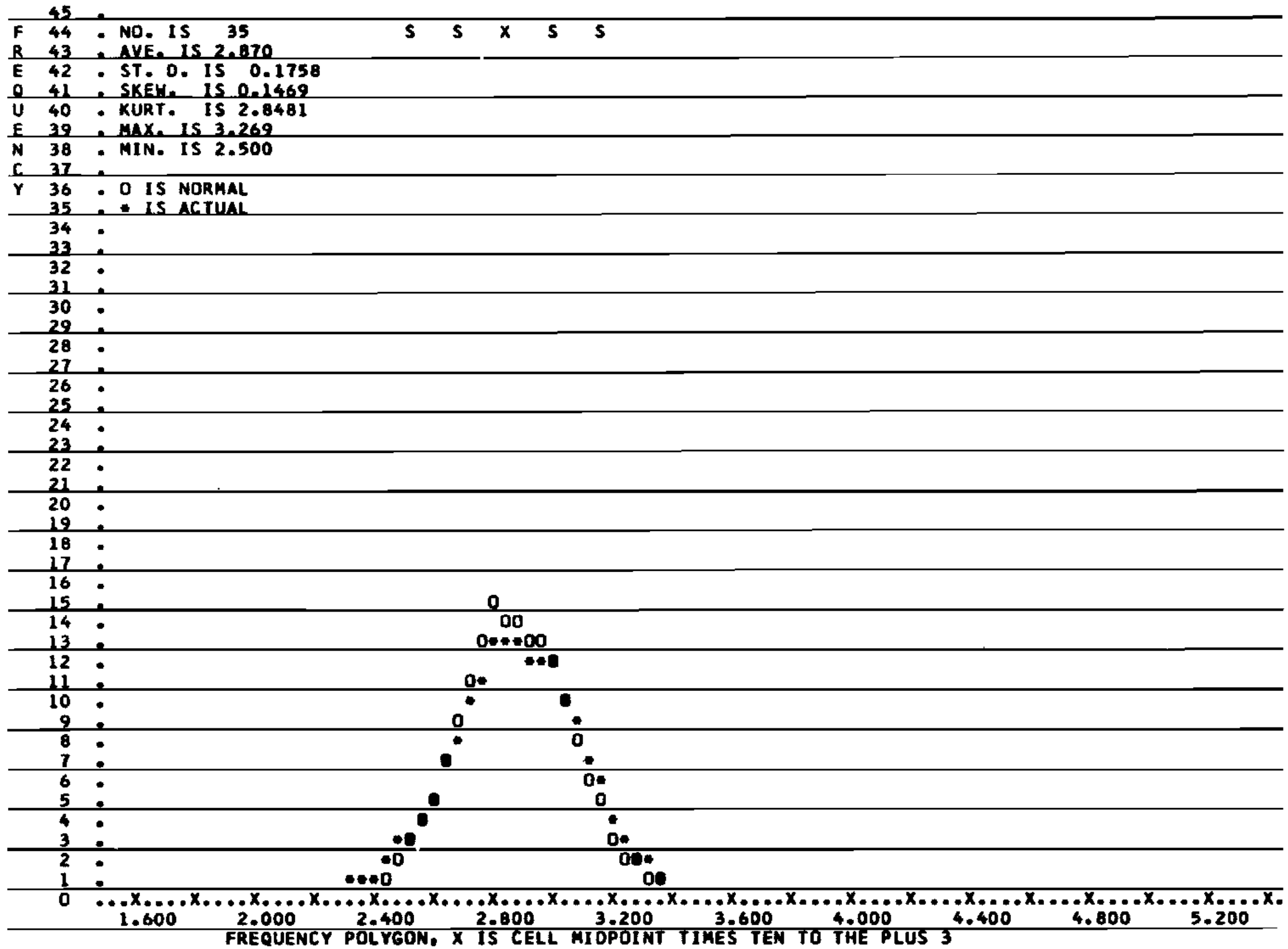


Figure 486. Frequency Distribution of Across-Grain Flexural Strength Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-19

