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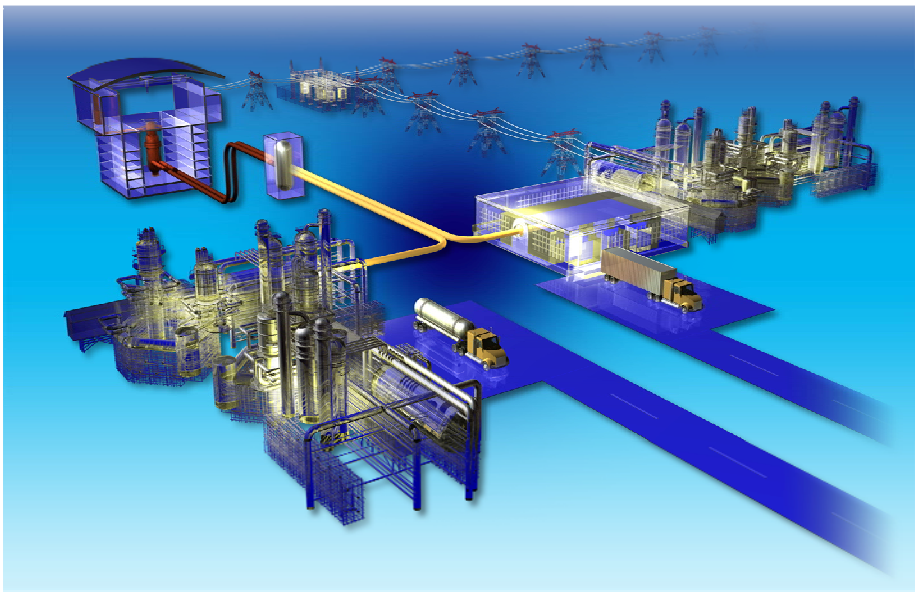
AGC-1 Sister Specimen Testing Data Report

Tim Burchell, Steve Nunn, Joe Strizak, and Marie Williams
Oak Ridge National Laboratory

May 18, 2009



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ABREVIATIONS

AFCI	Advanced Fuel Cycle Initiative
AG	Against-Grain
AGC	ATR Graphite Creep
ASTM	American Society of Testing and Materials
ATR	Advanced Test Reactor
CTE	Coefficient of Thermal Expansion
DSC	Differential Scanning Calorimeter
FWHM	Full Width Half Maximum
HOPG	Highly Oriented Pyrolytic Graphite
NIST	National Institute of Standards and Technology
NGNP	Next Generation Nuclear Plant
ORNL	Oak Ridge National Laboratory
VHTR	Very High Temperature Reactor
WG	With-Grain
XRD	X-Ray Diffraction

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Executive Summary

The AGC-1 irradiation capsule will provide irradiation creep design data and data for the effects of irradiation creep on key physical properties of several candidate graphites for the Next Generation Nuclear Plant (NGNP). A further objective of the AGC-1 creep capsule is to provide design data for the effects of neutron irradiation on the properties of a range of NGNP candidate graphites,

Characterization, both non-destructively and destructively, of AGC-1 graphite creep "sister" specimens for the major grades, i.e., NBG-17, NBG-18, H-451, PCEA, IG-110, and IG-430 has been performed and is reported here. The properties measured were: bulk density by mensuration and Hg-immersion; tensile properties, including strength, stress-strain behavior, static Young's modulus, and strain to failure; compressive properties, including strength, stress-strain behavior, static elastic modulus, and strain to failure; elastic constants, including dynamic Young's modulus (fundamental frequency method), and sonic elastic constants, including Young's modulus, shear modulus, and Poisson's ratio; pore size distribution (by Hg-intrusion); crystal structure (by x-ray diffraction, XRD); specific heat (elevated temperature), and thermal conductivity (elevated temperature). Significant differences were noted in the physical properties between the grades examined and are attributed to factors such as density, structure (filler particle size and pore size) and the forming method.

Some difficulties were encountered with mechanical testing of small (sub-standard) size specimens due to volume and grain size-section size effects. These difficulties are well understood and are an inevitable consequence of conducting property evaluations on small irradiation specimens. These data are judged to be sufficient to yield adequate fractional change in properties when combined with post-irradiation characterization data. However, the complication associated with small specimen testing reinforces the need to conduct full characterization programs to establish the baseline design properties of the NGNP candidate graphites.

A sufficient body of experimental data has been acquired from the AGC-1 creep "sister" specimens to fully characterize the properties of interest for the major grades included in the AGC-1 capsule. These data, in combination with the pre-irradiation characterization data packages for the actual AGC-1 creep and control specimens, provide a sound and sufficient pre-irradiation data set for determination of the effects of irradiation induced dimensional change and creep strain on the physical properties of the nuclear graphite grades in the AGC-1 capsule.

1. Background

The AGC-1 irradiation capsule [1, 2] will provide irradiation creep design data, and data for the effects of irradiation creep on key physical properties, of several candidate graphites for the Next Generation Nuclear Plant (NGNP) program. A further objective is to provide design data for the effects of neutron irradiation on the properties of a range of NGNP relevant graphites, such data to include: dimensional changes, strength, elastic modulus, thermal conductivity and coefficient of thermal expansion (CTE).

The experimental plan for the evaluation of AGC-1 "Sister" specimens [3] defined the work scope of an experimental program to characterize the structure and determine the tensile and compressive strengths of the graphites included in the AGC-1 irradiation creep capsule [1, 2]. Because these tests are of a destructive nature they were performed on duplicate or "sister" specimens with the same geometry as the AGC-1 creep specimens. These data are needed to support the design of graphite components for the Next Generation Nuclear Plant (NGNP).

The data to be obtained from the AGC-1 irradiation creep capsule includes:

- Irradiation creep design data and data on the effects of irradiation creep on key physical properties [strength, elastic modulus, CTE]
- The effects of neutron irradiation on the properties of a wide range of NGNP relevant graphites, including, dimensional changes, strength, elastic modulus, thermal conductivity, and CTE.
- Data on the single-crystal irradiation behavior of graphites to be derived from HOPG.

The graphites grades to be included in the AGC-1 capsule can be categorized as follows.

a. Major Grades

These graphites are reactor vendor's candidates for the core structures of NGNP, and include four new grades (NBG-17, NBG-18, PCEA, and IG-430) as well as

two historical (reference) grades (H-451 and IG-110). These grades are most likely to receive reasonably large neutron doses in their lifetime and will be subjected to significant stresses in operation. Consequently, these grades occupy the stressed and companion unstressed positions in the AGC-1 capsule and hence yield irradiation creep data.

b. Minor Grades

These grades are NGNP relevant grades that are most likely to be used in low neutron dose regions of the core; e.g., the permanent structure of the prismatic block very high temperature reactor (VHTR) design and includes grades PGX and HLM.

c. Alternate Grades

Grades that NGNP vendors have identified as being of interest as alternate graphites for certain components within the reactor, and includes grades PPEA and PCIB.

d. Experimental Grades

Two experimental graphites are included in AGC-1 (BAN and A3 matrix). BAN graphite is an experimental grade whose manufacturing process and raw materials are such that it should offer superior irradiation stability. A3 matrix is the blend of graphites and carbonized phenolic resin used as the matrix in the NGNP fuel compact or fuel pebble. Samples of A3 are to be obtained from the Advanced Fuel Cycle Initiative (AFCI) program and will be produced at Oak Ridge National Laboratory (ORNL).

e. Single Crystal Graphite

The dimensional change behavior of graphite is particularly significant to the behavior of polycrystalline (polygrannular) graphites. Therefore, samples of highly oriented pyrolytic graphite (HOPG) are included in AGC-1.

A more complete description of all of the graphite samples included in capsule AGC-1 is given in the AGC-1 Experimental Plan [1].

2. Experimental

2.1 Materials

The graphites included in this work are the six major grades as defined above, and include four new grades (NBG-17, NBG-18, PCEA, and IG-430) as well as two historical (reference) grades (H-451 and IG-110). Further details of the grades are given in Table 1. The grades recommended for inclusion in the NGNP graphite technology development program are among the major grades [4].

Table 1. AGC-1 graphite grades to be examined in this work

Graphite Grade	Source	Country of Origin	Process Details
NBG-17	SGL Carbon	Germany/France	Pitch coke, vibrationally molded, medium grain
NBG-18	SGL Carbon	Germany/France	Pitch coke, vibrationally molded, medium grain
H-451 (Reference Grade)	SGL Carbon	USA	Petroleum coke, extruded, medium grain
PCEA	GrafTech International	USA	Petroleum coke, extruded, medium grain
IG-110 (Reference Grade)	Toyo Tanso	Japan	Petroleum coke, isostatically pressed, fine grain
IG-430	Toyo Tanso	Japan	Pitch coke, isostatically pressed, fine grain

The following major grade specimen codes are used throughout this work

A – NBG-17

B – NBG-18

C – H-451

D – PCEA

E – IG-110

F – IG-430

Sister specimens for destructive testing will be cut from adjacent locations in the graphite billets from which the AGC-1 specimens were taken. Fig. 1 shows the cutting diagram for grade H-451. Cutting diagrams for grades IG-110 and IG-430 are in Figs. 2 and 3 respectively. Figs. 4-7 show the cutting diagrams for grades NBG-17 and -18, and the cutting diagram for PCEA is shown in Fig. 8.

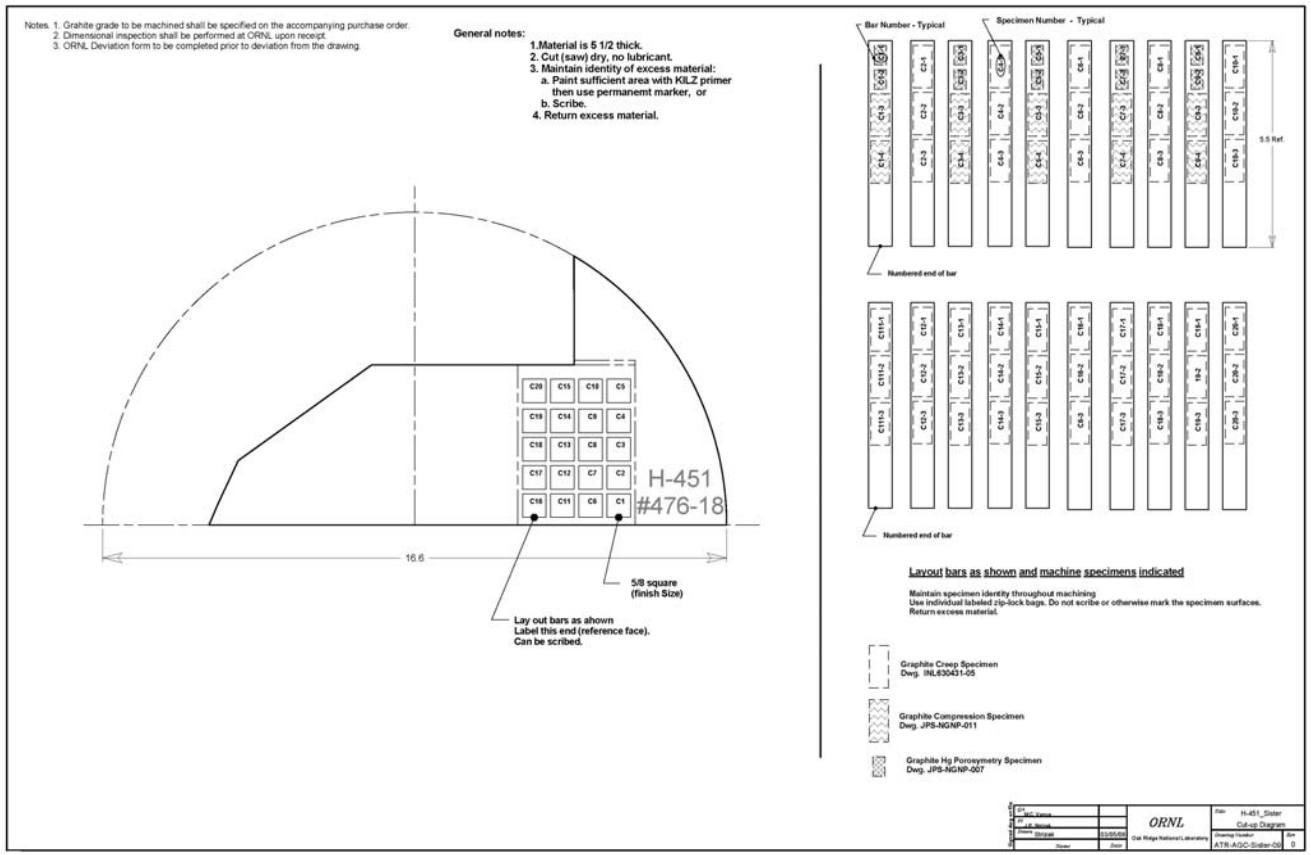

Figure 1. Billet cutting diagram for grade H-451

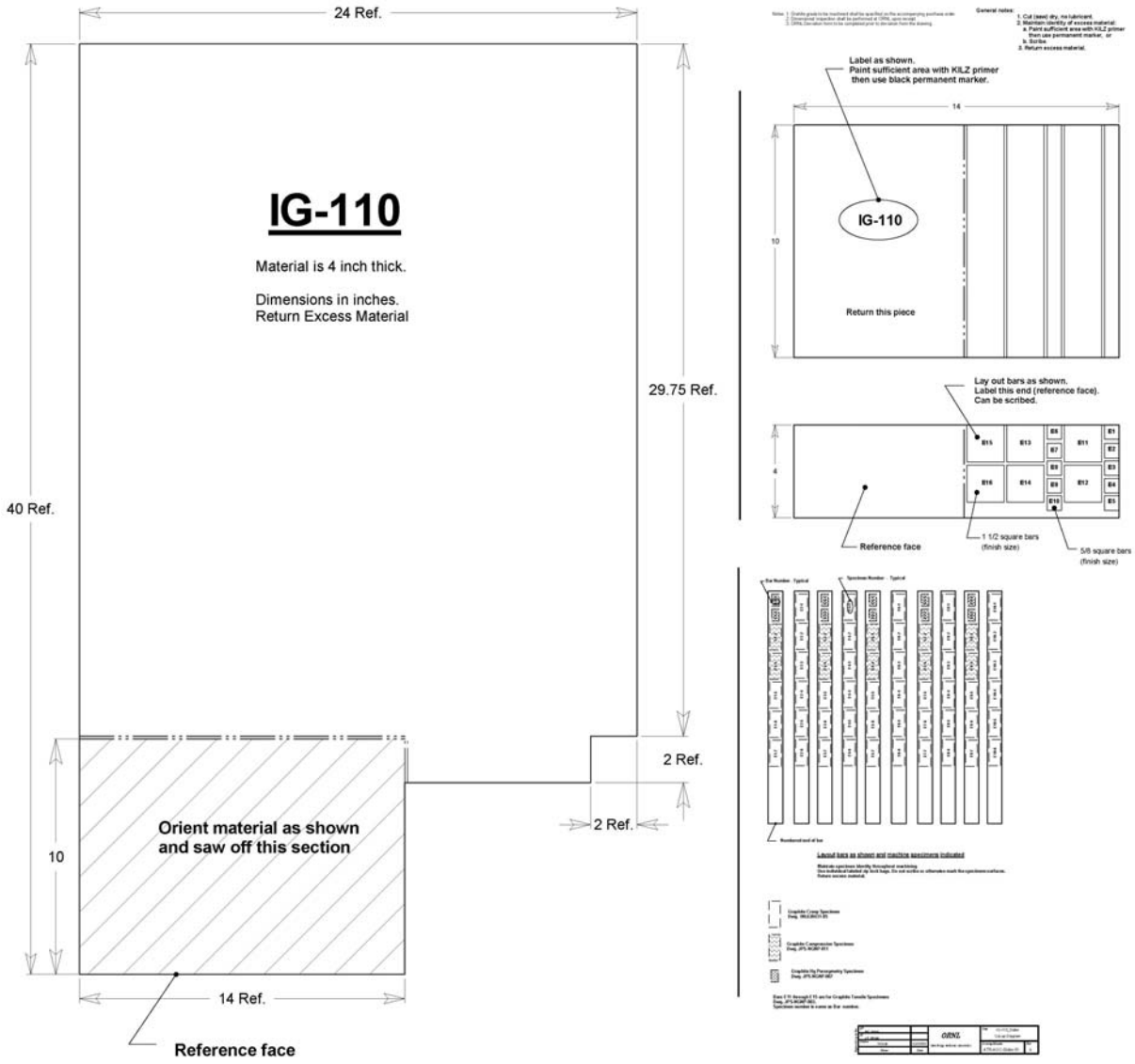

Figure 2. Billet cutting diagram for grade IG-110

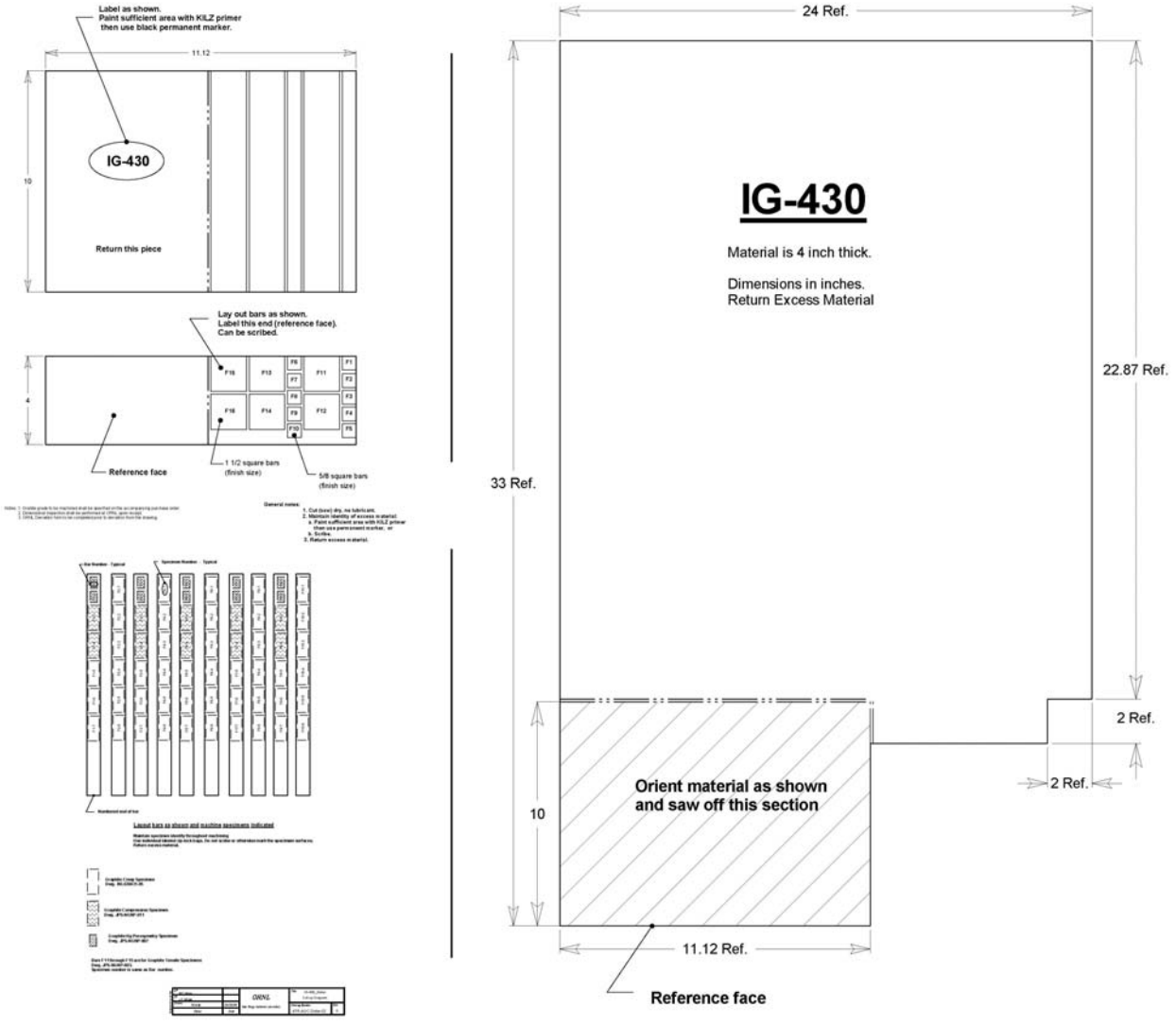

Figure 3. Billet cutting diagram for grade IG-430

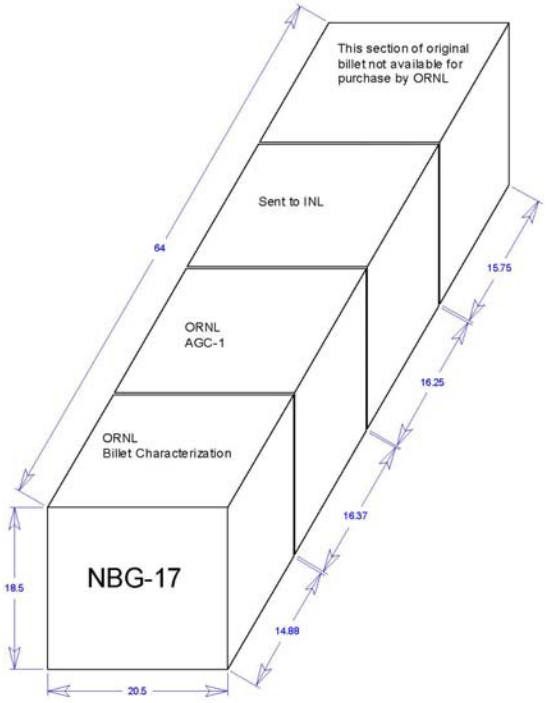

Figure 4. Billet cutting diagram for grade NBG-17

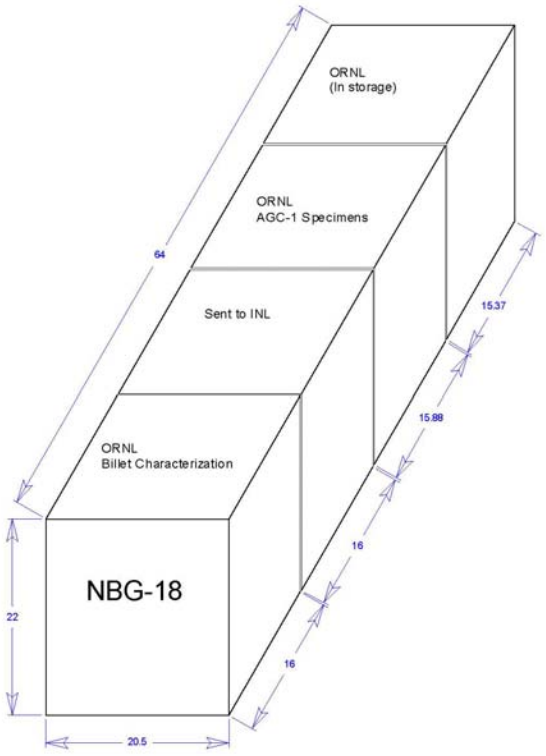

Figure 5. Billet cutting diagram for grade NBG-18

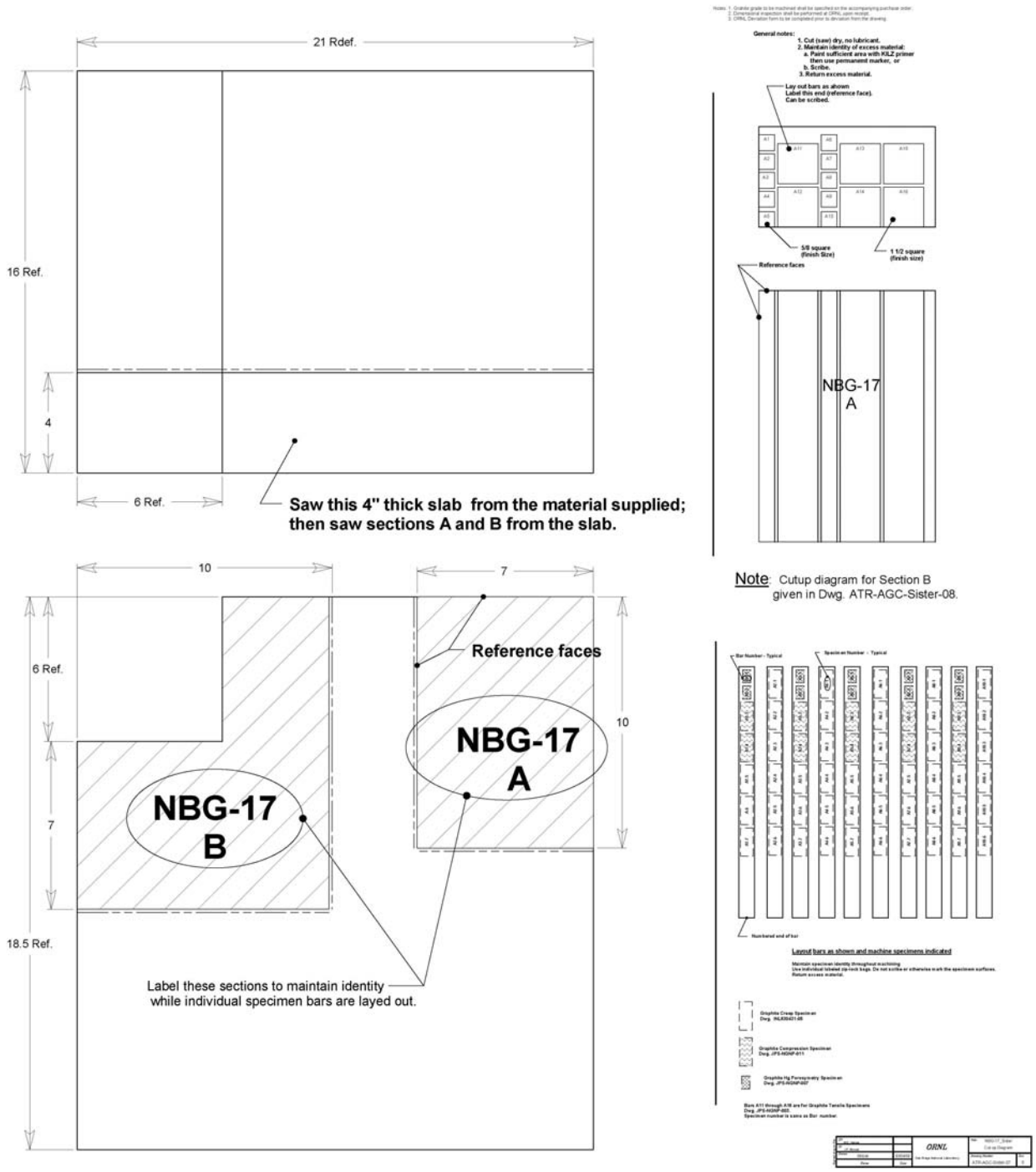

Figure 6a. Cutting diagram for grade NBG-17 billet sub-sections

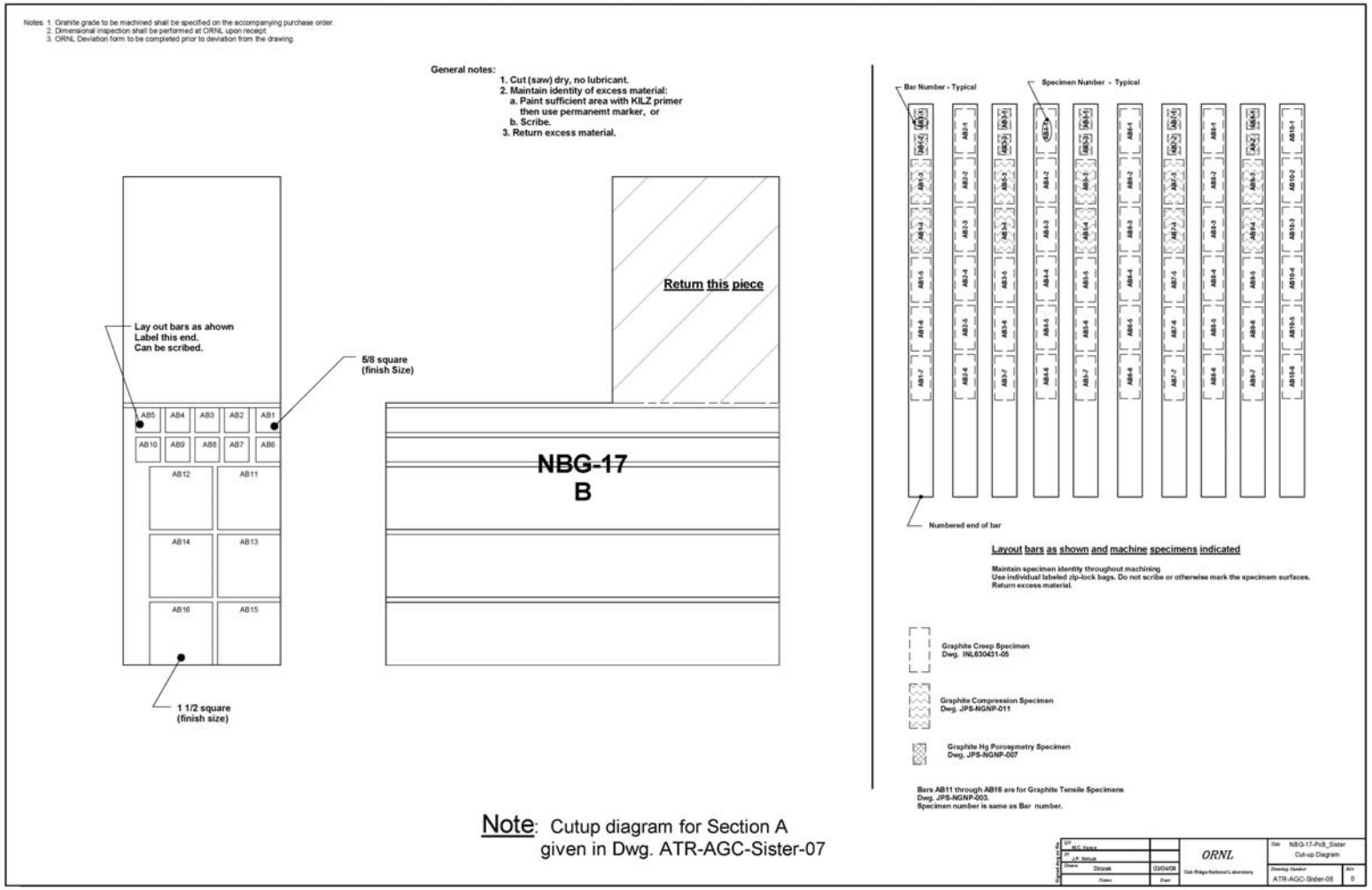

Figure 6b. Cutting diagram for grade NBG-17 billet sub-section B

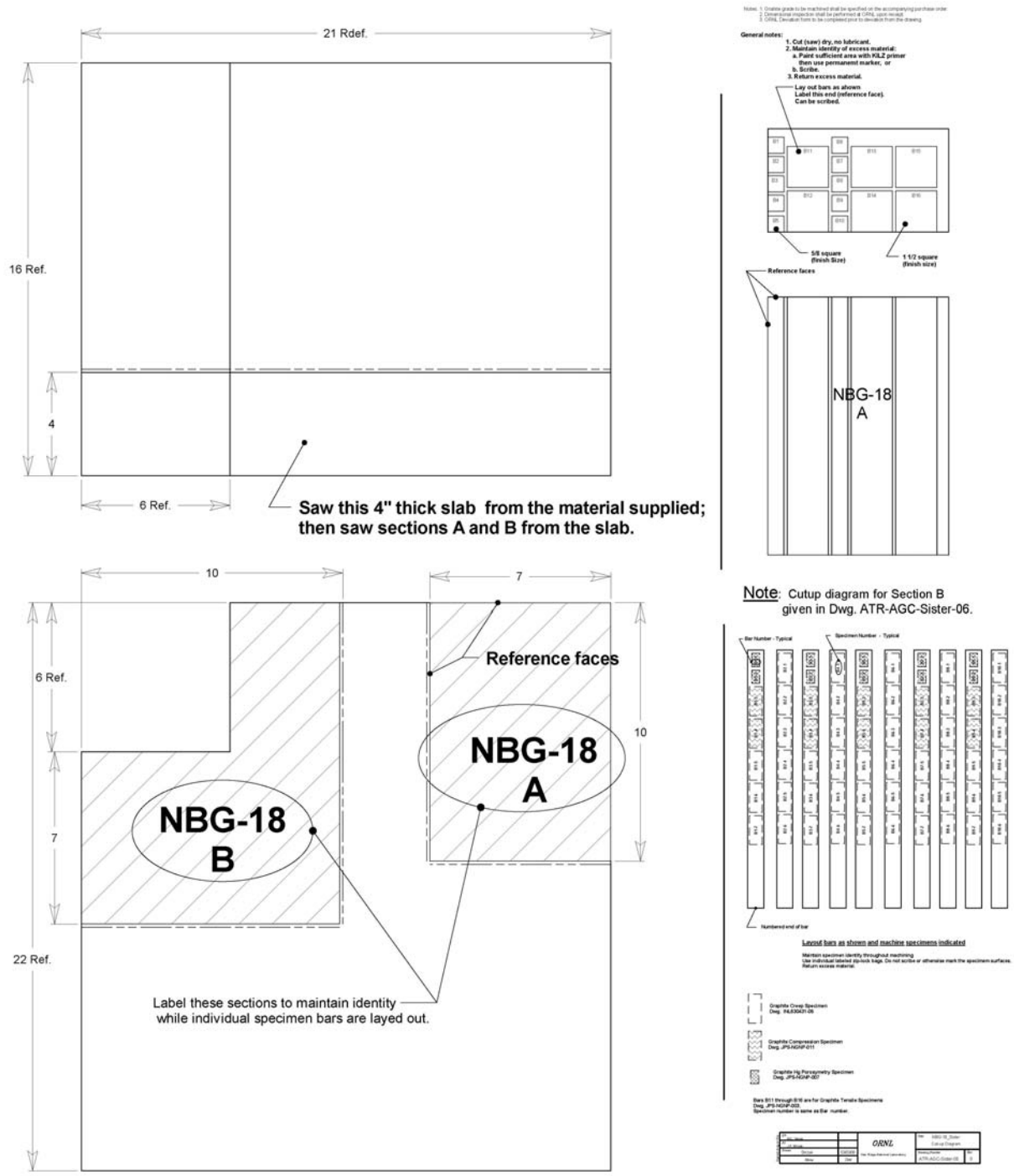

Figure 7a. Cutting diagram for grade NBG-18 billet sub-sections

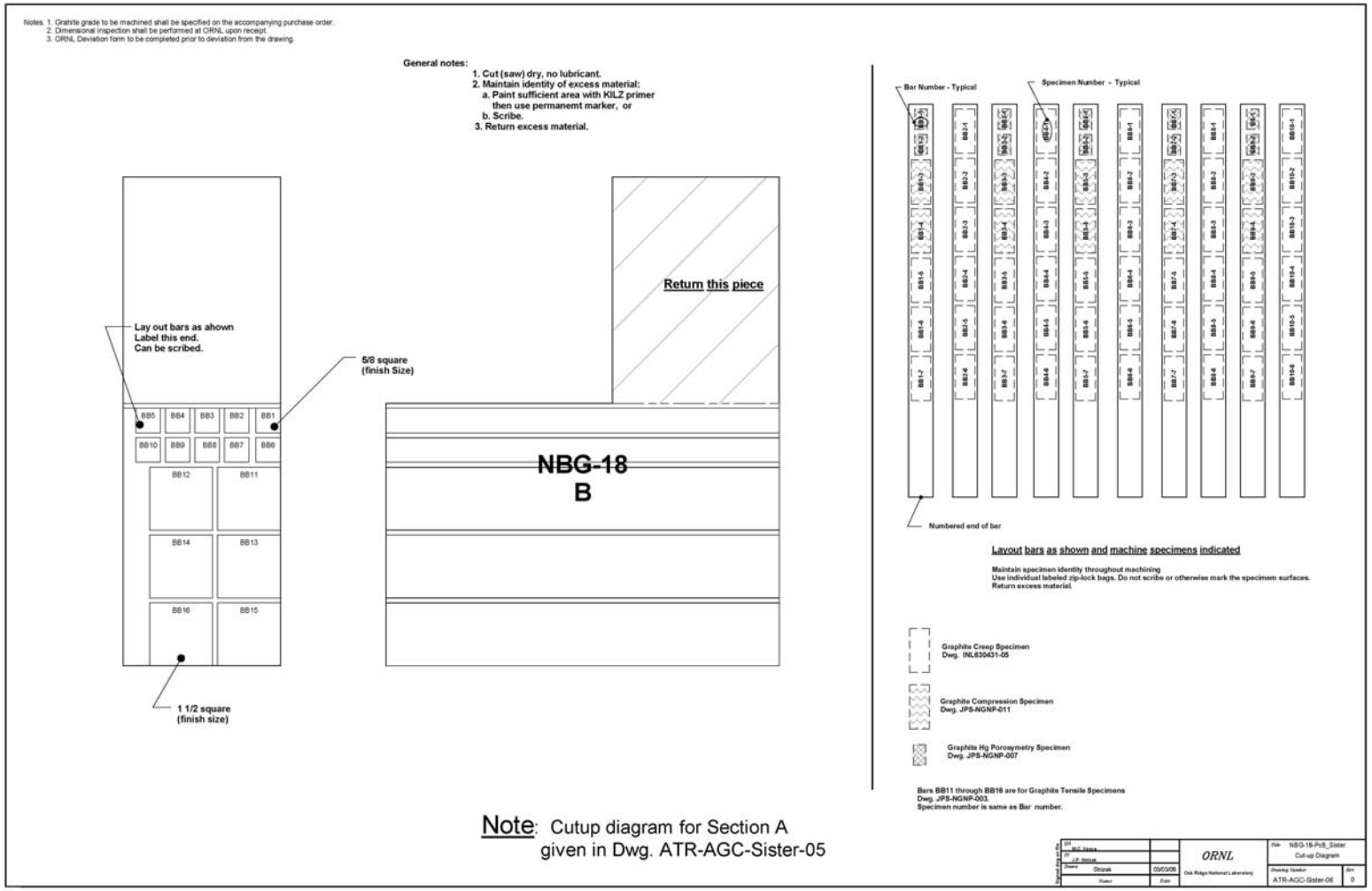

Figure 7b. Cutting diagram for grade NBG-18 billet sub-section A

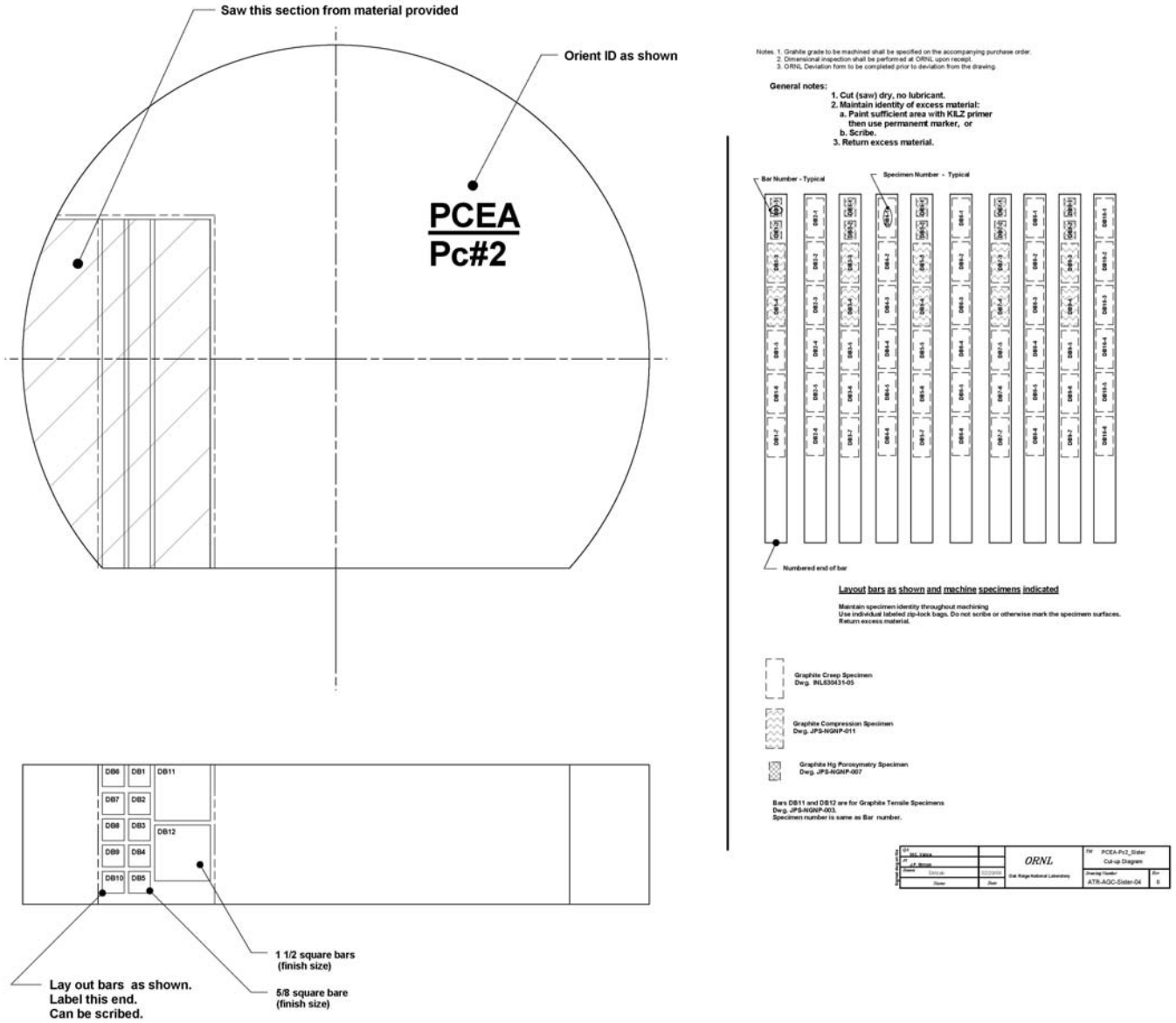

Figure 8a. Cutting diagram for grade PCEA (Pc#2)

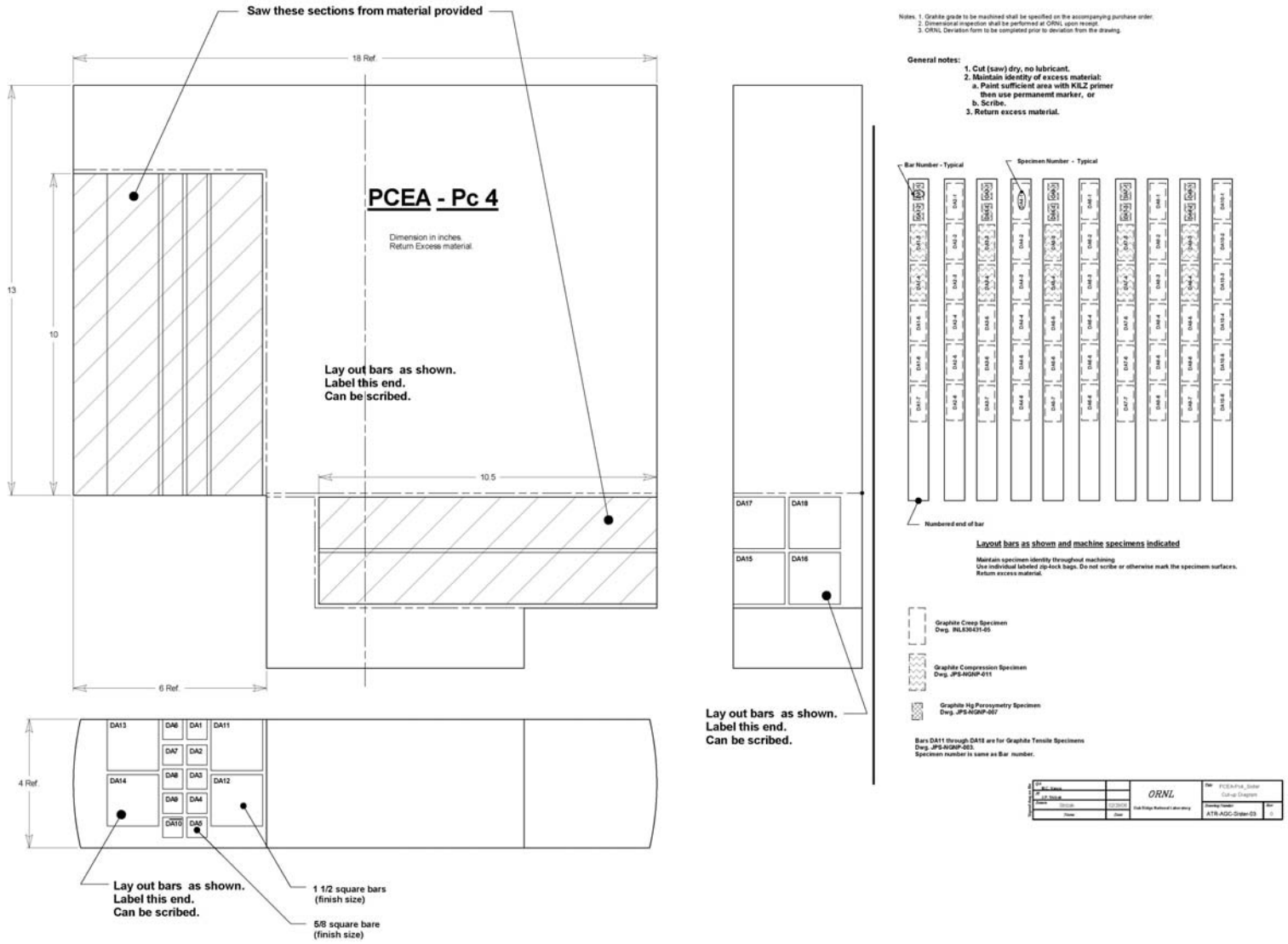

Figure 8b. Cutting diagram for grade PCEA (-Pc 4)

2.2 Uniaxial Tensile Strength Testing

AGC-1 "sister" tensile strength specimens were tested in accordance with ASTM standard C 749 "Standard Test Method for Tensile Stress-Strain of Carbon and Graphite" [5] as modified by C 781 "Standard Practice for Testing of Graphite and Boronated Graphite Components for High Temperature Nuclear Reactors" [6], Annex A3 "Modification to test method C749 for glued end specimens". Fig. 9 shows the AGC-1 creep sample geometry which was used for the "sister" sample testing.

Both with-grain (WG) and against grain (AG) samples were tested. Table 2 shows the specimen orientations and the numbers of specimens tensile tested.

Table 2. Tensile tests "sister" specimen grades, orientation, and numbers

Graphite Grade	Orientation	Maximum Grain Size (mm)	Number of Specimens to be Tested
H-451	WG	1.25	12
NBG-17	WG	0.8	12
NBG-17	AG	0.8	12
NBG-18	WG	1.6	12
NBG-18	AG	1.6	12
PCEA	WG	0.8	12
PCEA	AG	0.8	12
IG-110	Isotopic	0.010*	12
IG-430	Isotropic	0.010*	12

* mean particle size

ASTM method C 749 requires the specimen diameter to be greater than 3-5 times the maximum particle size of the graphite. The sister specimens had a 12.5 mm diameter (identical to the AGC-1 specimen geometry). Consequently, all of the specimens tensile tested were in compliance with C 749/C 781.

An engineering drawing of the aluminum "glued ends" used in the tensile testing of the "sister" specimens is shown in Fig. 10. The glued ends completely enclose the ends of the "sister" specimen so as to ensure the specimen is centered and aligned. The glued ends are manufactured from aluminum grade 6061-T6 and are bonded to the graphite "sister" specimens using a two-part epoxy resin adhesive.

In accordance with test method C-749 clip type strain gauges were employed so that a stress-strain curve could be generated during testing.

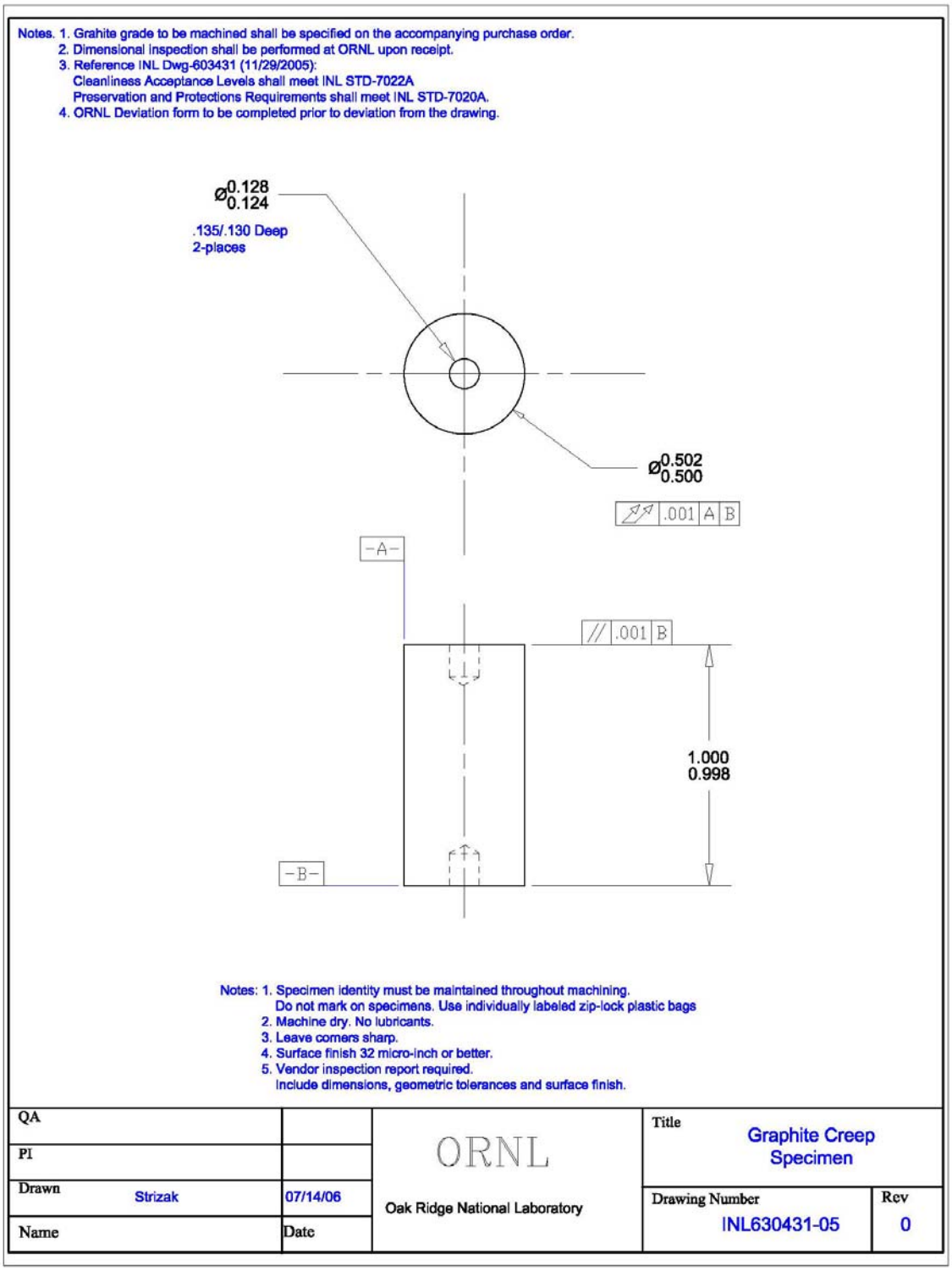

Figure 9. AGC-1 specimen and "sister" specimen geometry

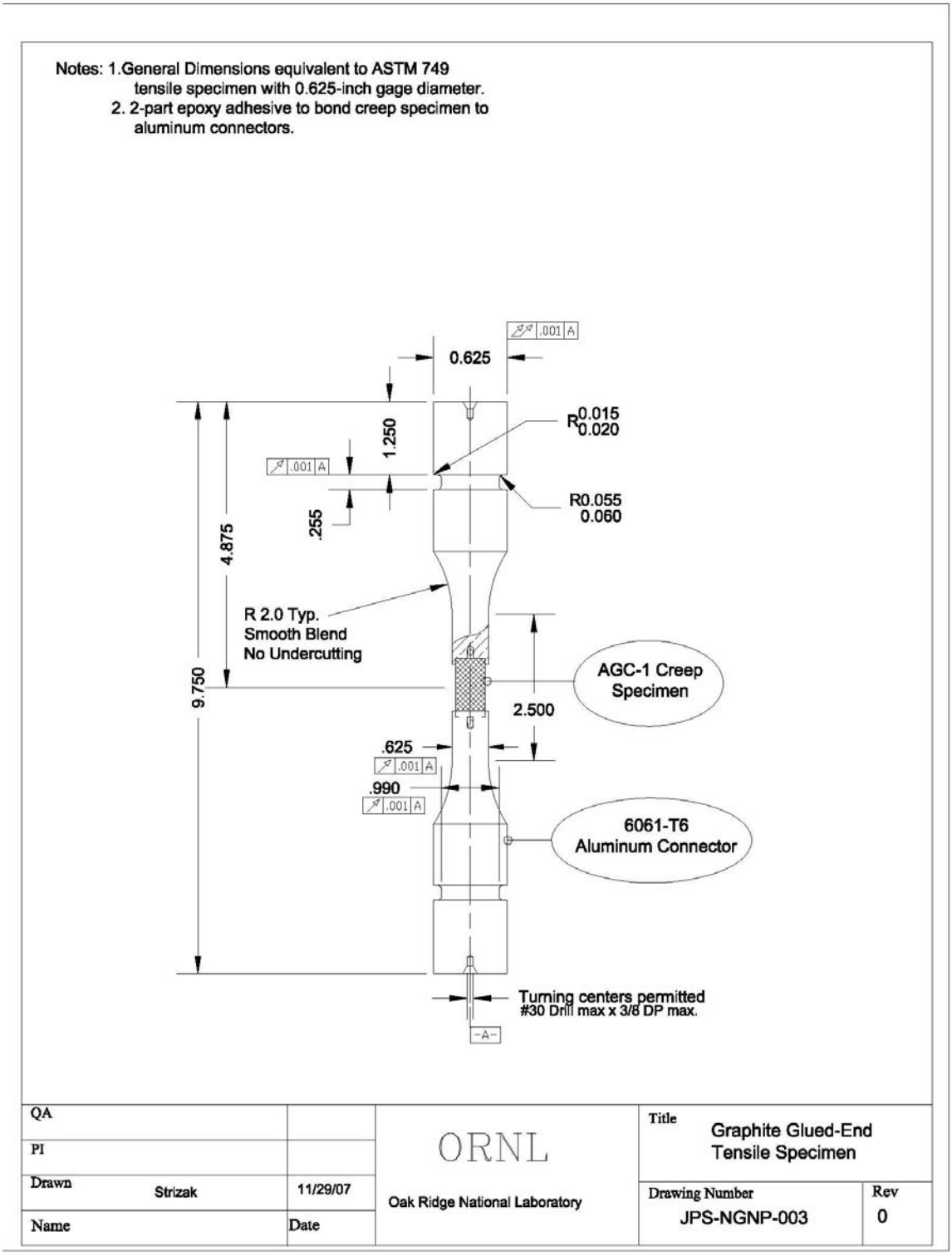

Figure 10. Engineering drawing of the glued end configuration for tensile testing of the AGC-1 "sister" specimens

Tensile testing experience showed there were some difficulties in obtaining a good adhesive bond. Subsequently, the attachment configuration was modified allowing a threaded stub to be attached to the specimen (Fig. 11). The stub connects to a grip end similar to that in Fig 10 and allows the use of a load train as prescribed in ASTM C 749 [5].

Figure 11. Modified glued end stubs attached to the AGC-1 "sister" specimens

Fig. 12 shows the component parts of the glued end assembly. The short lengths of 0.028 inch diameter wire are placed between the aluminum ends and the graphite specimen and assure the glue joint has uniform thickness and strength. Fig. 12 also shows a completed (glued) specimen. The specimens are assembled with a two part epoxy adhesive and are aligned using a bench center (Fig. 13). Fig. 14 shows the glued end specimen and a "standard" ASTM C 749 [5] tensile specimen. The glued end technique allows testing of the creep specimens which mimic the gauge section of the ASTM standard specimen (Fig. 15).

Figure 12. Component parts of the glued end specimen assembly.

Tensile tests were performed on a Instron Model 4210 Electromechanical Test System using an Instron 50 kN load cell, ID# M216561 at a crosshead speed of 0.02 in/min, and a MTS strain extensometer, Model 632.13B-20, ID# M214476, 0.5" gage length. This is a strain gauge type extensometer with knife blades that contact the specimen. The extensometer is attached to the specimen with rubber bands (Fig. 16). The specimen surface is locally sealed (approximately 0.2 ins. diameter area on the specimen surface with a 5-minute epoxy) to prevent slippage of the extensometer blade without reinforcing specimen strength. The load and extensometer displacement data was recorded in text files via LabView software. The test specimens and the test data were archived for future examination.

Figure 13. Alignment of the glued end specimen using a bench center

Figure 14. The glued end tensile specimen and an ASTM standard specimen

Figure 15. Glued end specimen test train arrangement.

Figure 16. Glued end specimen arrangement showing the attachment of the clip type strain gauge.

2.3 Compressive Strength Testing

AGC-1 "sister" specimens were tested in accordance with ASTM standard C-695 "Standard test method for Compressive Strength of Carbon and Graphite" [6] as modified by C-781 "Standard Practice for Testing of Graphite and Boronated Graphite Components for High Temperature Nuclear Reactors" [7], Annex A5 "Modification to test method C695". Fig. 9 shows the AGC-1 creep sample geometry that was used here for the "sister" sample compressive testing.

Both with-grain (WG) and against grain (AG) samples were tested. Table 3 shows the specimen orientations and the numbers of compressive specimens tested.

Table 3. Compressive tests "sister" specimen grades, orientation, and numbers

Graphite Grade	Orientation	Maximum Grain Size (mm)	Number of Specimens to be Tested
H-451	WG	1.25	12
NBG-17	WG	0.8	12
NBG-17	AG	0.8	12
NBG-18	WG	1.6	12
NBG-18	AG	1.6	12
PCEA	WG	0.8	12
PCEA	AG	0.8	12
IG-110	Isotropic	0.010*	12
IG-430	Isotropic	0.010*	12

* mean grain size

Test method C 695 requires that the specimen diameter shall be greater than 10 times the maximum grain size. Consequently, grade NBG-18 and H-451 specimens are in violation of this requirement for the 12.5 mm diameter "sister" specimens. However, Standard Practice C 781, Annex 5 "modification to test method C 695", states that the specimen minimum diameter shall be no less that five times the maximum grain size, and in no case less than 7.5 mm. Consequently, the "sister" specimen geometry complies with C 781 Annex 5 for grades H-451 and NBG-18. Test method C 695 requires the specimen aspect ratio to be between 1.9 and 2.1 [$2.1 > (h/d) > 1.9$]. The AGC-1 specimen geometry has an aspect ratio (h/d) of 2.0, and thus is in compliance with the requirements of C 695. Moreover, the AGC-1 specimens exceeded the recommended minimum specimen size of 9.5 mm diameter x 19 mm length.

Compressive tests were performed on a Instron Model 4210 Electromechanical Test System using an Instron 50 kN load cell, ID# M216561 at a crosshead speed of 0.02 in/min, and a MTS strain extensometer, Model 632.13B-20, ID# M214476, 0.5" gage length. This is a strain gauge type extensometer with knife blades that contact the specimen. The extensometer is attached to the specimen with rubber bands. The specimen surface is locally sealed (approximately 0.2 in. diameter area on the specimen surface with a 5-minute epoxy) to prevent slippage of the extensometer blade without reinforcing specimen strength. The load and extensometer displacement data was recorded in text files via LabView software. The test specimens and the test data were archived for future examination.

2.4 Pore Structure Characterization

Graphite pore structure was characterized using Mercury Porosimetry. The apparatus used was a Quantachrome Instruments (Boynton Beach, FL) Model: PM60-6 (also called PoreMaster 60) Serial Number: 12703071101. Three specimens from each of the grades listed in Table 1 were tested. The specimen geometry was 8 mm diameter x 10 mm length. The maximum intrusion pressure was 60,000 psi. Pore size distributions were obtained for each of the specimens tested in the pore size range 0.004 -100 μm. Moreover, the skeletal density was determined for each specimen examined.

2.5 X-Ray Diffraction Analysis

Samples of the graphites in Table 1 were subjected to x-ray diffraction (XRD) analysis. The analysis was conducted on solid samples. Data was obtained for the crystal lattice parameters <c> and <a>, and the crystallite size parameters l_c and l_a. In addition to the specimens in Table 1, samples of the HOPG included in AGC-1 were submitted for XRD analysis. XRD was performed using Cu-kα radiation with a wavelength, λ, of 0.154056 nm over an angular range of 10 to 140°. The crystal structure of graphite is illustrated in Fig. 17.

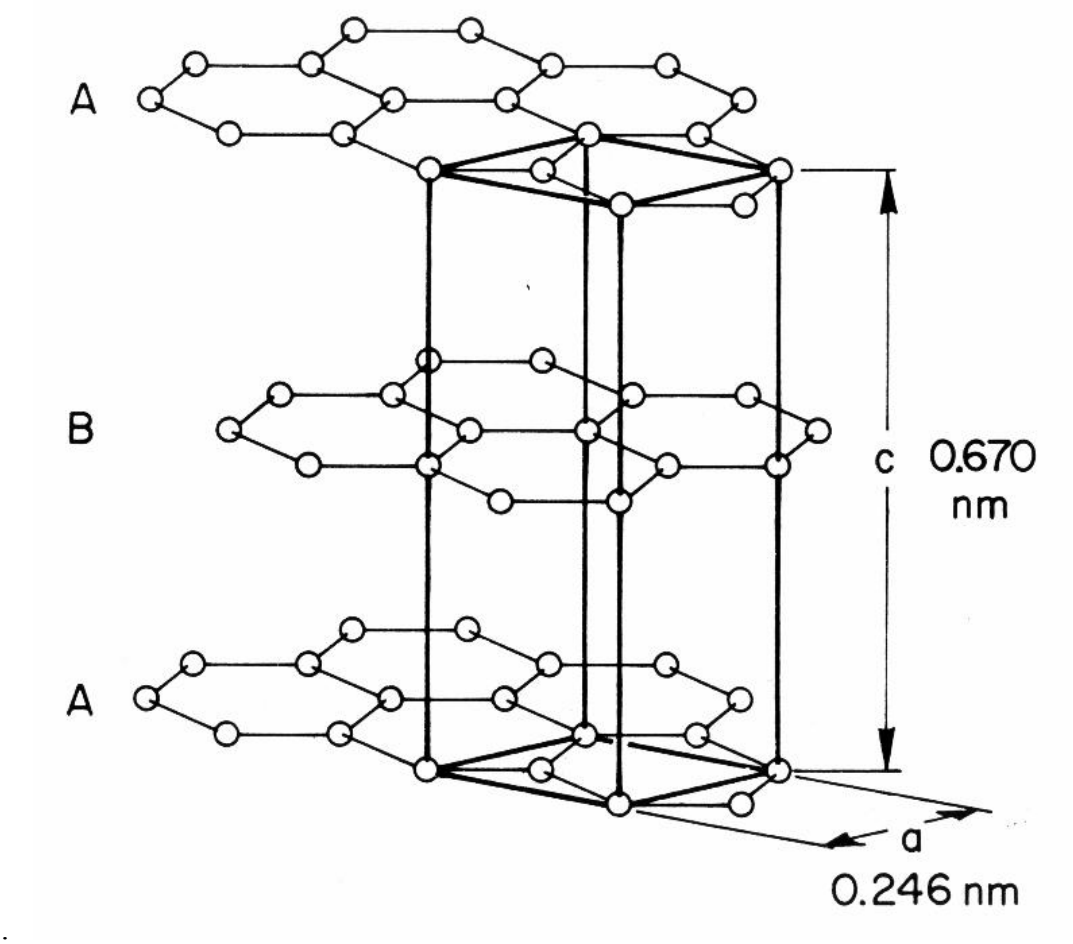

Figure 17. The crystal structure of graphite.

Graphite consists of planar arrays of carbon atoms bound in a hexagonal lattice and stacked in an ABAB... sequence. In a perfect graphite crystal the spacing between adjacent aligned planes, or <c>-spacing, is 0.6708 nm, and the spacing between prismatic edge carbon atoms, or <a>-spacing, is 0.2461 nm (Fig. 17). These crystallographic features give rise to X-ray diffraction according to the Bragg Law which relates the wavelength of the incident X-ray beam (λ) to the interplanar spacing (d) though the Bragg equation:

$$n\lambda = 2d \sin\theta \quad (1)$$

where n is an integer equal to the order of reflection and θ is the angle that the incident and reflected beams form with the plane. The <c> and <a> planes give rise to strong diffraction peaks at $2\theta = 26.603°$ (002) and $2\theta = 77.697°$ (110).

Two further crystallographic parameters were derived from the XRD data, the apparent crystallite sizes (or coherence length), in the <a> and <c> directions. These parameters denoted L_a and L_c for the <a> and <c> directions, respectively, are calculated from the Scherer equation:

$$L = K\lambda / \beta \, Cos\theta \qquad (2)$$

where K is a shape factor equal to 1 for highly graphitic materials and equal to 1.84 for poorly ordered carbons, β is the intrinsic breadth of the diffraction peak (the full width at half maximum or FWHM value of the relevant diffraction peak), and θ is the diffraction angle of the relevant peak. Note that the measured peak width must be corrected to allow for machine line broadening effects. In this work the experimental diffraction pattern was analyzed using "Jade™" software to derive the crystallographic parameters. The mean crystallite thickness, Lc, measured in the <c> direction is usually calculated from the (002) peak, whereas the mean crystallite length, La, measured in the <a> direction is normally measured from the (110) peak. X-ray pole figures were measured on a PTS-tube diffractometer with Cr-radiation.

2.6 Non-destructive Property Measurements

The following additional properties were determined experimentally during this work:

i. Density

Density was determined by mensuration and mass from the thermal conductivity and porosimetry "sister" specimens, and also from the Hg porosimetry measurements.

ii. Dynamic Young's modulus

The elastic (Young's) modulus was determined using the fundamental frequency method in accordance with ASTM method C 747 [8] using a GrindoSonic Mk5, S/N 0620843. The specimens were vibrated in the flexure mode. Each specimen was measured ten times to generate a mean fundamental frequency for calculation of the Young's modulus. Fig. 18 shows the experimental apparatus. During testing the Test/room air temperature 72-77 °F, 49-54% humidity. The Young's modulus is given by ASTM C 1295 [10] as:

$$E = 1.6067\left(\frac{L^3}{D^4}\right)\left(Mf_f^2\right)T_1' \tag{3}$$

where L is the specimen length (mm), D is the specimen diameter (mm), M is the specimen mass (g), f_f is the fundamental frequency in Hz, and T_1' is a geometric factor for rods whose (L/D)<20 and is given by:

$$T_1' = 1 + 4.939(1 + 0.0752\mu + 0.8109\mu^2)(D/L)^2 - 0.4883(D/L)^4 - \left[\frac{4.691(1 + 0.2023\mu + 2.173\mu^2)(D/L)^4}{1.00 + 4.754(1 + 0.1408\mu + 1.536\mu^2)(D/L)^2}\right] \tag{4}$$

where D is the specimen diameter (mm), L is the specimen length (mm), and μ is Poisson's ratio (taken here as 0.1667).

Figure 18. GrindoSonic Mk5 fundamental frequency modulus system

iii. Young's modulus, shear modulus, and Poisson's ratio

Young's modulus, shear modulus, and Poisson's ratio were determined ultrasonically on the compressive strength specimens prior to testing in accordance with C 769 "Standard Test Method for Sonic Velocity in Manufactured Carbon and Graphite Materials for use in obtaining an Approximate Young's Modulus" [9]. Young's modulus (E) was calculated from the velocity

of a longitudinal sound wave and the Shear modulus (G) was calculated from the velocity of a shear sound wave. The velocity was calculated from measurements of the time of flight of a sound wave over a known specimen length. The experimental apparatus is shown in Fig. 19. The ultrasonic probes had a frequency of 2.25 MHz (Table 4).

Figure 19. Ultrasonic velocity determination apparatus

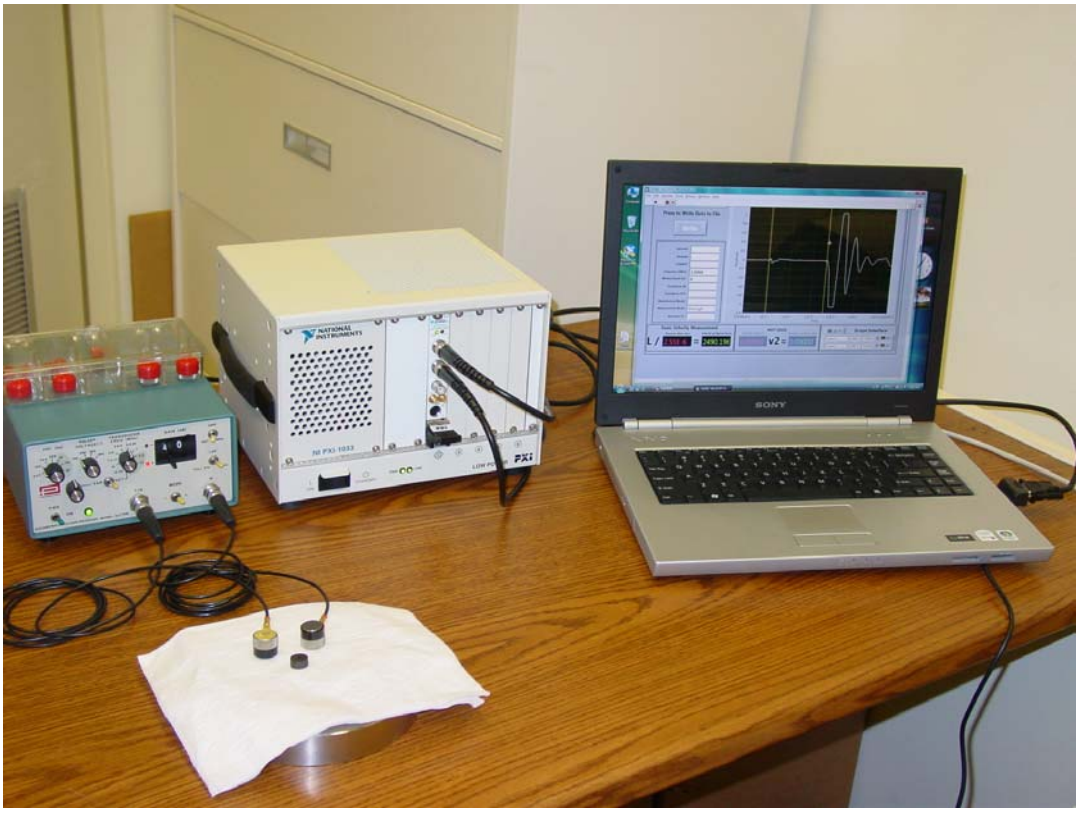

Table 4. Ultrasonic transducer details

Manufacturer	Model	Frequency	Serial No.
Panametrics	V106	2.25 MHz	593888
Panametrics	V106	2.25 MHz	593889
Panametrics	V154	2.25 MHz	589864
Panametrics	V154	2.25 MHz	598869

The experimental apparatus consisted of a Panametrics Squarewave pulser/receiver model 5077PD, S/N 01133702 integrated with a National Instruments Dual Trace Oscilloscope Card, Model PXI-5122, and read with LabView software. The couplant used between the sample and

the probes was ULTRAGEL II by SonoTech. The lab/room air temperature was 72-77 °F, 49-54% humidity.

Elastic Moduli are determined from measurements of sonic velocity (shear and longitudinal). The moduli are calculated from eqs. 5 through 10:

ATSM C769 gives the **approximate** Young's modulus as

$$E = \rho \cdot v^2 \tag{5}$$

where E = Young's Modulus (Pa)
ρ = specimen bulk density (kg/m^3)
v = Longitudinal velocity of sound in the specimen (m/s)

However, Young's Modulus may be more precisely calculated for anisotropic materials from

$$E = \rho \cdot v^2 \cdot [(1+\mu)(1-2\mu)/(1-\mu)] \tag{6}$$

where E = Young's Modulus (Pa)
ρ = specimen bulk density (kg/m^3)
v = Longitudinal velocity of sound in the specimen (m/s), and
μ = Poisson's ratio.

Since Poisson's ratio is unknown for each of these materials it must first be calculated from:

$$\mu = \frac{1 - \left[2(V_s / V_l)^2\right]}{2 - \left[2(V_s / V_l)^2\right]} \tag{7}$$

where v_s and v_l are the measured shear and longitudinal velocities (m/s) respectively.

Shear modulus, G, is calculated from:

$$G = (v_s)^2 \cdot \rho \tag{8}$$

where v_s is the measured shear velocity (m/s) and ρ is the specimen bulk density (kg/m^3).

Given E and G, μ may also be calculated from the relationship (for isotropic materials only)

$$E = 2G(1+ \mu) \tag{9}$$

The specimen size should be sufficiently large compared to the wavelength of sound in the material.

The wavelength (m) is given by

$$\lambda = c/f \tag{10}$$

where c is the velocity of sound in graphite (~2600 m/s) and f is the frequency of the sound wave. Thus a 2.25 MHz probe would produce a sound wave with a wavelength of 1.16 mm. In previous graphite irradiation experiments we have found that cylindrical specimens as small as 6 mm thickness can satisfactorily be tested to determine the velocities and hence elastic constants. Typically, the shear wave velocity is measured with the probes in two orientations, 0° and rotated 90° on the same face of the specimen, and the two values averaged to calculate the elastic constants.

2.7 Specific Heat Measurements

The specific heat of graphite was measured using a Netzsch Differential Scanning Calorimeter (DSC) 404C instrument over the temperature range 140 to 1220°C at heating/cooling rate of 20°C/min, using a Ti-gettered argon atmosphere. The instrument was calibrated using a Molybdenum standard. Fig. 20 shows the instrument calibration data for the Molybdenum standard. Only grade NBG-18 was subjected to testing and the data taken as representative of all the graphite grades.

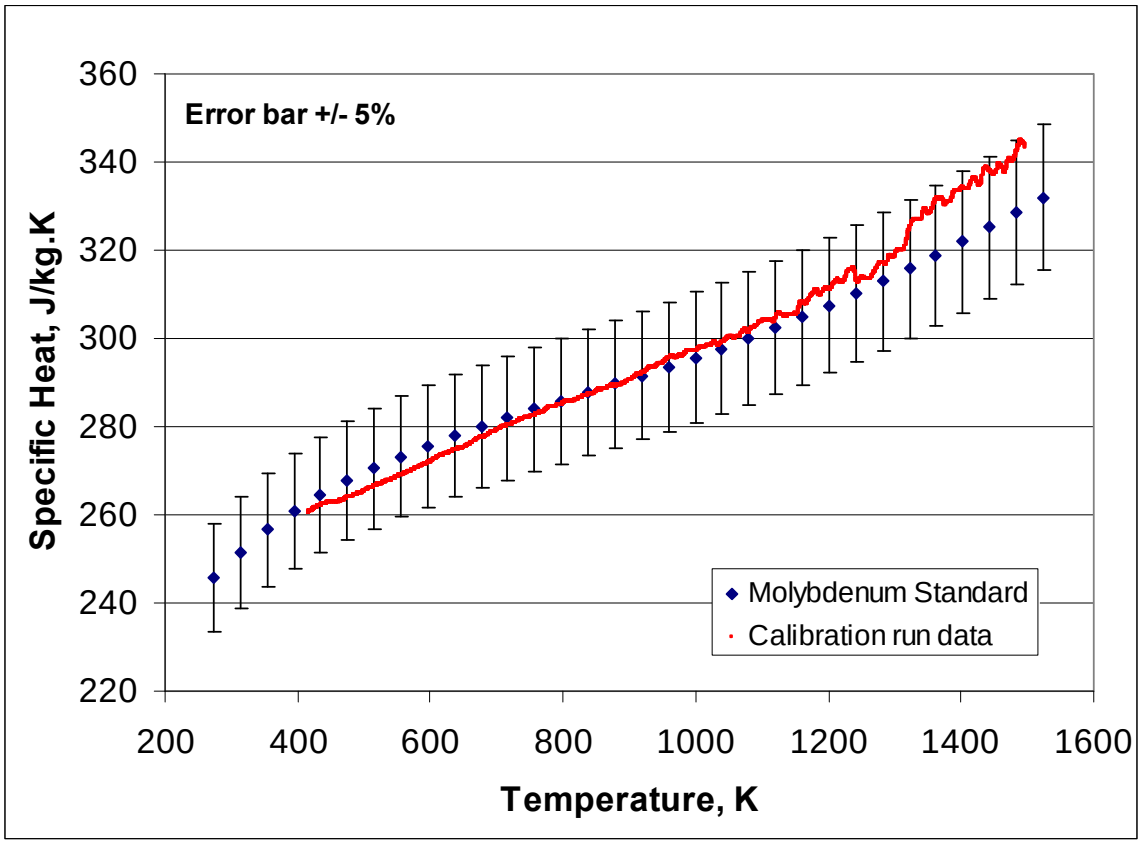

Figure 20. Molybdenum calibration data for the Netzsch DSC 404C instrument

2.8 Elevated Temperature Thermal Conductivity

Thermal diffusivity measurements were conducted on samples of the major grades. The specimen dimensions were 12 mm diameter with thickness 3 mm. Measurements were made on an Anter FlashLine 3000 Xenon lamp flash diffusivity measurement system over the temperature range 25-900°C. The Clark and Taylor model was used to calculate the diffusivity for the signal half-rise time. A total of 27 specimens were measured, 3 per major grade, in the WG and AG orientations (for NBG-17, NBG-18, and PCEA only).

Fig. 21 shows the experimental apparatus. Testing was conducted in accordance with the method prescribed in C 781 Appendix 6 [6]. The thermal conductivity was calculated from:

$$\lambda = \alpha \cdot C_p \cdot \rho \tag{11}$$

where:
λ = thermal conductivity, W.m/K,
α = diffusivity, m^2/s,
C_p = specific heat, J/kg.K, and
ρ = density, kg/m^3

Specific heat was calculated from the equation provided in ASTM C 781 (2008) Appendix 6, where the Specific heat, C_p (J/kg.K) is given as:

$$C_p = \frac{1}{11.07T^{-1.644} + 0.0003688T^{0.02191}} \tag{12}$$

where T is the temperature in Kelvin.

Figure 21. Anter FlashLine 3000 Xenon-lamp thermal diffusivity measurement system

2.9 Static Young's modulus and tensile strain to failure

Static Young's modulus and tensile strain to failure was determined from the tensile tests in accordance with C-749 [5] and C-781 [6] (see section 2.2). The elastic modulus was determined at a strain of 0.05%. C-749 [5] defines the strain to failure as the strain at the maximum stress (were failure occurs).

2.10 Compressive modulus and strain to failure.

Compressive elastic modulus was determined from the initial portion of the compressive stress-strain curve (see section 2.3), and the strain to failure was taken as the strain at the maximum compressive stress.

3. Results and Discussion

3.1 Uniaxial Tensile Strength

The mean uniaxial strengths of the grades tested here are summarized in Table 5, and are shown graphically as a bar chart in Fig. 22. The tensile strength data for each grade are given in Appendices 1-6. The glued end specimen (Fig. 12) resembles a shaft with a shoulder at each end and the equivalent fillet radius is quite small. However, according to Peterson [12] the stress concentration at the shoulder could to be > 2. Consequently tensile failure of the graphite is likely to occur close to the shoulders. Failures nearer the center of the specimen length would be governed by grain size and pore size distribution, i.e., fine structured graphites might be expected to fail under the influence of the stress concentration, whereas coarser structured graphites might not. All failures for the fine grain isotropic graphites occurred near the shoulder of the specimen (as suggested earlier). The tensile strengths of the Toyo Tanso isotropic graphites (IG-110 and IG-430) were around a factor of 2 lower than published values (24.5 and 37.0 MPa, respectively). The coarser structured grades (H-451 and NBG-18) exhibited failures away from the glued joints.

Table 5. Summary of tensile strength data for the major grades examined here

Graphite Grade	Grain Orientation		Tensile Strength MPa	Standard Deviation MPa	Number of Specimens	No. of Failures >3.5 mm from shoulder
	With (wg)	Against (ag)				
NBG-17 (wg)	x		17.79	2.51	12	1
NBG-17(ag)		x	17.12	2.13	12	1
NBG-18 (wg)	x		18.27	2.49	12	4
NBG-18 (ag)		x	19.16	2.75	12	6
H-451	x		12.09	2.04	12	9
PCEA (wg)	x		18.46	2.59	12	1
PCEA (ag)		x	17.04	1.91	12	1
IG-110	Isotropic		14.90	1.08	12	0
IG-430	Isotropic		19.44	1.72	12	0

From the standard deviations determined for the test results of the various graphites, it appears that the glued-end specimen can be useful in qualifying the tensile strengths of graphite, as well

as effects of irradiation on tensile strength. However, the tensile data given here should not be used for design purposes because of the unavoidable stress

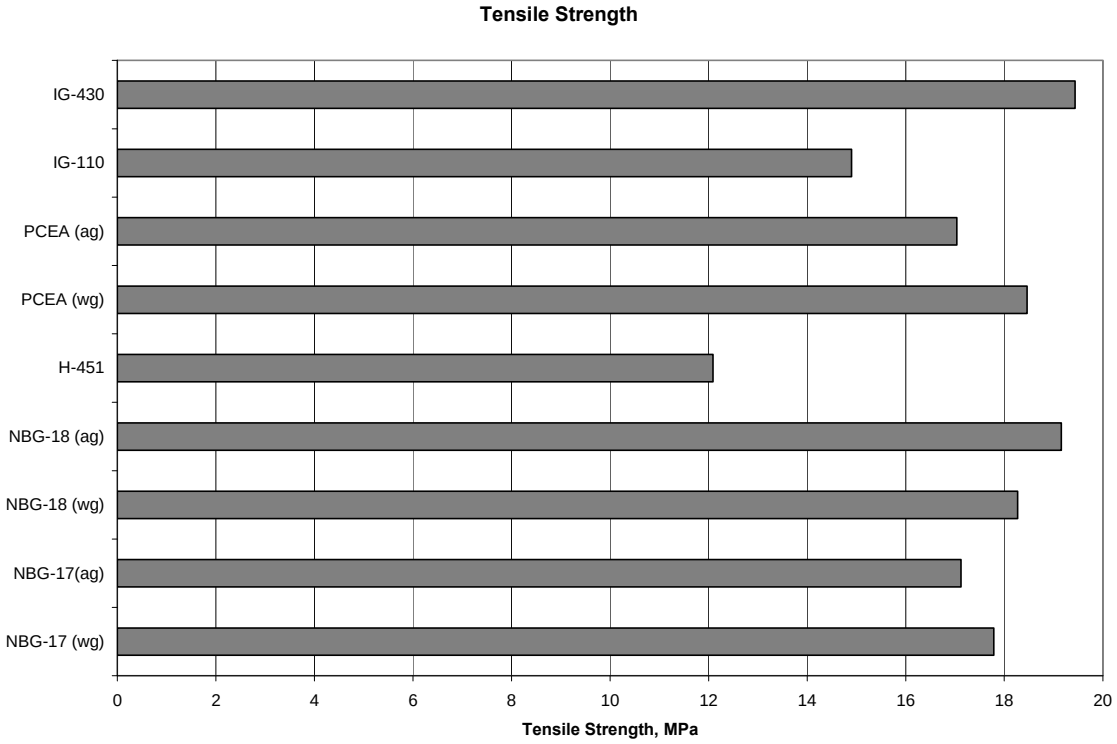

Figure 22. A comparison bar chart of the tensile strengths of the major grades examined here

concentration near the glued on adaptors. It would appear prudent to conduct an additional study of strength/geometry factors, perhaps using the ASTM specimen geometry (designed to fail in the uniform gage section away from stress concentrators) and the sister specimens, which should provide some insight as to the magnitude of the stress concentration, and perhaps suggest a reasonable correction factor considering the mechanical/geometric stress concentration as well as the graphite structure (grain size and pore distribution).

Stress-strain curves are given in Figs. 23-31. Based upon the data in Table 5 Grades H-451, IG-430 and IG-110 would not meet that ASTM D-7219 (2008) required minimum strength of 15 MPa for extruded grades and 22 MPa for isostatically pressed grades. However, for the reasons discussed above the absolute magnitudes of the strengths measured may not be accurate.

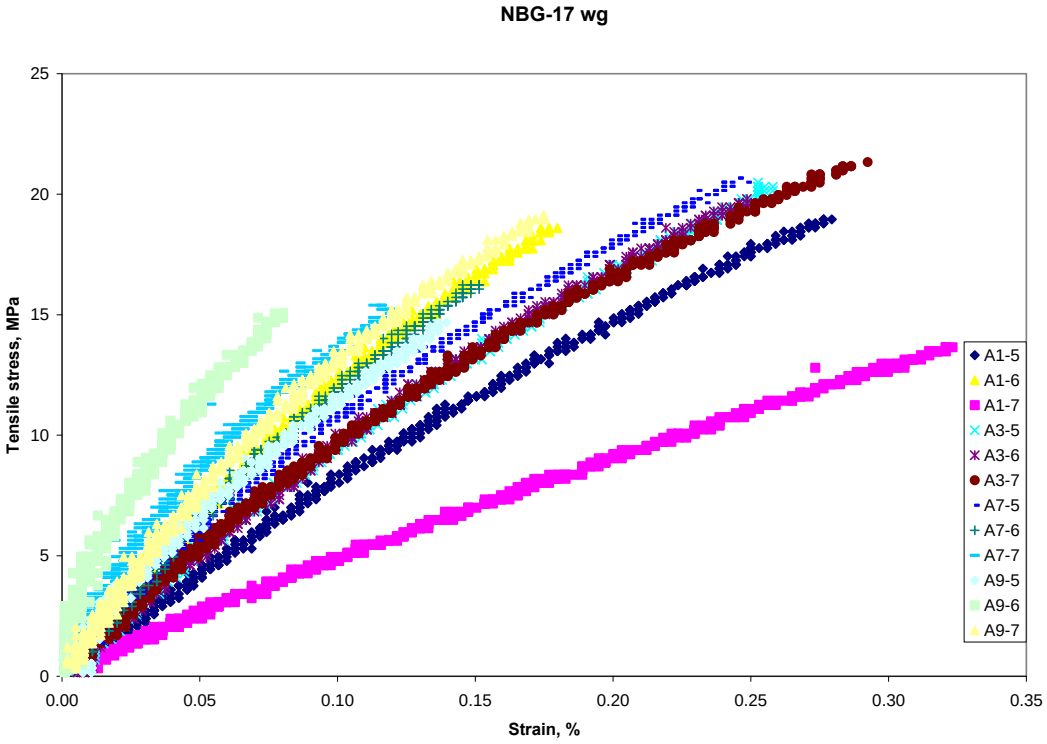

Figure 23. Tensile stress-strain curves for graphite grade NBG17 (with-grain)

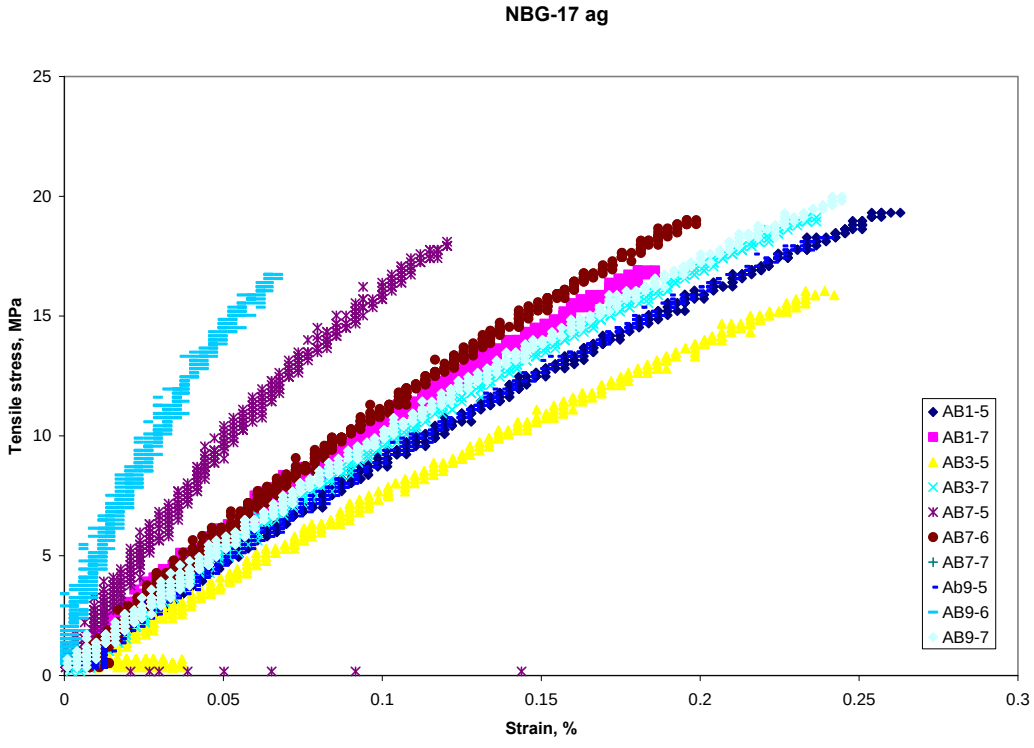

Figure 24. Tensile stress-strain curves for graphite grade NBG17 (against-grain)

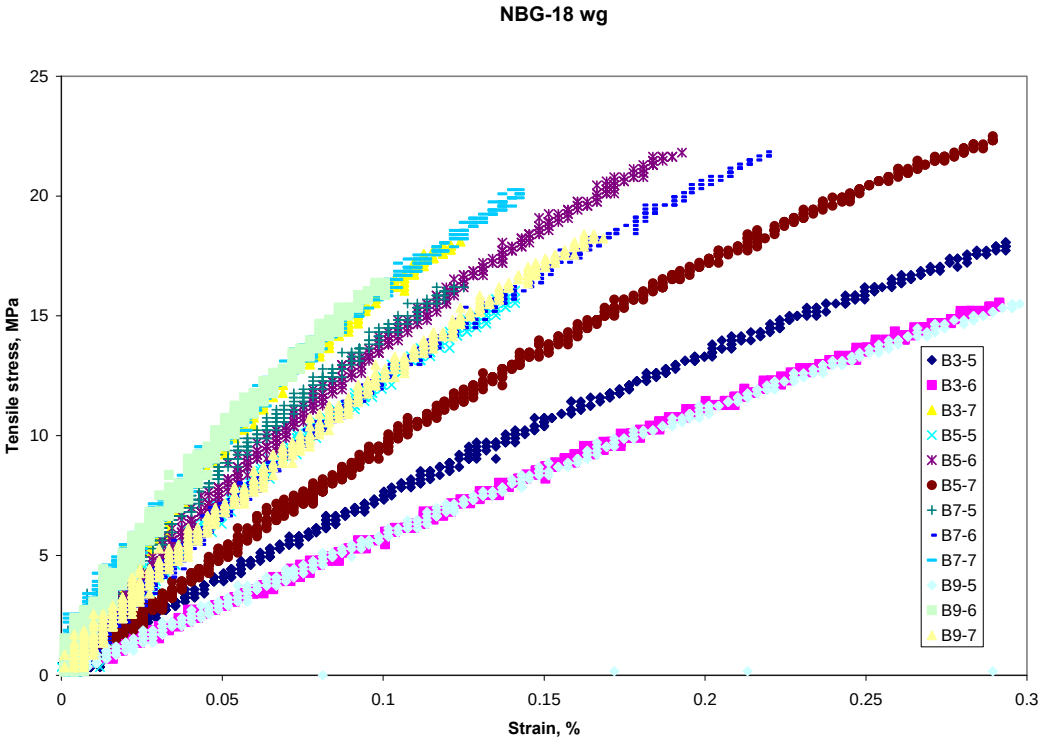

Figure 25. Tensile stress-strain curves for graphite grade NBG18 (with-grain)