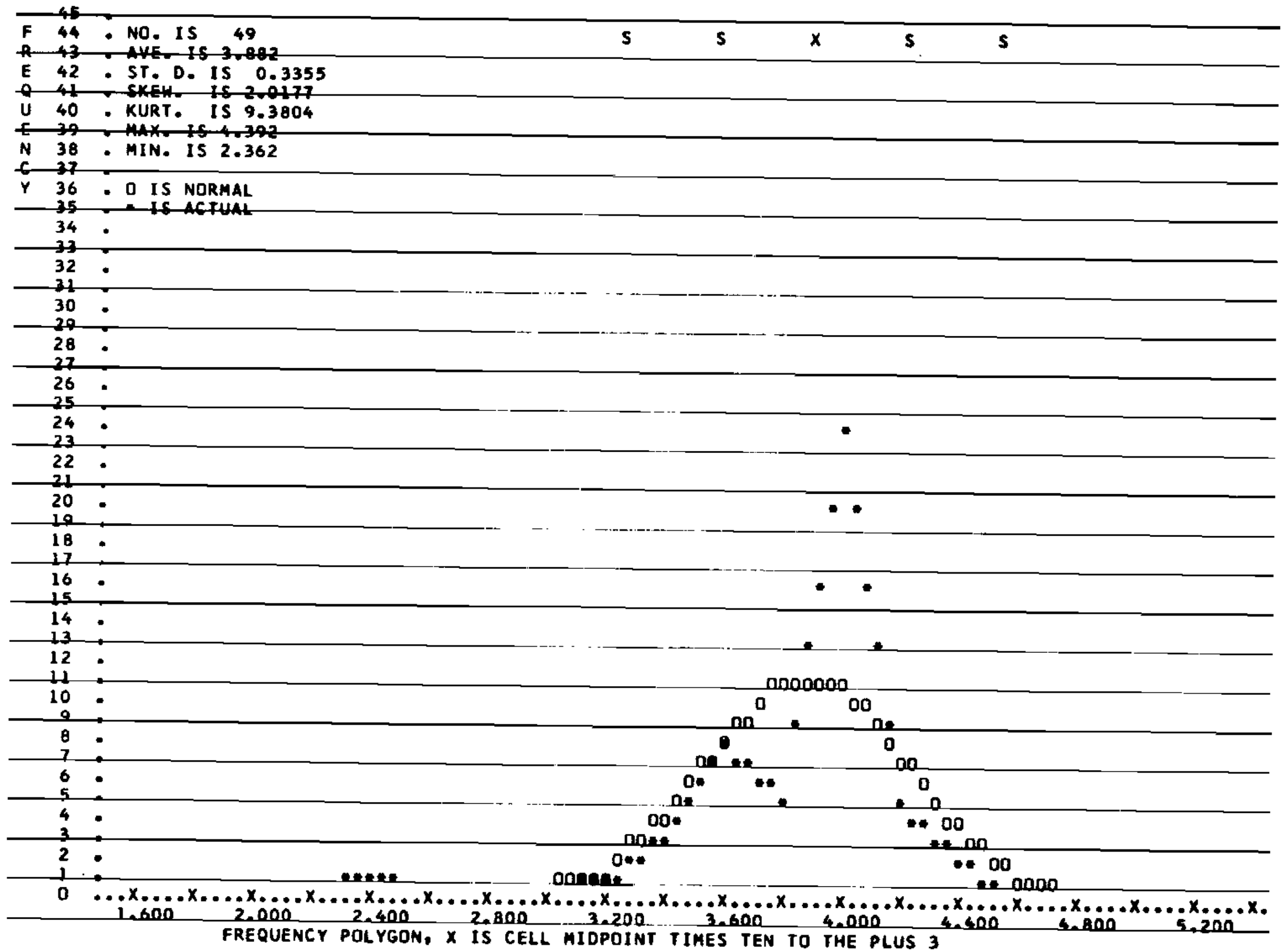


Figure 487. Frequency Distribution of With-Grain Flexural Strength Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-20

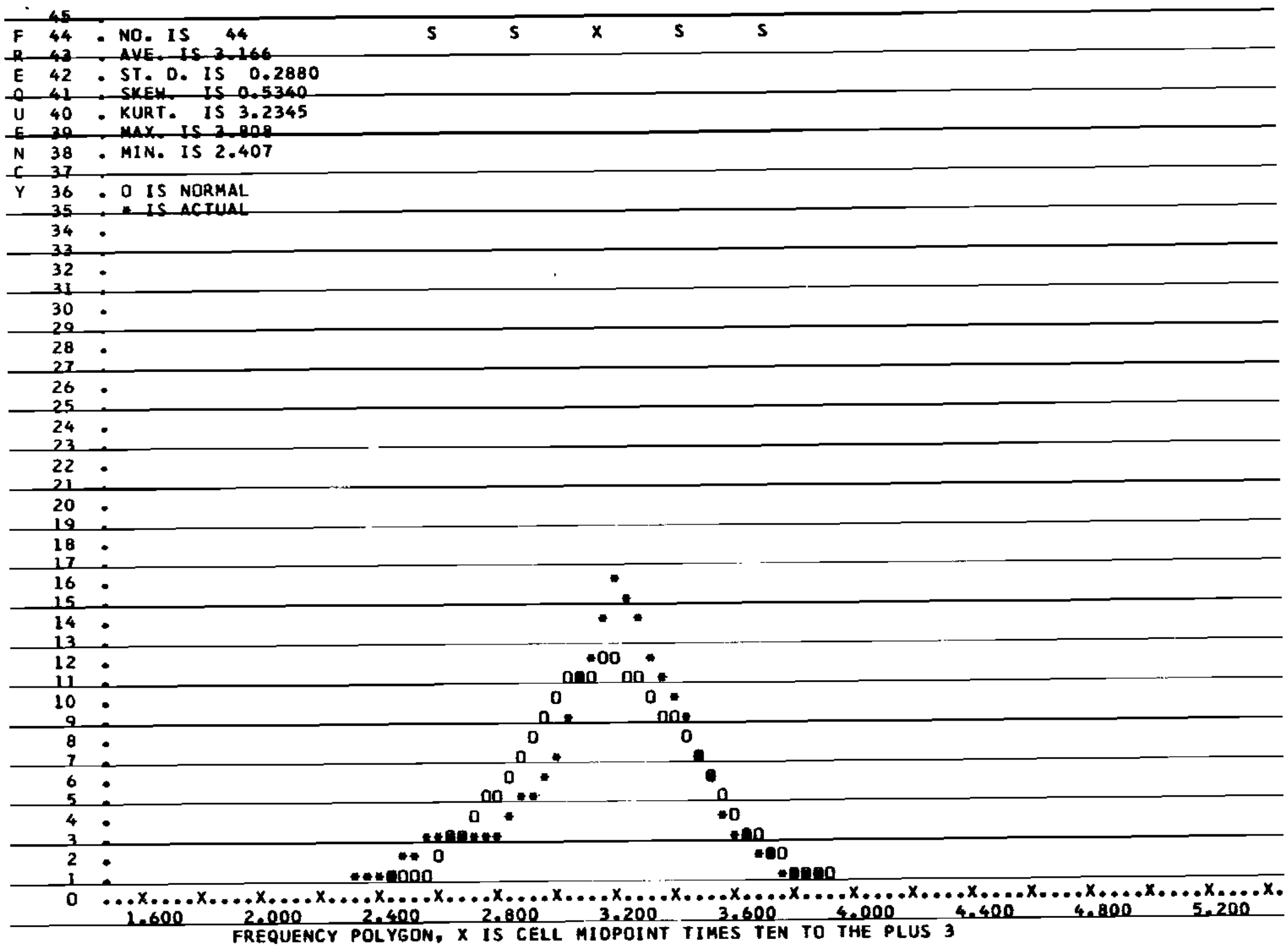


Figure 488. Frequency Distribution of Across-Grain Flexural Strength Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-20

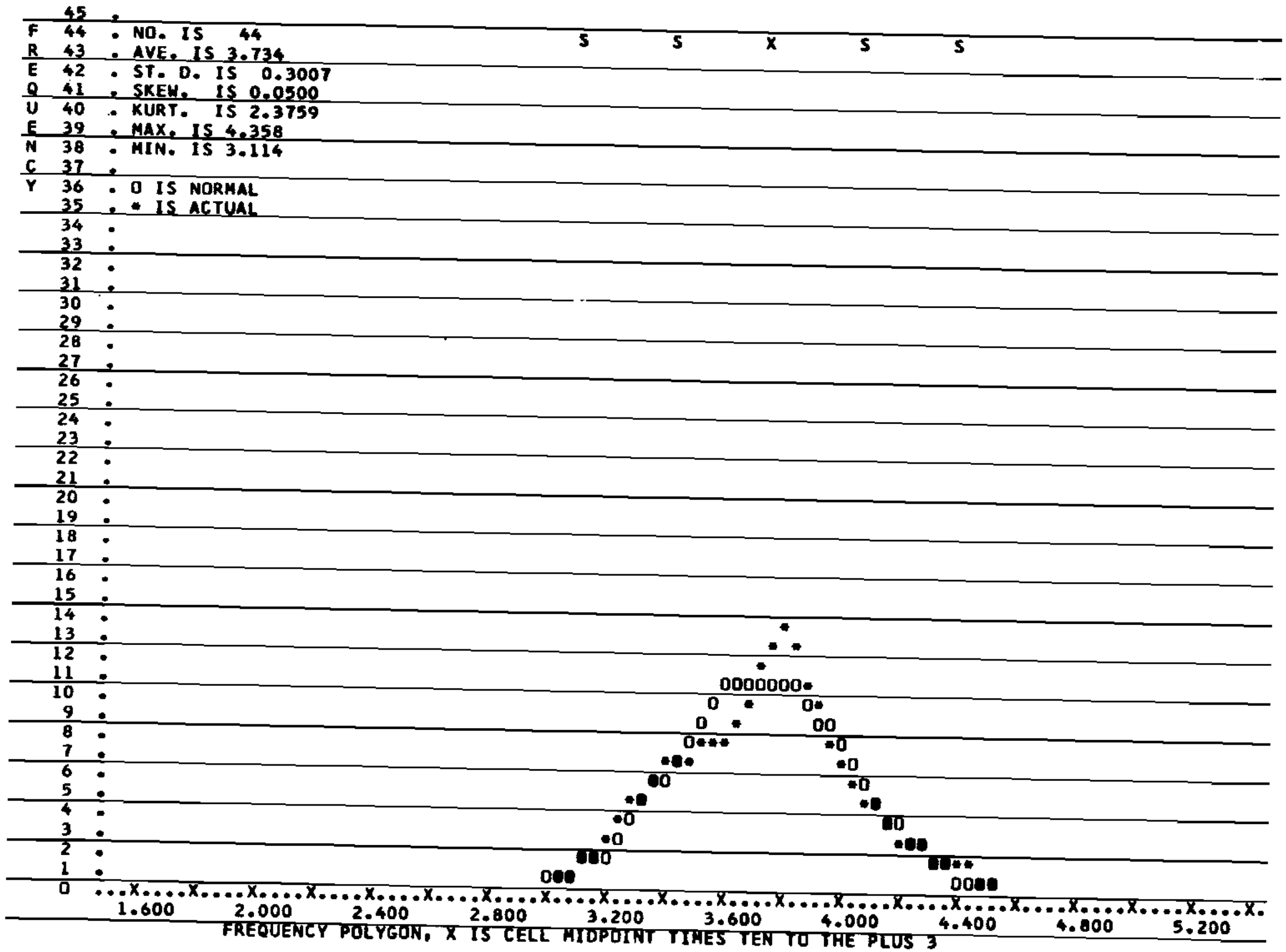


Figure 489. Frequency Distribution of With-Grain Flexural Strength Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-24

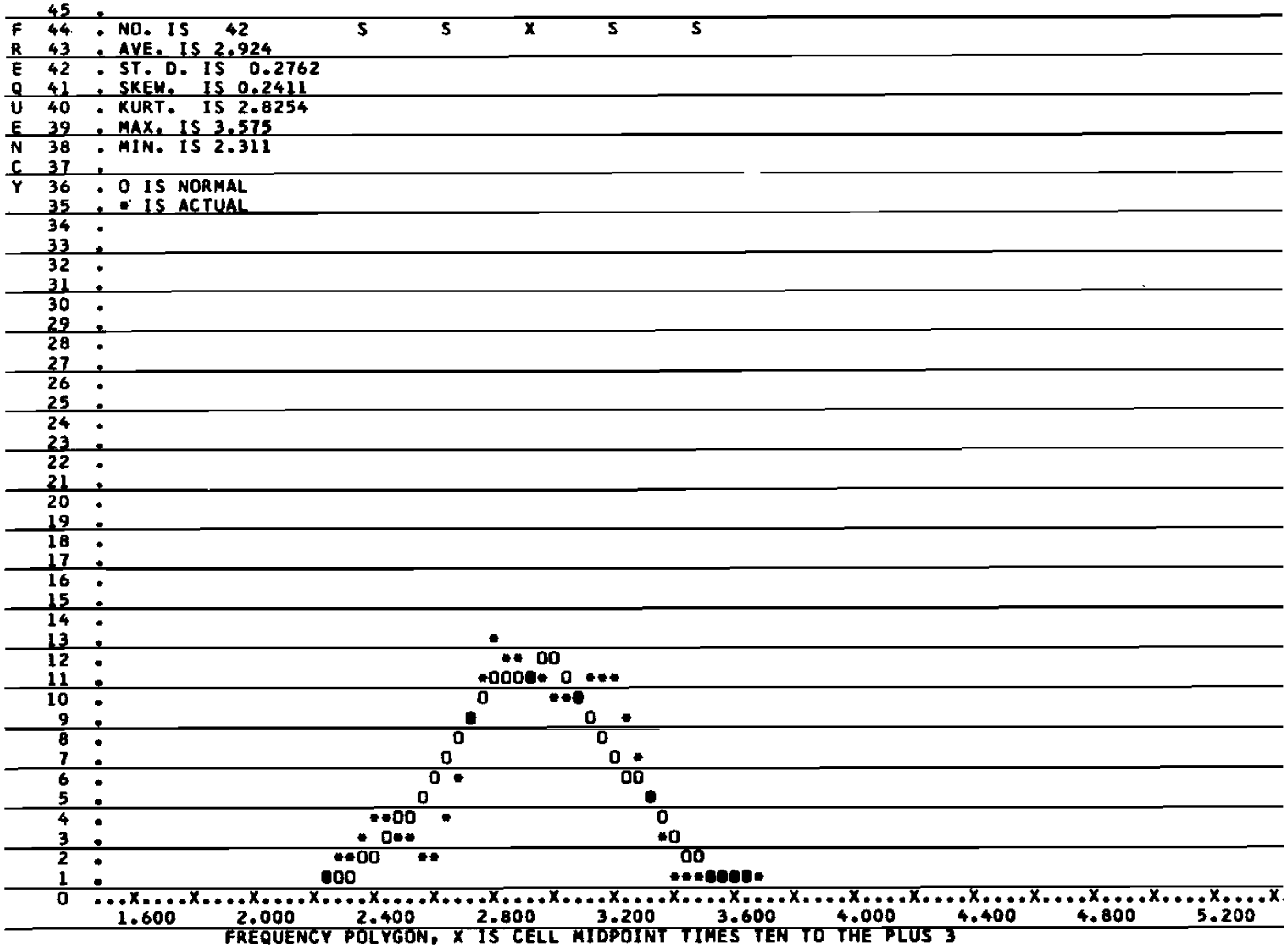


Figure 490. Frequency Distribution of Across-Grain Flexural Strength Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Block No. A-24