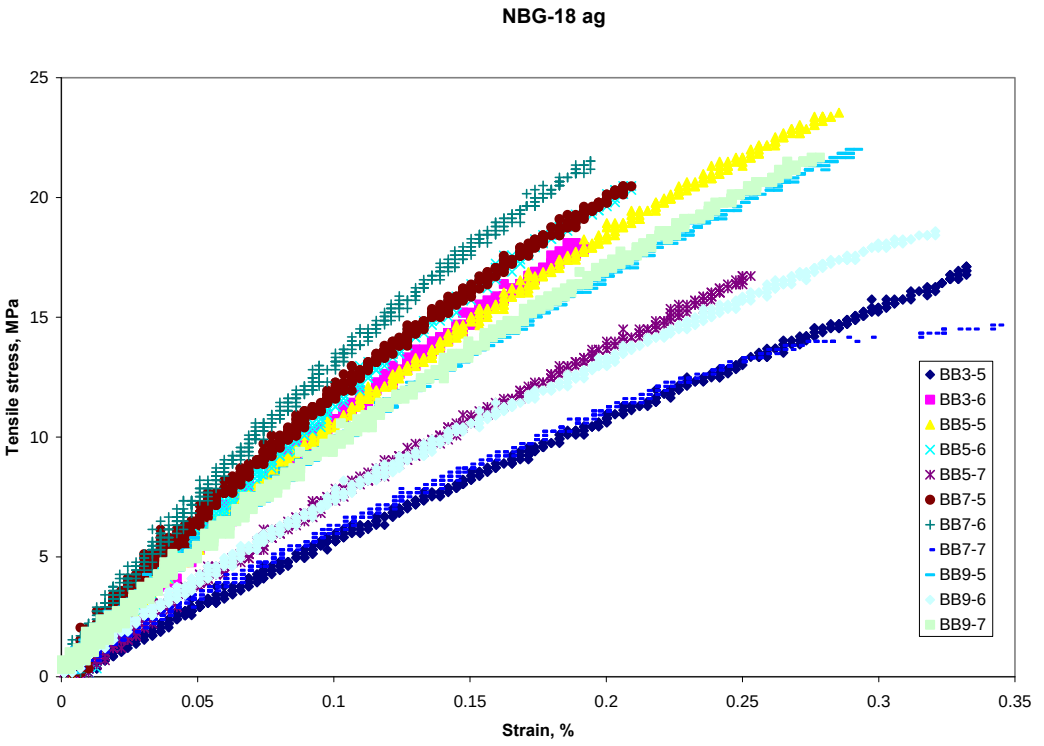

Figure 26. Tensile stress-strain curves for graphite grade NBG18 (against-grain)

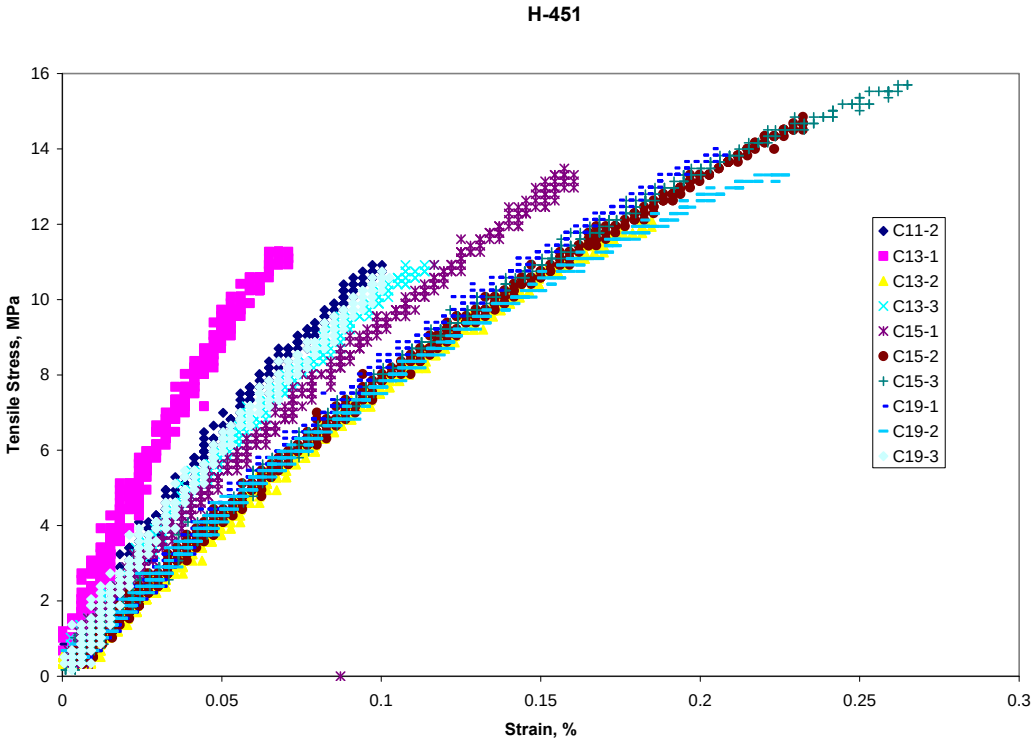

Figure 27. Tensile stress-strain curves for graphite grade H-451 (with-grain)

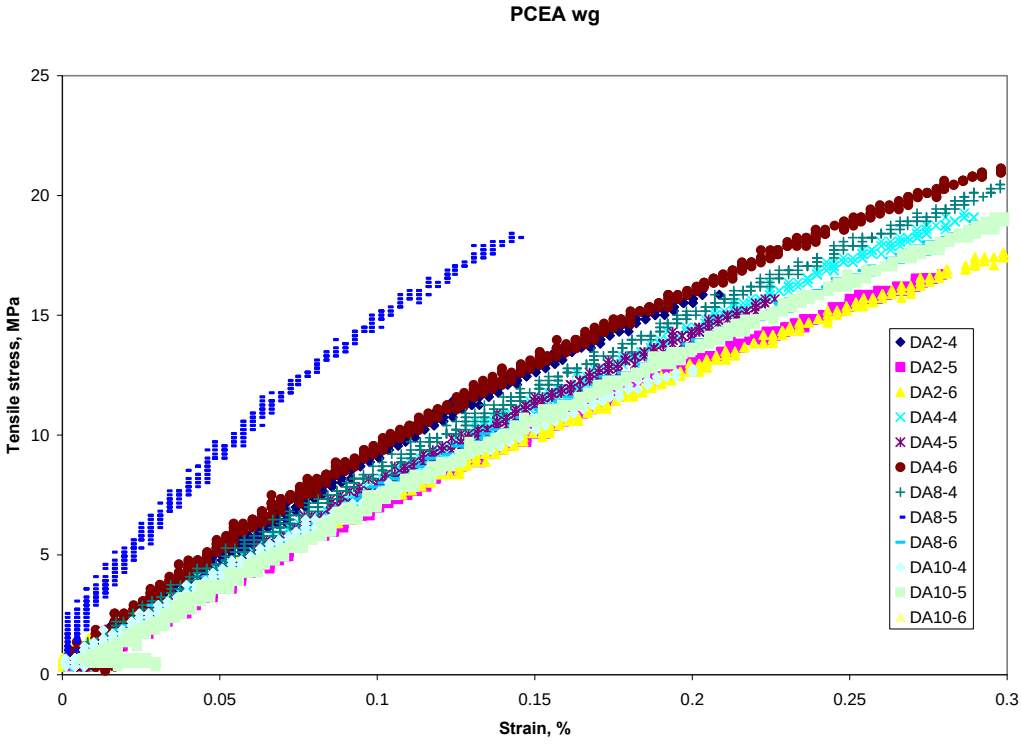

Figure 28. Tensile stress-strain curves for graphite grade PCEA (with-grain)

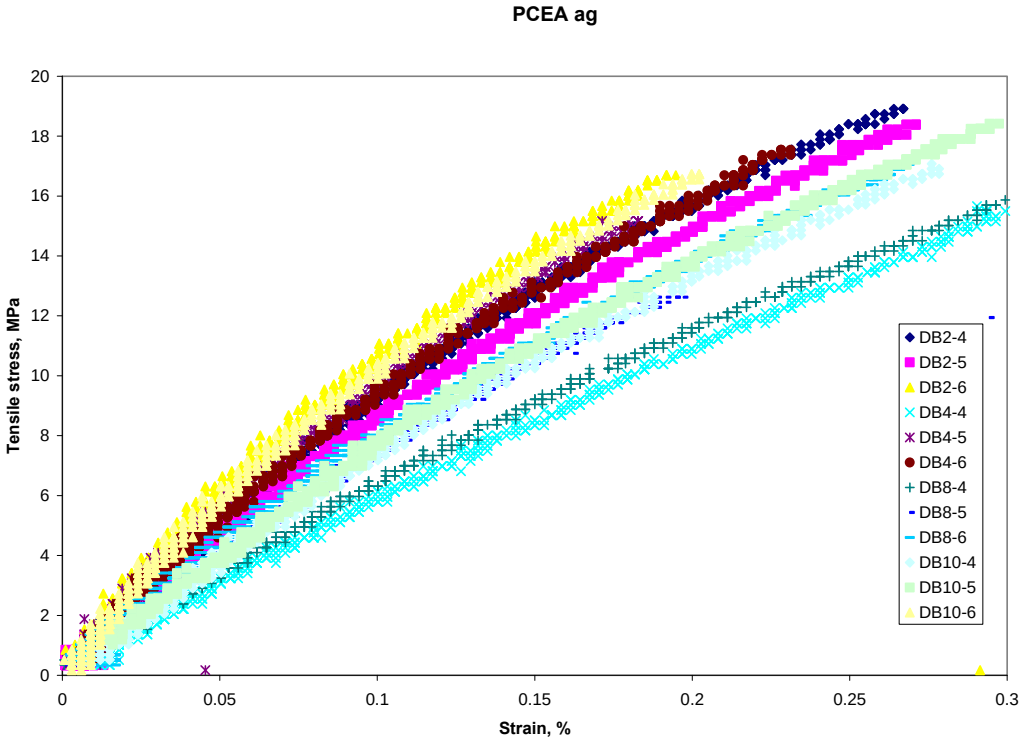

Figure 29. Tensile stress-strain curves for graphite grade PCEA (against-grain)

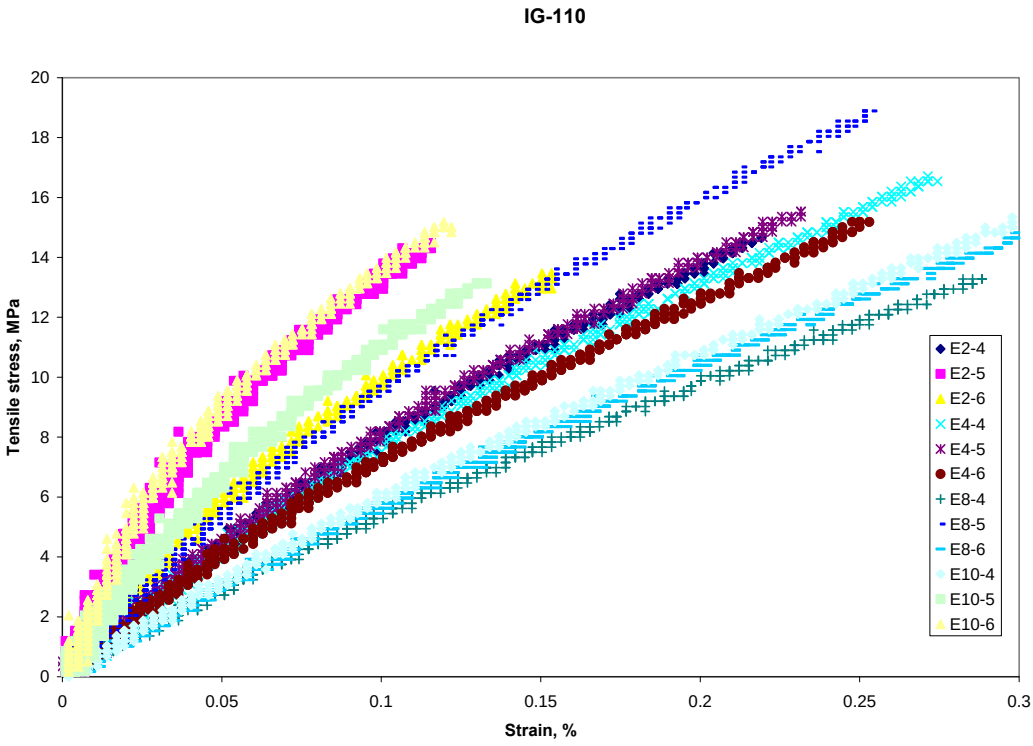

Figure 30. Tensile stress-strain curves for graphite grade IG-110

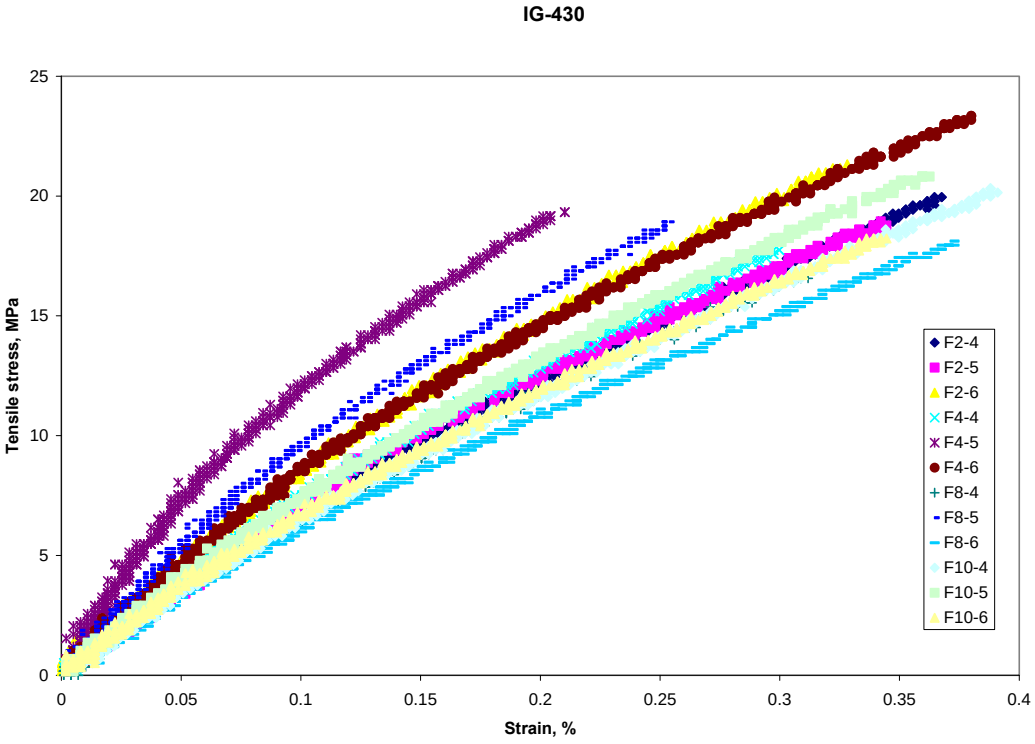

Figure 31. Tensile stress-strain curves for graphite grade IG-430

3.2. Compressive Strength

The dimensions, mass, and density of the compression specimens are given in Appendices 7 –15 for the major grades examined here. Fig. 32 shows the locations the specimens where the dimensions were taken. The measuring scheme adopted was identical to the one used on the AGC-1 capsule specimens. Considerable care was taken over these dimensions so as to render and accurate specimen volume for the determination of density, a physical property that is required for the non-destructive property determinations discussed subsequently.

The mean compressive strengths of the major grades are reported in Table 6. The individual strength data are reported in appendices 16-21. The mean strengths are compared in the bar chart in Fig. 33. The NBG grades exhibited the greatest compressive strengths, probably because of their greater density (section 3.4.1). The fine-grain isotropic grades IG-110 and IG-430 also exhibit high compressive strengths, which is attributable to their fine grain structure and small pore sizes. The grades PCEA and H-451 exhibit the lowest compressive strengths.

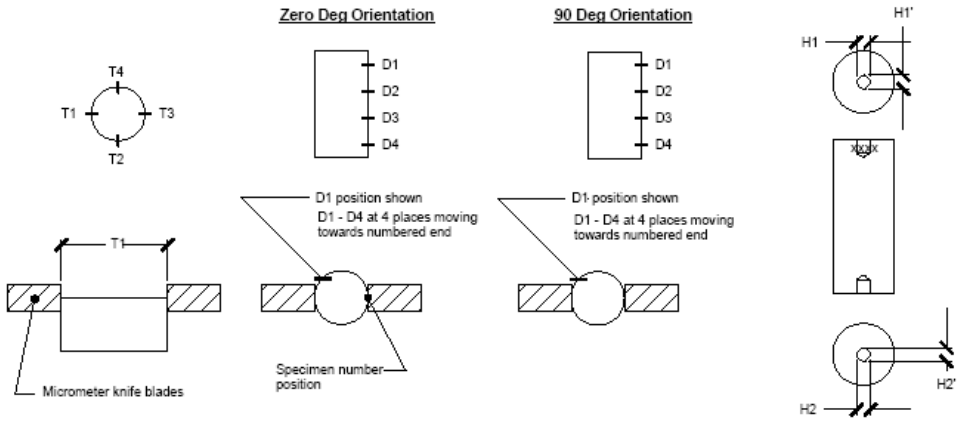

Figure 32. Measurement locations on the compression specimens

Table 6. Summary of compressive strength data for the major grades examined here

Graphite Grade	Grain Orientation		Compression Strength MPa	Standard Deviation MPa	Number of Specimens
	With (WG)	Against (AG)			
NBG-17 (WG)	X		80.97	1.32	12
NBG-17 (AG)		X	80.76	1.18	12
NBG-18 (WG)	X		80.54	2.17	12
NBG-18 (AG)		X	79.28	5.21	12
H-451	X		44.06	3.89	12
PCEA (WG)	X		57.94	3.61	12
PCEA (AG)		X	61.56	1.55	12
IG-110	Isotropic		73.44	2.41	12
IG-430	Isotropic		79.86	1.94	12

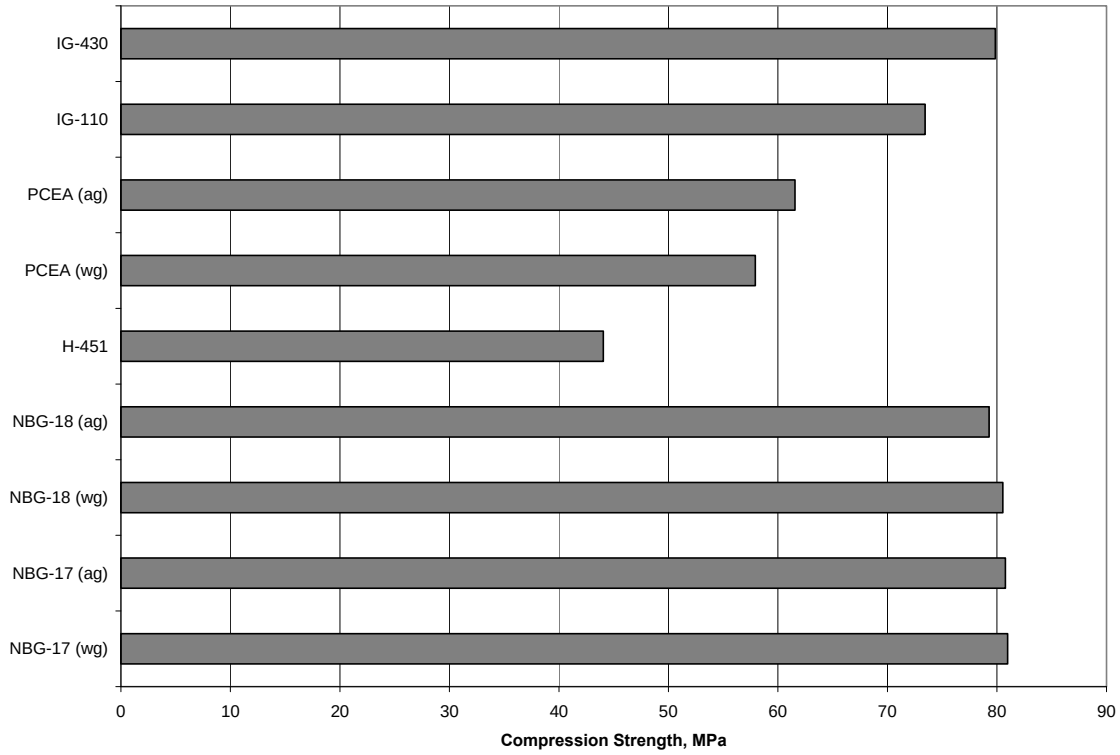

Figure 33. A comparison of the compressive strengths of the major grades examined here

Typical compressive stress-strain plots for the major grades examined here are shown in Figs. 34-42. The grades all exhibit the same behavior with a diminishing modulus with increasing stress. The compressive strains to failure varied from ~1.5% to ~3.5%, with grade H-451 exhibiting the lowest strain to failure and IG-430 exhibiting the greatest strain to failure.

The weakest of the graphites, H-451, exhibited a mean compressive strength (σ_c) of ~44 MPa. The specimens in the AGC-1 capsule will experience a compressive stress (σ_{app}) of 2, 2.5, or 3 ksi (13.8, 17.25, and 20.7 MPa). Consequently, the H-451 specimens will be stressed at < ½ their compressive strength during the experiment. For the other (stronger) grades, the ratio (σ_{app}/σ_c) is even smaller, i.e., ⅓ to ¼ . ASTM D 7219 [11] requires a minimum compressive strength of 45 MPa for extruded and molded grades and 65 MPa for isostatically pressed grades. Based upon the data reported here, only H-451 does not meet the specified requirement.

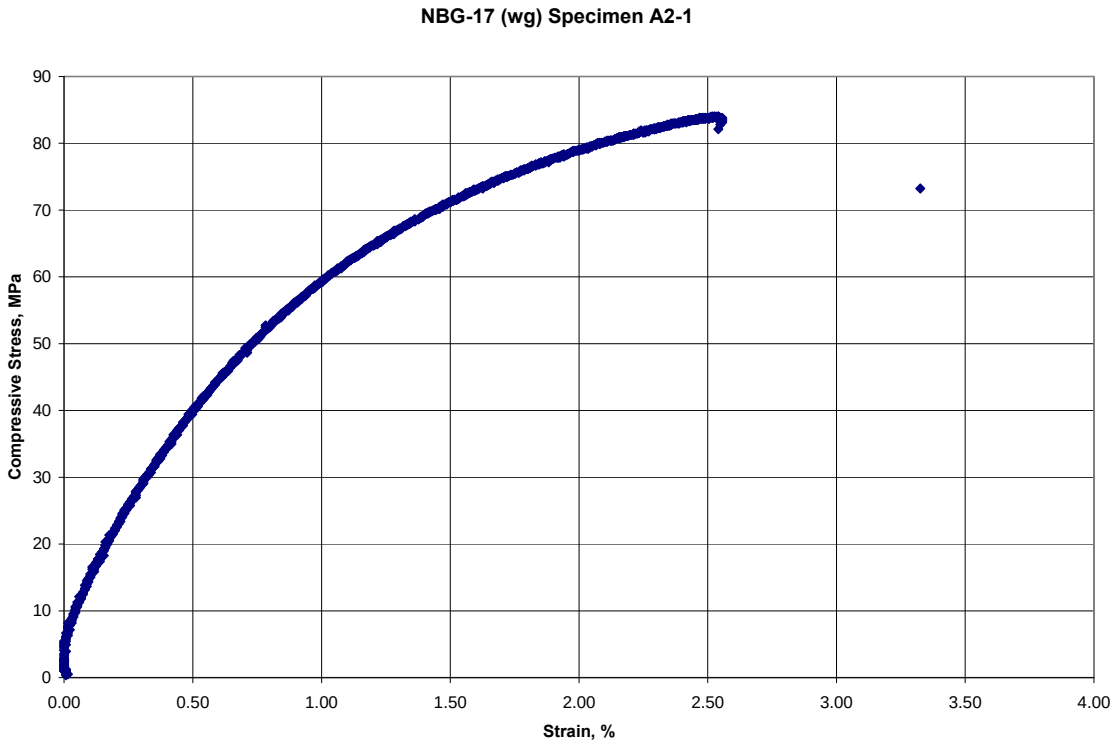

Figure 34. A typical compressive stress-strain curve for grade NBG-17 (WG)

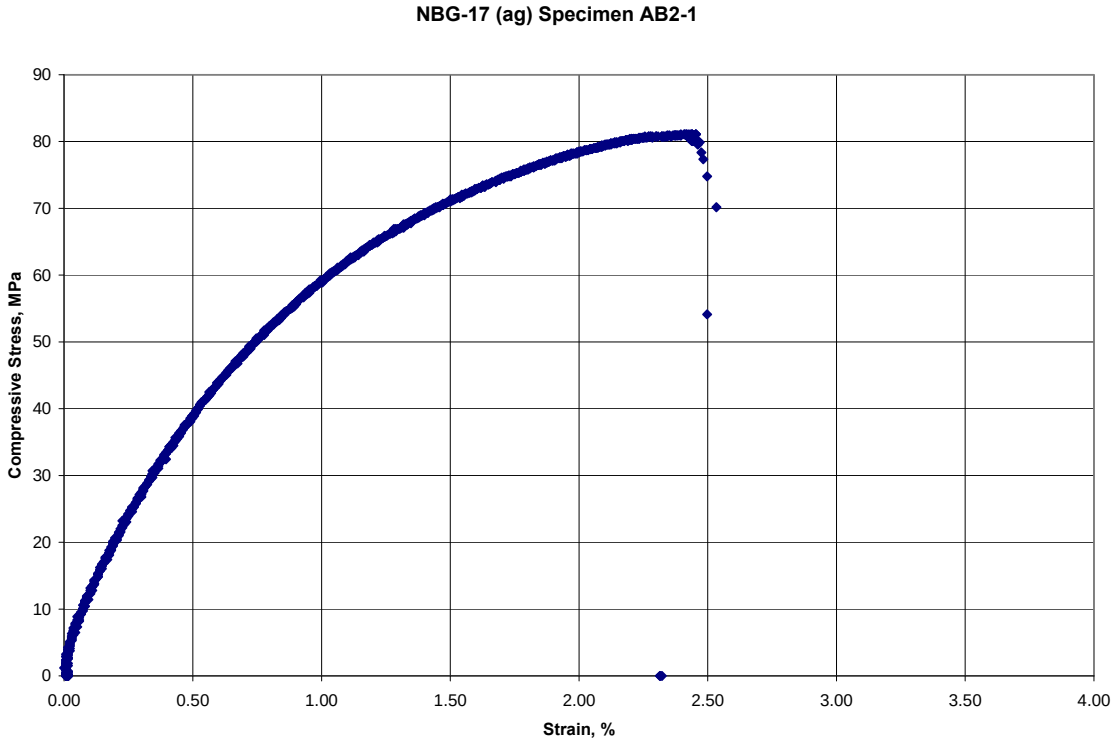

Figure 35. A typical compressive stress-strain curve for grade NBG-17 (AG)

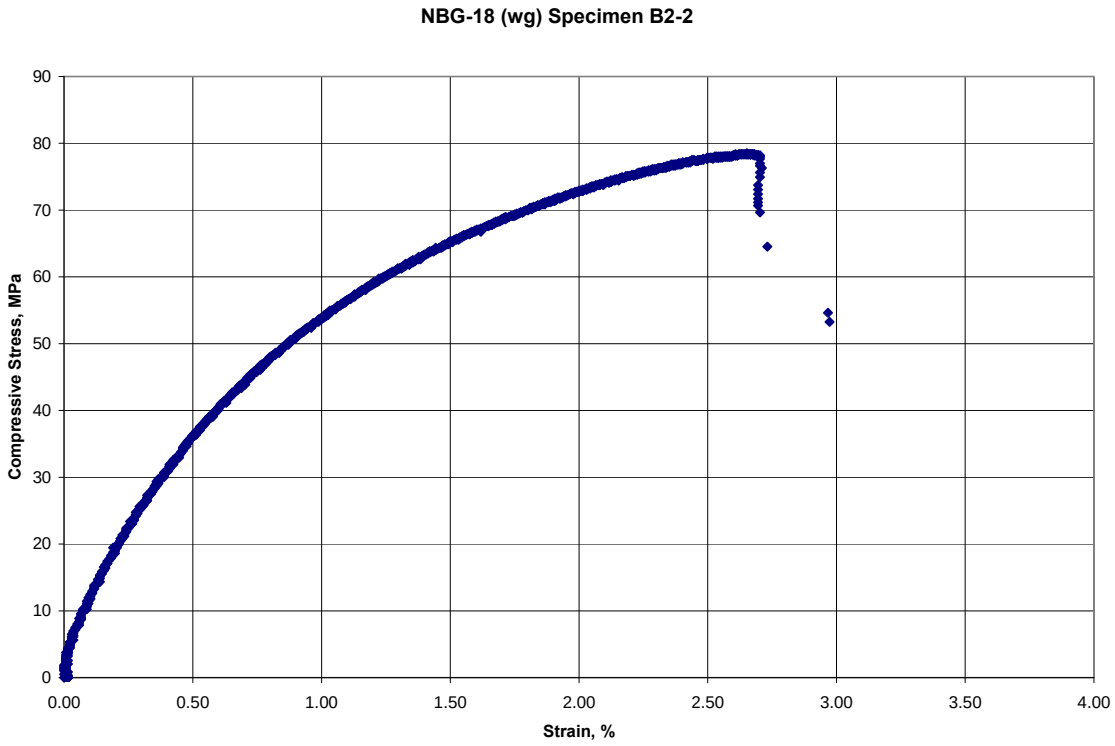

Figure 36. A typical compressive stress-strain curve for grade NBG-18 (WG)

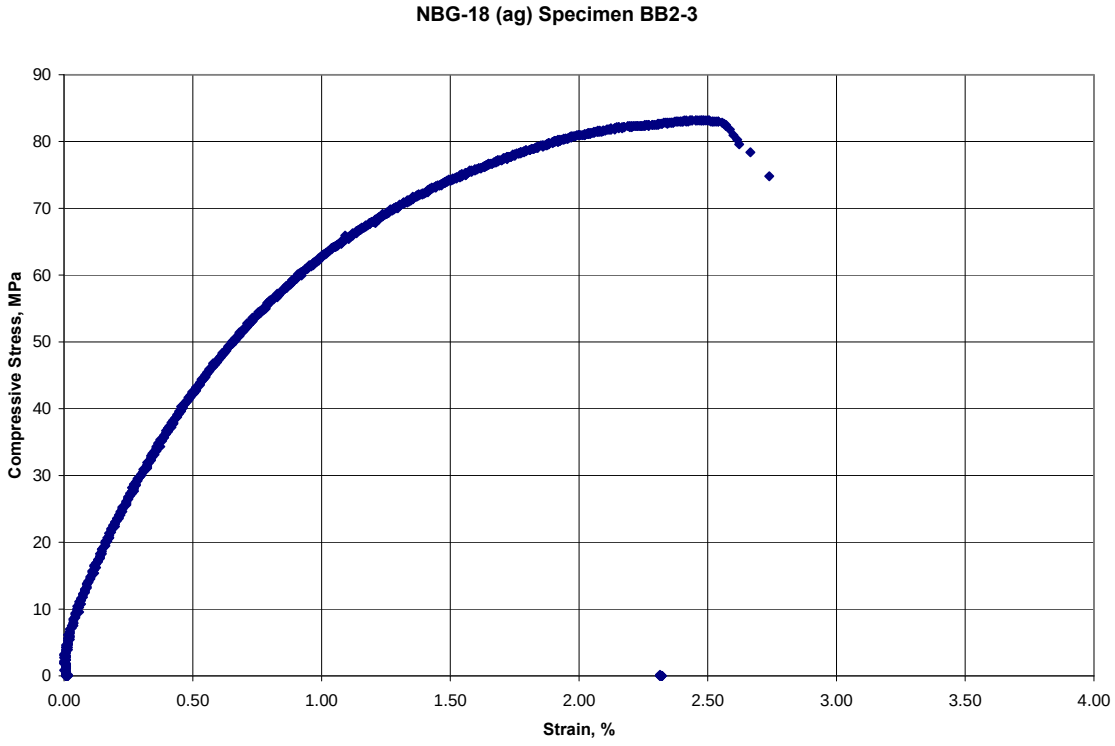

Figure 37. A typical compressive stress-strain curve for grade NBG-18 (AG)

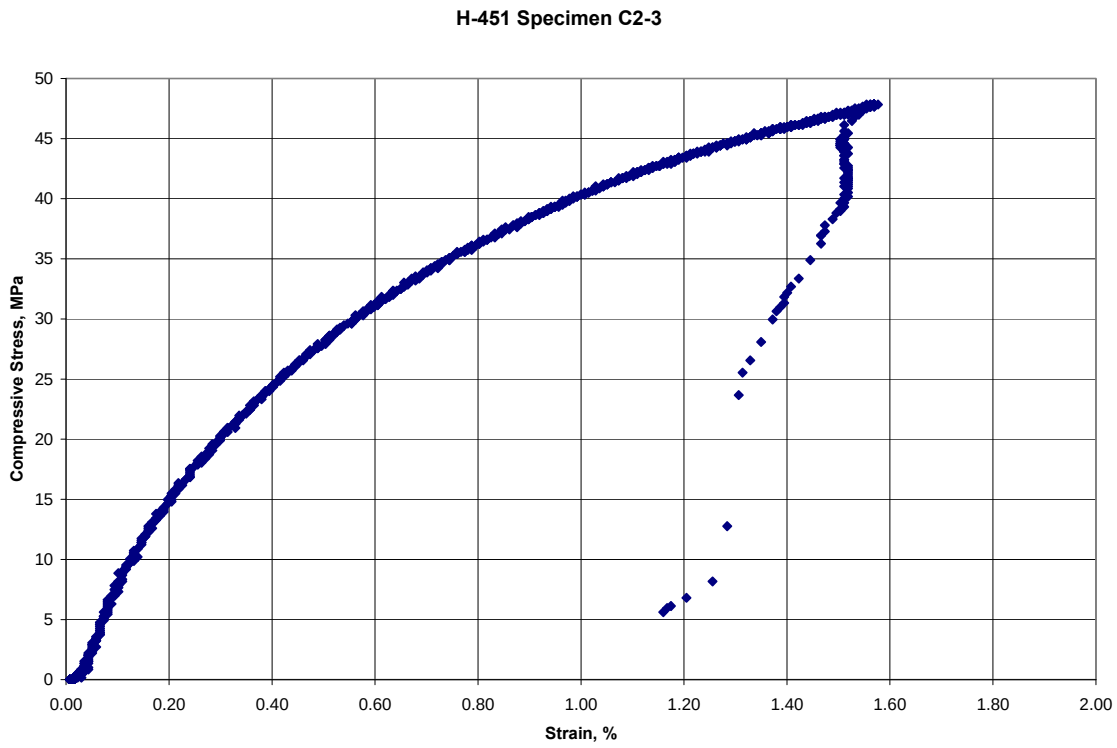

Figure 38. A typical compressive stress-strain curve for grade H-451 (WG)

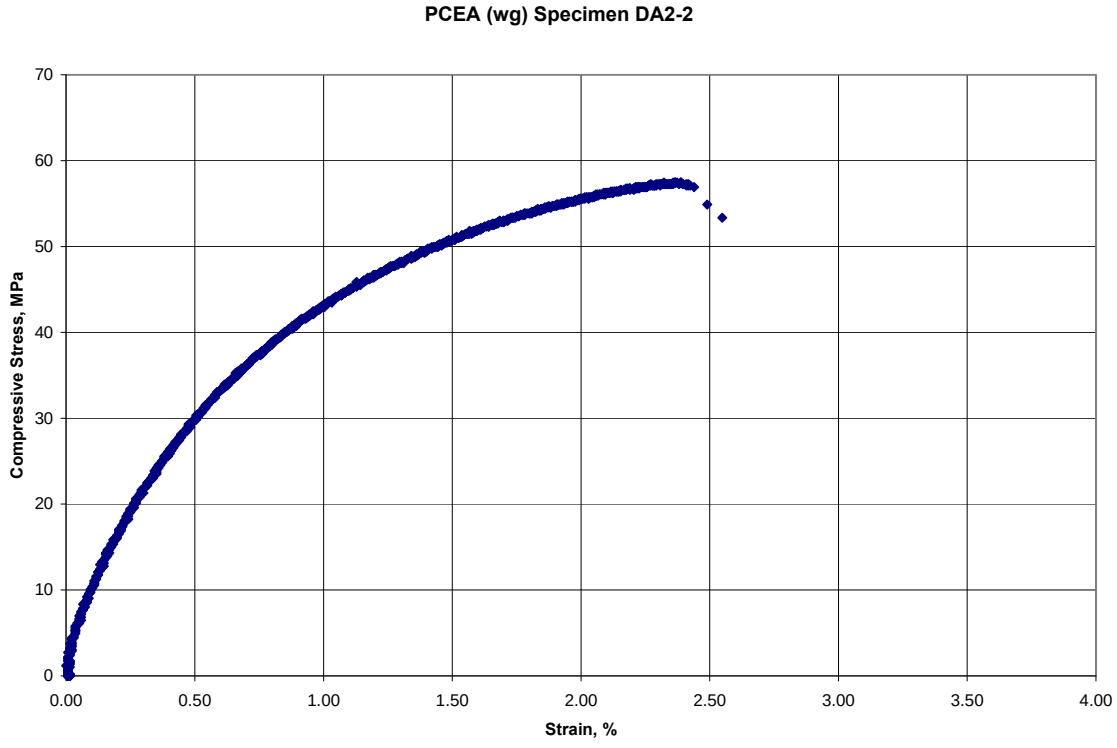

Figure 39. A typical compressive stress-strain curve for grade PCEA (WG)

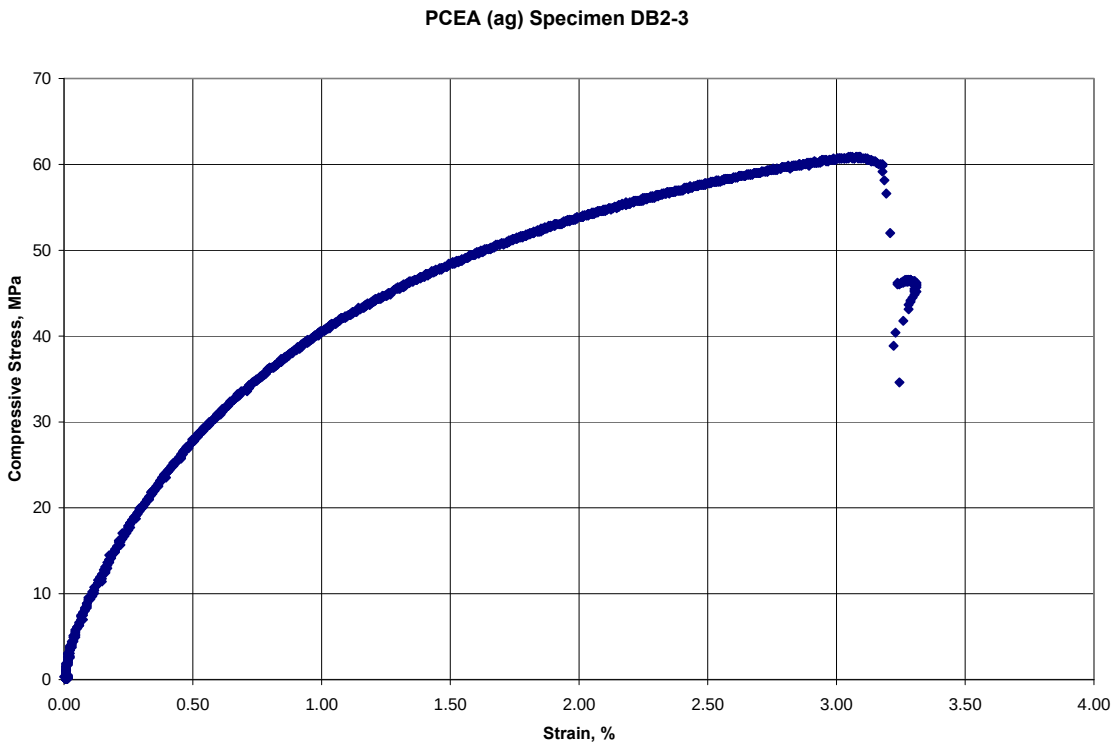

Figure 40. A typical compressive stress-strain curve for grade PCEA (AG)

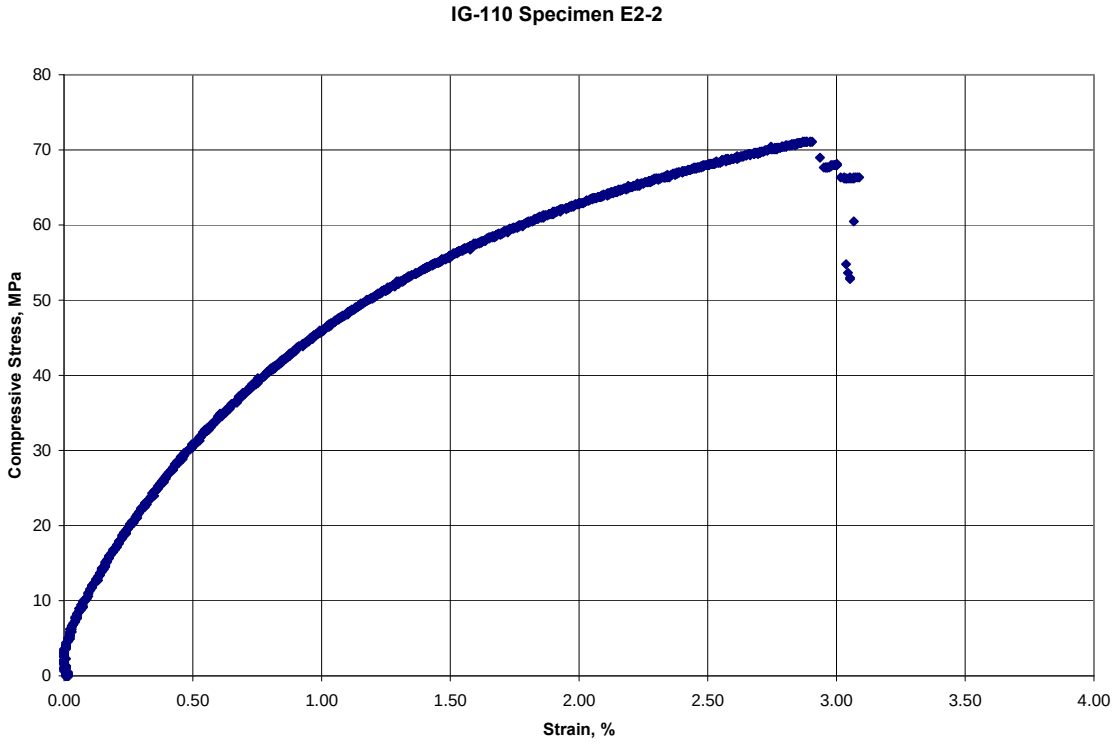

Figure 41. A typical compressive stress-strain curve for grade IG-110

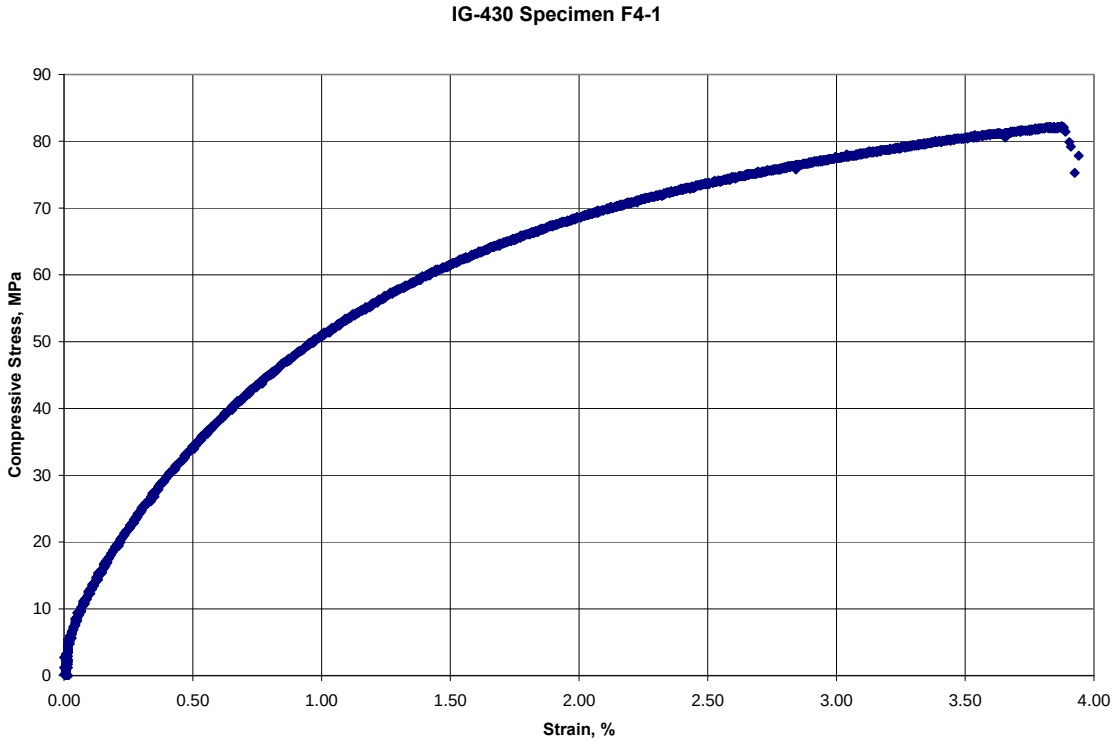

Figure 42. A typical compressive stress-strain curve for grade IG-430

3.3 Pore Structure Characterization

During neutron irradiation the pore structure of graphite undergoes tremendous changes. Cracks that develop between the crystal basal planes due to anisotropic thermal contraction are closed by c-axis swelling. Gas entrapment porosity (formed during baking) changes shape, and anisotropic crystal strains create new cracks in the structure. There is growing evidence that irradiation creep also effects the development of porosity in graphite that is undergoing irradiation induced dimensional change. Consequently, quantitative measures of pore size are of considerable interest for pre- and post-irradiated specimens that have (or have not) been irradiated under stress, i.e., experienced creep strain.