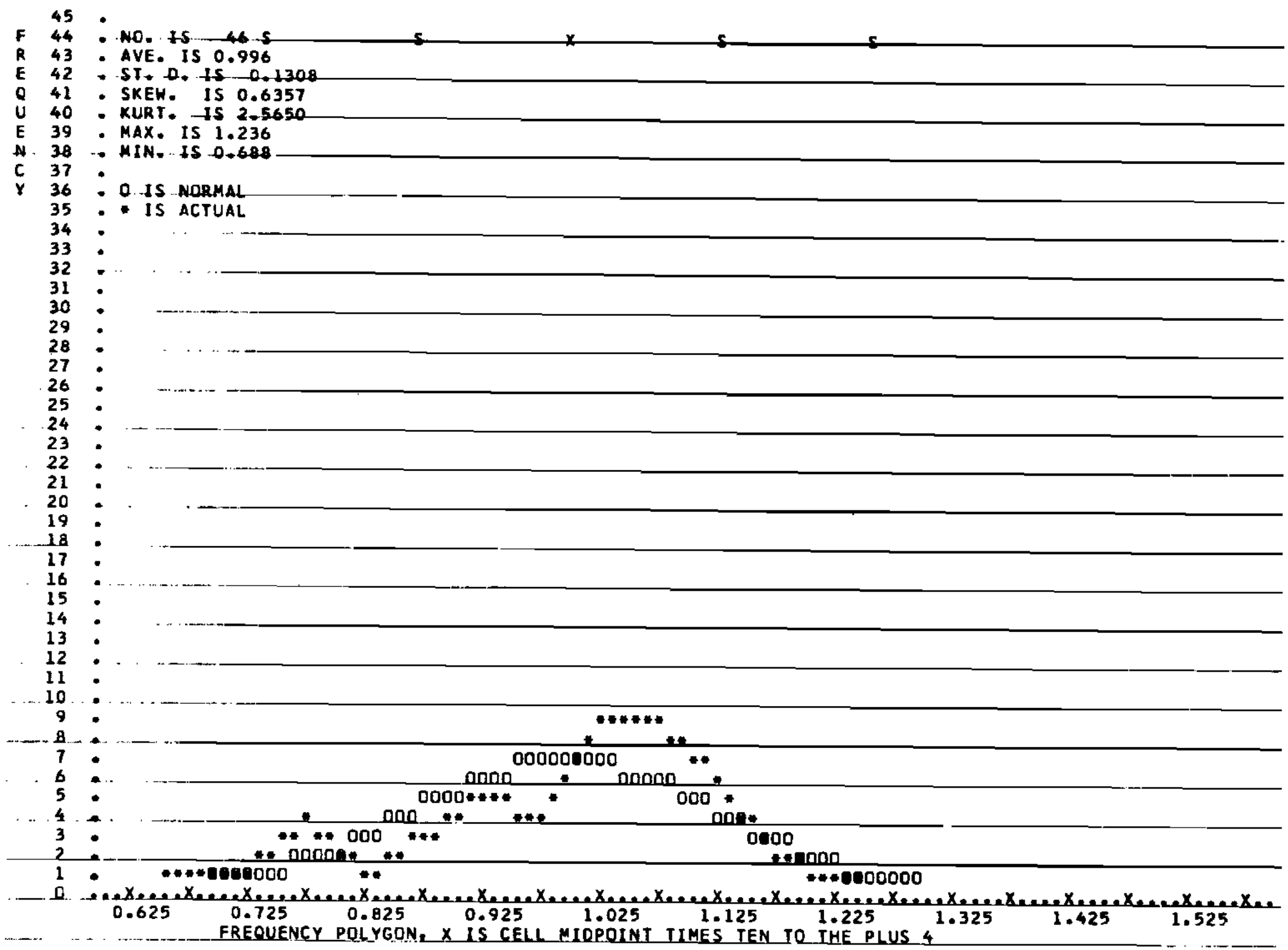


Figure 491. Frequency Distribution of With-Grain Compressive Strength Data, Cubical Specimen, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Blocks No. A-19, A-20 and A-24 Combined