Mercury intrusion analysis measures the pore diameter assuming capillary uptake in pores. However, if the pores are reentrant (i.e., ink bottle shaped) the diameter determined will be that of the pore opening and not its larger (true) diameter. Moreover, only open (accessible pores are measured). The dimensions, mass, and bulk density of the samples are reported in Appendix 22. Fig. 43 shows a bar chart of the pore size ranges for H-451 graphite. The bi-modal nature of the pore size distribution is revealed. Fig. 44 shows the pore size data plotted in a somewhat different format, where the percentage of the accessible porosity greater than a given size is plotted as a function of the pore size (μm). Again the bi-modal nature of the pore size distribution is discernable for the data in Fig. 44. A similar data plot is given in Fig. 45 for grade PCEA, and indicates that PCEA and H-451 have similar pore structures. Both grades are extruded, medium –grained, petroleum coke graphite. From Figs. 44 and 45 the >50% values for H-451 and PCEA are 0.2 μm and 0.1 μm, respectively. Fig. 46 shows the pore size distribution for grade IG-110, a fine-grained, isostatically pressed, petroleum coke graphite. In contrast, the IG-110 pore structure is significantly finer that H-451 and PCEA, and the IG-110 pore size distribution is uni-modal. The >50% pore size for IG-110 is 0.02 μm, an order of magnitude smaller than PCEA or H-451.

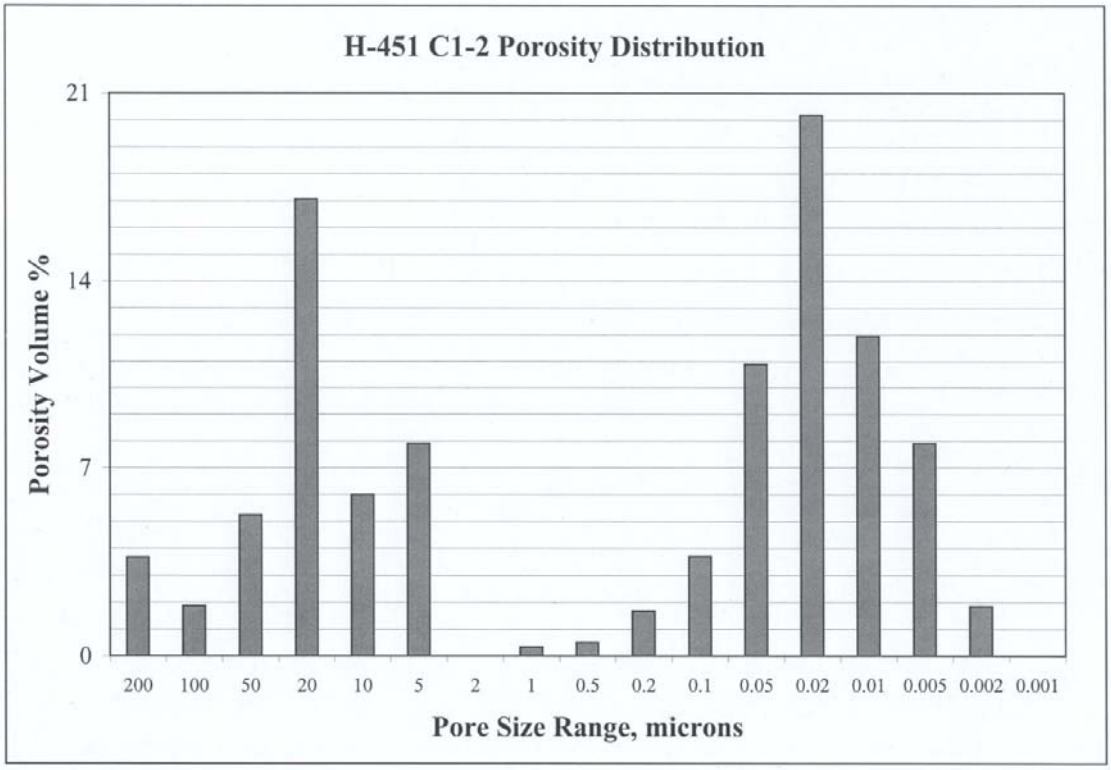

Figure 43. Pore size distribution of H-451 graphite indicating the bi-modal nature of the distribution

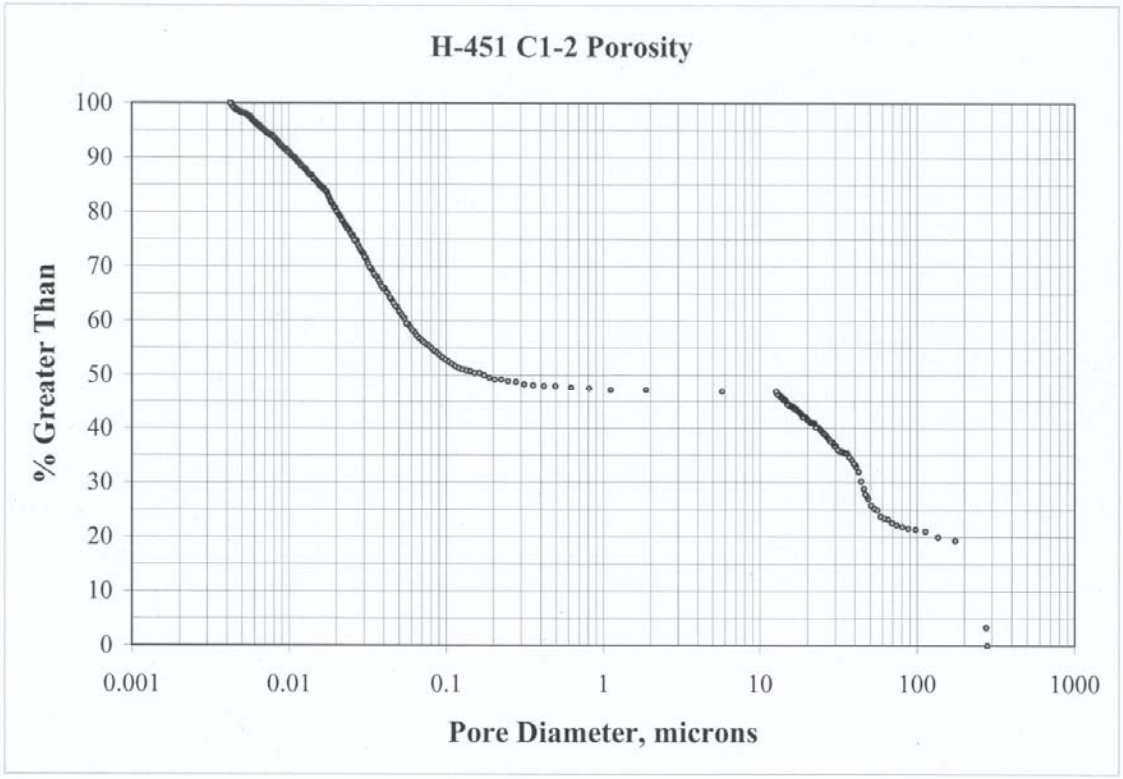

Figure 44. Cumulative pore size distribution for grade H-451 graphite

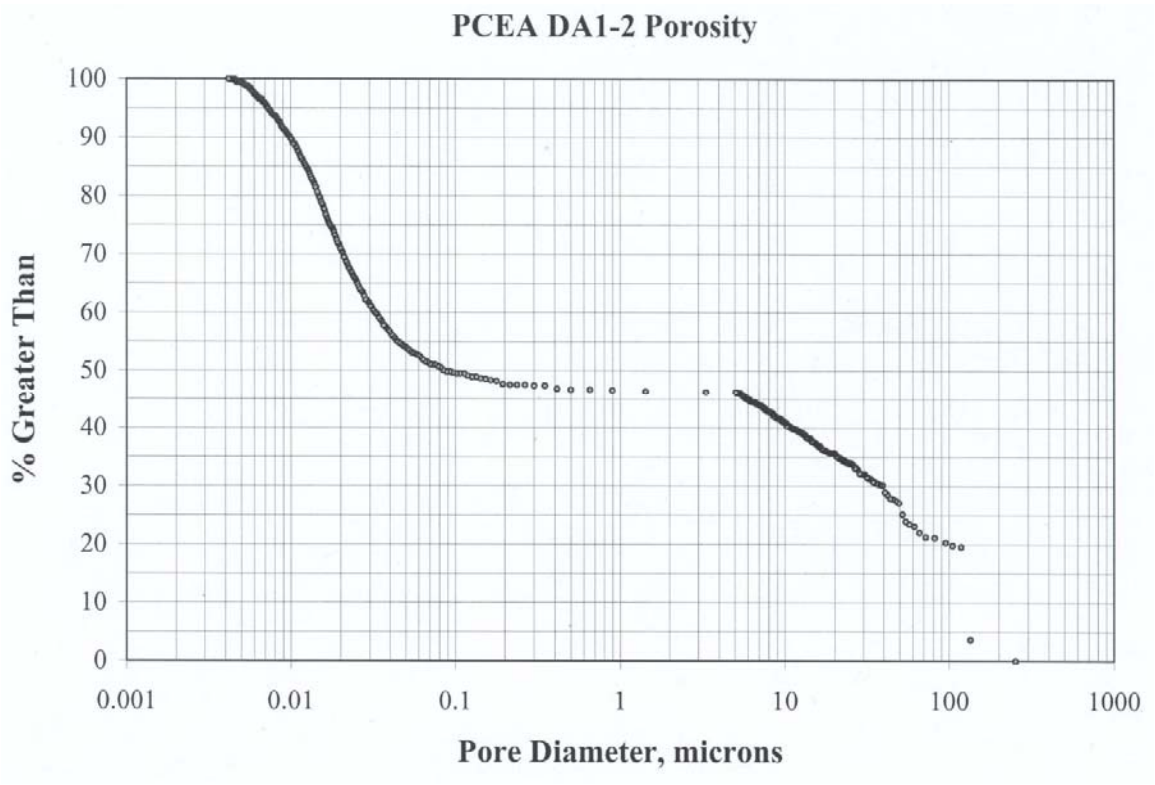

Figure 45. Cumulative pore size distribution for grade PCEA graphite

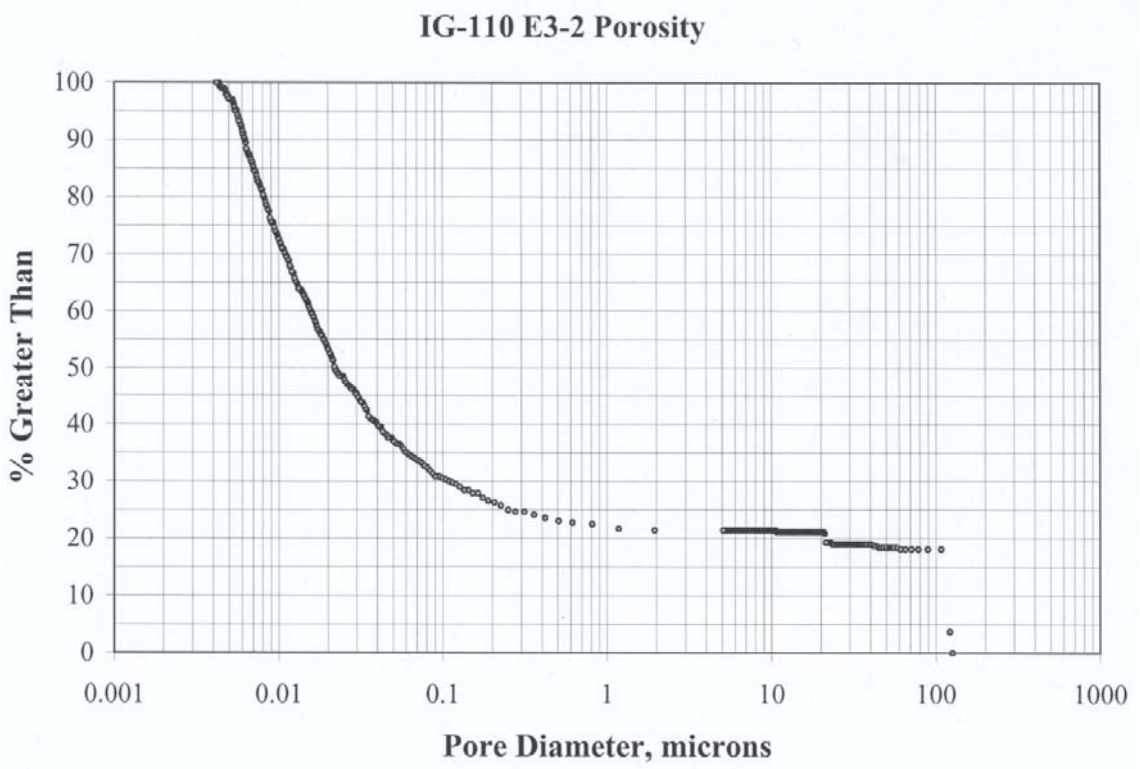

Figure 46. Cumulative pore size distribution for grade IG-110 graphite

Fig. 47 shows a pore size distribution for NBG-18. The bi-modal nature of the pore size distribution is revealed. A similar data plot is given in Fig. 48 for grade NBG-17, and indicates that NBG-18 and NBG-17 have similar pore structures. The NBG-18 distribution is shifted to smaller pore size. This observation is puzzling since NBG-17 has a finer texture (filler particle size) than NBG-18. Both grades are vibrationally-molded pitch coke graphites. From Figs. 47 and 48, the mean pore size (volume of porosity >50%) values for NBG-18 and NBG-17 are <0.1 μm and ~10 μm, respectively. The need for further measurements to understand this anomaly is indicated (see summary plots and discussion below).

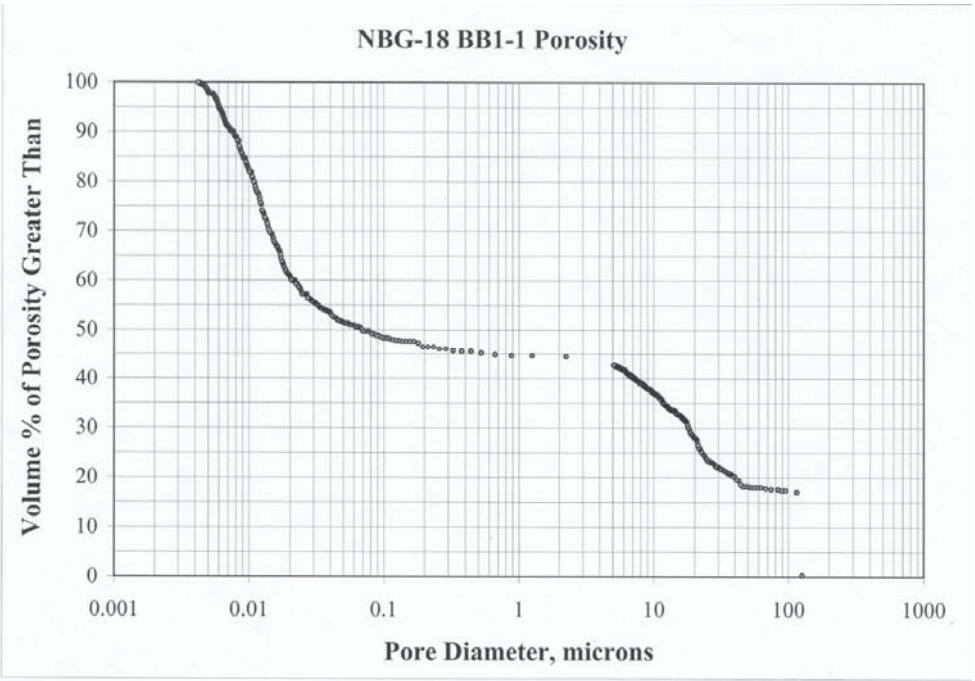

Figure 47. Hg intrusion pore size plots for graphite grade NBG-18

Fig. 49 shows the pore size distribution for grade IG-430, a fine-grained, isostatically presses, pitch coke graphite. In contrast the IG-430 pore structure is significantly finer that NBG-18 or NBG-17. The >50% pore size for IG-430 is 0.03 μm, smaller than NBG-18 or NBG-17.

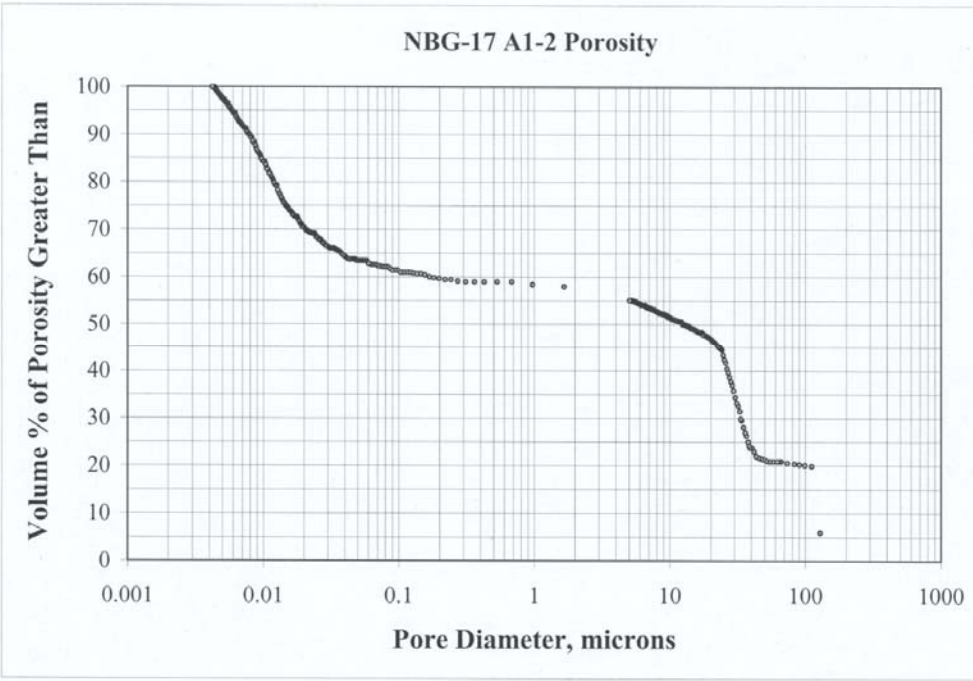

Figure 48. Hg intrusion pore size plots for graphite grade NBG-17

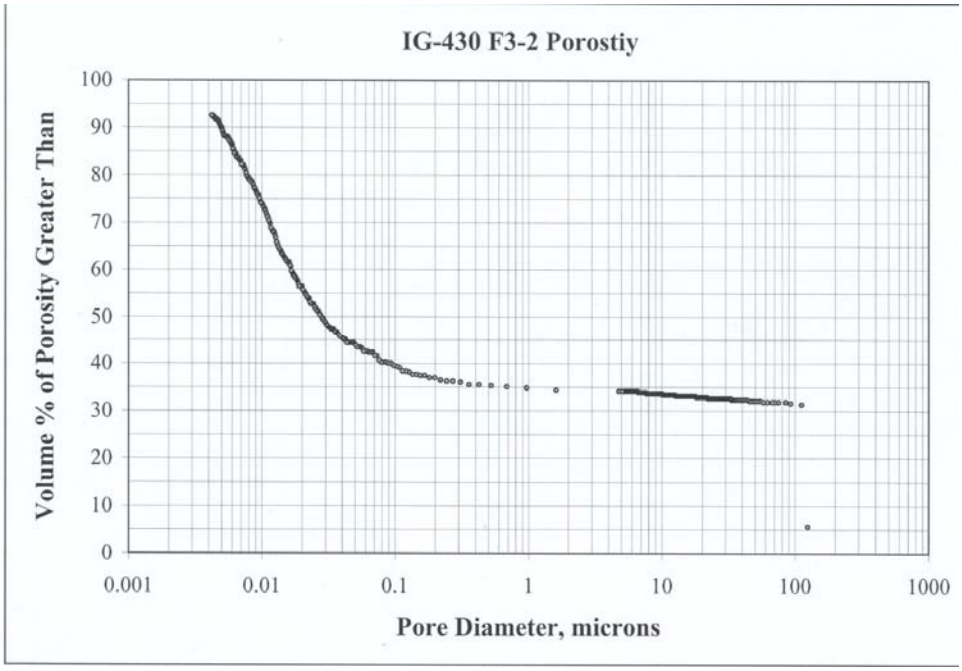

Figure 49. Hg intrusion pore size plots for graphite grade IG-430

Surface roughness and machining marks can be detected using Hg intrusion, and may be spuriously interpreted as porosity. Examples of surface roughness and machining marks are seen Figs. 50-53 for graphite grade NBG-18. The intrusion summary plots for NBG-18 are shown in

Figs. 57 and 58, and show a few spurious points at pore sizes > 120 μm. These are attributed to machining marks and surface roughness. Consequently, the plots in Figs. 59 and 60 show only pores < 120 μm. Figs. 54-56 show the specimen surface for grade IG-110. Machining marks are clearly visible. Therefore the plots for grade IG-110 (Figs. 63 and 64) have similarly had the large pore indications excluded. Similarly, the PCEA data has pores > 120 μm excluded from the data set. A complete gallery of photo macrographs of the graphite specimens is contained in Appendix 23.

Figs. 57-70 shows Hg-porosimetry data by graphite grade. The pore size distributions for all of the specimens tested are reported. The different modalities of the pore structures of the fine-grained isotropic graphite and the coarser-grained extruded and vibrationally molded grades are confirmed. Examination of the summary plots for grades NBG-18 and NBG-17 indicate the mean pore size (50% volume % porosity greater than) ranges were 0.05-0.30 μm and 0.04-0.14 μm, respectively. Therefore the data indicate that NBG-17 does indeed have a finer pore structure than NBG-17, contrary to earlier (preliminary) data, and in agreement with the general expectation for the pore structure to be finer in finer-grained graphite (0.8 mm max cf. 1.6 mm max).

The pore structure characterization data reported here will provide a basis for post-irradiation comparison of changes induced by irradiation in the unstressed and stressed (crept) condition.

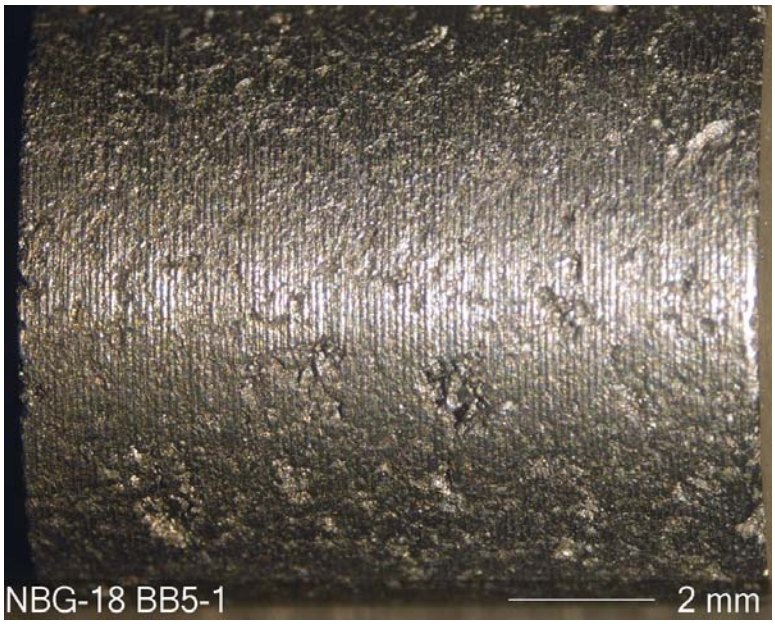

Figure 50. NBG-18 specimen BB5-1 macrograph showing surface roughness and machining marks

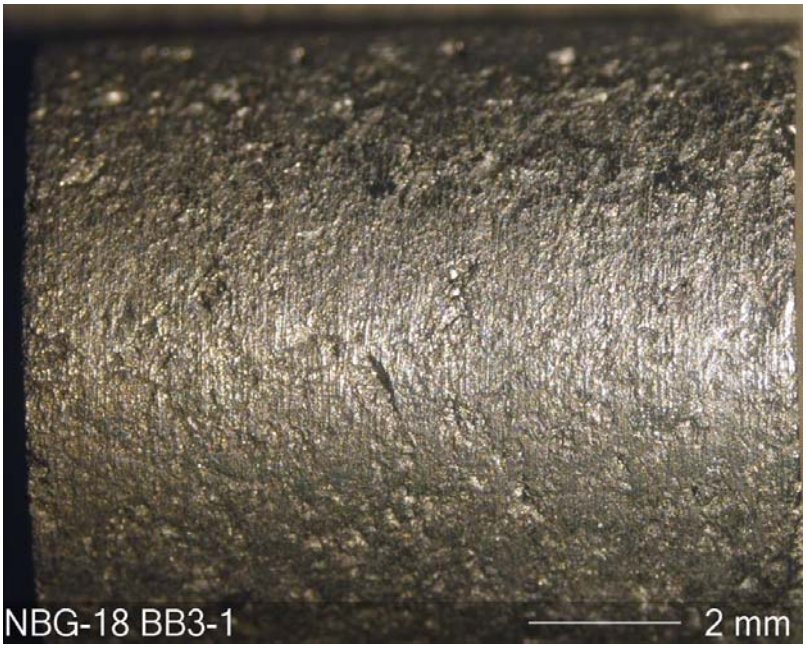

Figure 51. NBG-18 specimen BB3-1 macrograph showing surface roughness and machining marks

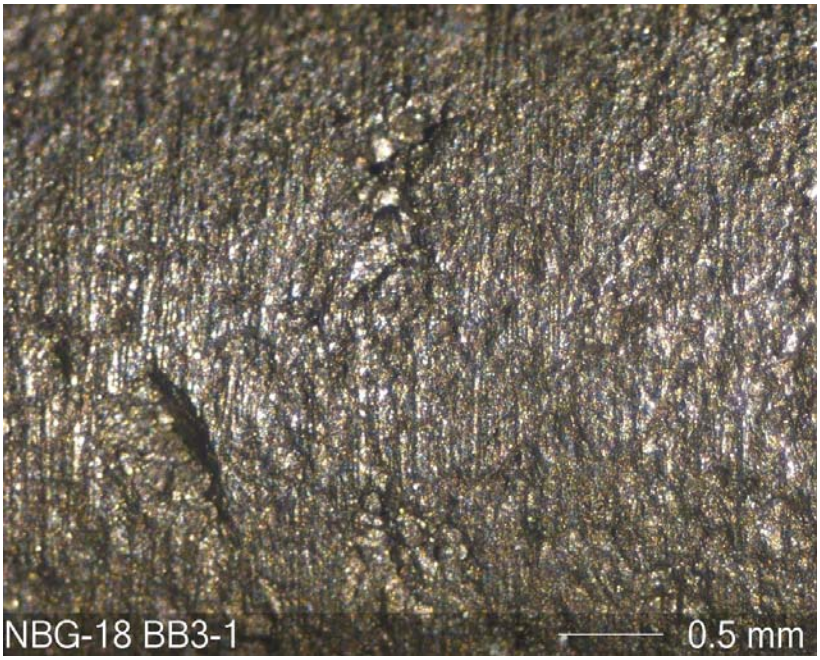

Figure 52. NBG-18 specimen BB3-1 macrograph showing surface roughness and machining marks

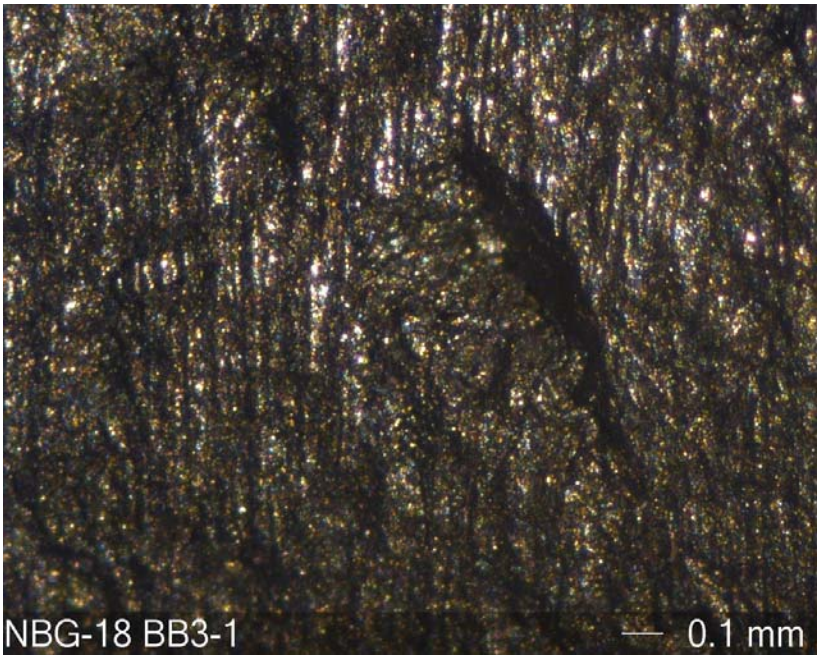

Figure 53. NBG-18 specimen BB3-1 macrograph showing surface roughness and machining marks

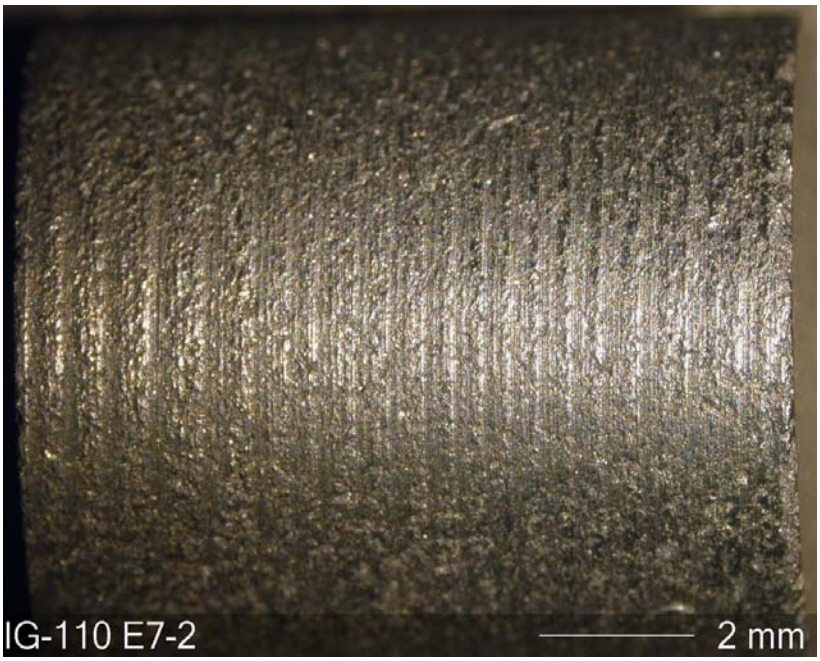

Figure 54. IG-110 specimen E7-2 macrograph showing surface roughness and machining marks

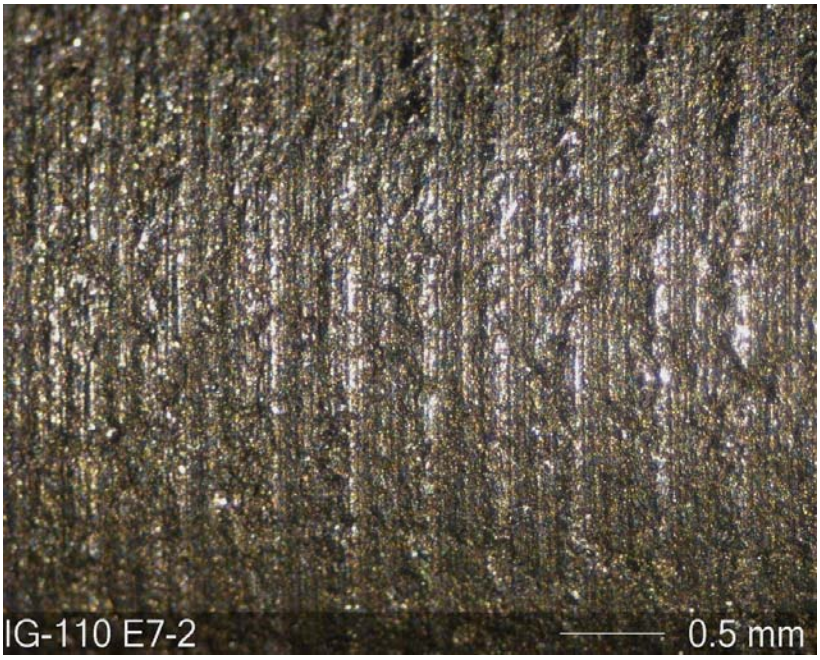

Figure 55. IG-110 specimen E7-2 macrograph showing surface roughness and machining marks

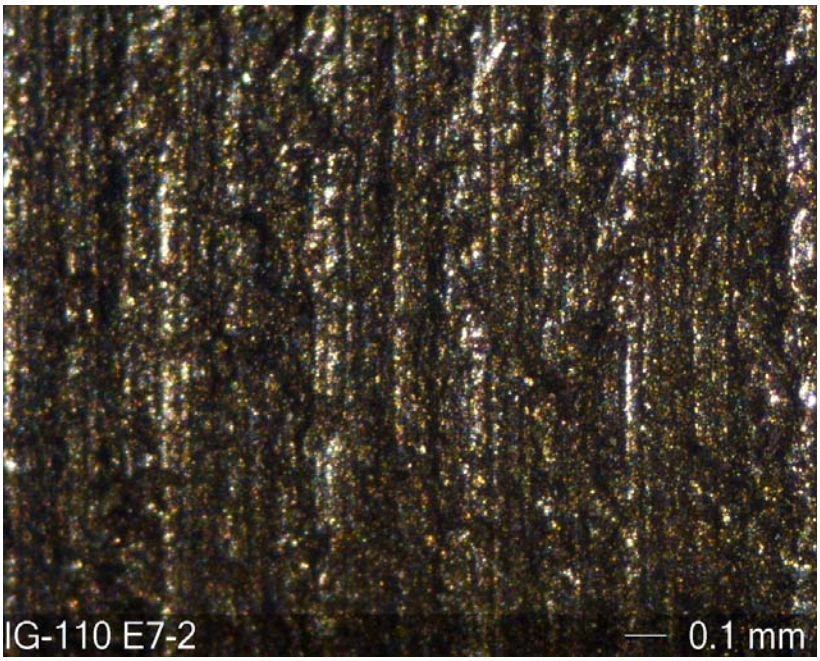

Figure 56. IG-110 specimen E7-2 macrograph showing surface roughness and machining marks

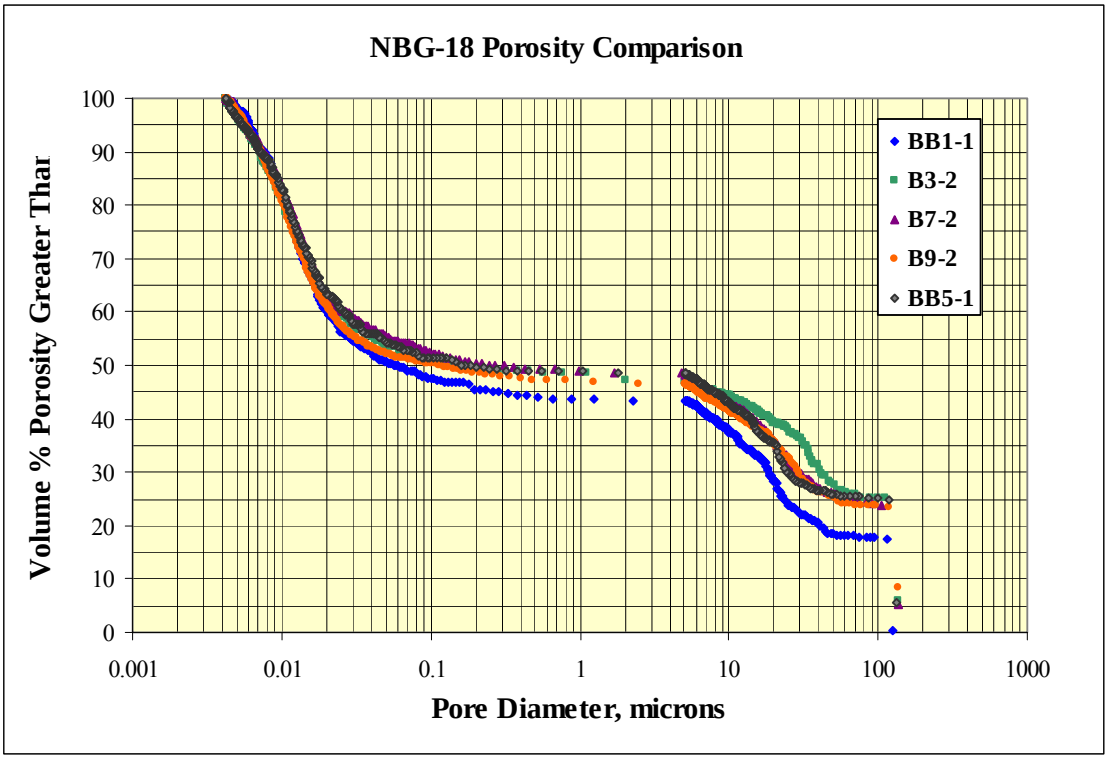

Figure 57. Hg Intrusion pore size distribution for vibro-molded graphite grade NBG-18

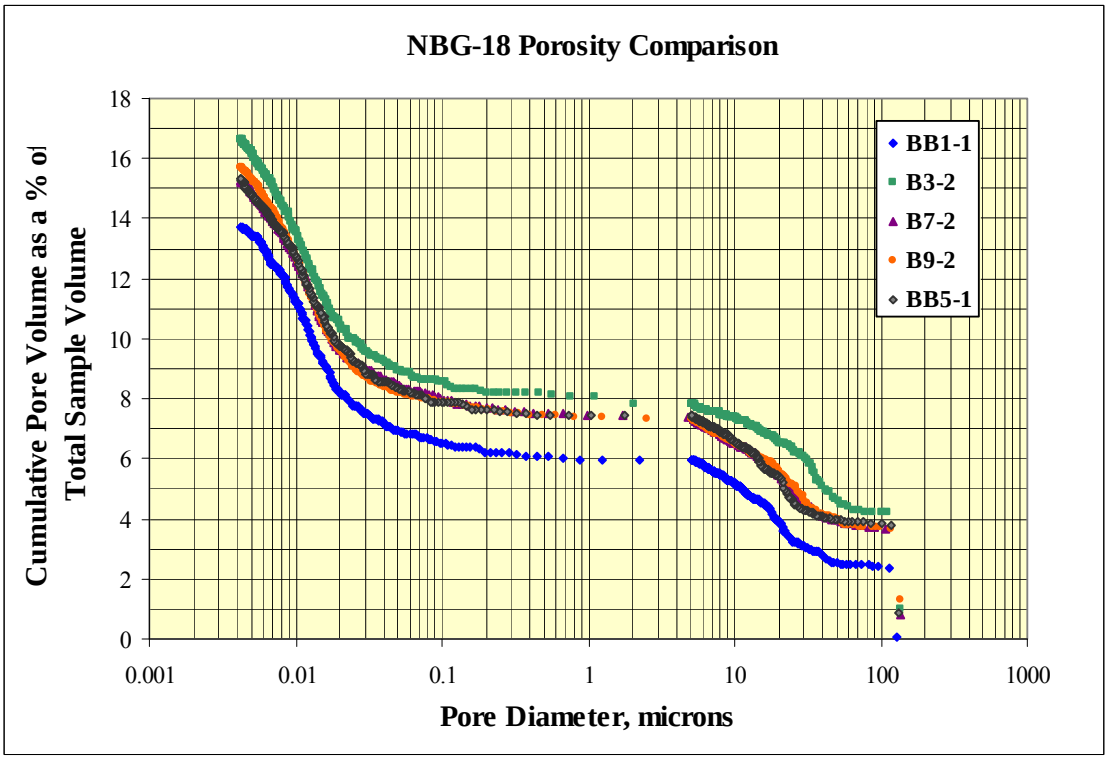

Figure 58. Hg Intrusion pore size distribution for vibro-molded graphite grade NBG-18

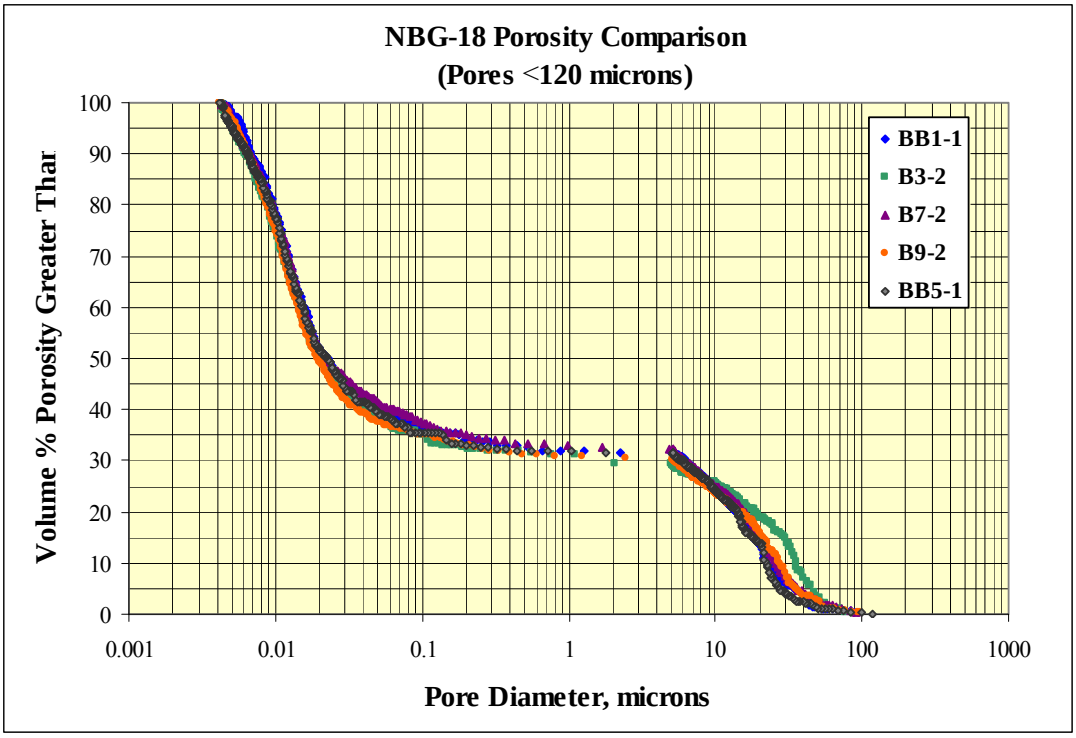

Figure 59. Hg Intrusion pore size distribution (pores < 120 μm) for vibro-molded graphite grade NBG-18

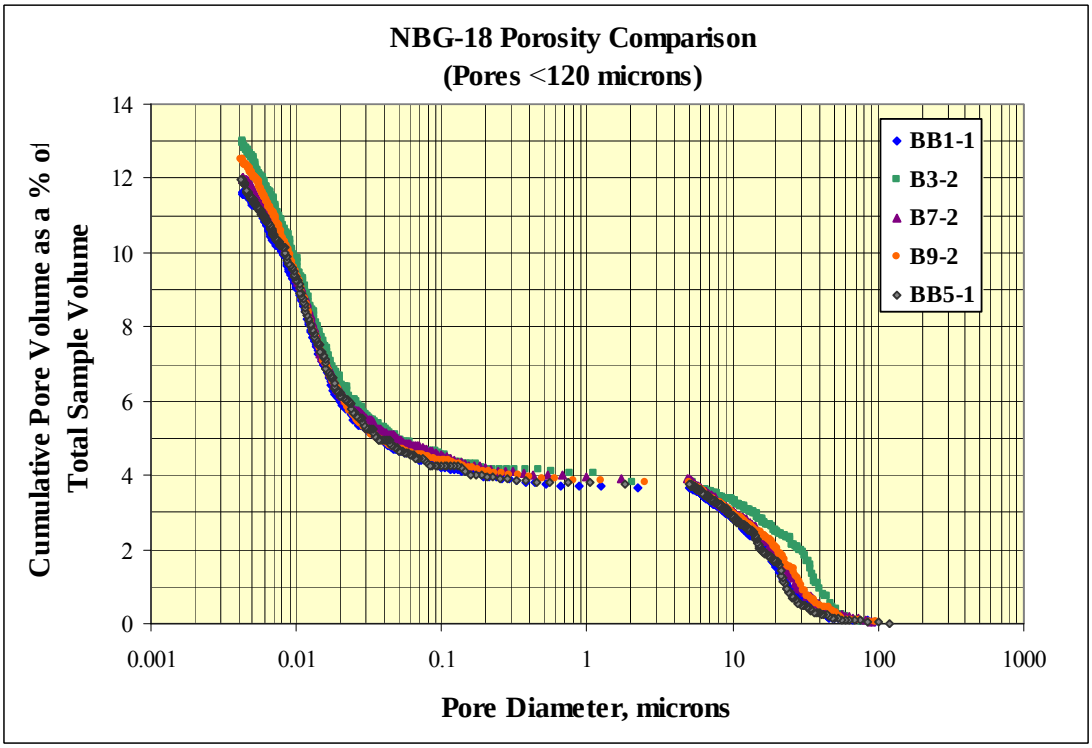

Figure 60. Hg Intrusion pore size distribution (pores < 120 μm) for vibro-molded graphite grade NBG-17

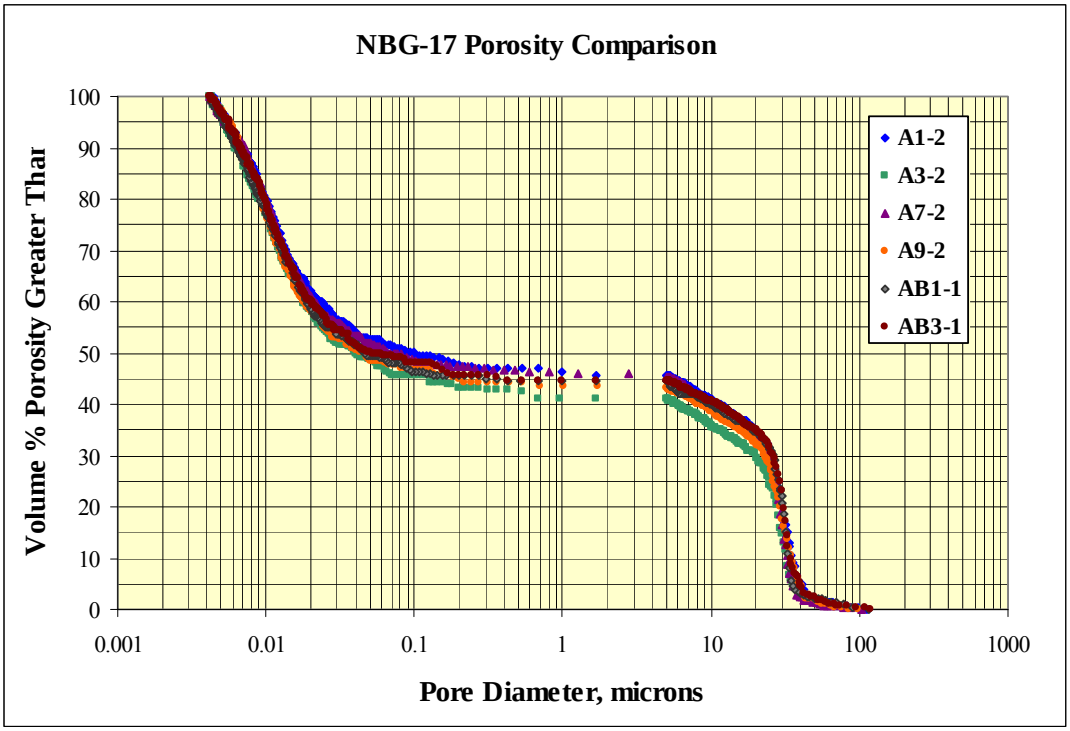

Figure 61. Hg Intrusion pore size distribution (pores < 120 μm) for vibro-molded graphite grade NBG-17

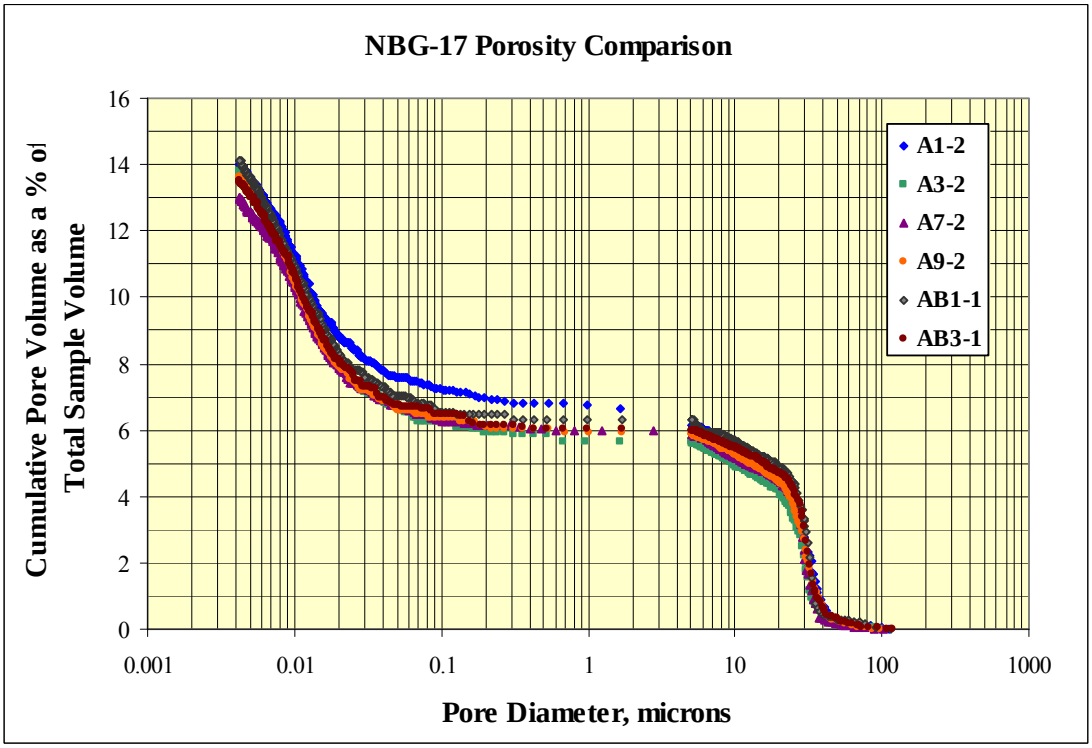

Figure 62. Hg Intrusion pore size distribution (pores < 120 μm) for vibro-molded graphite grade NBG-17

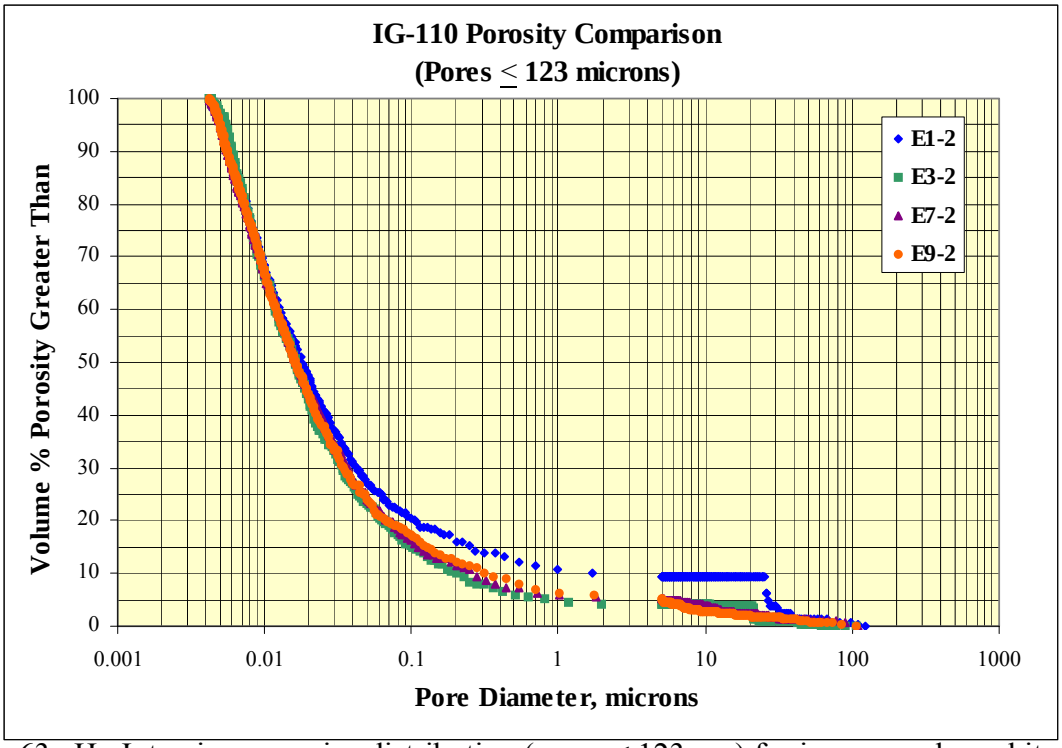

Figure 63. Hg Intrusion pore size distribution (pores < 123 μm) for iso-pressed graphite grade IG-110

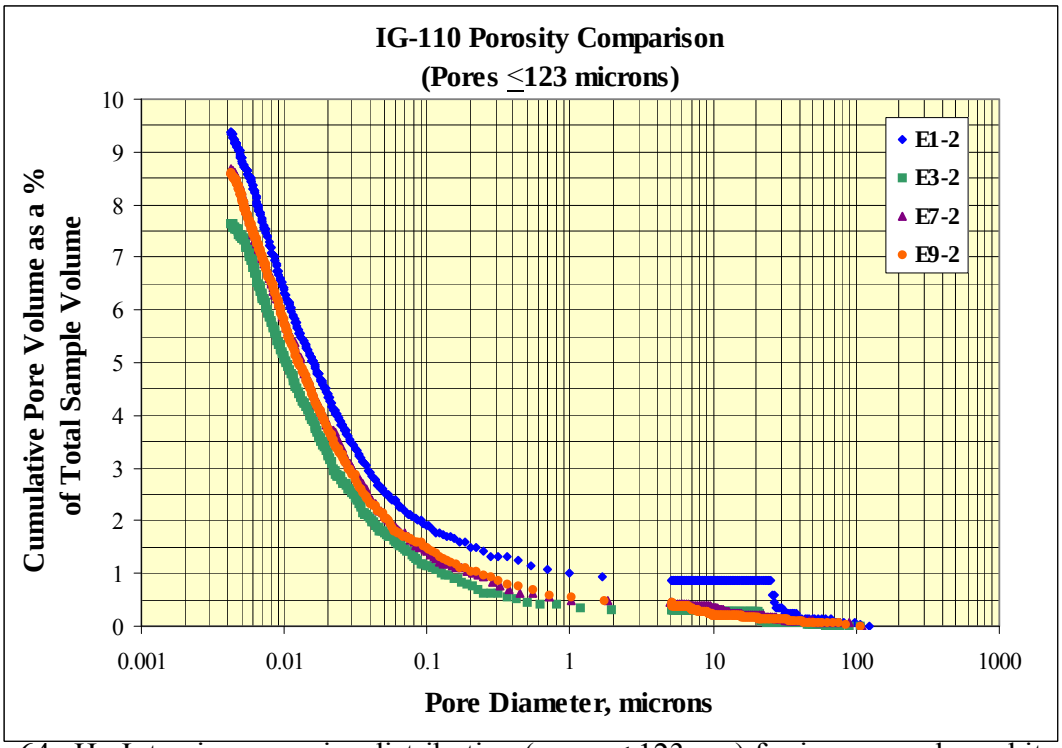

Figure 64. Hg Intrusion pore size distribution (pores < 123 μm) for iso-pressed graphite grade IG-110

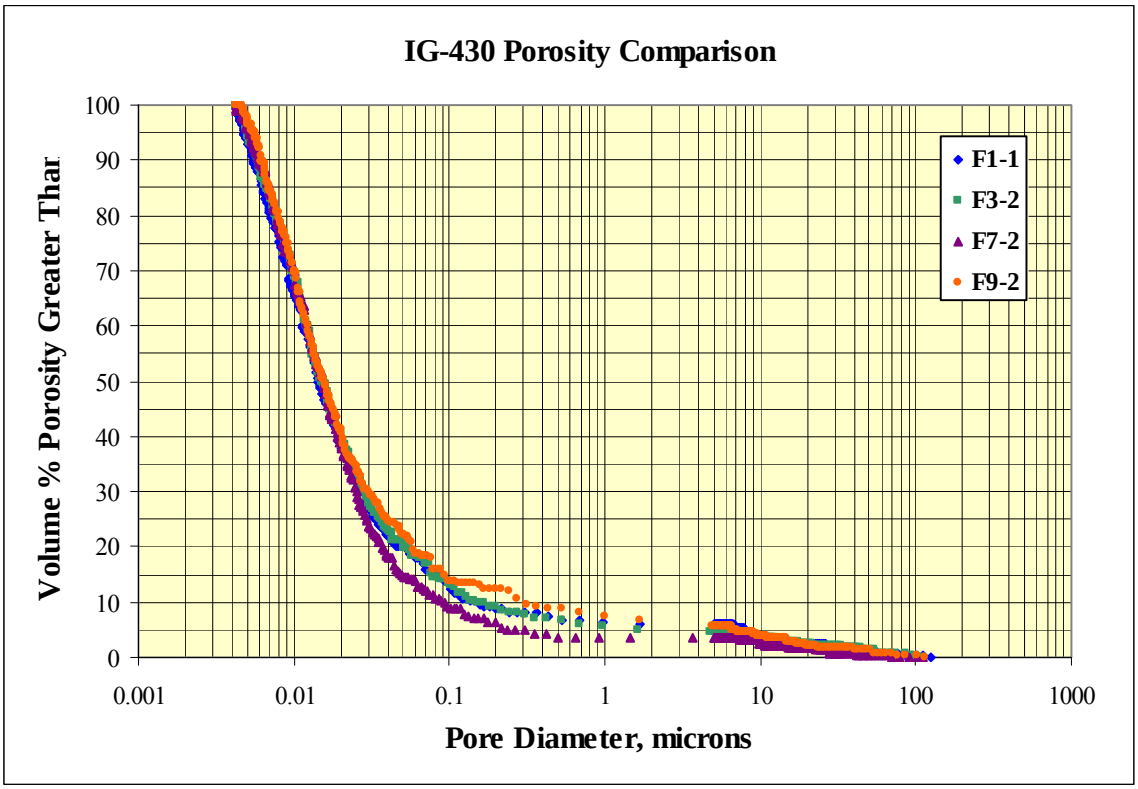

Figure 65. Hg Intrusion pore size distribution for iso-pressed graphite grade IG-430

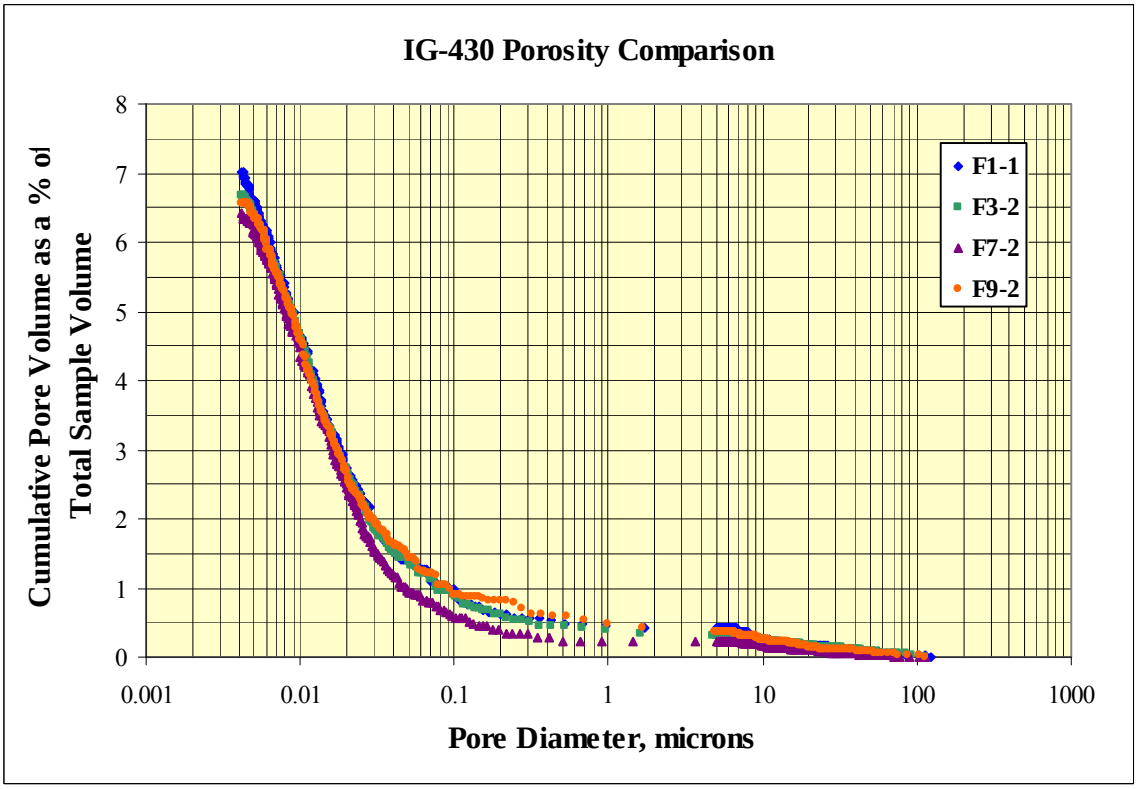

Figure 66. Hg Intrusion pore size distribution for iso-pressed graphite grade IG-430

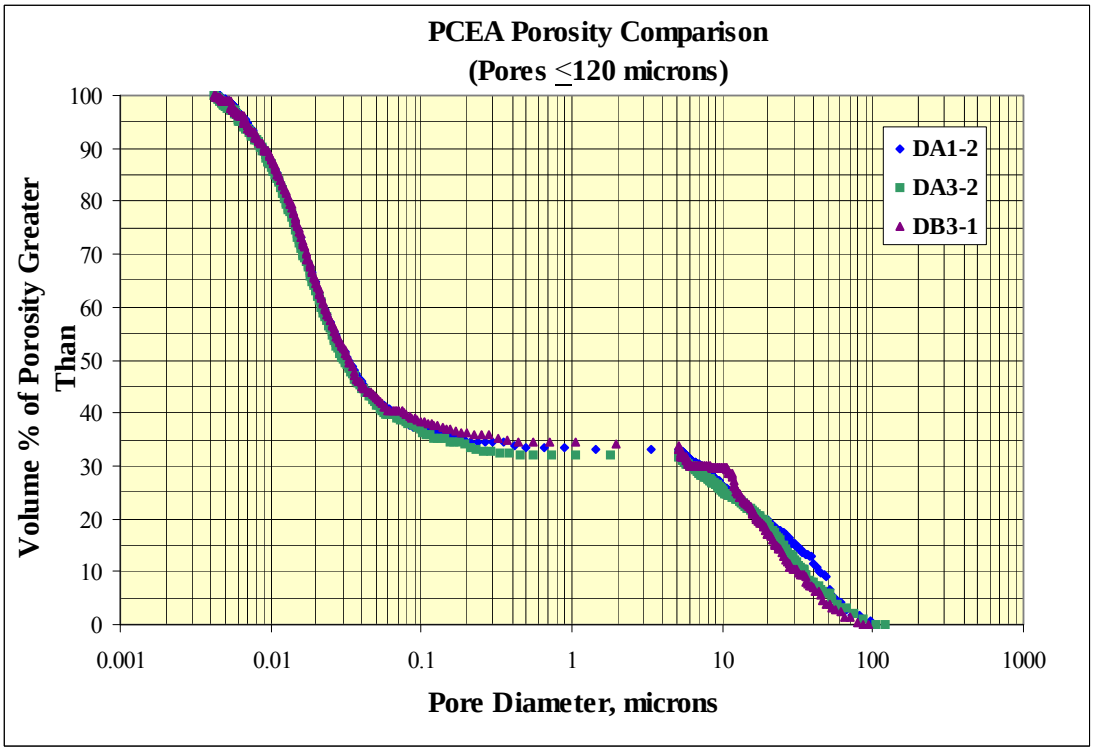

Figure 67. Hg Intrusion pore size distribution (pores < 120 μm) for extruded graphite grade PCEA

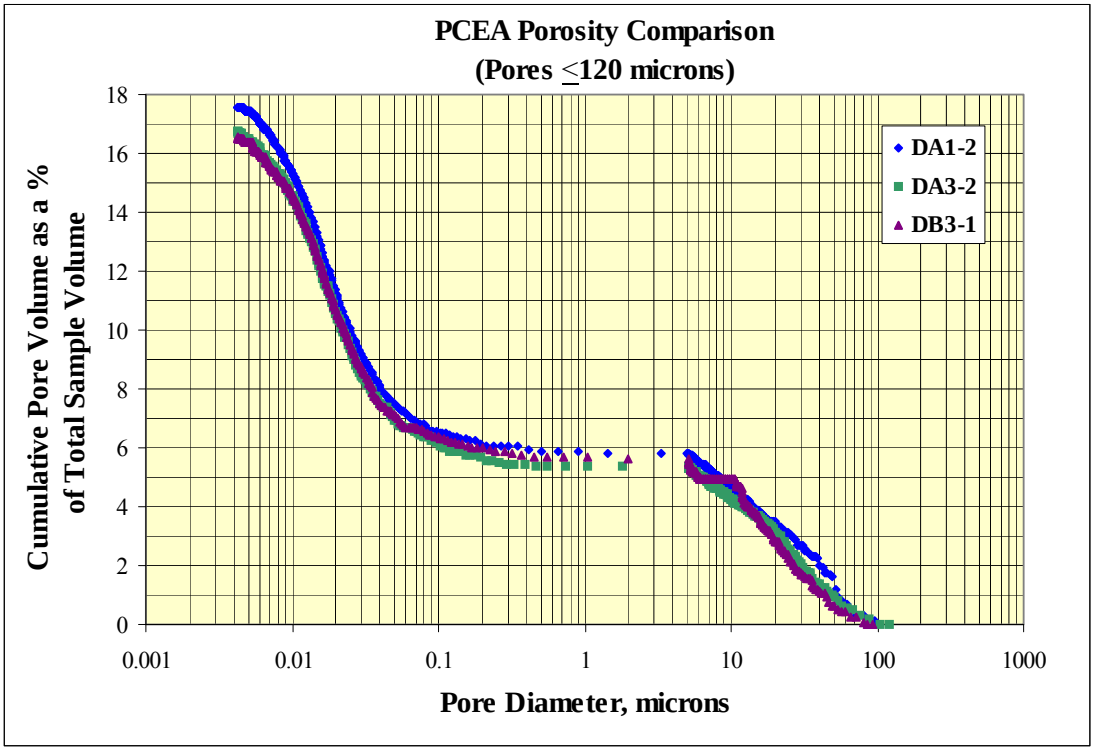

Figure 68. Hg Intrusion pore size distribution (pores < 120 μm) for extruded graphite grade PCEA

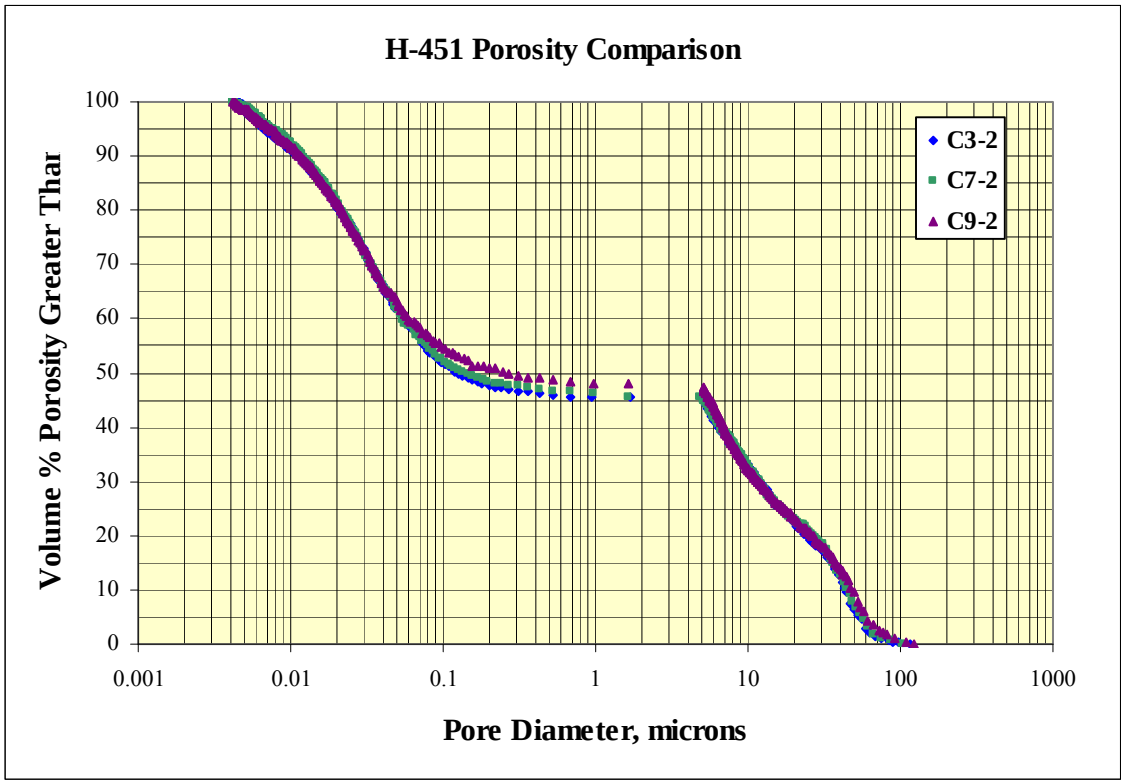

Figure 69. Hg Intrusion pore size distribution for extruded graphite grade H-451

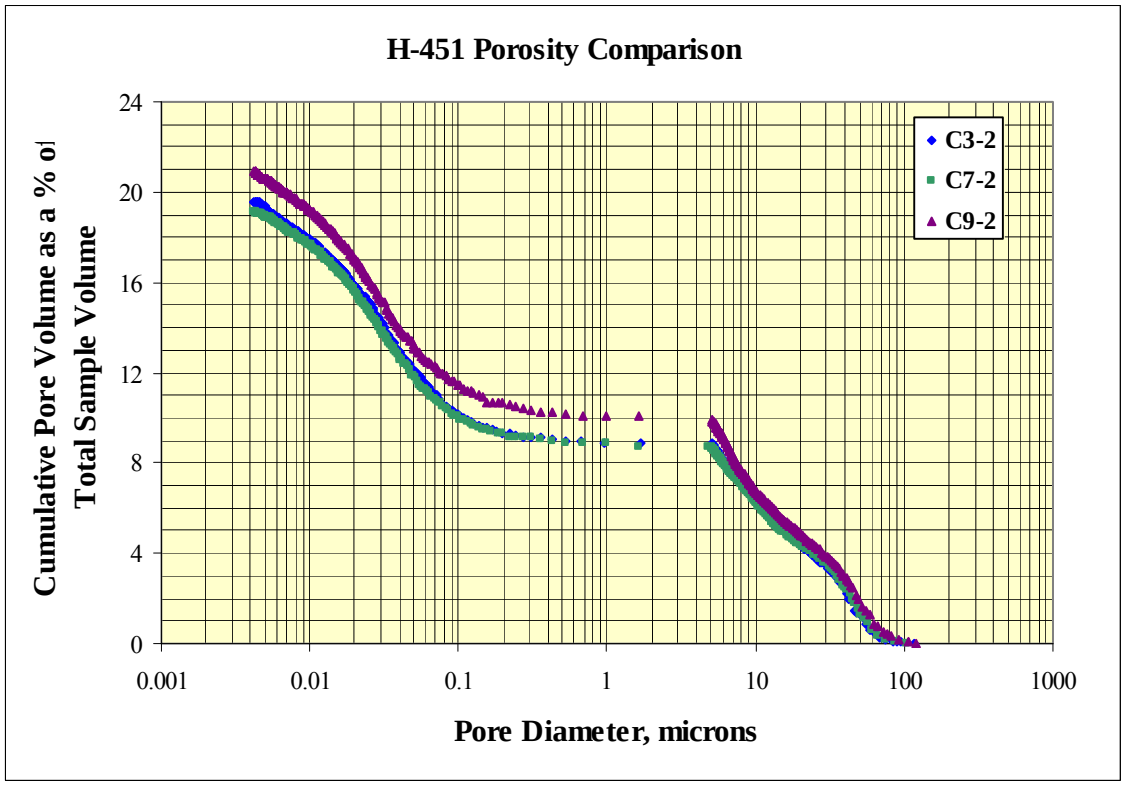

Figure 70. Hg Intrusion pore size distribution for extruded graphite grade H-451

3.4. X-Ray Diffraction Analysis

X-Ray Diffraction (XRD) was performed on selected graphites from the AGC-1 experiment, including grades H-451, IG-110, IG-430, PCEA, NBG-17, NBG-18, and BAN. Measurements were made on solid samples using Cu-kα radiation over the range of 2θ from 10° to 140°. The graphite crystallite planer spacing's <a> and <c> (Fig. 17) were calculated from the Bragg equation (eq. 1) and the nominal crystallite size, l_a and l_c, were calculated from the peak broadening using the Scherer equation (eq. 2). The <c> and l_c data was obtained from the (002) peak at 2θ values of ~26.381°, and the <a> and l_a data were obtained from the (110) peak at 2θ values of ~77.243°.

An XRD pattern for one of the graphites examined here is shown in Fig. 71 (H-451). The (002) and (110) peaks can be clearly observed. Figs. 72 to 77 show the diffraction patterns for the other grades examined here.

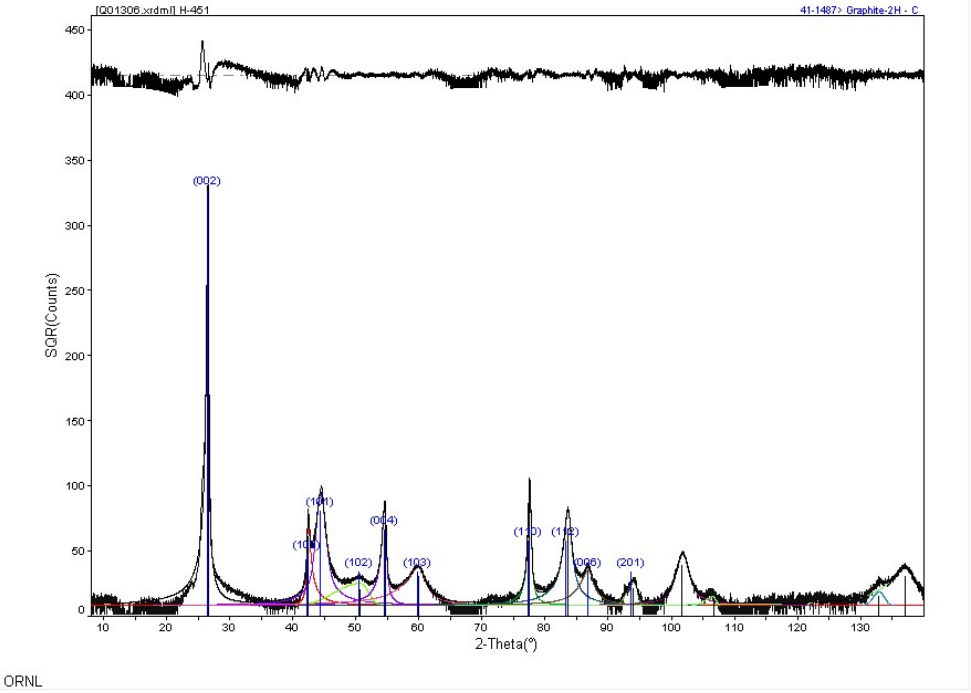

Figure 71. X-ray diffraction pattern for H-451 graphite showing the indexed diffraction peaks corresponding to the graphite crystal <c>-spacing (002) and <a>-spacing (110)

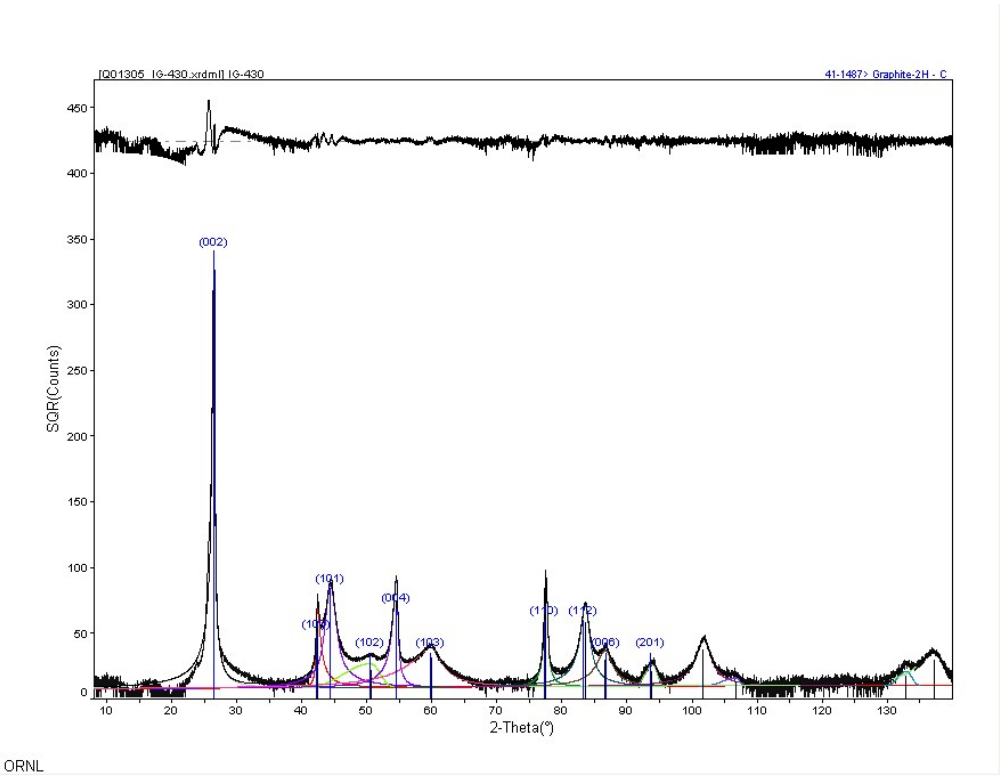

Figure 72. X-ray diffraction pattern for IG-430 graphite showing the indexed diffraction peaks corresponding to the graphite crystal <c>-spacing (002) and <a>-spacing (110)

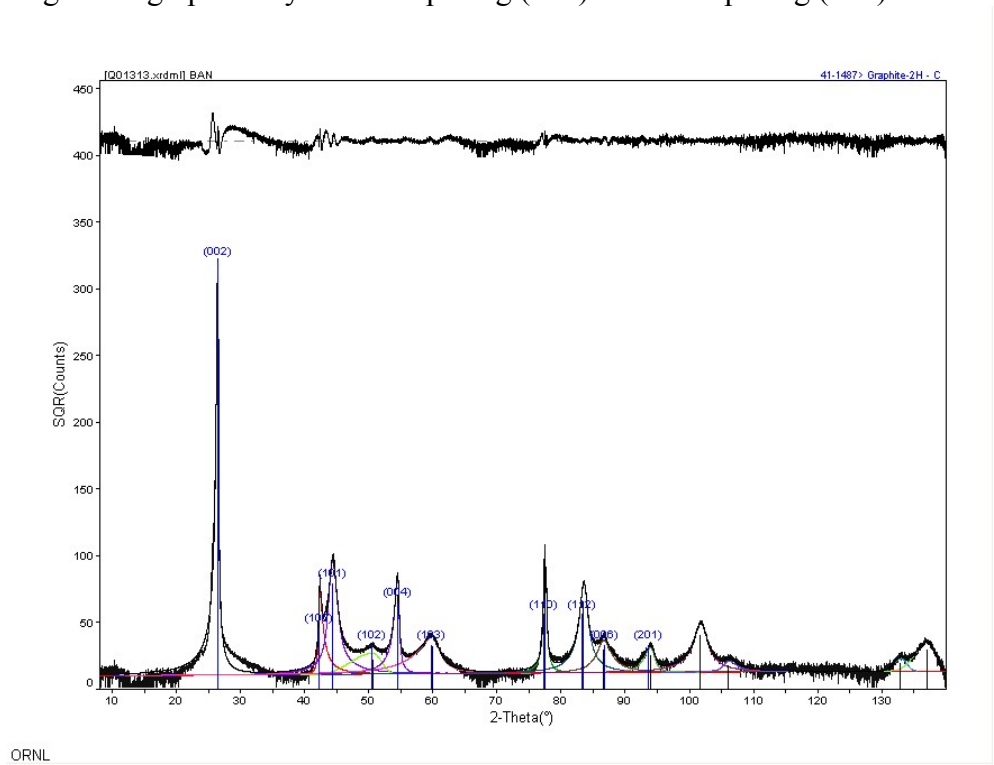

Figure 73. X-ray diffraction pattern for BAN graphite showing the indexed diffraction peaks corresponding to the graphite crystal <c>-spacing (002) and <a>-spacing (110)

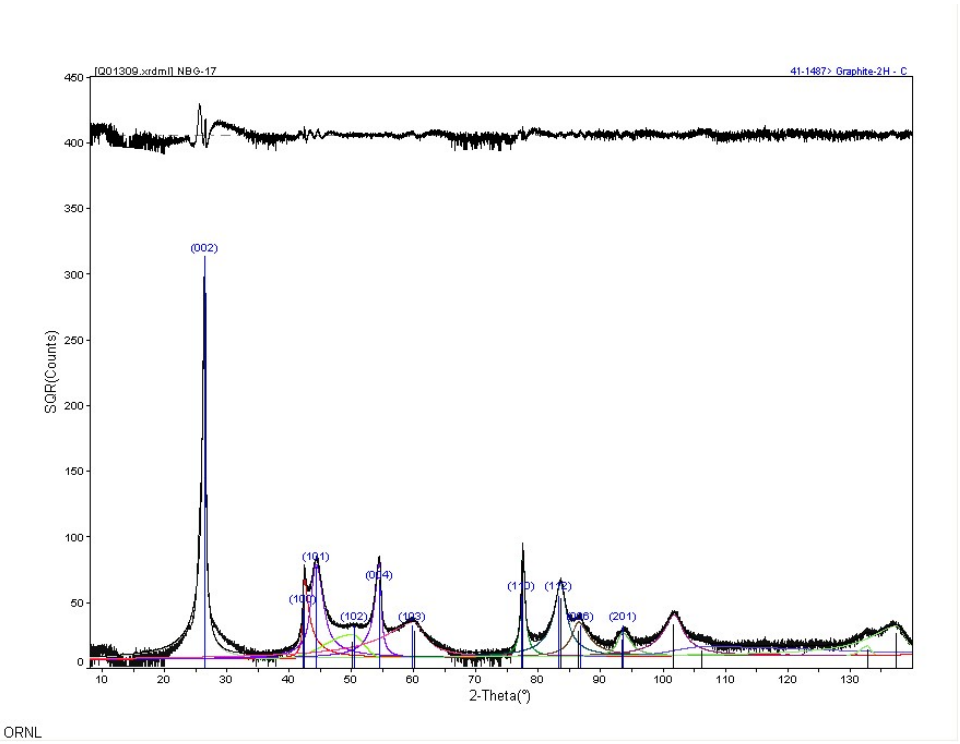

Figure 74. X-ray diffraction pattern for NBG-17 graphite showing the indexed diffraction peaks corresponding to the graphite crystal <c>-spacing (002) and <a>-spacing (110)

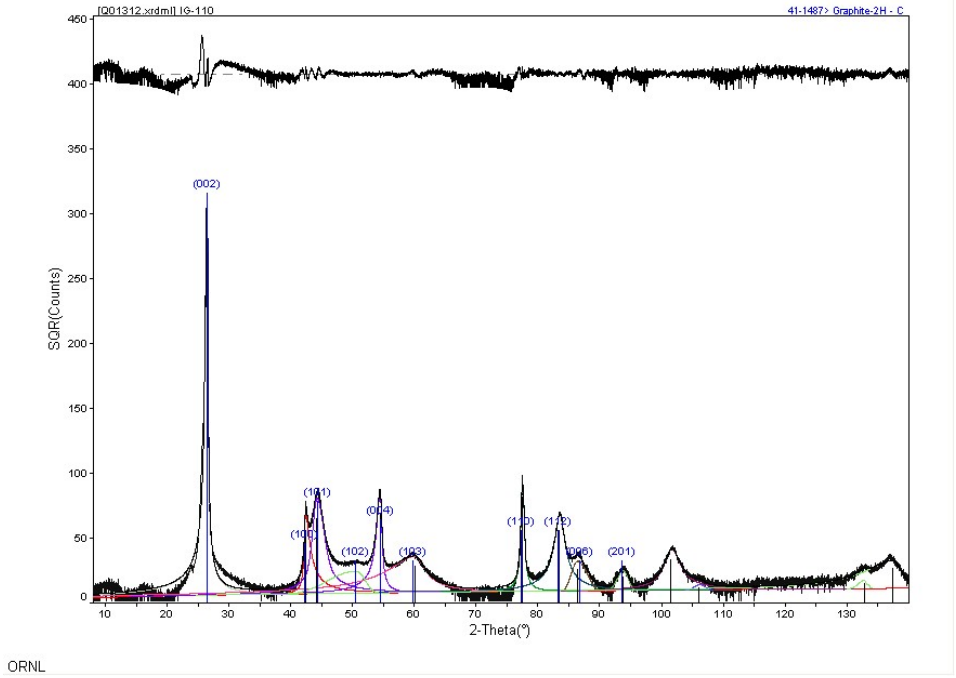

Figure 75. X-ray diffraction pattern for IG-110 graphite showing the indexed diffraction peaks corresponding to the graphite crystal <c>-spacing (002) and <a>-spacing (110)

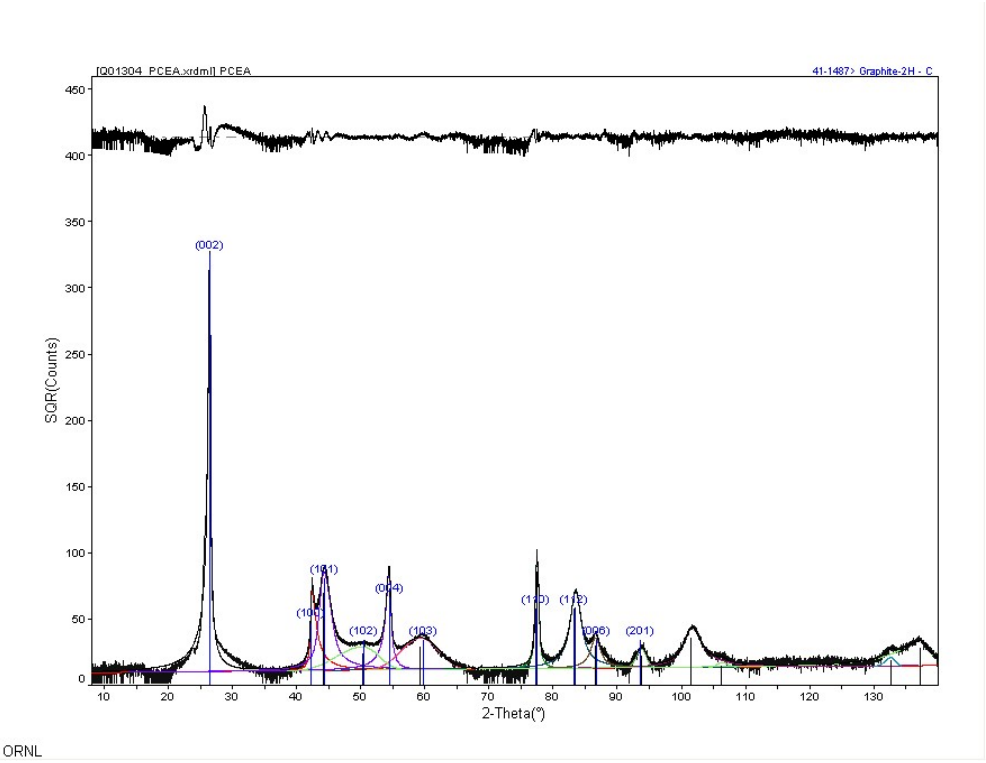

Figure 76. X-ray diffraction pattern for PCEA graphite showing the indexed diffraction peaks corresponding to the graphite crystal <c>-spacing (002) and <a>-spacing (110)

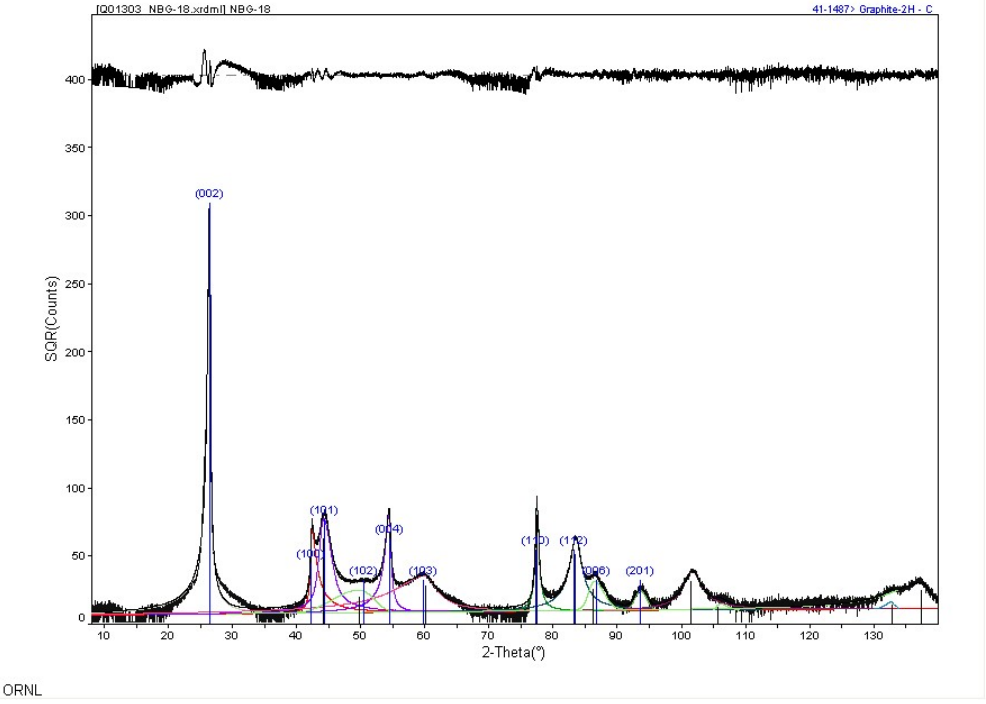

Figure 77. X-ray diffraction pattern for NBG-18 graphite showing the indexed diffraction peaks corresponding to the graphite crystal <c>-spacing (002) and <a>-spacing (110)

Table 7 reports the calculated graphite crystal parameters <c>, l_c, <a>, and l_a for each of the graphites examined here (Figs. 71–77).

Table 7. Summary of the graphite crystal parameters for the graphites examined here

Graphite grade	Coke type	<c> (Å)	Rank	lc (Å)	Rank	<a> (Å)	Rank	la (Å)	Rank	Overall Score
H-451	Petroleum	3.3525	1	269	1	1.2302	1	300	2	**5**
IG-430	Pitch	3.3607	2	218	4	1.2308	2	298	3	**11**
BAN	Petroleum	3.365	4	250	2	1.2313	6	322	1	**13**
NBG-17	Pitch	3.364	3	186	7	1.231	3	286	5	**18**
IG-110	Petroleum	3.3658	5	190	6	1.231	3	256	6	**20**
PCEA	Petroleum	3.3665	6	238	3	1.2311	5	250	7	**21**
NBG-18	Pitch	3.3695	7	191	5	1.2315	7	294	4	**23**

The graphites crystal parameters <c> and <a> are ranked 1 through 7 based on their size (smallest = 1, largest =7), and the parameters lc and la ranked 1 through 7 based upon their size (largest =1, smallest =7). The rankings are summed to give an "overall score". Thus more-crystalline graphite should exhibit a low overall score (smallest crystal spacing and largest crystallite size). The graphites are shown in Table 7 are ranked in order of this score.