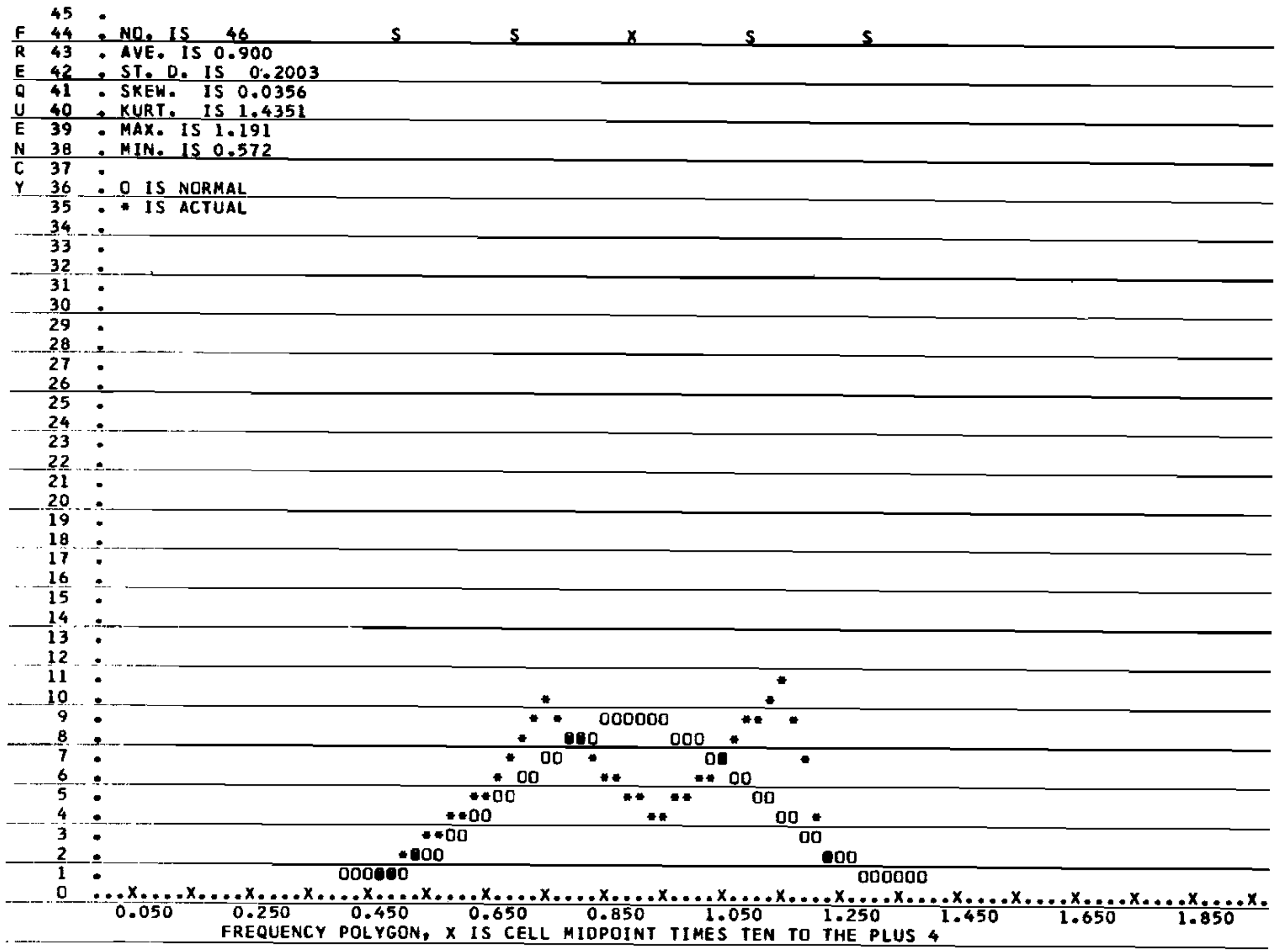


Figure 492. Frequency Distribution of Across-Grain Compressive Strength Data, Cubical Specimen, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Blocks No. A-19, A-20, and A-24 Combined

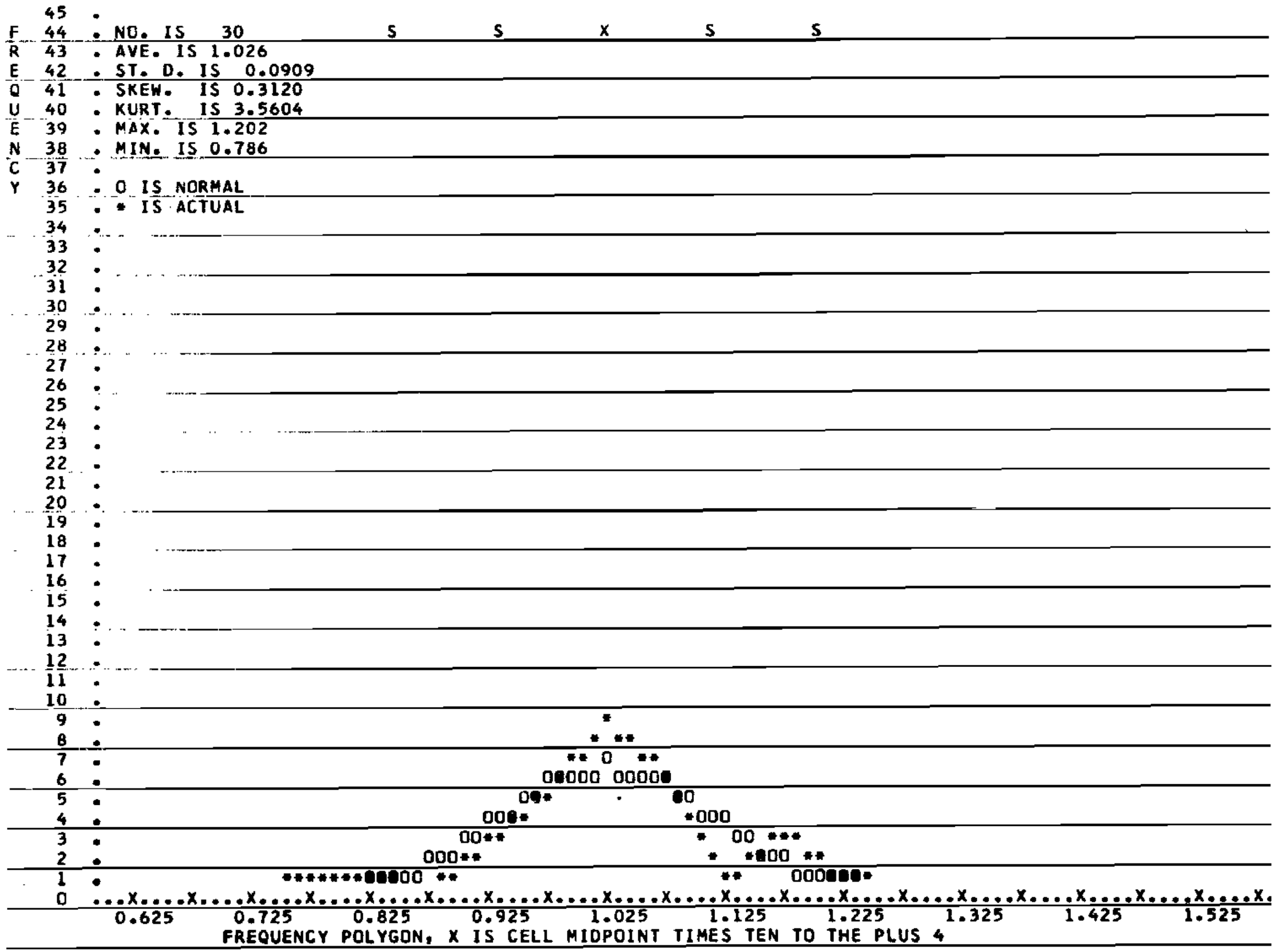


Figure 493. Frequency Distribution of With-Grain Compressive Strength Data, Cylindrical Specimen, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Blocks No. A-19, A-20 and A-24 Combined