The data in Table 7 should be considered **preliminary**, and additional XRD measurements are being conducted to confirm the reported scores. However, several interesting observations may be made from this data set. Grade H-451, the graphite used in the Fort St-Vrain reactor exhibits the lowest overall score. BAN, the secondary coke graphite also exhibits a low score. This graphite is of interest because it uses a widely available needle-coke combined with novel processing to yield near-isotropic graphite. Moreover, BAN graphite could be made with a high recycle fraction of graphite, thus offering a potential solution to the long-term disposal of spent graphite fuel blocks.

Generally, high crystallinity is a desirable attribute in nuclear graphite, since the accumulation of radiation damage in the crystal lattice is minimized in less defective (more crystalline) crystals. However, crystallinity should not be used as the **sole** discriminator between various grades of nuclear graphites.

X-Ray Diffraction (XRD) was additionally performed on a sample of HOPG from the AGC-1 experiment. Measurements were made on a solid sample using Cu-kα radiation over the range of 2θ from 10° to 140°. The HOPG crystallite plane spacing's <a> and <c> were calculated from the Bragg equation (eq. 1) and the nominal crystallite size, l_a and l_c, were calculated from the peak broadening using the Scherer equation (eq. 2). The <c> and l_c data was obtained from the (002) peak at 2θ values of ~26.4° (Fig. 78), and the <a> and l_a data were obtained from the (110) peak at 2θ values of ~77.2° (Fig. 79).

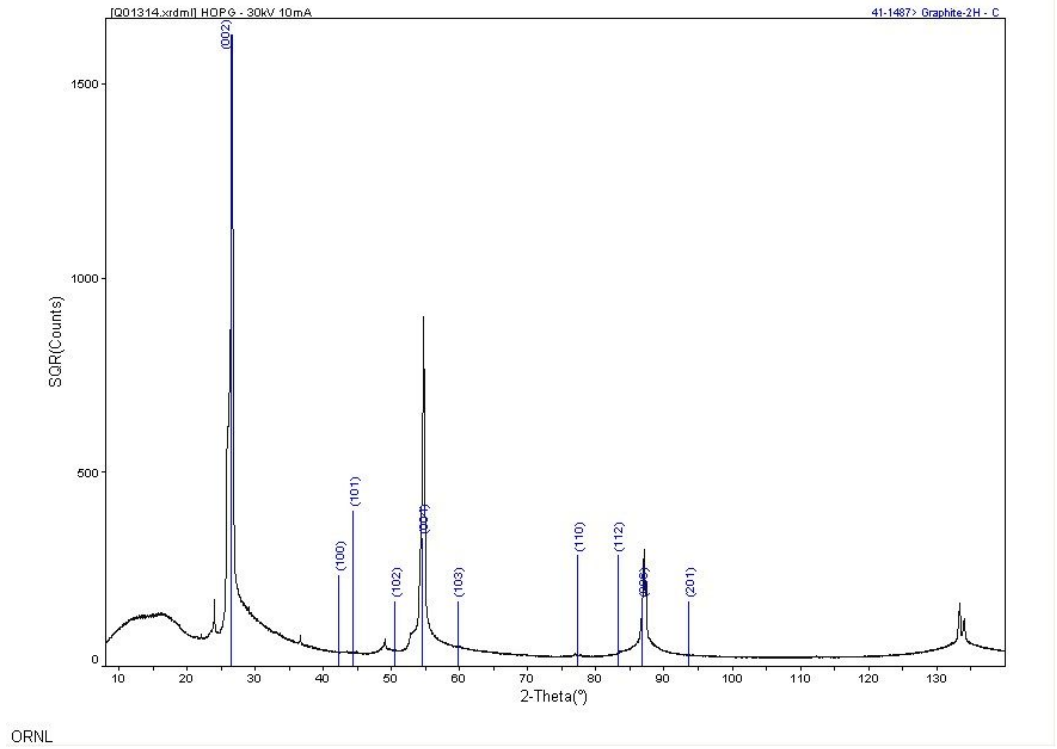

Figure 78. X-ray diffraction pattern for HOPG sample from AGC-1 "sister samples"

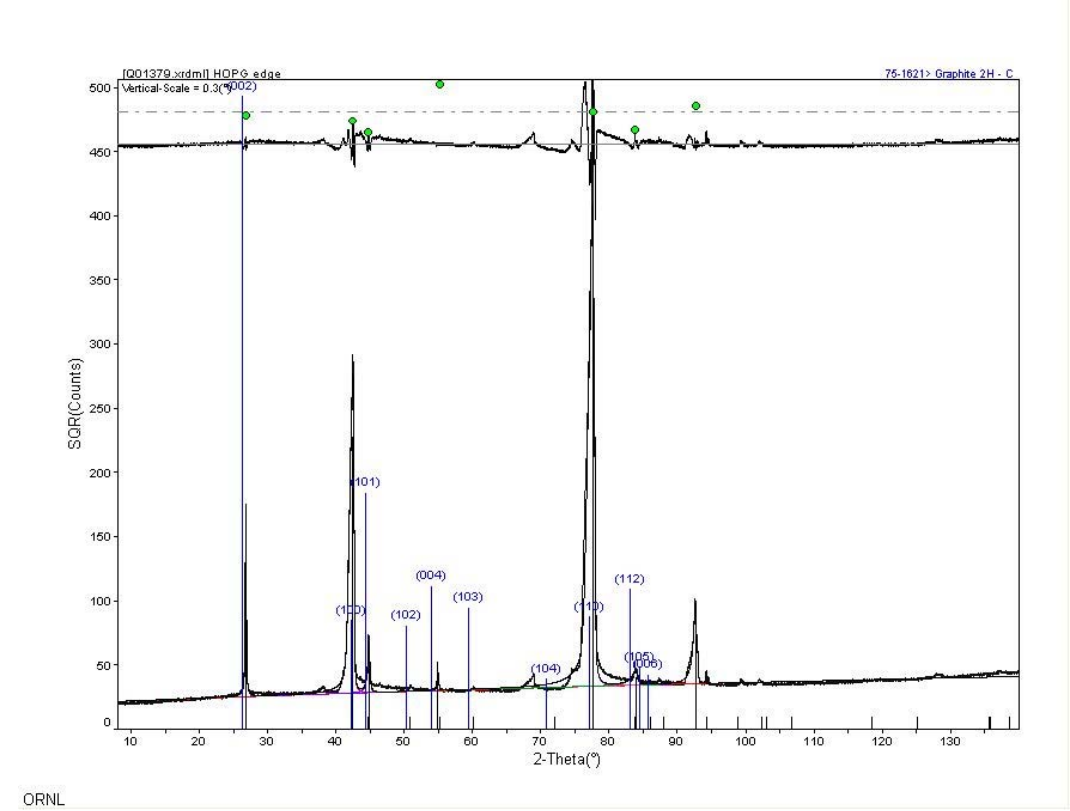

Figure 79. X-ray diffraction pattern for HOPG sample from AGC-1 "sister samples"

The crystal lattice spacing and crystallite size parameters are given in Table 8 for HOPG and for the series of polycrystalline graphites reported in Table 7. As expected, the HOPG exhibits smaller lattice spacing that the polygrannular graphites, indeed the values are very close to the perfect crystal value of <c> = 0.3354 nm and <a> = 0.2461 nm.

Table 8. Crystallite spacing and size data from XRD on a HOPG (edge) and several polycrystalline graphites

Graphite grade	Coke type	<c> (Å)	l_c (Å)	<a> (Å)	l_a (Å)
HOPG	n/a	3.3448	424	2.4584	138
H-451	Petroleum	3.3525	269	2.4604	300
IG-430	Pitch	3.3607	218	2.4616	298
BAN	Petroleum	3.365	250	2.4626	322
NBG-17	Pitch	3.364	186	2.4620	286
IG-110	Petroleum	3.3658	190	2.4620	256
PCEA	Petroleum	3.3665	238	2.4622	250
NBG-18	Pitch	3.3695	191	2.4630	294

The extent of crystal perfection in the HOPG is further illustrated by the multiple peaks from the crystal basal planes in the hexagonal crystal lattice, i.e., the (002), (004),(006), and (008) peaks in Fig. 78. Table 9 reports the calculated <c> spacing and l_c parameter from these peaks.

Table 9. Crystal lattice c-spacing calculated from the multiple basal plane reflections for HOPG

Indices (hkl)	2θ°	d (A)	<c> (A)	l_c (A)
(002)	26.629	3.3448	3.3448	424
(004)	54.731	1.6757	3.3514	475
(006)	87.091	1.1181	3.3543	509
(008)	133.365	0.8388	3.3552	660

The l_a values for HOPG (Table 8) appear rather small and this and further XRD work in needed to further investigate this.

HOPG is included in experiment AGC-1 in piggy-back locations to provide data for the dimensional change rates of graphite crystals. These data in turn will be used in models for the dimensional change rates of polycrystalline graphites.

In addition to representing the XRD data in two dimensional plots (e.g. Fig. 78) a three dimensional representation may be generated for a specific crystal orientation, referred to as "pole figures". Pole figures for the crystallographic (002), (101), (102), (100), and (110) orientations were obtained (Figs 80 – 84). The pole figures demonstrate the highly aligned nature of HOPG, which exhibits a fiber like texture with strong preferred crystal orientation.

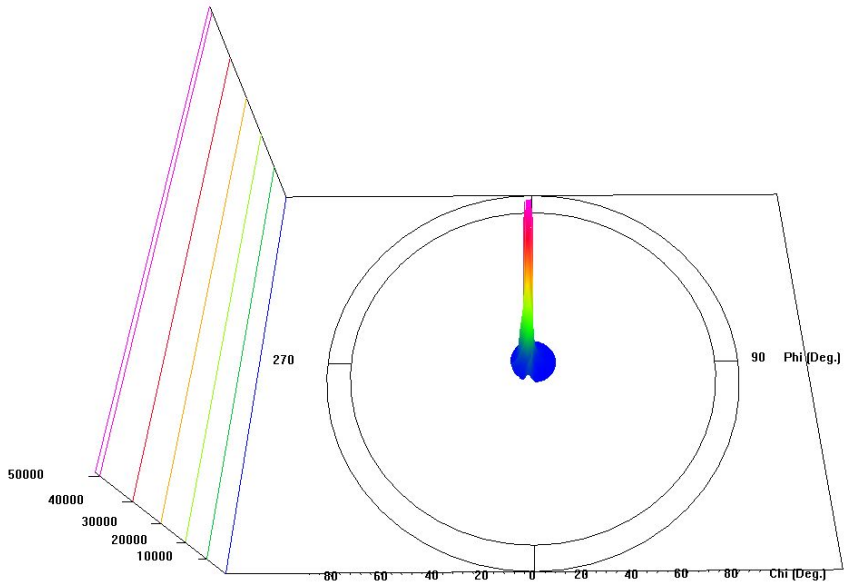

Figure 80. X-ray diffraction pole figures for HOPG sample from AGC-1 "sister samples" (002) orientation

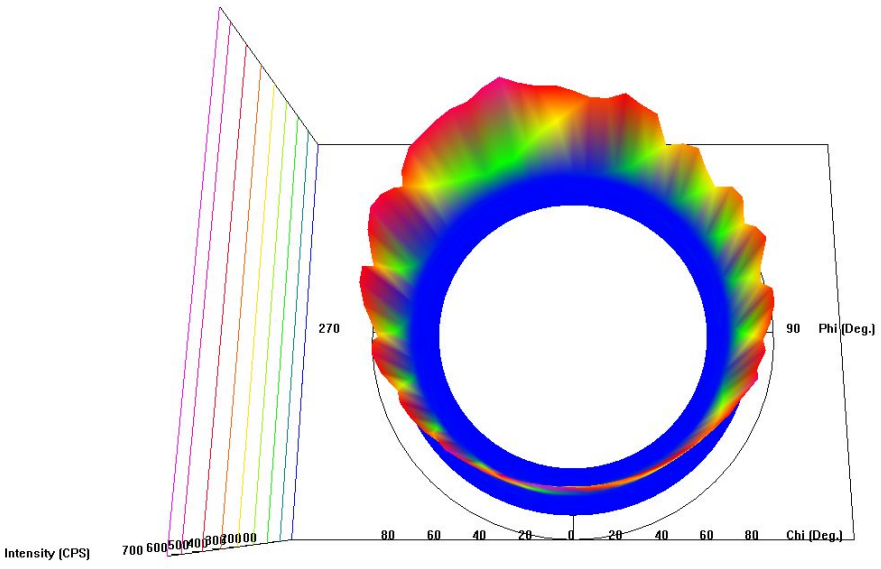

Figure 81. X-ray diffraction pole figures for HOPG sample from AGC-1 "sister samples" (101) orientation

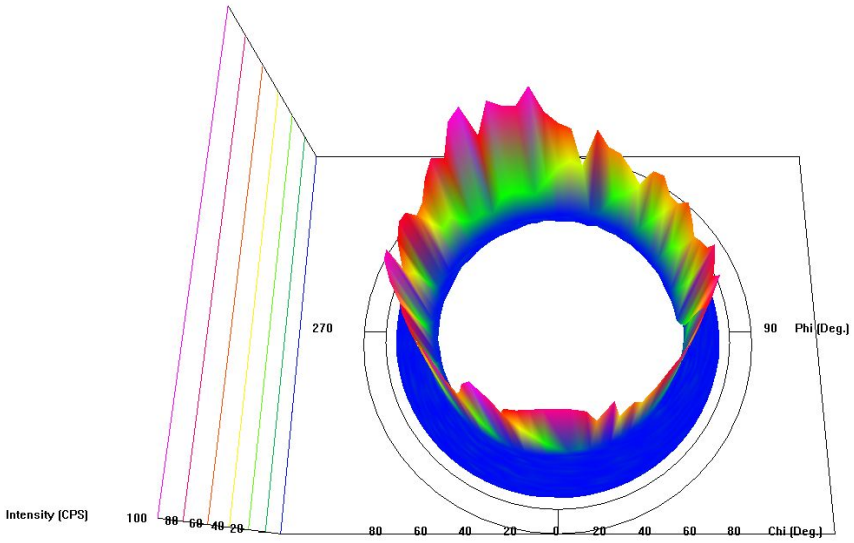

Figure 82. X-ray diffraction pole figures for HOPG sample from AGC-1 "sister samples" (102) orientation

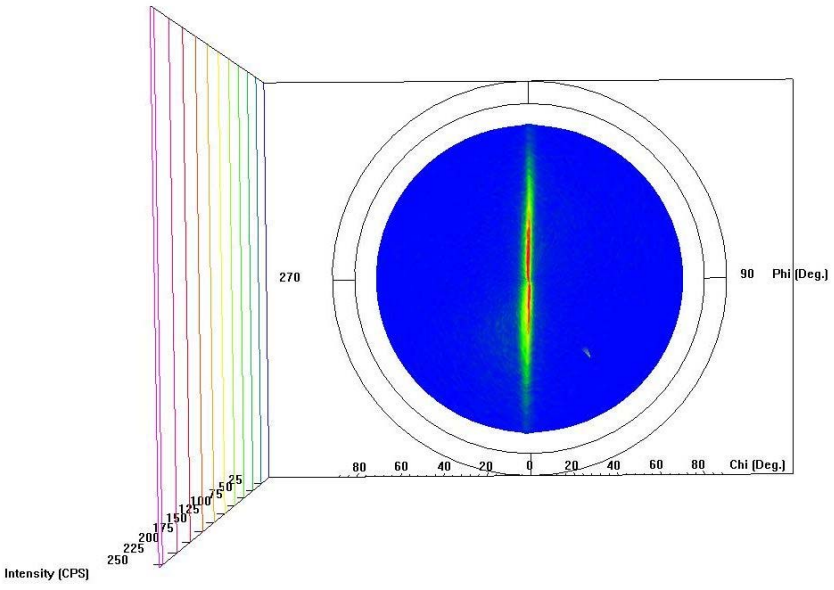

Figure 83. X-ray diffraction pole figures for HOPG sample from AGC-1 "sister samples" (100) orientation

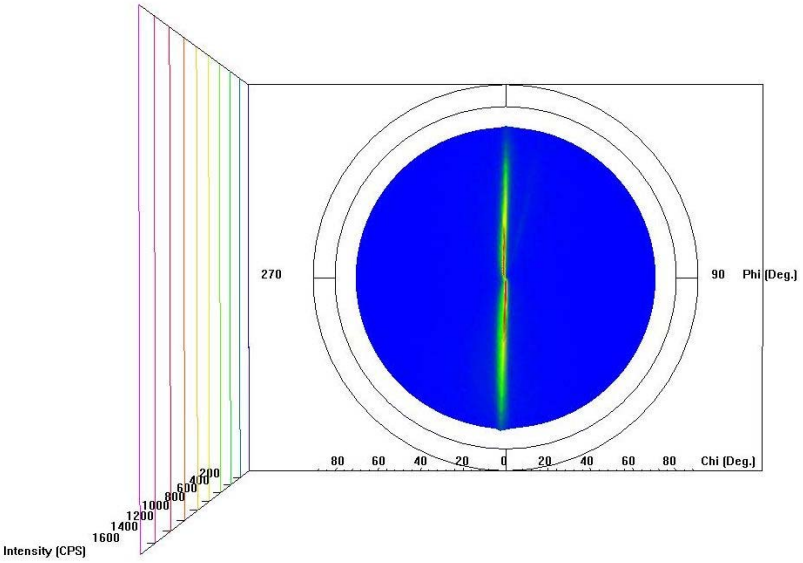

Figure 84. X-ray diffraction pole figures for HOPG sample from AGC-1 “sister samples” (110) orientation

3.5. Non-destructive Property Characterization

3.5.1. Density

The dimensional, mass, and density data for the grades examined here are reported in Appendices 7-15, and are summarized in Tables 10 and 11. The data in Table 10 were obtained by mensuration on the compressive strength samples and the thermal diffusivity samples. The grades with the greatest density were the vibrationally molded grades (NBG-17 and NBG-18), followed by the isostatically pressed grade IG-430, and the extruded grade PCEA. Grades IG-110 (isostatically pressed) and H-451 (extruded) had the smallest densities. It is interesting to note that grades made from pitch-cokes had greater densities than grades made from petroleum coke. For example, IG-430 (isostatically pressed, pitch-coke) had a greater density than IG-110 (isostatically pressed, petroleum coke). Moreover, both of the vibrationally molded grades (NBG-17 and NBG-18) are pitch-coke graphites. The ASTM D 7219 (2008) [11] specification for isotropic and near-isotropic graphite requires the bulk density to be > 1.7 $g.cm^{-3}$ (1700 $kg.m^{-3}$). All of the grades examined here exceed the specification requirement (although H-451 barely exceeds the minimum density requirement) as illustrated in Fig. 85.

Table 10. Bulk density data for the major grades determined by mensuration

Graphite Bulk Density by Mensuration							
		Compressive Strength Samples			Thermal Diffusivity Samples		
Graphite Grade	Orientation	No of Specimens	Mean (Kg/m^3)	Std. Dev. (Kg/m^3)	No of Specimens	Mean (Kg/m^3)	Std. Dev. (Kg/m^3)
NBG-17	WG	15	1858.0	2.2	6	1856.5	5.3
NBG-17	AG	15	1858.3	1.5	6	1865.3	6.0
NBG-18	WG	15	1871.3	3.4	6	1874.4	5.7
NBG-18	AG	15	1865.9	2.8	6	1869.6	7.8
H-451	WG	15	1710.7	8.0	6	1726.9	7.3
PCEA	WG	15	1793.8	5.6	6	1803.9	2.8
PCEA	AG	15	1790.5	3.8	6	1794.5	8.1
IG-110	Isotropic	15	1761.7	6.6	6	1766.5	8.1
IG-430	Isotropic	15	1802.6	5.2	6	1812.6	6.3

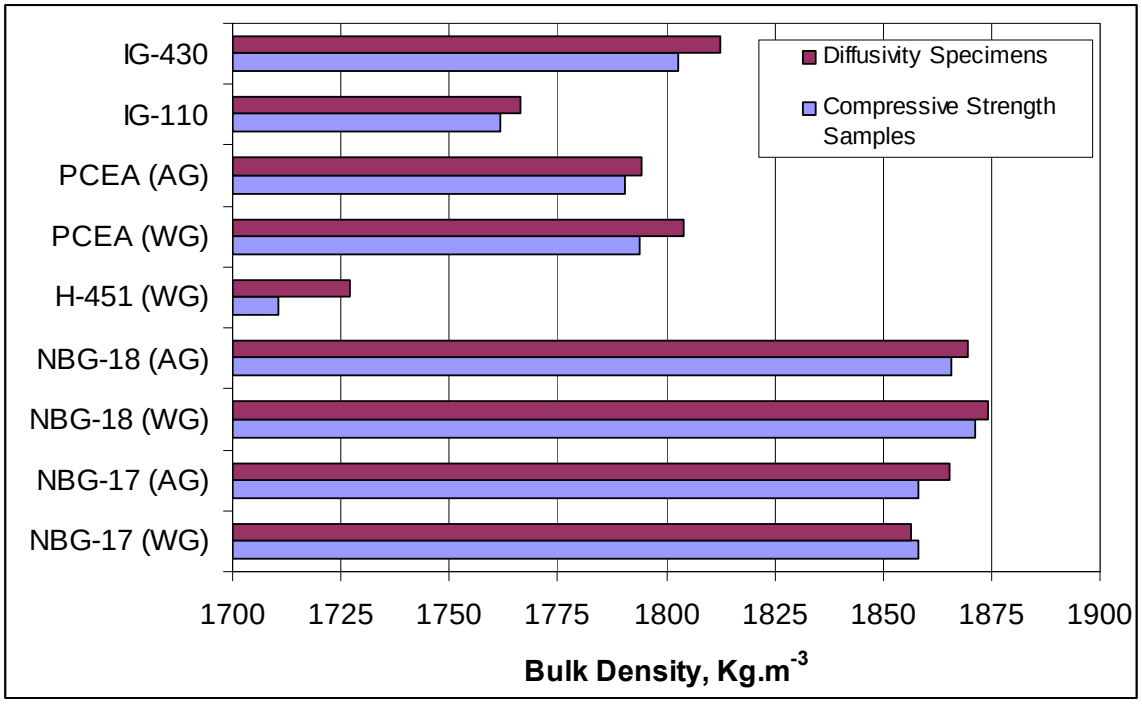

Figure 85. Summary bar chart of the density data for the major grades examined here

Table 11 shows the density data from the Hg-porosimetry specimens obtained by mensuration and also the Hg-immersion density. There is good agreement between the mensuration density data and the Hg-density data. Moreover, the same trends observed in the data reported in Table 10 are observed in Table 11. The Hg-skeletal density data for the major grades are also reported in Table 11. Appendix 24 reports all the Hg-density data for the porosimeter specimens (by grade).

Table 11. Density data by Hg-porosimetry and Mensuration on porosimetry samples

Hg-Porosimetry and Mensuration density for Major Grades								
	Mensuration Data				Hg-bulk Density		Hg-Skeletal Density	
Graphite Grade	No. of Specimens	Mean (Kg/m^3)	Std. Dev. (Kg/m^3)	No. of Specimens	Mean (Kg/m^3)	Std. Dev. (Kg/m^3)	Mean (Kg/m^3)	Std. Dev. (Kg/m^3)
NBG-17	6	1854.03	2.73	6	1866.5	9.4	2199.6	28.6
NBG-18	6	1863.93	6.43	6	1882.7	12	2162.2	89.2
H-451	4	1715.03	1.87	4	1727.9	6.5	2171.3	65.2
PCEA	6	1795.91	4.24	6	1804.5	7.1	2215.9	25.7
IG-110	4	1760.78	9.48	4	1773.4	13.4	2007.2	37.1
IG-430	4	1802.94	11.51	4	1807.1	9.8	1992.4	11.4

3.5.2. Dynamic Young's Modulus by Fundamental Frequency

The mean Young's modulus of each of the major grades examined here is presented in Table 12. The modulus was measured in both the WG and AG orientation for grades PCEA, NBG-17, and NBG-18. The complete data set for each grade is given in appendices 25-33. The greatest mean modulus value was recorded for the NBG-18 (AG) grade and the smallest modulus value recorded for the IG-110 grade. The anisotropy of the modulus in all three grades (PCEA, NBG-17, and NBG-18) was small. The ASTM standard specification for nuclear graphites, ASTM D 7219 (2008) [11] gives the allowable range for elastic modulus (WG) as 8-15 GPa. Clearly, the grades examined here all fall within the specified range.

Table 12. Summary of dynamic Young's modulus data for the AGC-1 sister samples (by fundamental frequency method)

Graphite Grade	Grain Orientation		Mean Modulus of Elasticity, E (GPa)	Standard Deviation (GPa)	Number of Specimens
	With (WG)	Against (AG)			
NBG-17 (WG)	X		10.828	0.097	27
NBG-17 (AG)		X	11.372	0.073	27
NBG-18 (WG)	X		11.648	0.260	27
NBG-18 (AG)		X	12.108	0.087	27
H-451	X		9.179	0.320	27
PCEA (WG)	X		10.234	0.215	27
PCEA (AG)		X	9.396	0.114	27
IG-110	Isotropic		8.676	0.232	27
IG-430	Isotropic		9.384	0.185	27

A visual representation of the modulus data is given in the bar chart in Fig. 86. The vibrationally molded grades (NBG-17 and NBG-18) exhibit greater Young's Moduli than the grades formed by isostatic pressing or extrusion.

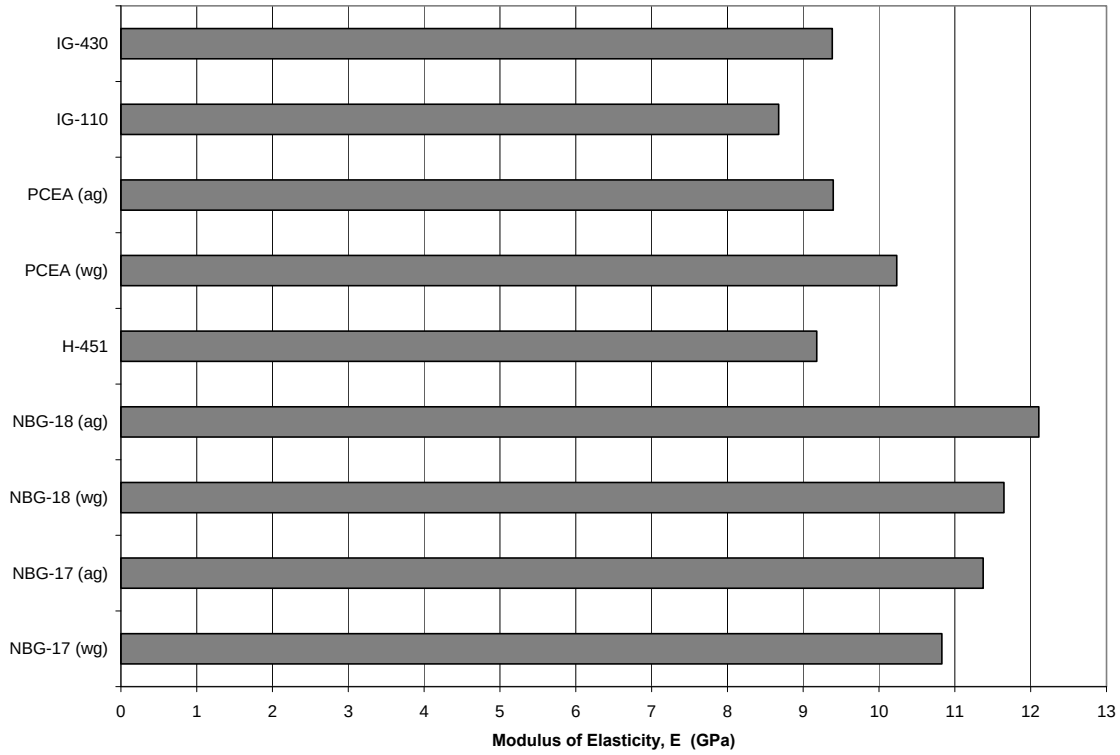

Figure 86. A comparison of the dynamic elastic moduli from fundamental frequency for the major grades examined here

3.5.3. Sonic Elastic Constants

Table 13 presents a summary of the mean sonic elastic constants (Young's Modulus, Shear Modulus, and Poisson's Ratio) for the major grades examined here. All sonic elastic constants data reported by grade are in Appendices 34-39. The elastic (Young's) moduli values again indicate the anisotropy of the modulus in all three grades (PCEA, NBG-17, and NBG-18) was small. The ASTM standard specification for nuclear graphites, ASTM D 7219 (2008) [11] gives the allowable range for Elastic Modulus (WG) as 8-15 GPa. The grades examined here all fall within the specified range. The mean sonic elastic (Young's) modulus data are shown graphically in Fig. 87. There sonic values are consistently smaller than the values obtained by the fundamental frequency (dynamic) method. Fig. 88 shows a comparison plot of the mean Young's moduli data for the two methods. The same trends are seen in both data sets, i.e., the vibrationally molded grades (NBG-17 and -18) exhibit grater moduli than the other grades, and the

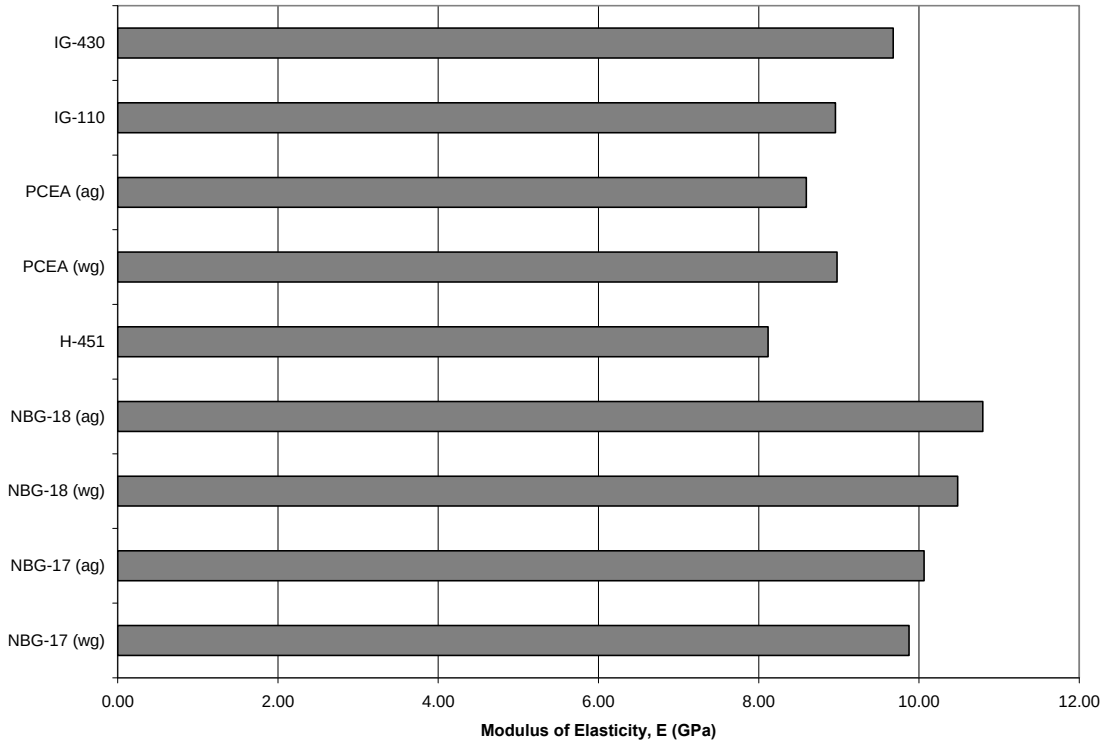

Figure 87. Graphic representation of the Young's moduli data determined from longitudinal sonic velocity

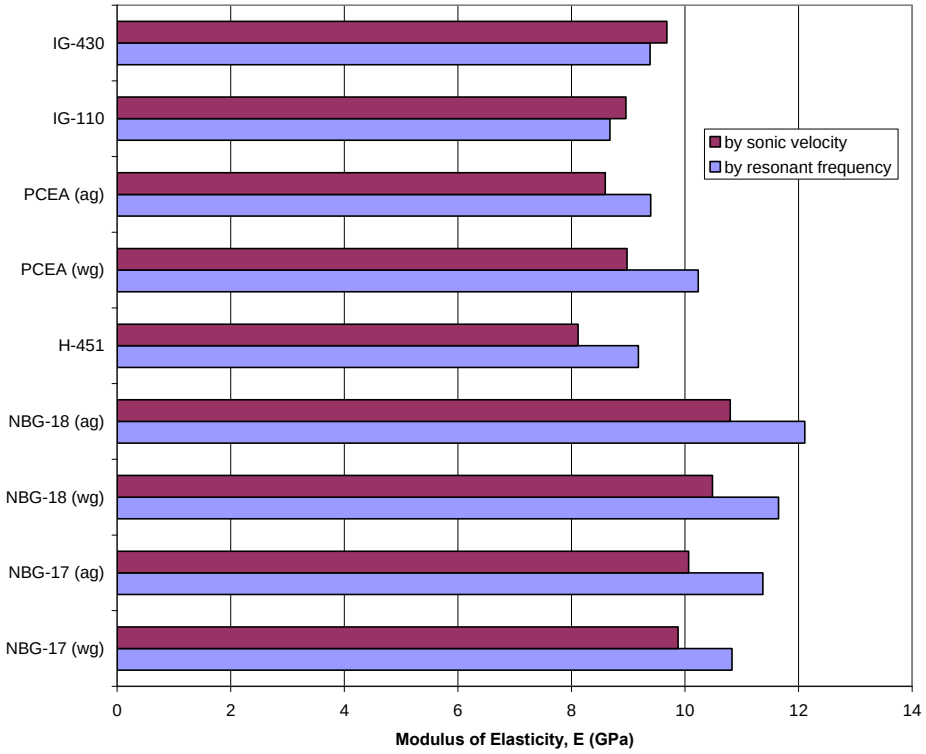

Figure 88. A comparison of the Elastic Modulus determined by the fundamental frequency and sonic velocity methods for each major grade examined here.

extruded grade (H-451) exhibited the smallest Young's modulus. The consistency of the moduli data is very encouraging, and indicates the value of the sonic technique, which can be applied during post irradiation examination to give fractional change in modulus with irradiation.

The Shear moduli data are summarized in the bar chart given in Figure 89. The trends displayed in the data generally mimic the Young's modulus data, with the greatest moduli being displayed by the vibrationally molded NBG-17 and -18 grades and the isostatically pressed IG-430. Grade H-451 exhibited the smallest shear modulus.

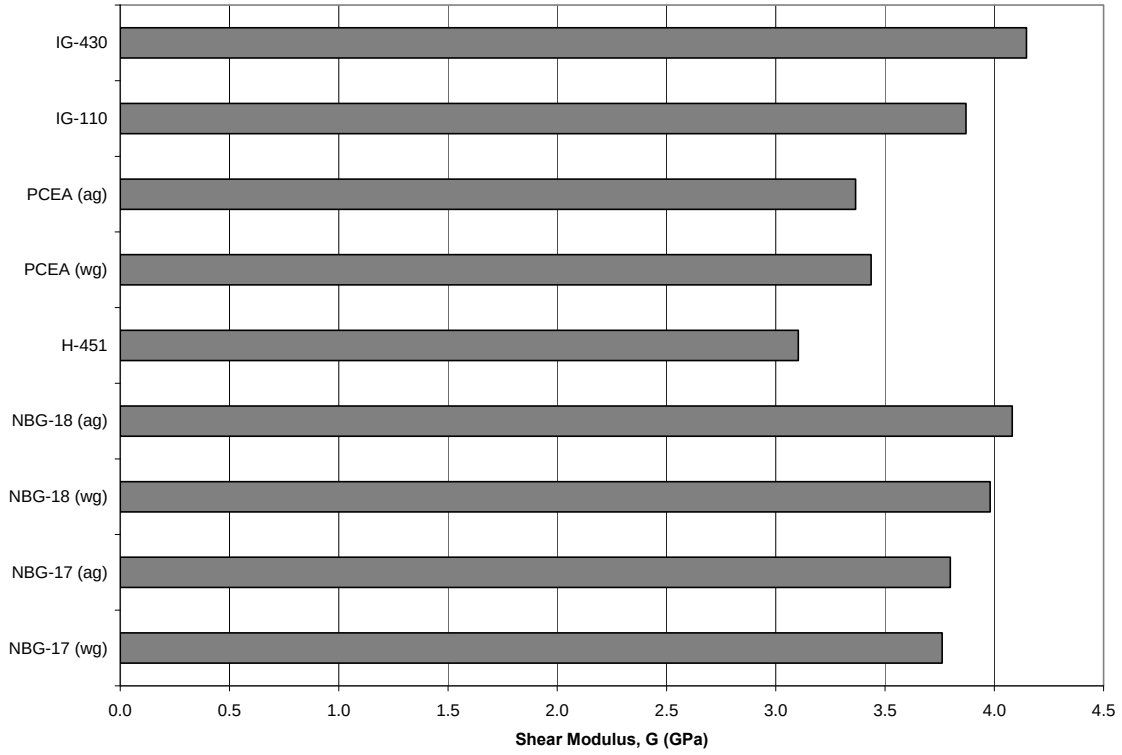

Figure 89. Graphic representation of the Shear moduli data determined from shear-waves sonic velocity

Fig. 90 shows the mean Poisson's ratio data for the grades examined. There is a large difference (almost a factor of two) between the values for the fine-grained isostatically pressed grades (IG-110 and IG-430) and the medium-grained grades. The medium-grained grades all exhibited a Poisson's ratio value of ~0.3. The large Poisson's ratio of some of the grades may have been a contributory factor in the difficulties encountered with the "glued-end" tensile testing. Indeed, ASTM C 781 (2008) [6] cautions that difficulties might be encountered with high strength graphite or were the Poisson's ratio mismatch is large.

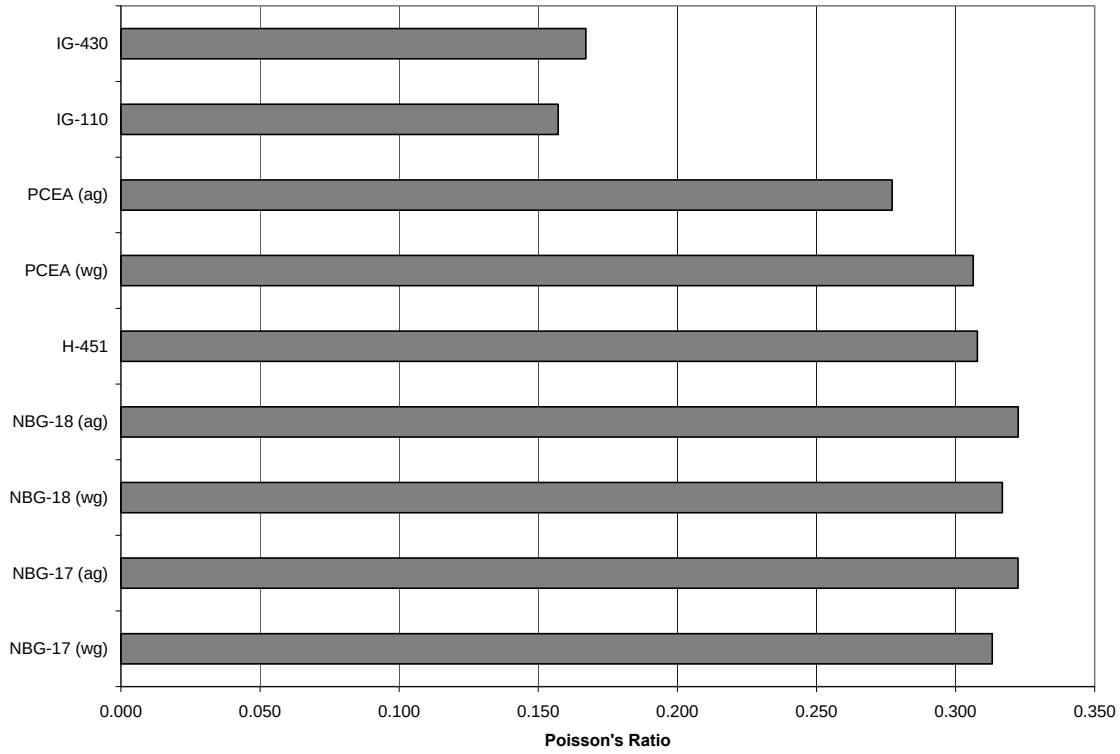

Figure 90. Graphic representation of the mean Poisson's ratio data determined from longitudinal- and shear-waves sonic velocity

Table 13. Summary of the sonic elastic constants data for the graphite grades examined here

Graphite Grade	Grain Orientation		Density, ρ (kg/m3)		Sonic Velocities, υ [m/s]				Modulus, E (GPa)		Shear Modulus, G (GPa)		Poisson's Ratio, μ		Number of Specimens
					Longitudinal		Shear								
	(WG)	(AG)	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	
NBG-17 (wg)	X		1858.0	2.24	2728.6	14.6	1422.7	10.1	9.88	0.11	3.76	0.054	0.313	0.005	15
NBG-17 (ag)		X	1858.3	1.47	2804.4	3.3	1429.8	9.1	10.06	0.10	3.80	0.047	0.322	0.003	15
NBG-18 (wg)	X		1871.3	3.38	2817.2	28.5	1458.3	27.8	10.48	0.35	3.98	0.154	0.317	0.008	15
NBG-18 (ag)		X	1865.9	2.84	2889.8	7.9	1479.0	8.6	10.80	0.10	4.08	0.047	0.323	0.003	15
H-451	X		1710.7	8.02	2556.6	26.6	1346.7	16.1	8.12	0.21	3.10	0.086	0.308	0.006	15
PCEA (wg)	X		1793.8	5.55	2619.3	22.8	1384.0	6.8	8.98	0.12	3.44	0.05	0.306	0.003	15
PCEA (ag)		X	1790.4	3.82	2469.0	14.6	1370.8	11.3	8.59	0.12	3.37	0.055	0.277	0.004	15
IG-110	Iso		1761.6	6.60	2324.4	32.5	1482.1	15.3	8.96	0.23	3.87	0.091	0.157	0.01	15
IG-430	Iso		1802.6	5.20	2399.6	27.7	1516.5	10.3	9.68	0.15	4.15	0.055	0.167	0.011	15

3.6. Specific Heat

The specific heat of graphite is a fundamental property of the crystal. Consequently, for well graphitized artificial graphites (such as the major grades in AGC-1) the specific heat should be identical. Indeed, the National Institute of Standards (NIST) has published a standard specific heat data set for POCO AXF-5Q graphite, and a recommended equation for the calculation of specific heat. This data and equation are incorporated into ASTM standard C 781(2008) [6]. For confirmatory purposes, the specific heat of several samples of grade NBG-18 was measured. The data are reported in Fig. 91 and compared to the predicted specific heat from eq. 12 [6]. The data are well fitted by the equation, falling within the ±5% error bards shown for the predictive equation. Consequently, the use of the standard equation (eq. 12) is justified in the calculation of elevated temperature thermal conductivity (eq. 11).

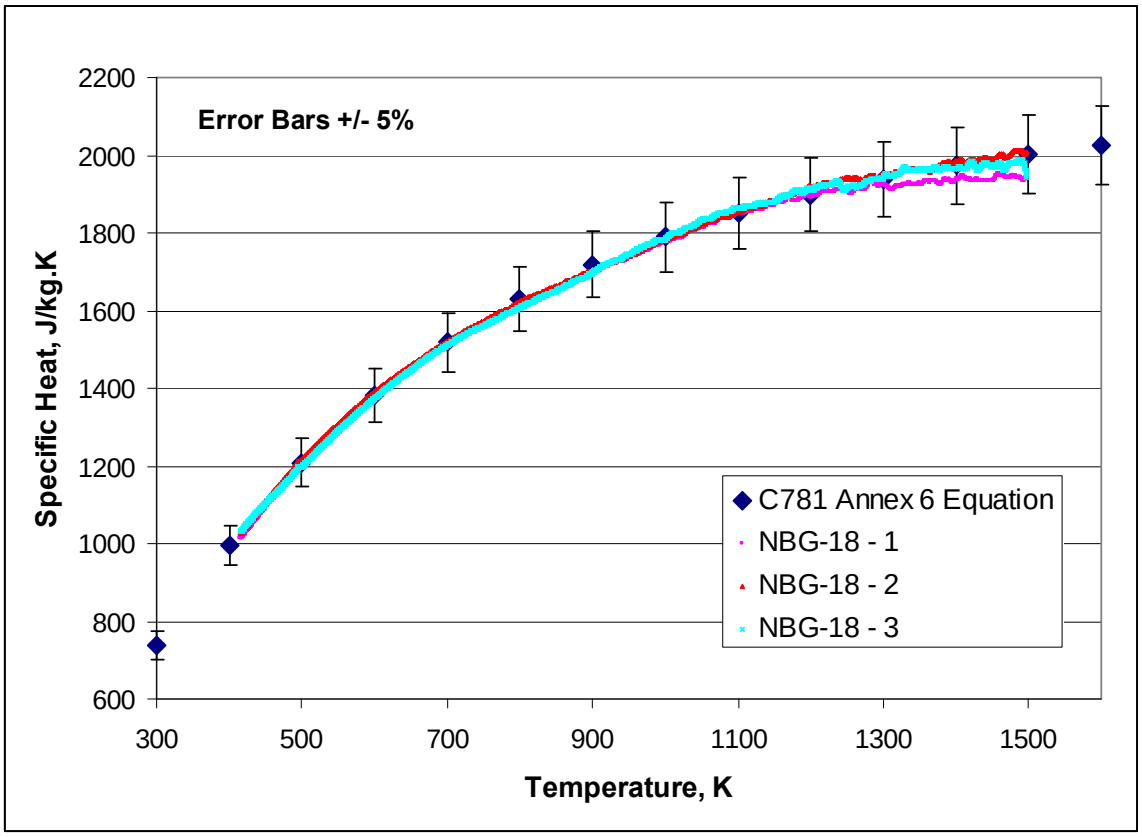

Figure 91. A comparison of the experimentally measured specific heat for grade NBG-18 graphite and the ASTM C 781 method recommended equation's prediction for specific heat of graphite.