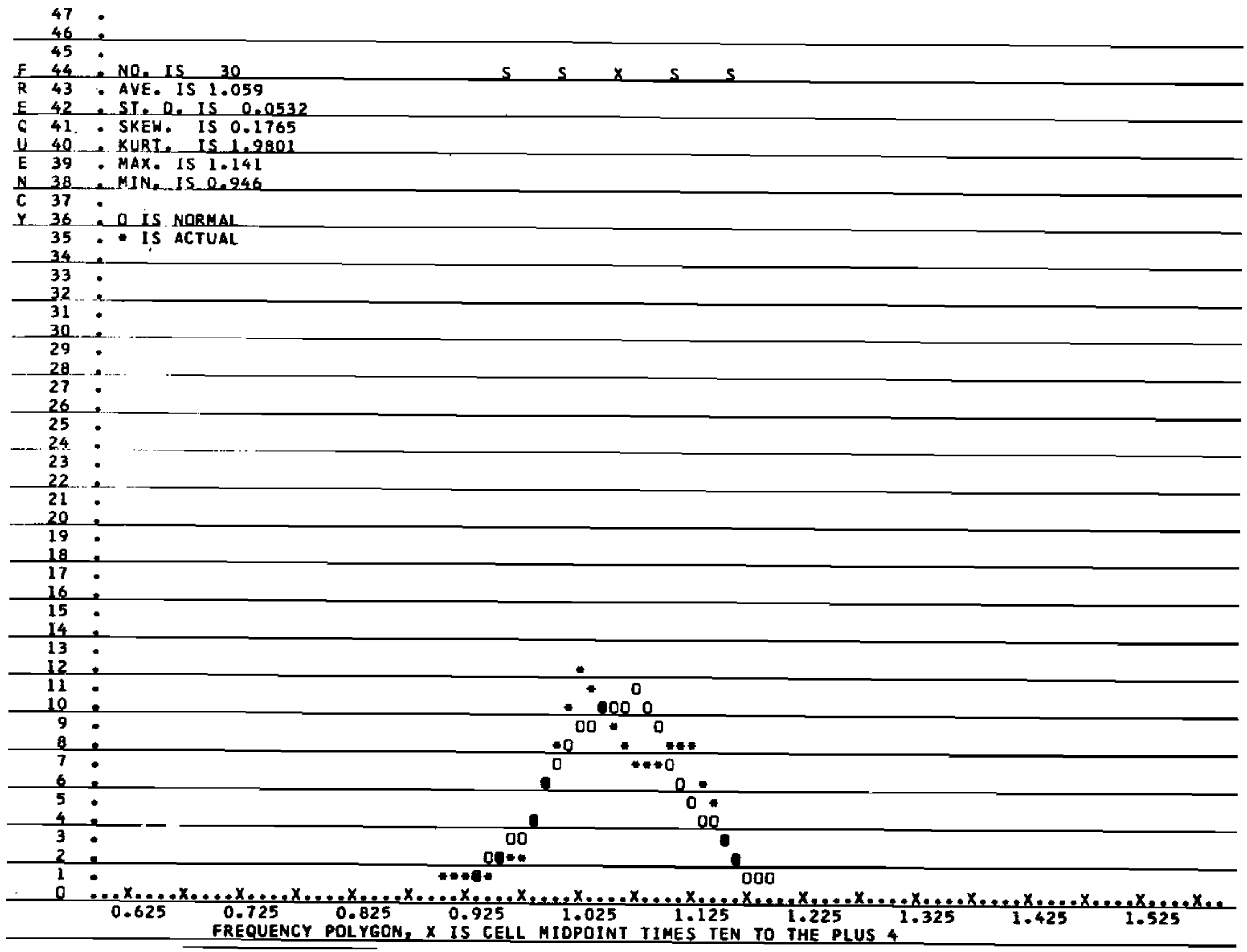


Figure 494. Frequency Distribution of Across-Grain Compressive Strength Data, Cylindrical Specimen, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Blocks No. A-19, A-20 and A-24 Combined

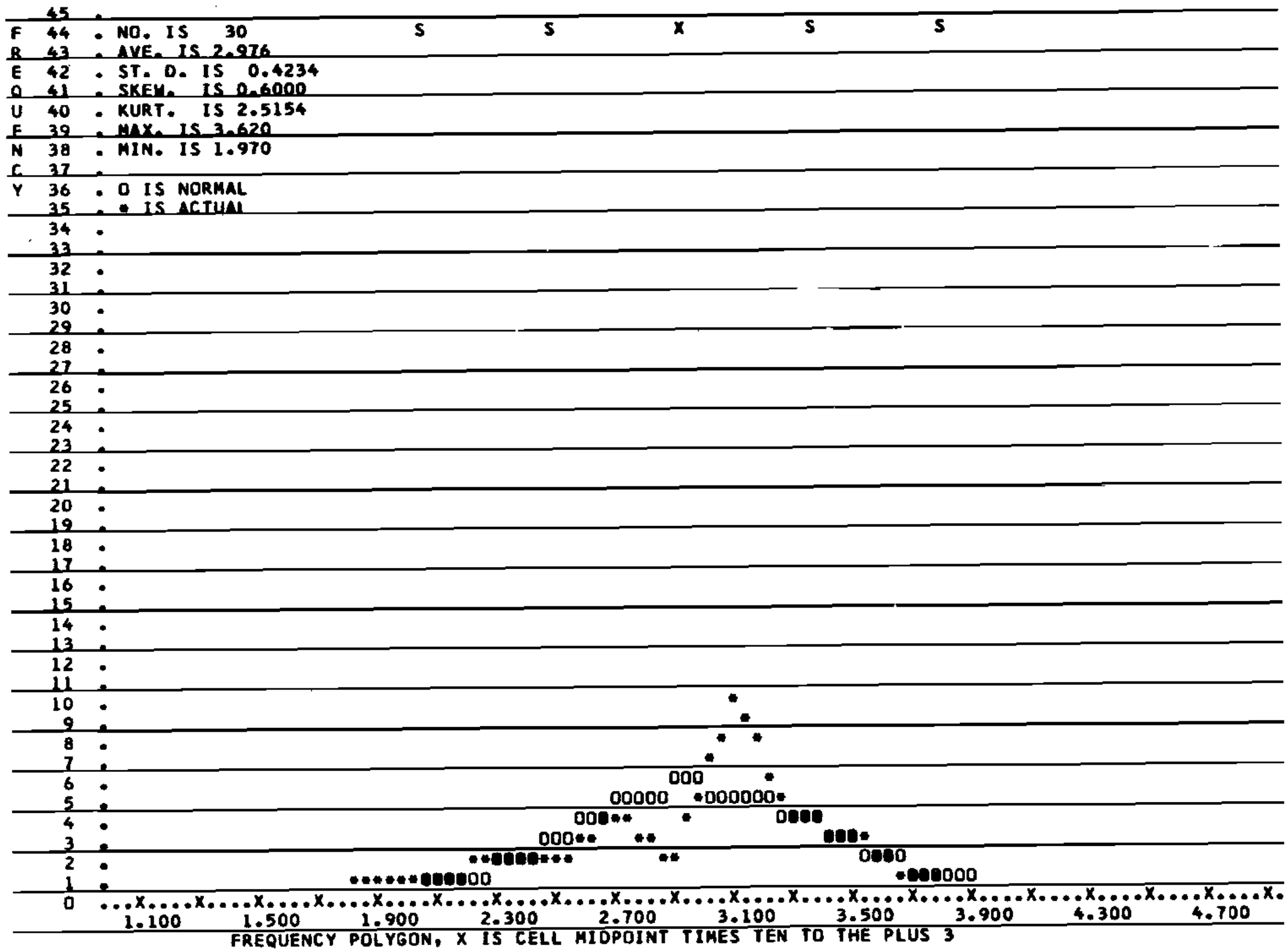


Figure 495. Frequency Distribution of With-Grain Tensile Strength Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Blocks No. A-19, A-20 and A-24 Combined