3.7. Elevated Temperature Thermal Conductivity

3.7.1. Specimen thickness determination

High temperature thermal diffusivity measurements on solid 2, 3, and 6.35 mm thick, 12.7 mm diameter NBG-18 graphite samples yielded thermal conductivity data in good agreement with literature data for this grade. Moreover, only a small effect was seen with sample thickness (Fig. 92). The similarity of the 2 mm and 3 mm thermal conductivity data may be because of the small IR-detector spot (~3 mm diameter) used here, which essentially sets a lower limit on the effective sample size. The small detector spot size (a feature of most modern Xenon lamp thermal pulse diffusivity systems) has caused difficulty in determining the thermal conductivity of AGC-1 piggy-back specimens with a central hole (to accommodate the SiC temperature monitor). Consequently, high temperature thermal conductivity was determined on sister samples of the major graphite grades in AGC-1. The post irradiation thermal conductivity will be determined from specimens cut from the irradiated creep and control samples after other measurements have been completed.

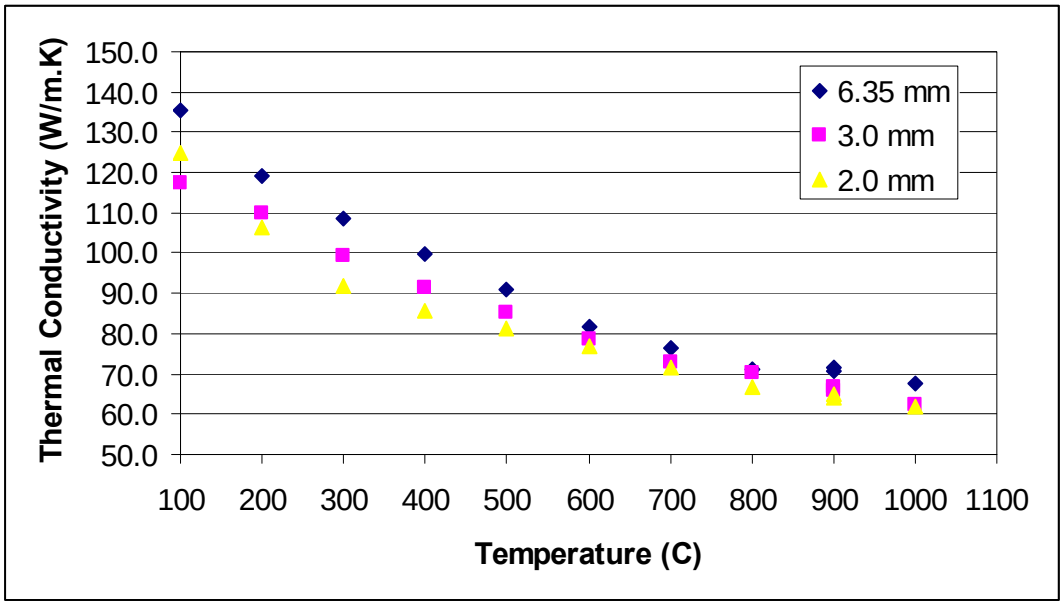

Figure 92. The temperature dependence of thermal conductivity for Grade NBG-18 for several different specimen thicknesses

Based upon the data show in Fig. 92 it was determined that a specimen thickness of 3 mm was representative. Grade NBG-18 has the largest grain size of the major grades and so represents the worst case in so far as texture considerations are concerned. Moreover, using the thicker 6.35 mm specimen in the irradiated condition would not be practical since the anticipated drop in thermal conductivity would make IR signal detection difficult post irradiation. Consequently, the 3 mm thick specimen was adopted for subsequent thermal conductivity measurements on all the grades examined.

3.7.2. NBG-18 thermal conductivity

Elevated temperature thermal diffusivity and thermal conductivity data for grade NBG-18 in the with-grain direction are reported in Tables 14-16 and for the against-grain direction in Tables 17-19. The reported thermal diffusivity values represent the mean of three measurements taken at each temperature. The mensuration data used to determine the specimen density is given in Appendix 40.

Table 14. Elevated temperature thermal diffusivity and conductivity data for grade NBG-18 (with grain) specimen B1-4-3

Thermal Conductivity, NBG-18 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm^2/sec	Specific Heat J/kg.K	Density Kg/m^3	Thermal Conductivity W/m.K
B1-4-3	WG	100	373	0.7603	930.3	1870.28	132.3
B1-4-3	WG	202	475	0.5361	1159.6	1870.28	116.3
B1-4-3	WG	302	575	0.4201	1341.5	1870.28	105.4
B1-4-3	WG	401	674	0.3456	1485.8	1870.28	96.0
B1-4-3	WG	501	774	0.2964	1602.7	1870.28	88.8
B1-4-3	WG	599	872	0.2563	1695.1	1870.28	81.3
B1-4-3	WG	697	970	0.2369	1770.3	1870.28	78.4
B1-4-3	WG	792	1065	0.2134	1830.2	1870.28	73.0
B1-4-3	WG	879	1152	0.1922	1876.2	1870.28	67.4
B1-4-3	WG	913	1186	0.1915	1892.2	1870.28	67.8
B1-4-3	WG	913	1186	0.1993	1892.2	1870.28	70.5
B1-4-3	WG	912	1185	0.1878	1891.8	1870.28	66.4
B1-4-3	WG	882	1155	0.1944	1877.7	1870.28	68.3
B1-4-3	WG	793	1066	0.2105	1830.8	1870.28	72.1
B1-4-3	WG	697	970	0.2288	1770.3	1870.28	75.8
B1-4-3	WG	600	873	0.261	1695.9	1870.28	82.8
B1-4-3	WG	502	775	0.2947	1603.8	1870.28	88.4
B1-4-3	WG	402	675	0.3495	1487.2	1870.28	97.2
B1-4-3	WG	303	576	0.4237	1343.1	1870.28	106.4
B1-4-3	WG	303	576	0.4281	1343.1	1870.28	107.5
B1-4-3	WG	203	476	0.5564	1161.7	1870.28	120.9
B1-4-3	WG	101	374	0.6881	932.8	1870.28	120.0

Table 15. Elevated temperature thermal diffusivity and conductivity data for grade NBG-18 (with grain) specimen B5-4-3

Thermal Conductivity, NBG-18 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm^2/sec	Specific Heat J/kg.K	Density Kg/m^3	Thermal Conductivity W/m.K
B5-4-3	WG	100	373	0.7504	930.3	1885.17	131.6
B5-4-3	WG	202	475	0.5384	1159.6	1885.17	117.7
B5-4-3	WG	302	575	0.4237	1341.5	1885.17	107.2
B5-4-3	WG	401	674	0.3443	1485.8	1885.17	96.4
B5-4-3	WG	500	773	0.2995	1601.7	1885.17	90.4
B5-4-3	WG	599	872	0.2666	1695.1	1885.17	85.2
B5-4-3	WG	697	970	0.2389	1770.3	1885.17	79.7
B5-4-3	WG	792	1065	0.2145	1830.2	1885.17	74.0
B5-4-3	WG	879	1152	0.197	1876.2	1885.17	69.7
B5-4-3	WG	912	1185	0.1901	1891.8	1885.17	67.8
B5-4-3	WG	913	1186	0.1892	1892.2	1885.17	67.5
B5-4-3	WG	913	1186	0.1936	1892.2	1885.17	69.1
B5-4-3	WG	880	1153	0.2065	1876.7	1885.17	73.1
B5-4-3	WG	793	1066	0.2105	1830.8	1885.17	72.7
B5-4-3	WG	697	970	0.2353	1770.3	1885.17	78.5
B5-4-3	WG	600	873	0.2663	1695.9	1885.17	85.1
B5-4-3	WG	501	774	0.3001	1602.7	1885.17	90.7
B5-4-3	WG	402	675	0.3533	1487.2	1885.17	99.0
B5-4-3	WG	303	576	0.4345	1343.1	1885.17	110.0
B5-4-3	WG	302	575	0.427	1341.5	1885.17	108.0
B5-4-3	WG	101	374	0.7447	932.8	1885.17	131.0

Table 16. Elevated temperature thermal diffusivity and conductivity data for grade NBG-18 (with grain) specimen B9-4-3

Thermal Conductivity, NBG-18 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm^2/sec	Specific Heat J/kg.K	Density Kg/m^3	Thermal Conductivity W/m.K
B9-4-3	WG	100	373	0.7745	930.3	1874.11	135.0
B9-4-3	WG	202	475	0.5375	1159.6	1874.11	116.8
B9-4-3	WG	302	575	0.4298	1341.5	1874.11	108.1
B9-4-3	WG	401	674	0.3439	1485.8	1874.11	95.8
B9-4-3	WG	500	773	0.2982	1601.7	1874.11	89.5
B9-4-3	WG	599	872	0.2635	1695.1	1874.11	83.7
B9-4-3	WG	696	969	0.2361	1769.6	1874.11	78.3
B9-4-3	WG	792	1065	0.2092	1830.2	1874.11	71.8
B9-4-3	WG	880	1153	0.1983	1876.7	1874.11	69.7
B9-4-3	WG	911	1184	0.1902	1891.3	1874.11	67.4
B9-4-3	WG	912	1185	0.1925	1891.8	1874.11	68.2
B9-4-3	WG	911	1184	0.1853	1891.3	1874.11	65.7
B9-4-3	WG	880	1153	0.1974	1876.7	1874.11	69.4
B9-4-3	WG	793	1066	0.2163	1830.8	1874.11	74.2
B9-4-3	WG	697	970	0.2355	1770.3	1874.11	78.1
B9-4-3	WG	600	873	0.2613	1695.9	1874.11	83.1
B9-4-3	WG	501	774	0.2962	1602.7	1874.11	89.0
B9-4-3	WG	402	675	0.3524	1487.2	1874.11	98.2
B9-4-3	WG	303	576	0.4302	1343.1	1874.11	108.3
B9-4-3	WG	302	575	0.4297	1341.5	1874.11	108.0
B9-4-3	WG	203	476	0.5445	1161.7	1874.11	118.5
B9-4-3	WG	102	375	0.7596	935.2	1874.11	133.1

Figs. 93-95 report the thermal conductivity data as a function of temperature. The two curves on each plot show the heating and cooling thermal conductivity data. There is good agreement between the heating and cooling curves for all of the NBG-18 WG data.

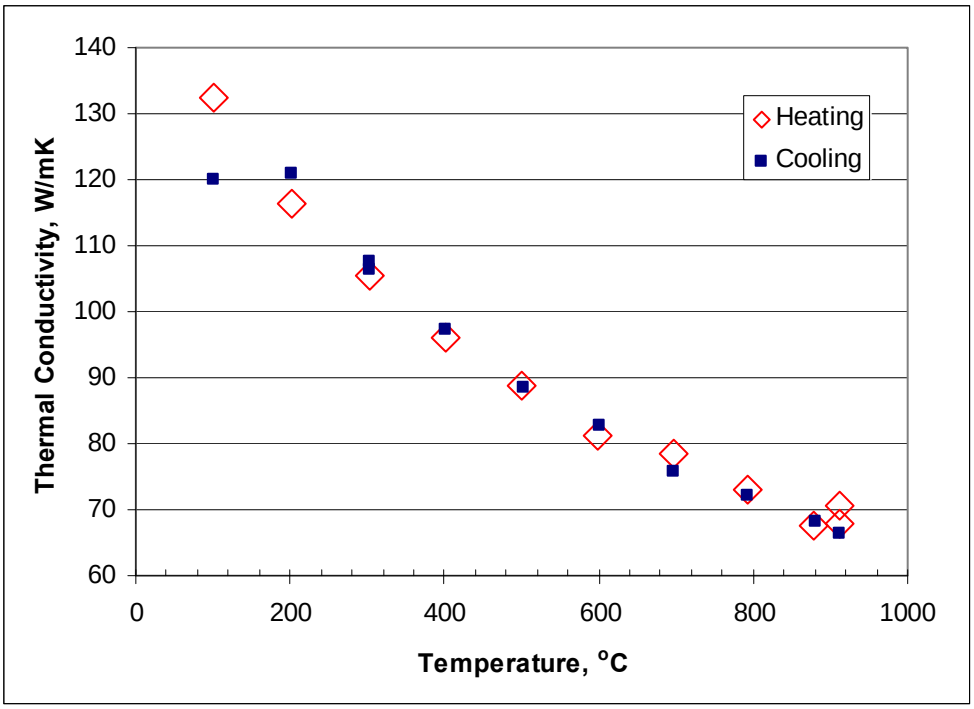

Figure 93. With-grain elevated temperature thermal conductivity for grade NBG-18 (specimen B1-4-3)

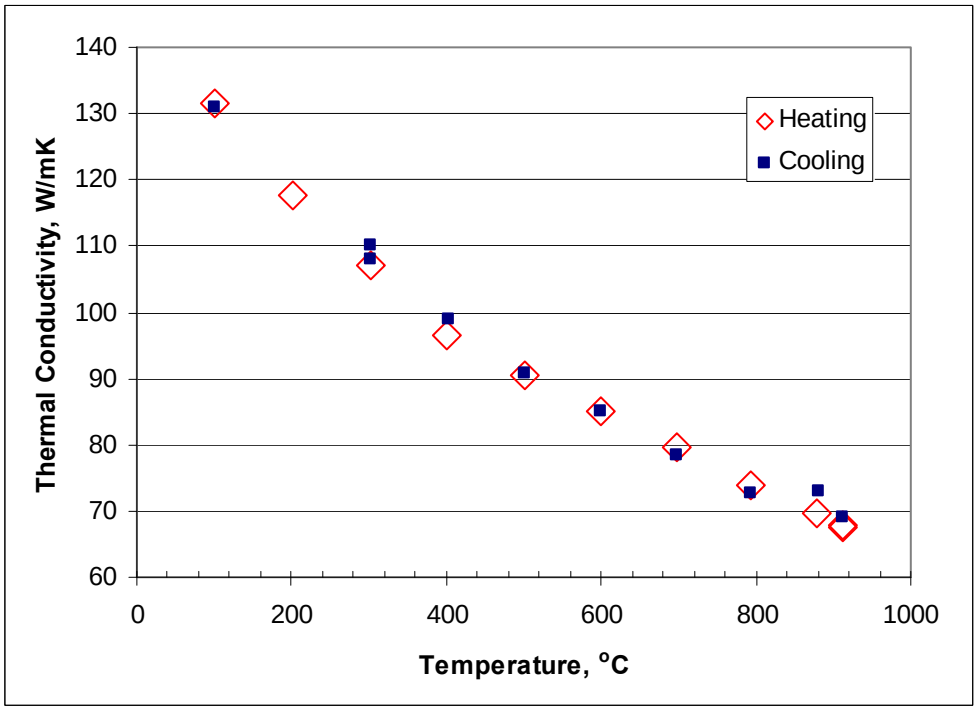

Figure 94. With-grain elevated temperature thermal conductivity for grade NBG-18 (specimen B5-4-3)

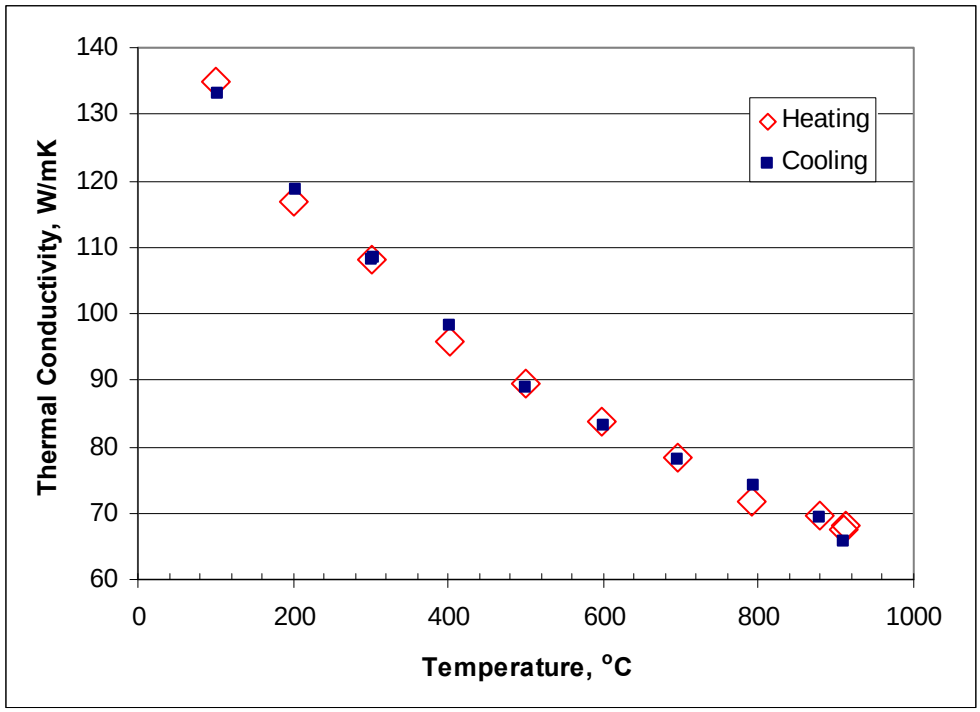

Figure 95. With-grain elevated temperature thermal conductivity for grade NBG-18 (specimen B9-4-3)

Elevated temperature thermal diffusivity and thermal conductivity data for grade NBG-18 in the against-grain direction are reported in Tables 17-19.

Table 17. Elevated temperature thermal diffusivity and conductivity data for grade NBG-18 (against-grain) specimen BB1-4-3

Thermal Conductivity, NBG-18 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm^2/sec	Specific Heat J/kgK	Density Kg/m^3	Thermal Conductivity W/mK
BB1-4-3	AG	100	373	0.7699	930.3	1870.4	134.0
BB1-4-3	AG	201	474	0.5712	1157.6	1870.4	123.7
BB1-4-3	AG	302	575	0.4408	1341.5	1870.4	110.6
BB1-4-3	AG	400	673	0.3584	1484.5	1870.4	99.5
BB1-4-3	AG	500	773	0.3149	1601.7	1870.4	94.3
BB1-4-3	AG	599	872	0.2745	1695.1	1870.4	87.0
BB1-4-3	AG	697	970	0.2549	1770.3	1870.4	84.4
BB1-4-3	AG	793	1066	0.2242	1830.8	1870.4	76.8
BB1-4-3	AG	879	1152	0.21	1876.2	1870.4	73.7
BB1-4-3	AG	913	1186	0.2034	1892.2	1870.4	72.0
BB1-4-3	AG	913	1186	0.2091	1892.2	1870.4	74.0
BB1-4-3	AG	911	1184	0.201	1891.3	1870.4	71.1
BB1-4-3	AG	879	1152	0.2108	1876.2	1870.4	74.0
BB1-4-3	AG	793	1066	0.2211	1830.8	1870.4	75.7
BB1-4-3	AG	697	970	0.2521	1770.3	1870.4	83.5
BB1-4-3	AG	599	872	0.2808	1695.1	1870.4	89.0
BB1-4-3	AG	501	774	0.3163	1602.7	1870.4	94.8
BB1-4-3	AG	401	674	0.3715	1485.8	1870.4	103.2
BB1-4-3	AG	302	575	0.4492	1341.5	1870.4	112.7
BB1-4-3	AG	301	574	0.4651	1339.9	1870.4	116.6
BB1-4-3	AG	201	474	0.5899	1157.6	1870.4	127.7
BB1-4-3	AG	100	373	0.7836	930.3	1870.4	136.3

Table 18. Elevated temperature thermal diffusivity and conductivity data for grade NBG-18 (against-grain) specimen BB5-4-3

Thermal Conductivity, NBG-18 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm^2/sec	Specific Heat J/kgK	Density Kg/m^3	Thermal Conductivity W/mK
BB5-4-3	AG	100	373	0.7818	930.3	1865.44	135.7
BB5-4-3	AG	201	474	0.5899	1157.6	1865.44	127.4
BB5-4-3	AG	301	574	0.4488	1339.9	1865.44	112.2
BB5-4-3	AG	400	673	0.369	1484.5	1865.44	102.2
BB5-4-3	AG	500	773	0.3206	1601.7	1865.44	95.8
BB5-4-3	AG	599	872	0.2709	1695.1	1865.44	85.7
BB5-4-3	AG	696	969	0.2529	1769.6	1865.44	83.5
BB5-4-3	AG	793	1066	0.2293	1830.8	1865.44	78.3
BB5-4-3	AG	880	1153	0.2078	1876.7	1865.44	72.7
BB5-4-3	AG	911	1184	0.2	1891.3	1865.44	70.6
BB5-4-3	AG	914	1187	0.2122	1892.7	1865.44	74.9
BB5-4-3	AG	911	1184	0.2046	1891.3	1865.44	72.2
BB5-4-3	AG	879	1152	0.205	1876.2	1865.44	71.7
BB5-4-3	AG	793	1066	0.2298	1830.8	1865.44	78.5
BB5-4-3	AG	696	969	0.2517	1769.6	1865.44	83.1
BB5-4-3	AG	599	872	0.3019	1695.1	1865.44	95.5
BB5-4-3	AG	500	773	0.3135	1601.7	1865.44	93.7
BB5-4-3	AG	401	674	0.3648	1485.8	1865.44	101.1
BB5-4-3	AG	301	574	0.44	1339.9	1865.44	110.0
BB5-4-3	AG	301	574	0.4599	1339.9	1865.44	114.9
BB5-4-3	AG	201	474	0.5766	1157.6	1865.44	124.5
BB5-4-3	AG	100	373	0.8075	930.3	1865.44	140.1

Table 19. Elevated temperature thermal diffusivity and conductivity data for grade NBG-18 (against-grain) specimen BB9-4-3

Thermal Conductivity, NBG-18 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm^2/sec	Specific Heat J/kgK	Density Kg/m^3	Thermal Conductivity W/mK
BB9-4-3	AG	100	373	0.7869	930.3	1881.87	137.8
BB9-4-3	AG	201	474	0.5571	1157.6	1881.87	121.4
BB9-4-3	AG	301	574	0.4428	1339.9	1881.87	111.6
BB9-4-3	AG	400	673	0.3571	1484.5	1881.87	99.8
BB9-4-3	AG	499	772	0.3138	1600.6	1881.87	94.5
BB9-4-3	AG	598	871	0.2738	1694.3	1881.87	87.3
BB9-4-3	AG	696	969	0.2384	1769.6	1881.87	79.4
BB9-4-3	AG	792	1065	0.2236	1830.2	1881.87	77.0
BB9-4-3	AG	878	1151	0.2053	1875.7	1881.87	72.5
BB9-4-3	AG	909	1182	0.2104	1890.4	1881.87	74.8
BB9-4-3	AG	912	1185	0.2039	1891.8	1881.87	72.6
BB9-4-3	AG	909	1182	0.2127	1890.4	1881.87	75.7
BB9-4-3	AG	878	1151	0.2112	1875.7	1881.87	74.6
BB9-4-3	AG	792	1065	0.2252	1830.2	1881.87	77.6
BB9-4-3	AG	696	969	0.2411	1769.6	1881.87	80.3
BB9-4-3	AG	599	872	0.2509	1695.1	1881.87	80.0
BB9-4-3	AG	500	773	0.3074	1601.7	1881.87	92.7
BB9-4-3	AG	400	673	0.363	1484.5	1881.87	101.4
BB9-4-3	AG	301	574	0.4637	1339.9	1881.87	116.9
BB9-4-3	AG	301	574	0.4604	1339.9	1881.87	116.1
BB9-4-3	AG	201	474	0.5579	1157.6	1881.87	121.5
BB9-4-3	AG	100	373	0.7789	930.3	1881.87	136.4

Figs. 96-98 report the NBG-18 (AG) thermal conductivity data as a function of temperature. The two curves on each plot show the heating and cooling thermal conductivity data. Again, there is good agreement between the heating and cooling curves for all of the NBG-18 AG data.

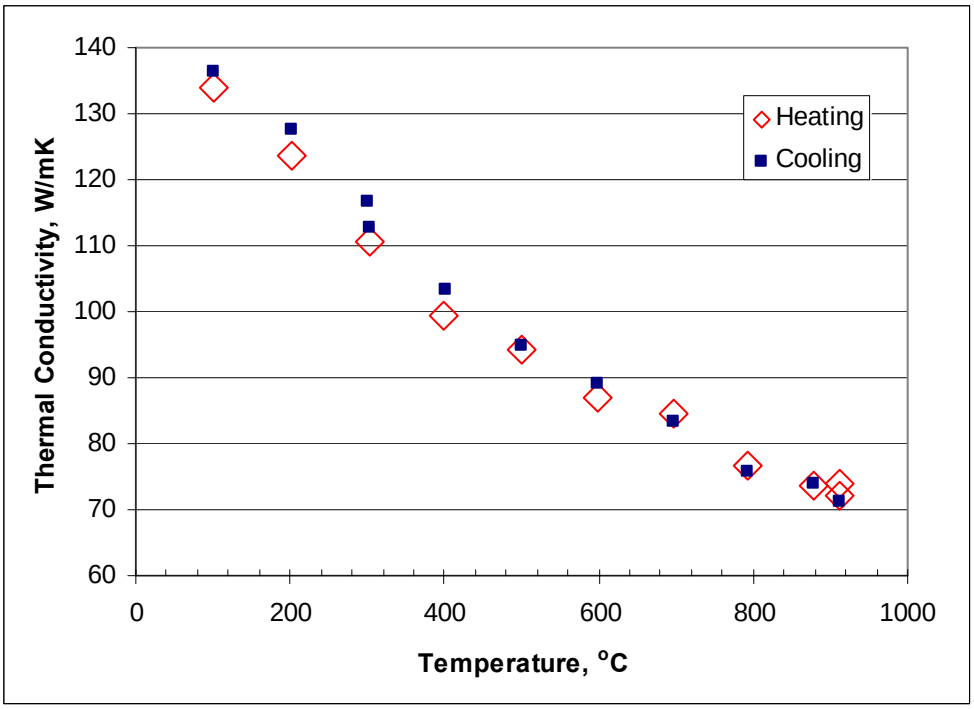

Figure 96. Against-grain elevated temperature thermal conductivity for grade NBG-18 (specimen BB1-4-3)

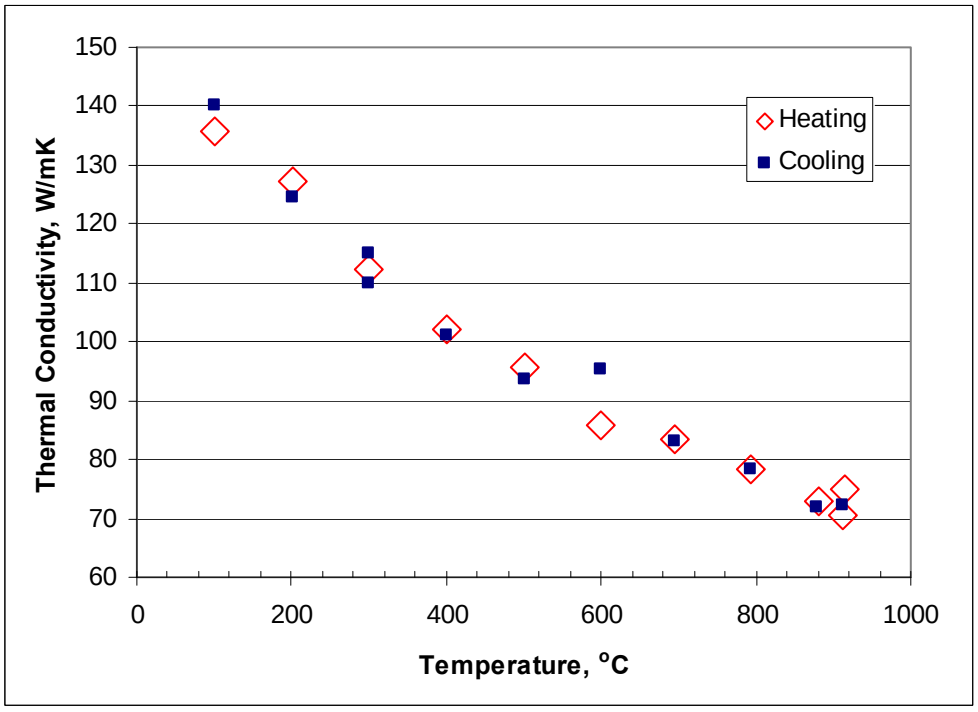

Figure 97. Against-grain elevated temperature thermal conductivity for grade NBG-18 (specimen BB5-4-3)

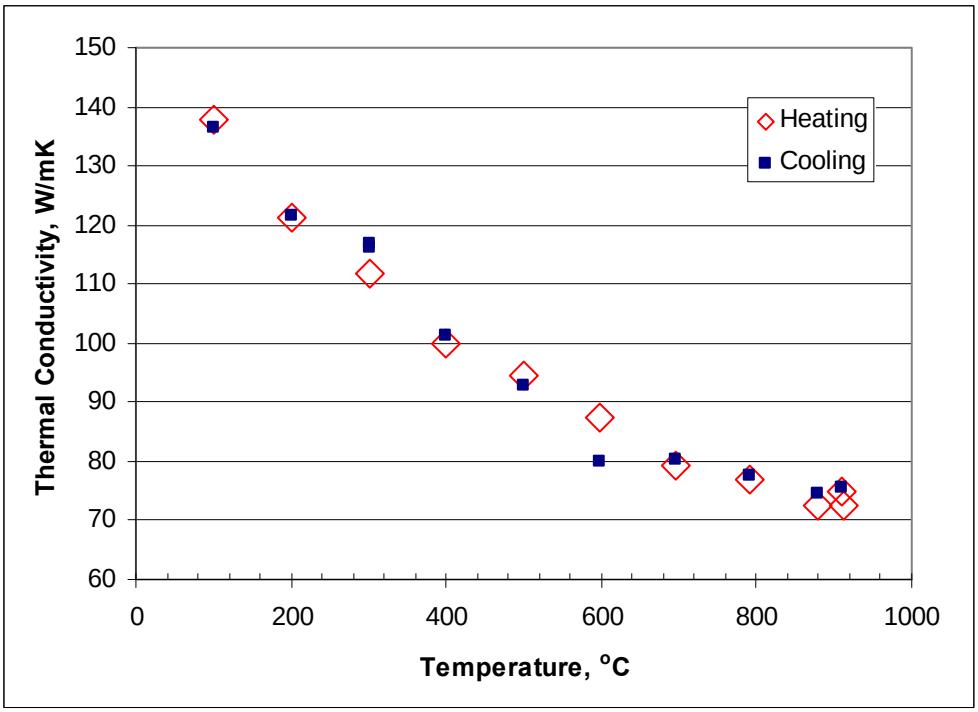

Figure 98. Against-grain elevated temperature thermal conductivity for grade NBG-18 (specimen BB9-4-3)

Figs. 99-101 compare the with- and against-grain orientations and indicate NBG-18 is nearly isotropic.

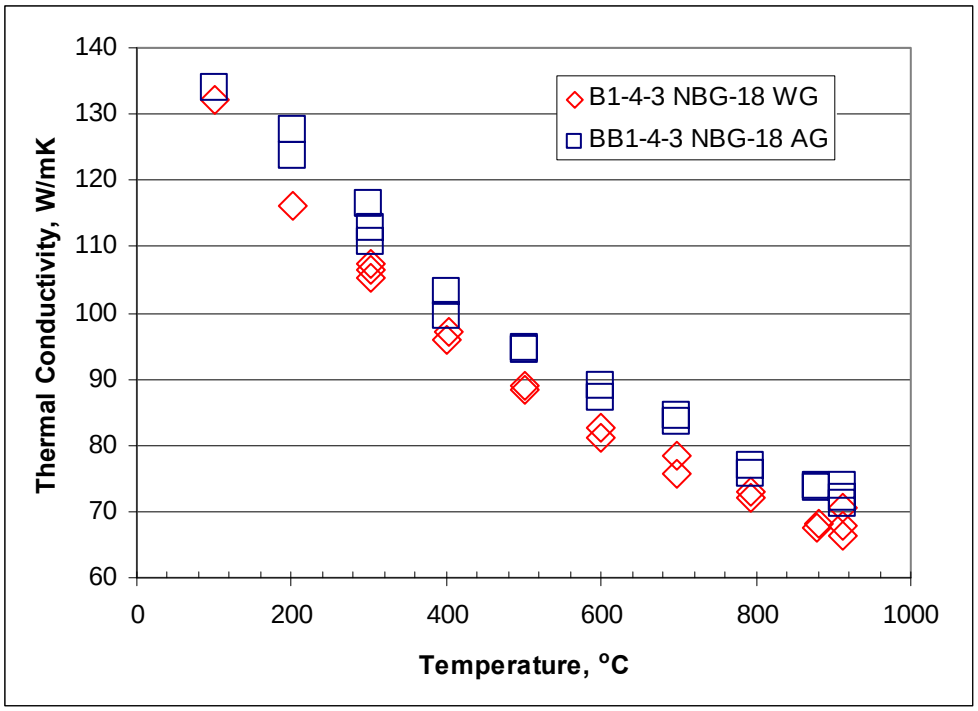

Figure 99. Comparison of with- and against-grain elevated temperature thermal conductivity for grade NBG-18

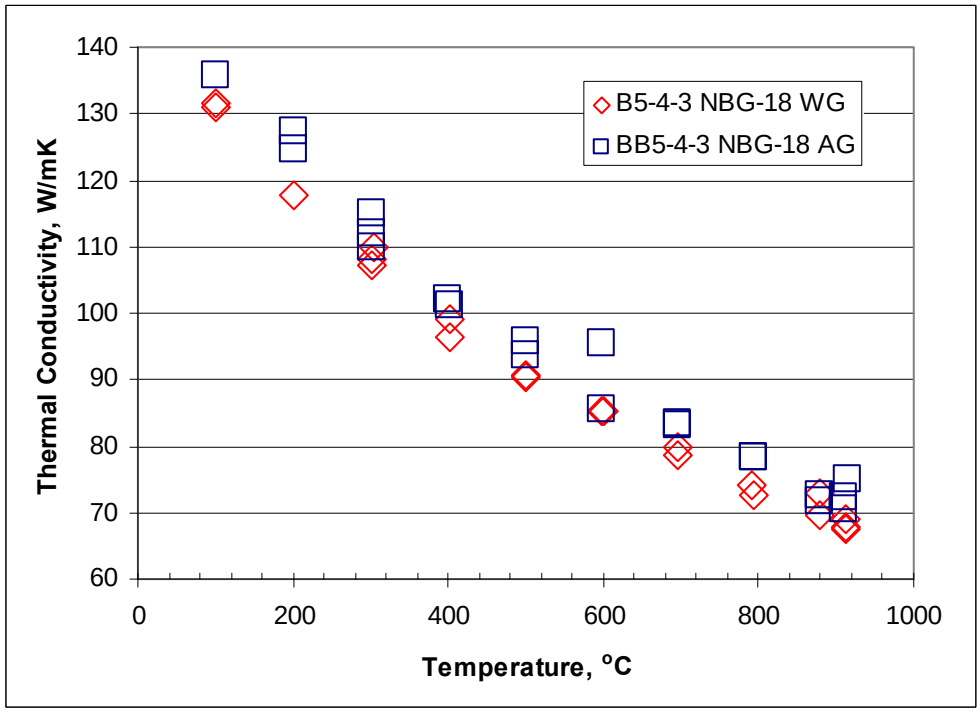

Figure 100. Comparison of with- and against-grain elevated temperature thermal conductivity for grade NBG-18

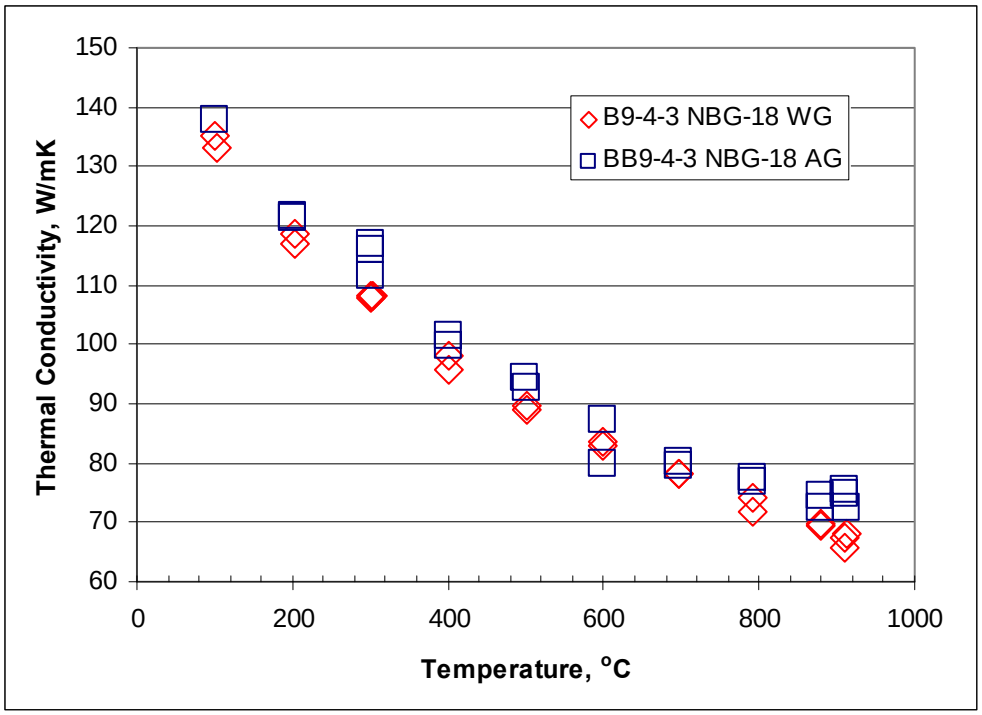

Figure 101. Comparison of with- and against-grain elevated temperature thermal conductivity for grade NBG-18

3.7.3. NBG-17 thermal conductivity

Elevated temperature thermal diffusivity and thermal conductivity data for grade NBG-17 in the with-grain direction are reported in Tables 20-22 and for the against-grain direction in Tables 23-25. The reported thermal diffusivity values represent the mean of three measurements taken at each temperature. The mensuration data used to determine the specimen density is given in Appendix 40.

Table 20. Elevated temperature thermal diffusivity and conductivity data for grade NBG-17 (with grain) specimen A1-4-3

Thermal Conductivity, NBG-17 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm2/sec	Specifi c Heat J/kg.K	Density Kg/m3	Thermal Conductivity W/m.K
A1-4-3	WG	102	375	0.7242	935.2	1863.05	126.2
A1-4-3	WG	202	475	0.529	1159.6	1863.05	114.3
A1-4-3	WG	302	575	0.4238	1341.5	1863.05	105.9
A1-4-3	WG	401	674	0.3488	1485.8	1863.05	96.6
A1-4-3	WG	501	774	0.2942	1602.7	1863.05	87.8
A1-4-3	WG	600	873	0.2525	1695.9	1863.05	79.8
A1-4-3	WG	697	970	0.2336	1770.3	1863.05	77.0
A1-4-3	WG	794	1067	0.2099	1831.4	1863.05	71.6
A1-4-3	WG	879	1152	0.1937	1876.2	1863.05	67.7
A1-4-3	WG	913	1186	0.1924	1892.2	1863.05	67.8
A1-4-3	WG	917	1190	0.1949	1894.1	1863.05	68.8
A1-4-3	WG	914	1187	0.1967	1892.7	1863.05	69.4
A1-4-3	WG	882	1155	0.2029	1877.7	1863.05	71.0
A1-4-3	WG	794	1067	0.2028	1831.4	1863.05	69.2
A1-4-3	WG	698	971	0.2339	1771.0	1863.05	77.2
A1-4-3	WG	600	873	0.2578	1695.9	1863.05	81.5
A1-4-3	WG	501	774	0.2967	1602.7	1863.05	88.6
A1-4-3	WG	401	674	0.3415	1485.8	1863.05	94.5
A1-4-3	WG	401	674	0.3456	1485.8	1863.05	95.7
A1-4-3	WG	302	575	0.4186	1341.5	1863.05	104.6
A1-4-3	WG	202	475	0.5512	1159.6	1863.05	119.1
A1-4-3	WG	102	375	0.7209	935.2	1863.05	125.6

Table 21. Elevated temperature thermal diffusivity and conductivity data for grade NBG-17 (with grain) specimen A5-4-3

Thermal Conductivity, NBG-17 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm2/sec	Specific Heat J/kgK	Density Kg/m3	Thermal Conductivity W/mK
A5-4-3	WG	101	374	0.7501	932.8	1857.14	129.9
A5-4-3	WG	202	475	0.561	1159.6	1857.14	120.8
A5-4-3	WG	301	574	0.4195	1339.9	1857.14	104.4
A5-4-3	WG	400	673	0.3477	1484.5	1857.14	95.9
A5-4-3	WG	501	774	0.2961	1602.7	1857.14	88.1
A5-4-3	WG	599	872	0.2556	1695.1	1857.14	80.5
A5-4-3	WG	697	970	0.2228	1770.3	1857.14	73.2
A5-4-3	WG	793	1066	0.2022	1830.8	1857.14	68.7
A5-4-3	WG	881	1154	0.1969	1877.2	1857.14	68.6
A5-4-3	WG	913	1186	0.1912	1892.2	1857.14	67.2
A5-4-3	WG	917	1190	0.1881	1894.1	1857.14	66.2
A5-4-3	WG	912	1185	0.1874	1891.8	1857.14	65.8
A5-4-3	WG	880	1153	0.1893	1876.7	1857.14	66.0
A5-4-3	WG	793	1066	0.2173	1830.8	1857.14	73.9
A5-4-3	WG	697	970	0.2356	1770.3	1857.14	77.5
A5-4-3	WG	600	873	0.2623	1695.9	1857.14	82.6
A5-4-3	WG	501	774	0.2932	1602.7	1857.14	87.3
A5-4-3	WG	401	674	0.3423	1485.8	1857.14	94.5
A5-4-3	WG	401	674	0.3621	1485.8	1857.14	99.9
A5-4-3	WG	302	575	0.4229	1341.5	1857.14	105.4
A5-4-3	WG	202	475	0.5314	1159.6	1857.14	114.4
A5-4-3	WG	102	375	0.8135	935.2	1857.14	141.3

Table 22. Elevated temperature thermal diffusivity and conductivity data for grade NBG-17 (with grain) specimen A9-4-3

Thermal Conductivity, NBG-17 (3 mm thick specimens)							
Specimen	Orientation	Temperature	Temperature	Mean Thermal Diffusivity	Specific Heat	Density	Thermal Conductivity
		C	K	cm2/sec	J/kgK	Kg/m3	W/mK
A9-4-3	WG	101	374	0.7175	932.8	1852.44	124.0
A9-4-3	WG	201	474	0.5314	1157.6	1852.44	114.0
A9-4-3	WG	301	574	0.4196	1339.9	1852.44	104.1
A9-4-3	WG	400	673	0.3361	1484.5	1852.44	92.4
A9-4-3	WG	500	773	0.2884	1601.7	1852.44	85.6
A9-4-3	WG	600	873	0.2657	1695.9	1852.44	83.5
A9-4-3	WG	697	970	0.2258	1770.3	1852.44	74.0
A9-4-3	WG	794	1067	0.2036	1831.4	1852.44	69.1
A9-4-3	WG	879	1152	0.1905	1876.2	1852.44	66.2
A9-4-3	WG	915	1188	0.1878	1893.2	1852.44	65.9
A9-4-3	WG	919	1192	0.1897	1895.0	1852.44	66.6
A9-4-3	WG	916	1189	0.1861	1893.6	1852.44	65.3
A9-4-3	WG	882	1155	0.1984	1877.7	1852.44	69.0
A9-4-3	WG	793	1066	0.213	1830.8	1852.44	72.2
A9-4-3	WG	697	970	0.2313	1770.3	1852.44	75.9
A9-4-3	WG	599	872	0.2525	1695.1	1852.44	79.3
A9-4-3	WG	501	774	0.2878	1602.7	1852.44	85.4
A9-4-3	WG	401	674	0.3374	1485.8	1852.44	92.9
A9-4-3	WG	400	673	0.3518	1484.5	1852.44	96.7
A9-4-3	WG	202	475	0.5612	1159.6	1852.44	120.6
A9-4-3	WG	101	374	0.7101	932.8	1852.44	122.7

Figs. 102-104 report the thermal conductivity data as a function of temperature. The two curves on each plot show the heating and cooling thermal conductivity data. There is good agreement between the heating and cooling curves for all of the NBG-17 WG data.