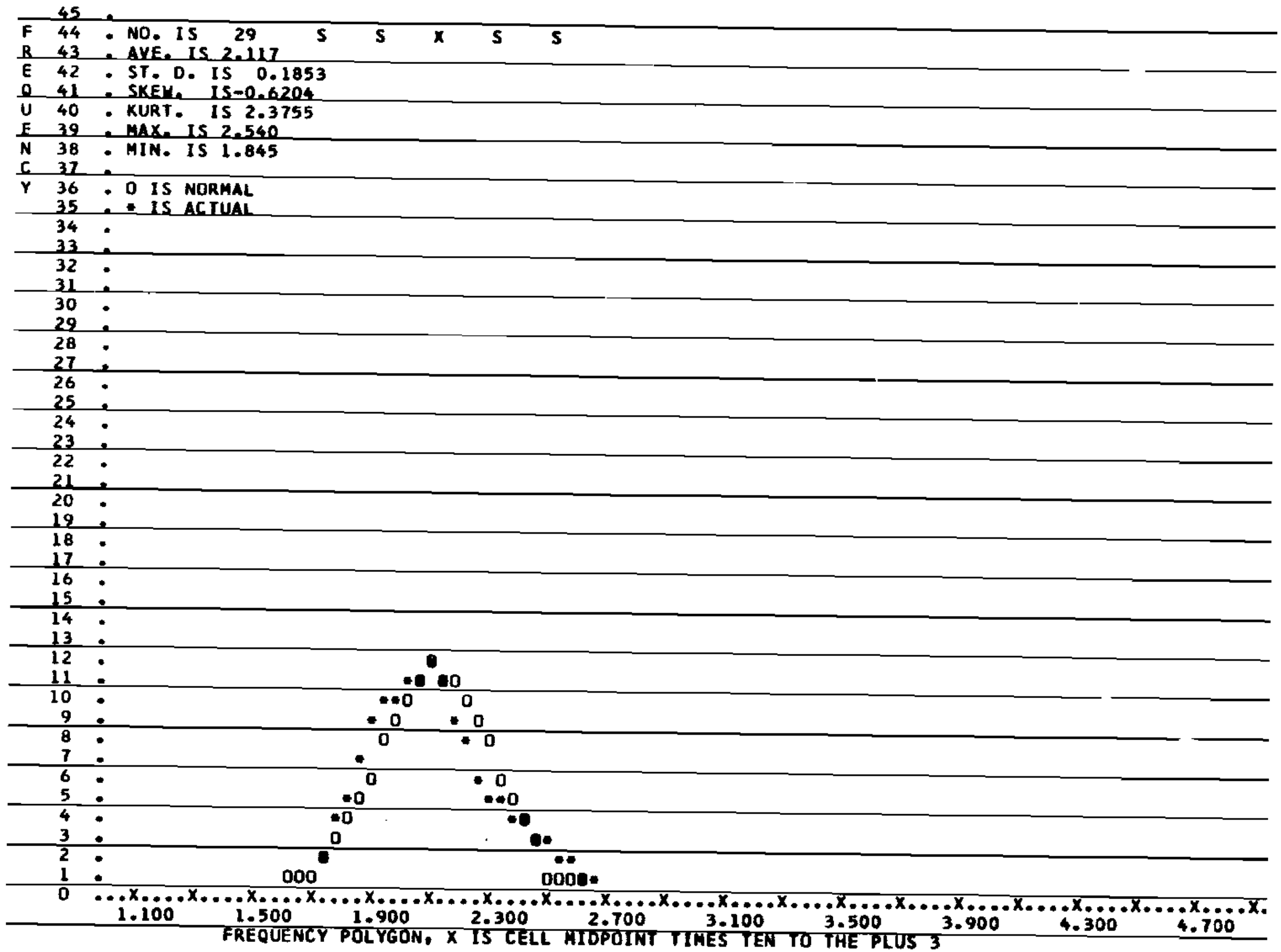


Figure 496. Frequency Distribution of Across-Grain Tensile Strength Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Blocks No. A-19, A-20 and A-24 Combined

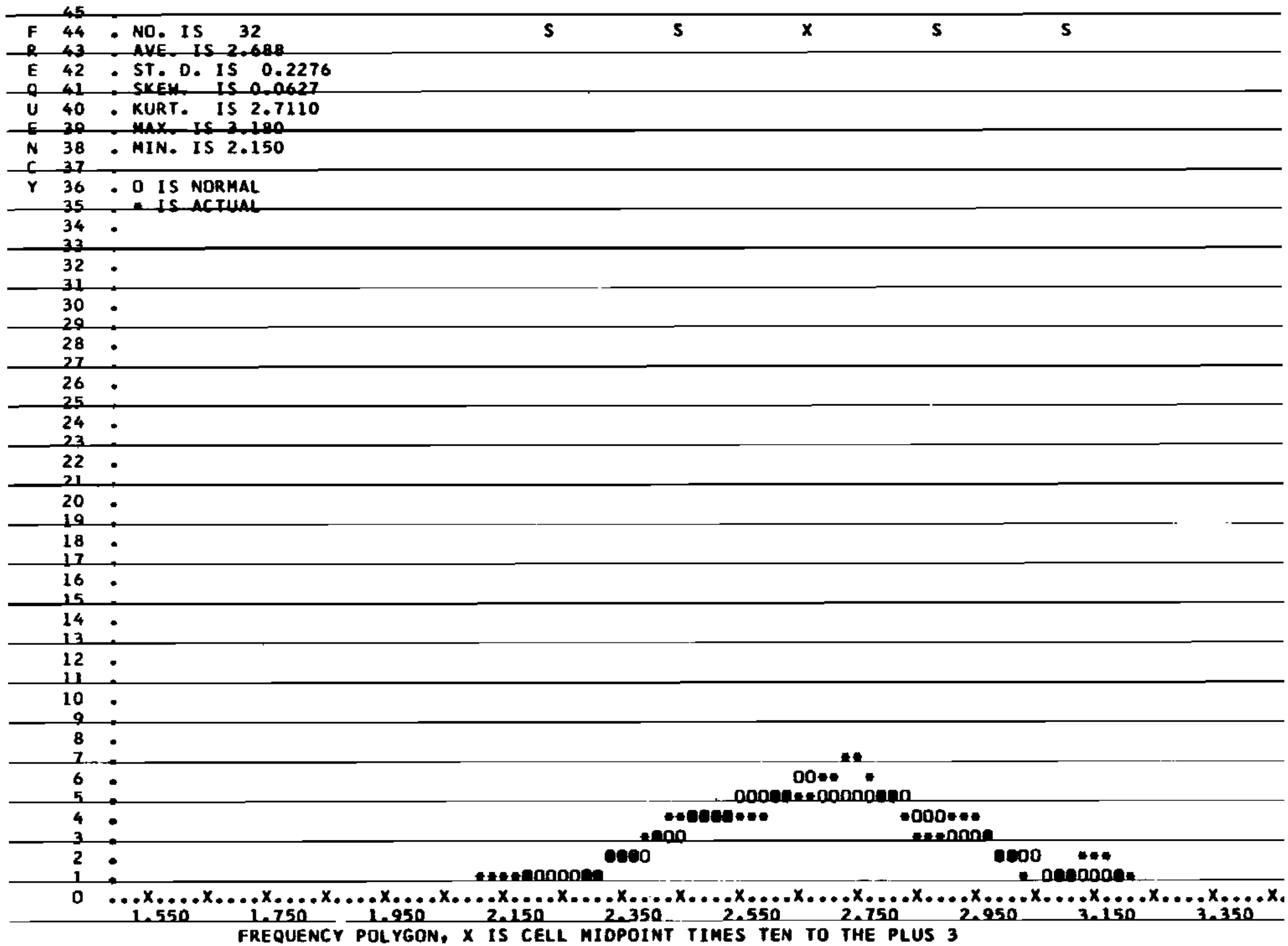


Figure 497. Frequency Distribution of With-Grain Apparent Shear Strength Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Blocks No. A-19, A-20 and A-24 Combined

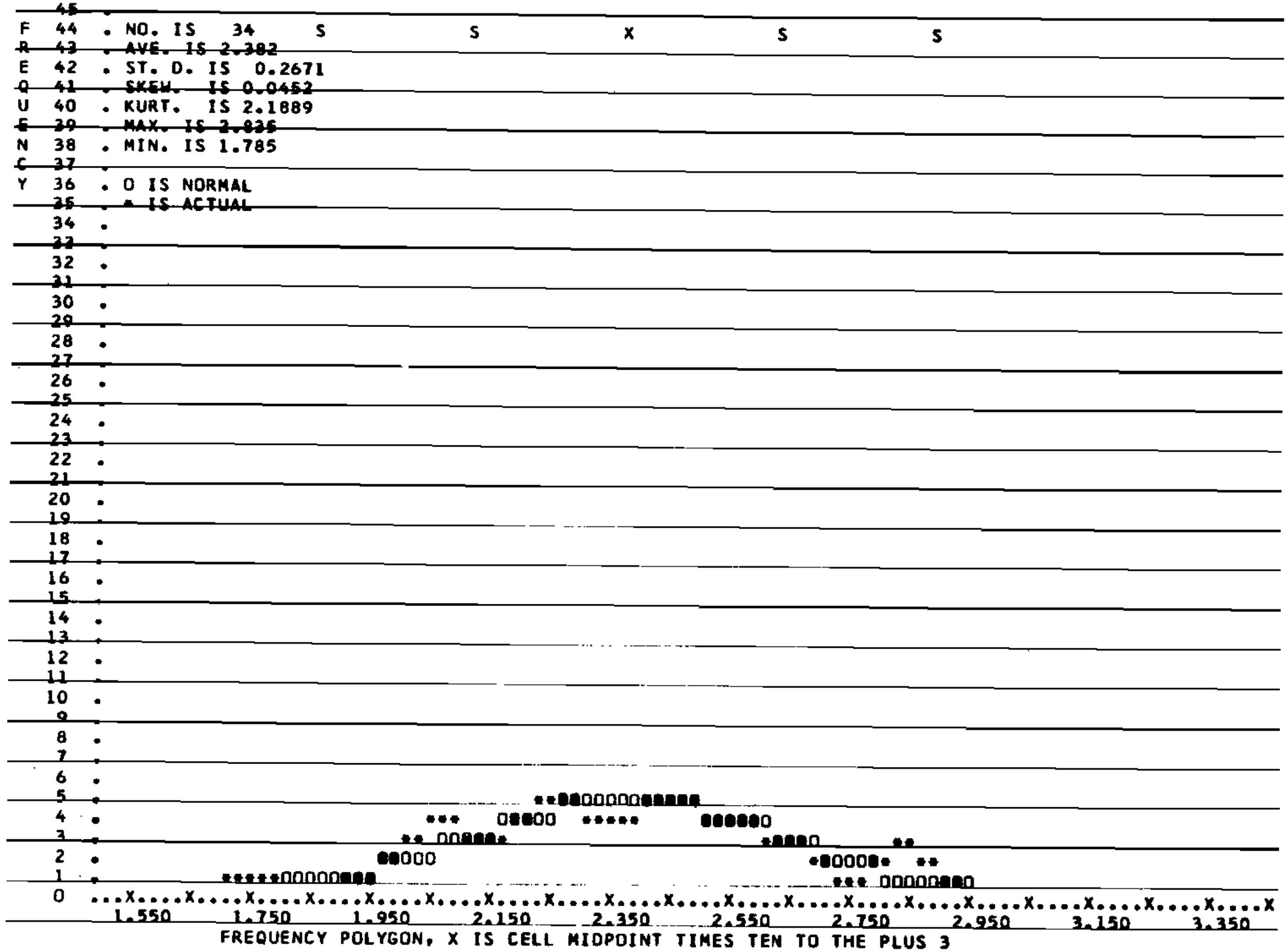


Figure 498. Frequency Distribution of Across-Grain Apparent Shear Strength Data, RVA Graphite, 33-Inch Diameter x 42-Inch Length, Blocks No. A-19, A-20 and A-24 Combined