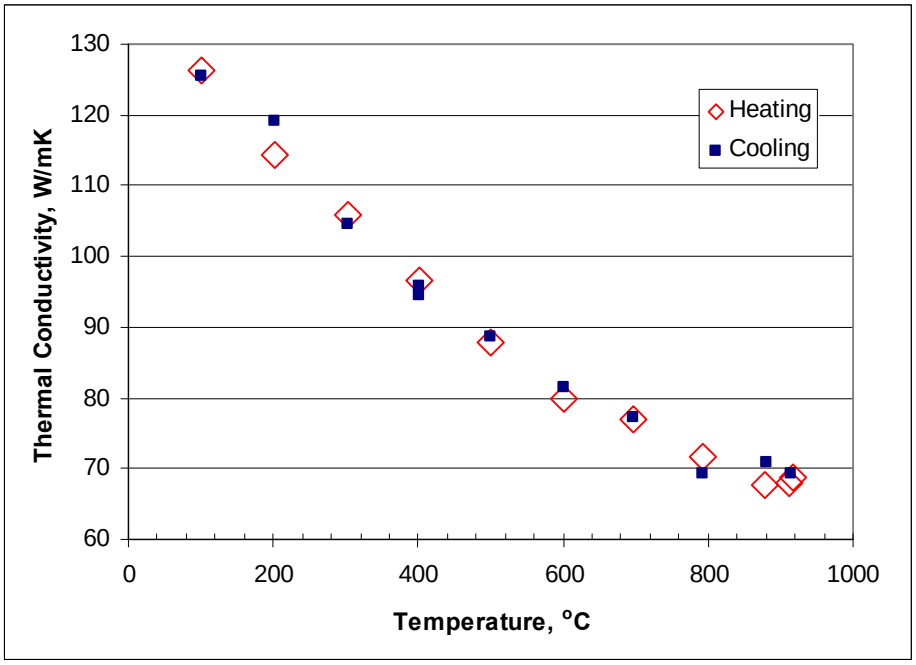

Figure 102. With-grain elevated temperature thermal conductivity for grade NBG-17 (specimen A1-4-3)

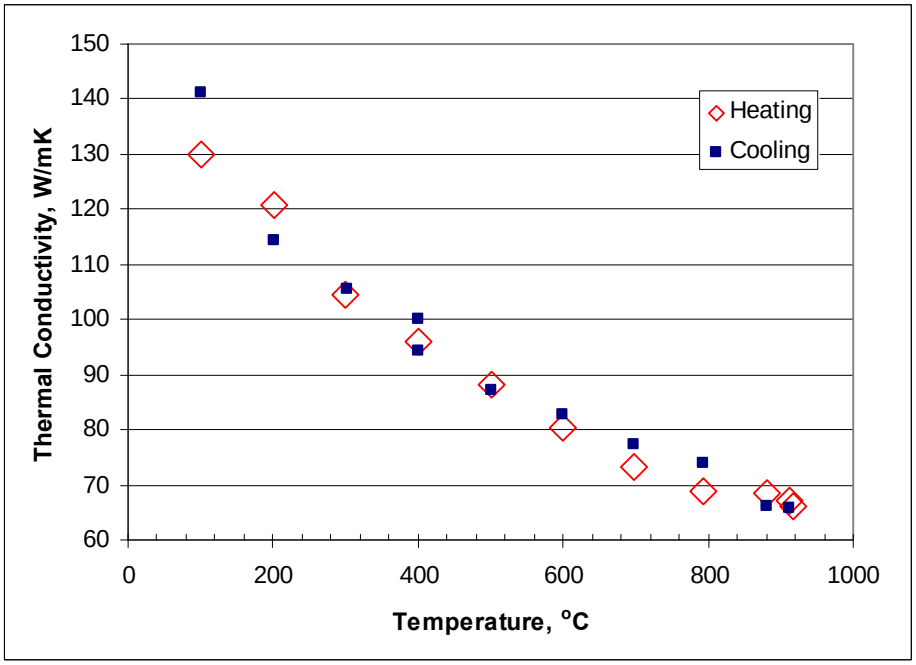

Figure 103. With-grain elevated temperature thermal conductivity for grade NBG-17 (specimen A5-4-3)

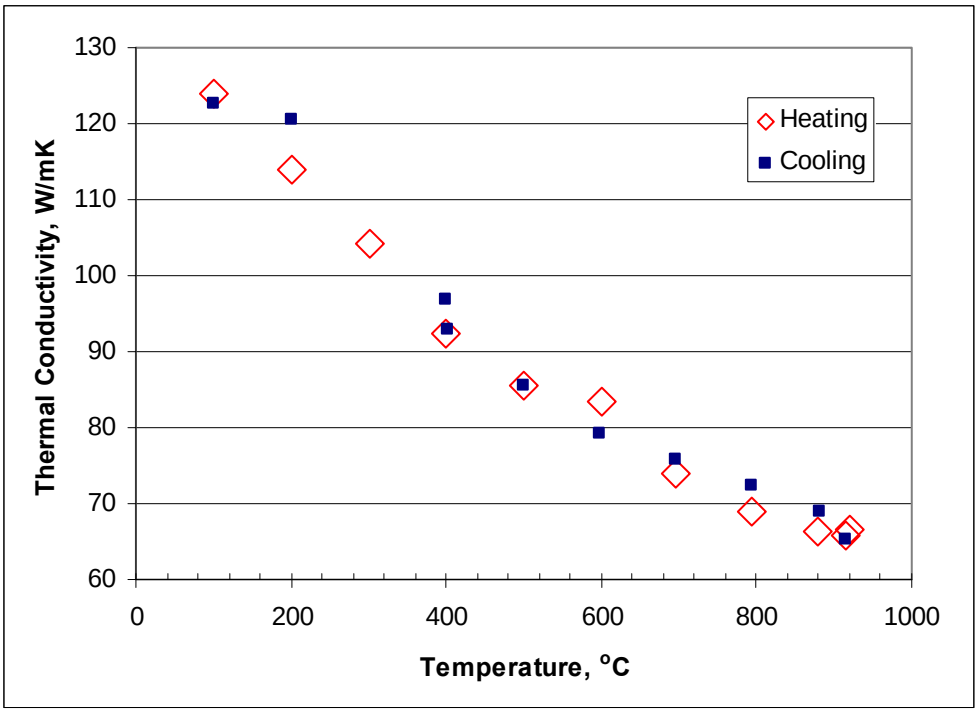

Figure 104. With-grain elevated temperature thermal conductivity for grade NBG-17 (specimen A9-4-3)

Elevated temperature thermal diffusivity and thermal conductivity data for grade NBG-17 in the against-grain direction are in Tables 23-25.

Table 23. Elevated temperature thermal diffusivity and conductivity data for grade NBG-17 (against-grain) specimen AB1-4-3

Thermal Conductivity, NBG-17 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm2/sec	Specific Heat J/kgK	Density Kg/m3	Thermal Conductivity W/mK
AB1-4-3	AG	101	374	0.7676	932.8	1864.91	133.5
AB1-4-3	AG	202	475	0.5514	1159.6	1864.91	119.2
AB1-4-3	AG	302	575	0.4336	1341.5	1864.91	108.5
AB1-4-3	AG	401	674	0.3542	1485.8	1864.91	98.1
AB1-4-3	AG	501	774	0.3064	1602.7	1864.91	91.6
AB1-4-3	AG	600	873	0.2664	1695.9	1864.91	84.3
AB1-4-3	AG	697	970	0.2365	1770.3	1864.91	78.1
AB1-4-3	AG	793	1066	0.2174	1830.8	1864.91	74.2
AB1-4-3	AG	882	1155	0.1979	1877.7	1864.91	69.3
AB1-4-3	AG	915	1188	0.1872	1893.2	1864.91	66.1
AB1-4-3	AG	916	1189	0.1924	1893.6	1864.91	67.9
AB1-4-3	AG	917	1190	0.2012	1894.1	1864.91	71.1
AB1-4-3	AG	882	1155	0.2019	1877.7	1864.91	70.7
AB1-4-3	AG	794	1067	0.2187	1831.4	1864.91	74.7
AB1-4-3	AG	698	971	0.2386	1771.0	1864.91	78.8
AB1-4-3	AG	601	874	0.2636	1696.8	1864.91	83.4
AB1-4-3	AG	501	774	0.3032	1602.7	1864.91	90.6
AB1-4-3	AG	401	674	0.3589	1485.8	1864.91	99.5
AB1-4-3	AG	302	575	0.4414	1341.5	1864.91	110.4
AB1-4-3	AG	202	475	0.5404	1159.6	1864.91	116.9
AB1-4-3	AG	102	375	0.7834	935.2	1864.91	136.6

Table 24. Elevated temperature thermal diffusivity and conductivity data for grade NBG-17 (against-grain) specimen AB5-4-3

Thermal Conductivity, NBG-17 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm2/sec	Specific Heat J/kgK	Density Kg/m3	Thermal Conductivity W/mK
AB5-4-3	AG	101	374	0.7416	932.8	1864.48	129.0
AB5-4-3	AG	202	475	0.5561	1159.6	1864.48	120.2
AB5-4-3	AG	301	574	0.4418	1339.9	1864.48	110.4
AB5-4-3	AG	401	674	0.3534	1485.8	1864.48	97.9
AB5-4-3	AG	501	774	0.3068	1602.7	1864.48	91.7
AB5-4-3	AG	599	872	0.2645	1695.1	1864.48	83.6
AB5-4-3	AG	698	971	0.2377	1771.0	1864.48	78.5
AB5-4-3	AG	793	1066	0.2241	1830.8	1864.48	76.5
AB5-4-3	AG	880	1153	0.2049	1876.7	1864.48	71.7
AB5-4-3	AG	911	1184	0.195	1891.3	1864.48	68.8
AB5-4-3	AG	919	1192	0.1963	1895.0	1864.48	69.4
AB5-4-3	AG	914	1187	0.2005	1892.7	1864.48	70.8
AB5-4-3	AG	881	1154	0.1979	1877.2	1864.48	69.3
AB5-4-3	AG	793	1066	0.2167	1830.8	1864.48	74.0
AB5-4-3	AG	698	971	0.2386	1771.0	1864.48	78.8
AB5-4-3	AG	600	873	0.2662	1695.9	1864.48	84.2
AB5-4-3	AG	502	775	0.3055	1603.8	1864.48	91.4
AB5-4-3	AG	401	674	0.3592	1485.8	1864.48	99.5
AB5-4-3	AG	302	575	0.4351	1341.5	1864.48	108.8
AB5-4-3	AG	202	475	0.5497	1159.6	1864.48	118.9
AB5-4-3	AG	102	375	0.8115	935.2	1864.48	141.5

Table 25. Elevated temperature thermal diffusivity and conductivity data for grade NBG-17 (against-grain) specimen AB9-4-3

Thermal Conductivity, NBG-17 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm2/sec	Specific Heat J/kgK	Density Kg/m3	Thermal Conductivity W/mK
AB9-4-3	AG	101	374	1.0151	932.8	1873.39	177.4
AB9-4-3	AG	202	475	0.5583	1159.6	1873.39	121.3
AB9-4-3	AG	302	575	0.4414	1341.5	1873.39	110.9
AB9-4-3	AG	401	674	0.3519	1485.8	1873.39	98.0
AB9-4-3	AG	500	773	0.3003	1601.7	1873.39	90.1
AB9-4-3	AG	600	873	0.2688	1695.9	1873.39	85.4
AB9-4-3	AG	697	970	0.244	1770.3	1873.39	80.9
AB9-4-3	AG	793	1066	0.2134	1830.8	1873.39	73.2
AB9-4-3	AG	881	1154	0.2016	1877.2	1873.39	70.9
AB9-4-3	AG	915	1188	0.2058	1893.2	1873.39	73.0
AB9-4-3	AG	917	1190	0.1893	1894.1	1873.39	67.2
AB9-4-3	AG	916	1189	0.1991	1893.6	1873.39	70.6
AB9-4-3	AG	881	1154	0.2064	1877.2	1873.39	72.6
AB9-4-3	AG	794	1067	0.2144	1831.4	1873.39	73.6
AB9-4-3	AG	698	971	0.2387	1771.0	1873.39	79.2
AB9-4-3	AG	600	873	0.2614	1695.9	1873.39	83.1
AB9-4-3	AG	501	774	0.3017	1602.7	1873.39	90.6
AB9-4-3	AG	401	674	0.3577	1485.8	1873.39	99.6
AB9-4-3	AG	302	575	0.4426	1341.5	1873.39	111.2
AB9-4-3	AG	202	475	0.5882	1159.6	1873.39	127.8
AB9-4-3	AG	102	375	0.8125	935.2	1873.39	142.4

Figures 105-107 report the thermal conductivity data as a function of temperature. The two curves on each plot show the heating and cooling thermal conductivity data. Again, there is good agreement between the heating and cooling curves for all of the NBG-17 AG data.

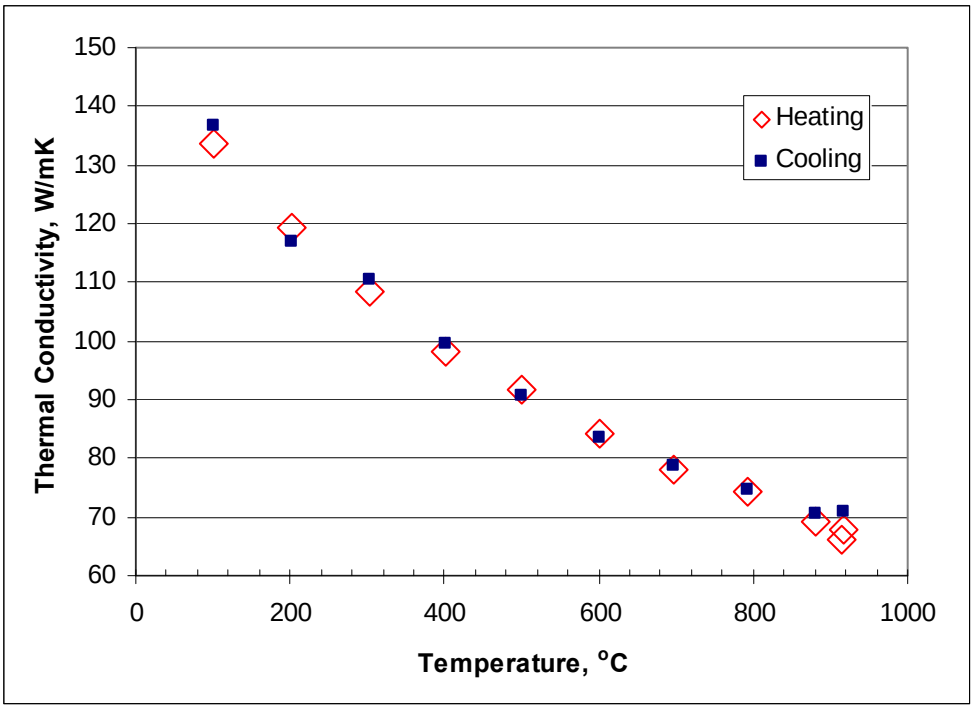

Figure 105. Against-grain elevated temperature thermal conductivity for grade NBG-17 (specimen AB1-4-3)

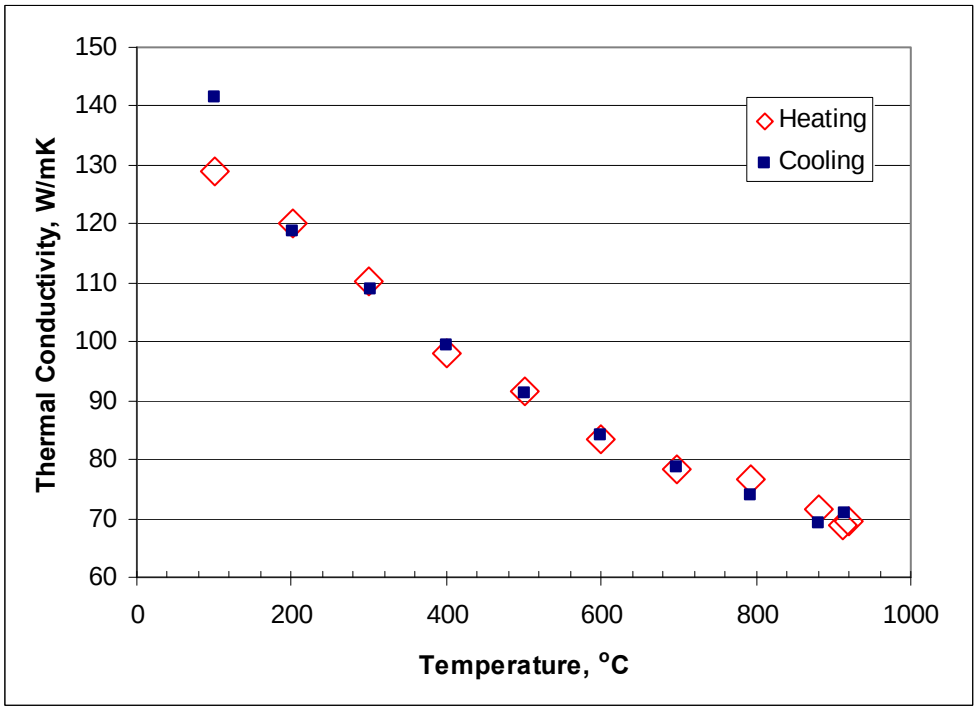

Figure 106. Against-grain elevated temperature thermal conductivity for grade NBG-17 (specimen AB5-4-3)

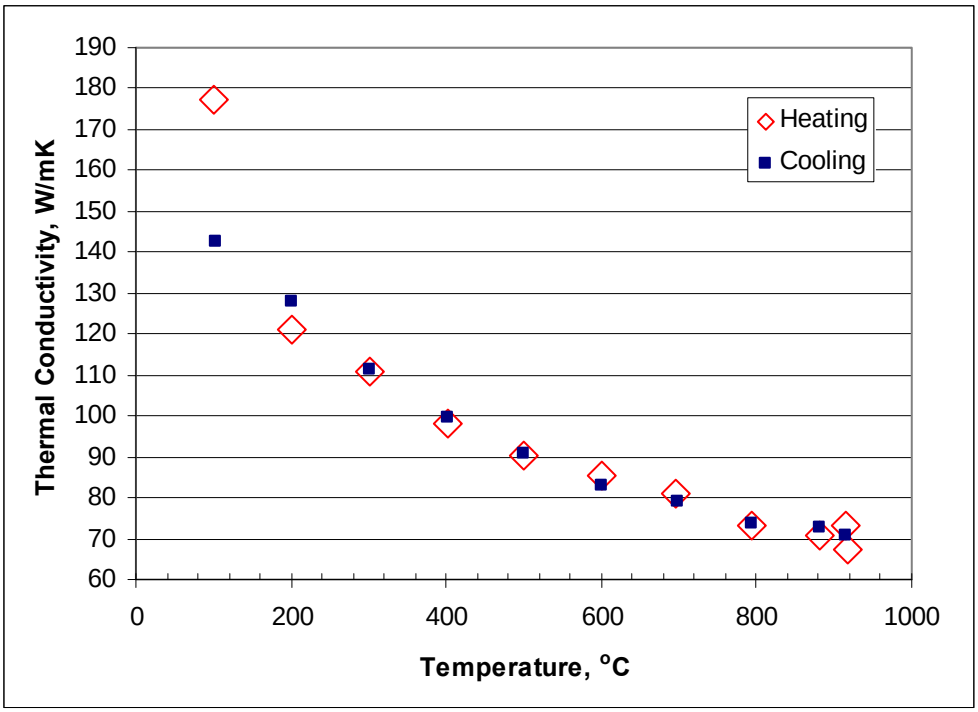

Figure 107. Against-grain elevated temperature thermal conductivity for grade NBG-17 (specimen AB9-4-3)

Figs. 108-110 compare the with- and against-grain orientations and indicate NBG-17 is nearly isotropic.

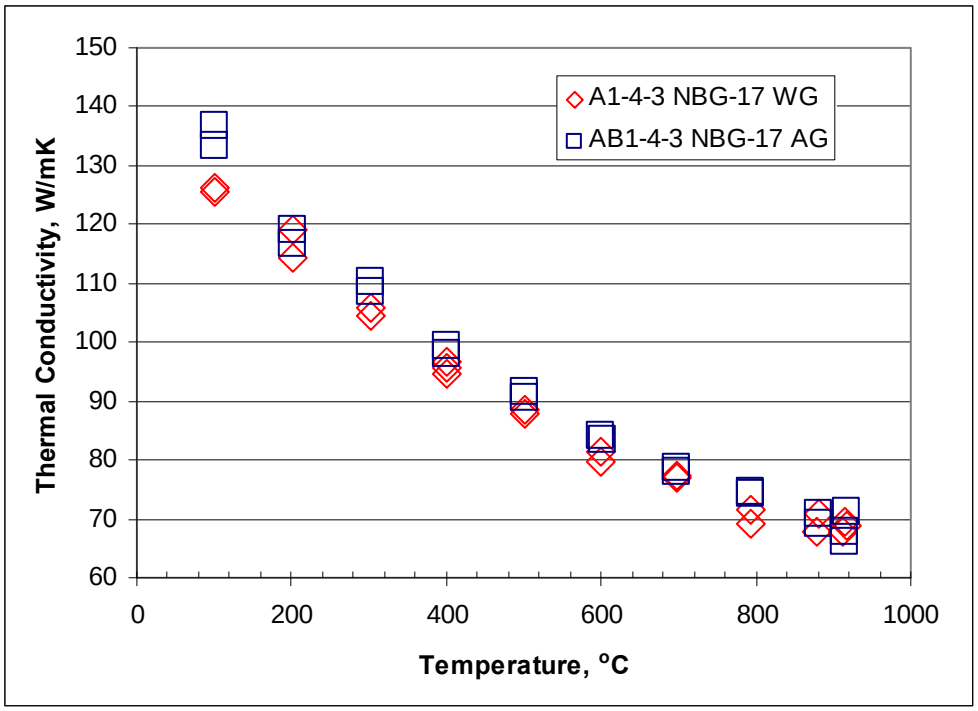

Figure 108. Comparison of with- and against-grain elevated temperature thermal conductivity for grade NBG-17

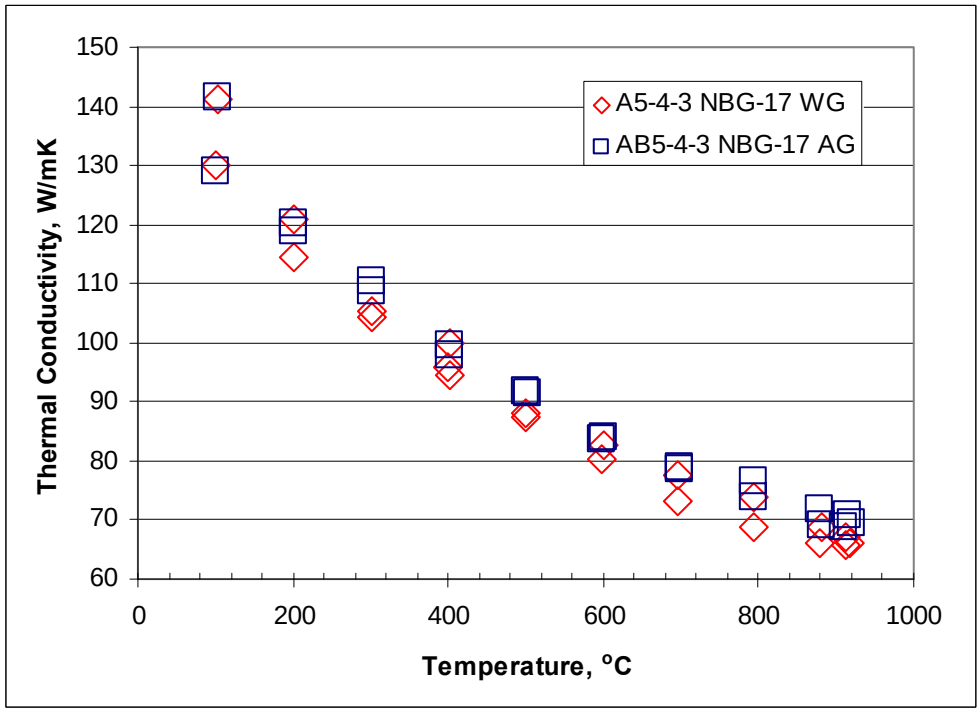

Figure 109. Comparison of with- and against-grain elevated temperature thermal conductivity for grade NBG-17

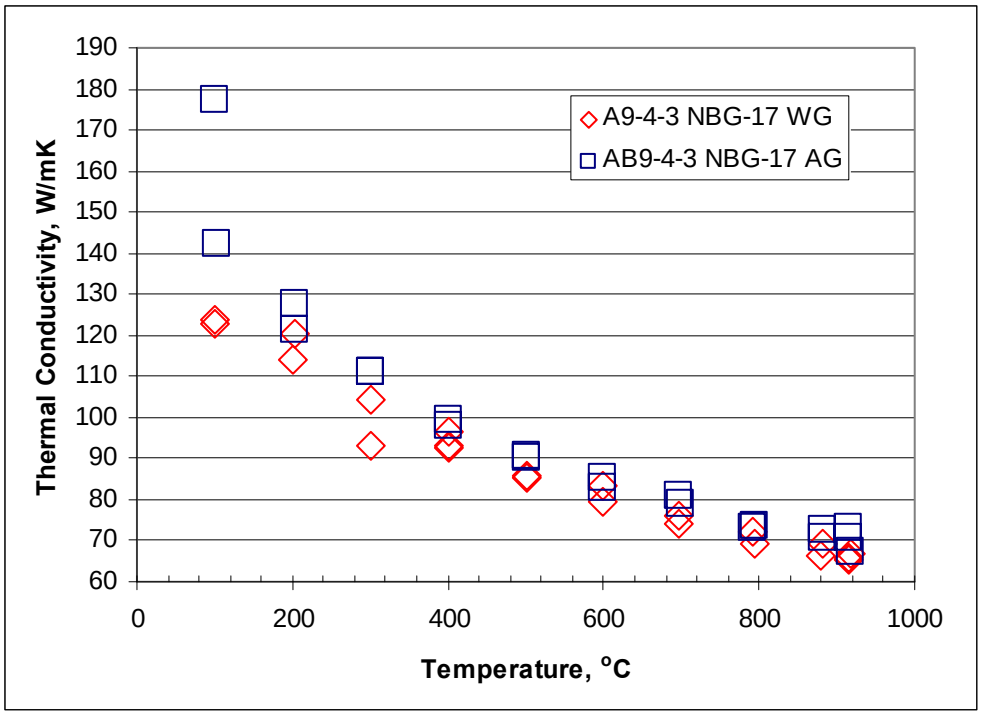

Figure 110. Comparison of with- and against-grain elevated temperature thermal conductivity for grade NBG-17

3.7.4. IG-110 thermal conductivity

Elevated temperature thermal diffusivity and thermal conductivity data for grade IG-110 are reported in Tables 26-28. IG-110 is an isostatically pressed grade and is isotropic. The reported thermal diffusivity values represent the mean of three measurements taken at each temperature. The mensuration data used to determine the specimen density is given in Appendix 40.

Table 26. Elevated temperature thermal diffusivity and conductivity data for grade IG-110 specimen E1-4-3

Thermal Conductivity, IG-110 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm2/sec	Specific Heat J/kg.K	Density Kg/m3	Thermal Conductivity W/m.K
E1-4-3	Isotropic	100	373	0.6576	930.3	1768.33	108.2
E1-4-3	Isotropic	201	474	0.4939	1157.6	1768.33	101.1
E1-4-3	Isotropic	301	574	0.3772	1339.9	1768.33	89.4
E1-4-3	Isotropic	400	673	0.3104	1484.5	1768.33	81.5
E1-4-3	Isotropic	500	773	0.2645	1601.7	1768.33	74.9
E1-4-3	Isotropic	599	872	0.2332	1695.1	1768.33	69.9
E1-4-3	Isotropic	697	970	0.2156	1770.3	1768.33	67.5
E1-4-3	Isotropic	793	1066	0.1909	1830.8	1768.33	61.8
E1-4-3	Isotropic	880	1153	0.1837	1876.7	1768.33	61.0
E1-4-3	Isotropic	913	1186	0.1758	1892.2	1768.33	58.8
E1-4-3	Isotropic	915	1188	0.1743	1893.2	1768.33	58.4
E1-4-3	Isotropic	915	1188	0.1742	1893.2	1768.33	58.3
E1-4-3	Isotropic	881	1154	0.1787	1877.2	1768.33	59.3
E1-4-3	Isotropic	793	1066	0.1869	1830.8	1768.33	60.5
E1-4-3	Isotropic	697	970	0.2061	1770.3	1768.33	64.5
E1-4-3	Isotropic	600	873	0.2301	1695.9	1768.33	69.0
E1-4-3	Isotropic	500	773	0.2689	1601.7	1768.33	76.2
E1-4-3	Isotropic	401	674	0.3085	1485.8	1768.33	81.1

Table 27. Elevated temperature thermal diffusivity and conductivity data for grade IG-110 specimen E5-7-3

Thermal Conductivity, IG-110 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm2/sec	Specific Heat J/kg.K	Density Kg/m3	Thermal Conductivity W/m.K
E7-4-3	Isotropic	100	373	0.6247	930.3	1772.37	103.0
E7-4-3	Isotropic	201	474	0.4841	1157.6	1772.37	99.3
E7-4-3	Isotropic	301	574	0.3661	1339.9	1772.37	86.9
E7-4-3	Isotropic	400	673	0.3046	1484.5	1772.37	80.1
E7-4-3	Isotropic	500	773	0.2571	1601.7	1772.37	73.0
E7-4-3	Isotropic	599	872	0.2234	1695.1	1772.37	67.1
E7-4-3	Isotropic	696	969	0.2057	1769.6	1772.37	64.5
E7-4-3	Isotropic	792	1065	0.1896	1830.2	1772.37	61.5
E7-4-3	Isotropic	878	1151	0.1711	1875.7	1772.37	56.9
E7-4-3	Isotropic	912	1185	0.1726	1891.8	1772.37	57.9
E7-4-3	Isotropic	912	1185	0.1737	1891.8	1772.37	58.2
E7-4-3	Isotropic	912	1185	0.1698	1891.8	1772.37	56.9
E7-4-3	Isotropic	879	1152	0.1773	1876.2	1772.37	59.0
E7-4-3	Isotropic	793	1066	0.1872	1830.8	1772.37	60.7
E7-4-3	Isotropic	697	970	0.2088	1770.3	1772.37	65.5
E7-4-3	Isotropic	599	872	0.2257	1695.1	1772.37	67.8
E7-4-3	Isotropic	500	773	0.2569	1601.7	1772.37	72.9
E7-4-3	Isotropic	400	673	0.3008	1484.5	1772.37	79.1

Table 28. Elevated temperature thermal diffusivity and conductivity data for grade IG-110 specimen E9-4-3

Thermal Conductivity, IG-110 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm2/sec	Specific Heat J/kg.K	Density Kg/m3	Thermal Conductivity W/m.K
E9-4-3	Isotropic	100	373	0.6214	930.3	1762.7	101.9
E9-4-3	Isotropic	201	474	0.4664	1157.6	1762.7	95.2
E9-4-3	Isotropic	301	574	0.3669	1339.9	1762.7	86.7
E9-4-3	Isotropic	400	673	0.2937	1484.5	1762.7	76.9
E9-4-3	Isotropic	500	773	0.2533	1601.7	1762.7	71.5
E9-4-3	Isotropic	599	872	0.2275	1695.1	1762.7	68.0
E9-4-3	Isotropic	696	969	0.2012	1769.6	1762.7	62.8
E9-4-3	Isotropic	792	1065	0.1795	1830.2	1762.7	57.9
E9-4-3	Isotropic	879	1152	0.1728	1876.2	1762.7	57.1
E9-4-3	Isotropic	913	1186	0.1671	1892.2	1762.7	55.7
E9-4-3	Isotropic	916	1189	0.168	1893.6	1762.7	56.1
E9-4-3	Isotropic	912	1185	0.1686	1891.8	1762.7	56.2
E9-4-3	Isotropic	880	1153	0.1743	1876.7	1762.7	57.7
E9-4-3	Isotropic	792	1065	0.1809	1830.2	1762.7	58.4
E9-4-3	Isotropic	696	969	0.2013	1769.6	1762.7	62.8
E9-4-3	Isotropic	599	872	0.2226	1695.1	1762.7	66.5
E9-4-3	Isotropic	500	773	0.2555	1601.7	1762.7	72.1
E9-4-3	Isotropic	400	673	0.2991	1484.5	1762.7	78.3

Figs. 111-113 report the thermal conductivity data as a function of temperature. The two curves on each plot show the heating and cooling thermal conductivity data. There is good agreement between the heating and cooling curves for all of the IG-110 data.

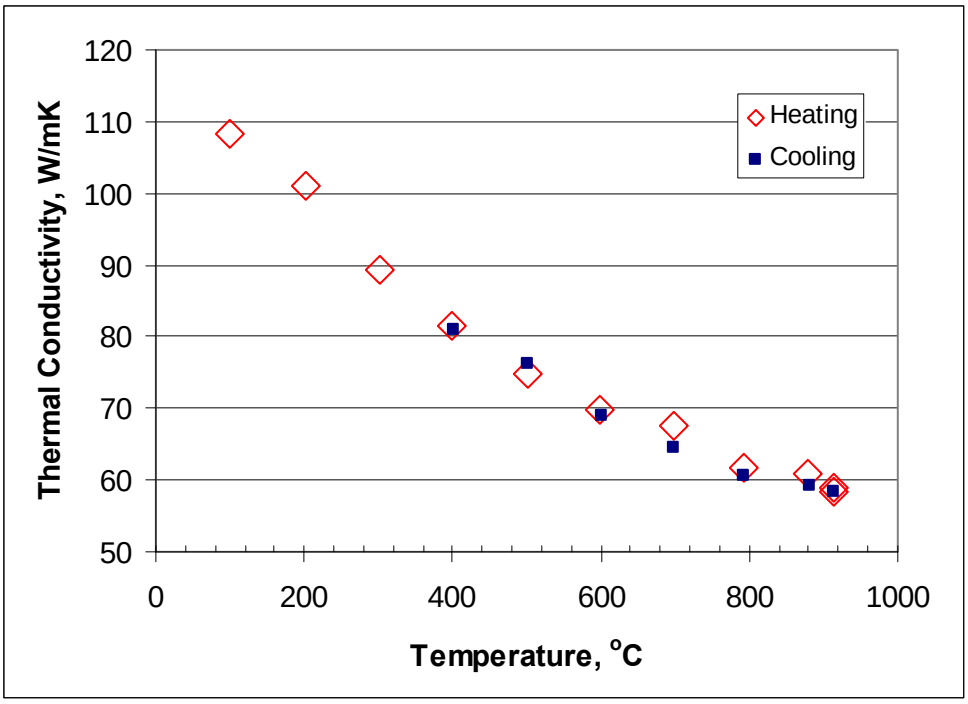

Figure 111. Elevated temperature thermal conductivity for grade IG-110 (specimen E1-4-3)

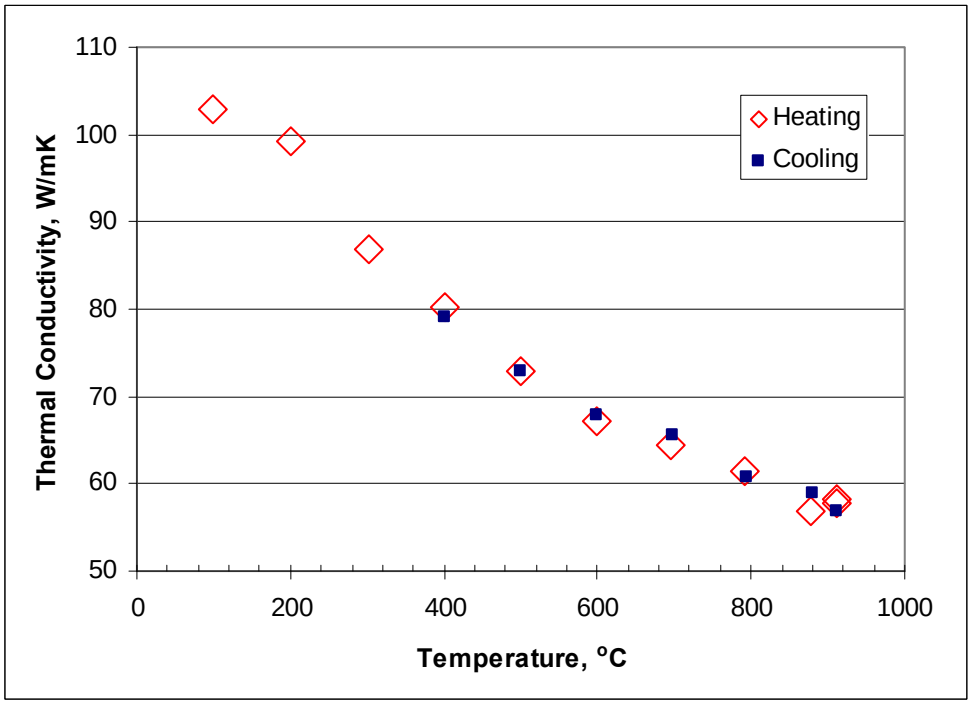

Figure 112. Elevated temperature thermal conductivity for grade IG-110 (specimen E5-4-3)

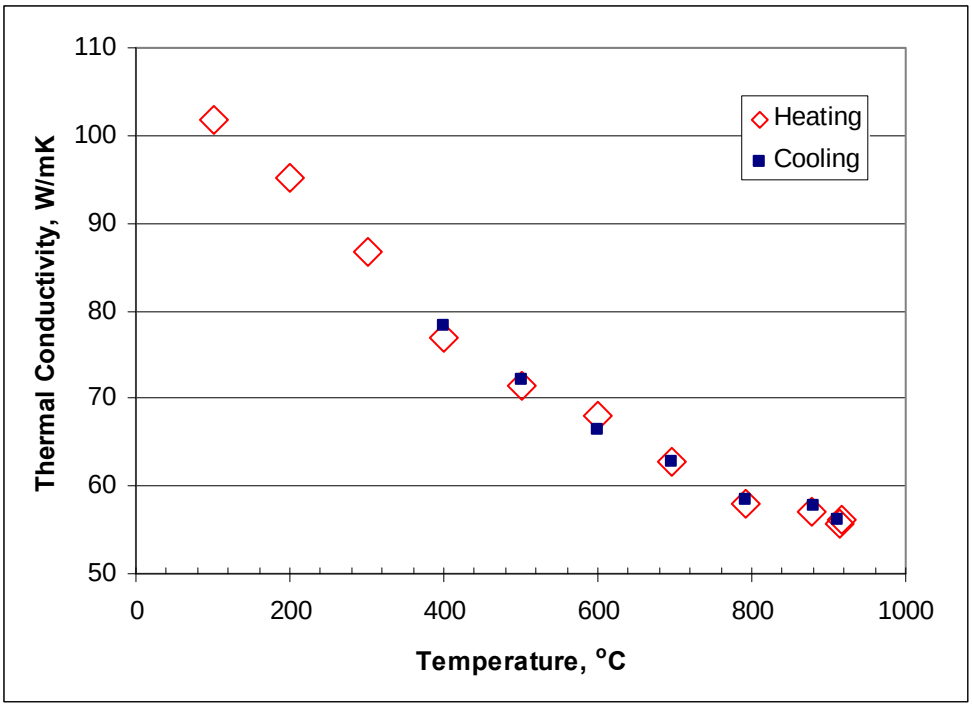

Figure 113. Elevated temperature thermal conductivity for grade IG-110 (specimen E9-4-3)

3.7.5. IG-430 thermal conductivity

Elevated temperature thermal diffusivity and thermal conductivity data for grade IG-430 are reported in Tables 29-31. IG-430 is an isostatically pressed grade and is isotropic. The reported thermal diffusivity values represent the mean of three measurements taken at each temperature. The mensuration data used to determine the specimen density is given in Appendix 40.

Table 29. Elevated temperature thermal diffusivity and conductivity data for grade IG-430 specimen F1-4-3

Thermal Conductivity, IG-430 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm2/sec	Specific Heat J/kg.K	Density Kg/m3	Thermal Conductivity W/m.K
F1-4-3	Isotropic	100	373	0.8339	930.3	1808.99	140.3
F1-4-3	Isotropic	201	474	0.54	1157.6	1808.99	113.1
F1-4-3	Isotropic	301	574	0.4518	1339.9	1808.99	109.5
F1-4-3	Isotropic	402	675	0.3508	1487.2	1808.99	94.4
F1-4-3	Isotropic	501	774	0.3022	1602.7	1808.99	87.6
F1-4-3	Isotropic	600	873	0.2678	1695.9	1808.99	82.2
F1-4-3	Isotropic	697	970	0.2372	1770.3	1808.99	76.0
F1-4-3	Isotropic	792	1065	0.212	1830.2	1808.99	70.2
F1-4-3	Isotropic	879	1152	0.1992	1876.2	1808.99	67.6
F1-4-3	Isotropic	912	1185	0.1979	1891.8	1808.99	67.7
F1-4-3	Isotropic	914	1187	0.1904	1892.7	1808.99	65.2
F1-4-3	Isotropic	913	1186	0.1922	1892.2	1808.99	65.8
F1-4-3	Isotropic	880	1153	0.1939	1876.7	1808.99	65.8
F1-4-3	Isotropic	794	1067	0.213	1831.4	1808.99	70.6
F1-4-3	Isotropic	698	971	0.2353	1771.0	1808.99	75.4
F1-4-3	Isotropic	600	873	0.2642	1695.9	1808.99	81.1
F1-4-3	Isotropic	501	774	0.2994	1602.7	1808.99	86.8
F1-4-3	Isotropic	401	674	0.3413	1485.8	1808.99	91.7
F1-4-3	Isotropic	302	575	0.4318	1341.5	1808.99	104.8

Table 30. Elevated temperature thermal diffusivity and conductivity data for grade IG-430 specimen F7-4-3

Thermal Conductivity, IG-430 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm2/sec	Specific Heat J/kg.K	Density Kg/m3	Thermal Conductivity W/m.K
F7-4-3	Isotropic	100	373	0.8263	930.3	1806.07	138.8
F7-4-3	Isotropic	201	474	0.544	1157.6	1806.07	113.7
F7-4-3	Isotropic	301	574	0.4352	1339.9	1806.07	105.3
F7-4-3	Isotropic	402	675	0.3478	1487.2	1806.07	93.4
F7-4-3	Isotropic	501	774	0.2971	1602.7	1806.07	86.0
F7-4-3	Isotropic	600	873	0.2558	1695.9	1806.07	78.4
F7-4-3	Isotropic	696	969	0.2435	1769.6	1806.07	77.8
F7-4-3	Isotropic	792	1065	0.2167	1830.2	1806.07	71.6
F7-4-3	Isotropic	879	1152	0.1935	1876.2	1806.07	65.6
F7-4-3	Isotropic	908	1181	0.1915	1890.0	1806.07	65.4
F7-4-3	Isotropic	910	1183	0.195	1890.9	1806.07	66.6
F7-4-3	Isotropic	910	1183	0.1943	1890.9	1806.07	66.4
F7-4-3	Isotropic	881	1154	0.1991	1877.2	1806.07	67.5
F7-4-3	Isotropic	793	1066	0.2119	1830.8	1806.07	70.1
F7-4-3	Isotropic	697	970	0.2349	1770.3	1806.07	75.1
F7-4-3	Isotropic	600	873	0.2562	1695.9	1806.07	78.5
F7-4-3	Isotropic	500	773	0.3011	1601.7	1806.07	87.1
F7-4-3	Isotropic	401	674	0.3492	1485.8	1806.07	93.7
F7-4-3	Isotropic	302	575	0.4333	1341.5	1806.07	105.0

Table 31. Elevated temperature thermal diffusivity and conductivity data for grade IG-430 specimen F9-4-3

Thermal Conductivity, IG-430 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm2/sec	Specific Heat J/kg.K	Density Kg/m3	Thermal Conductivity W/m.K
F9-4-3	Isotropic	100	373	0.7503	930.3	1818.4	126.9
F9-4-3	Isotropic	201	474	0.5259	1157.6	1818.4	110.7
F9-4-3	Isotropic	302	575	0.4137	1341.5	1818.4	100.9
F9-4-3	Isotropic	402	675	0.3362	1487.2	1818.4	90.9
F9-4-3	Isotropic	501	774	0.2849	1602.7	1818.4	83.0
F9-4-3	Isotropic	599	872	0.2469	1695.1	1818.4	76.1
F9-4-3	Isotropic	696	969	0.2229	1769.6	1818.4	71.7
F9-4-3	Isotropic	791	1064	0.2069	1829.6	1818.4	68.8
F9-4-3	Isotropic	879	1152	0.1901	1876.2	1818.4	64.9
F9-4-3	Isotropic	910	1183	0.1801	1890.9	1818.4	61.9
F9-4-3	Isotropic	913	1186	0.1857	1892.2	1818.4	63.9
F9-4-3	Isotropic	910	1183	0.1869	1890.9	1818.4	64.3
F9-4-3	Isotropic	879	1152	0.1963	1876.2	1818.4	67.0
F9-4-3	Isotropic	793	1066	0.198	1830.8	1818.4	65.9
F9-4-3	Isotropic	697	970	0.2278	1770.3	1818.4	73.3
F9-4-3	Isotropic	599	872	0.2505	1695.1	1818.4	77.2
F9-4-3	Isotropic	501	774	0.2866	1602.7	1818.4	83.5
F9-4-3	Isotropic	401	674	0.3344	1485.8	1818.4	90.4
F9-4-3	Isotropic	302	575	0.4177	1341.5	1818.4	101.9

Figs. 114-116 report the thermal conductivity data as a function of temperature. The two curves on each plot show the heating and cooling thermal conductivity data. There is good agreement between the heating and cooling curves for all of the IG-430 data.

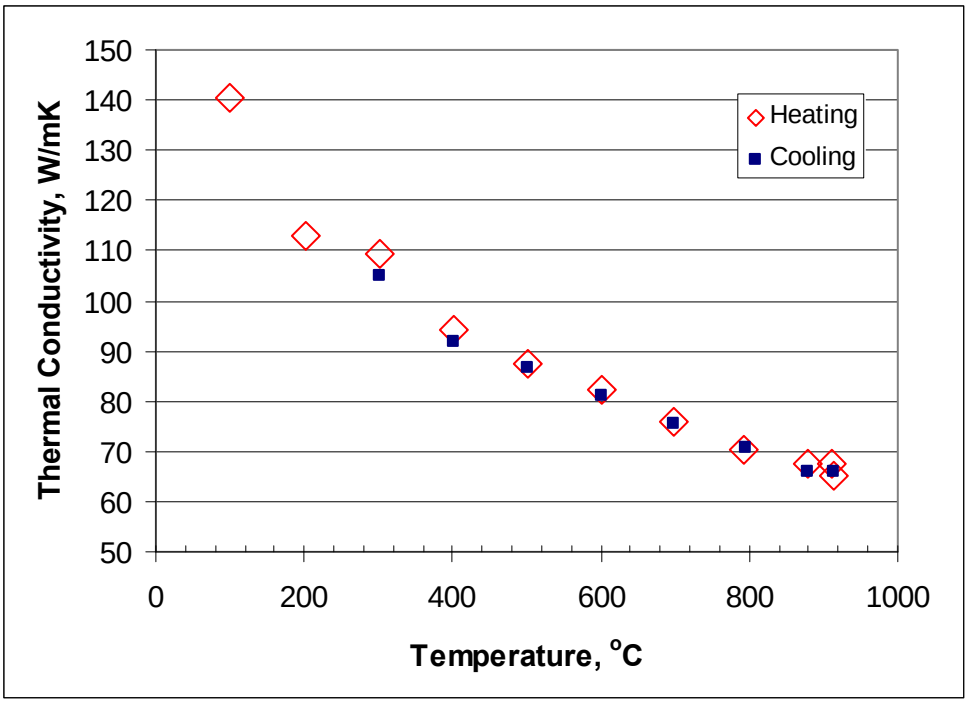

Figure 114. With-grain elevated temperature thermal conductivity for grade IG-430 (specimen F1-4-3)

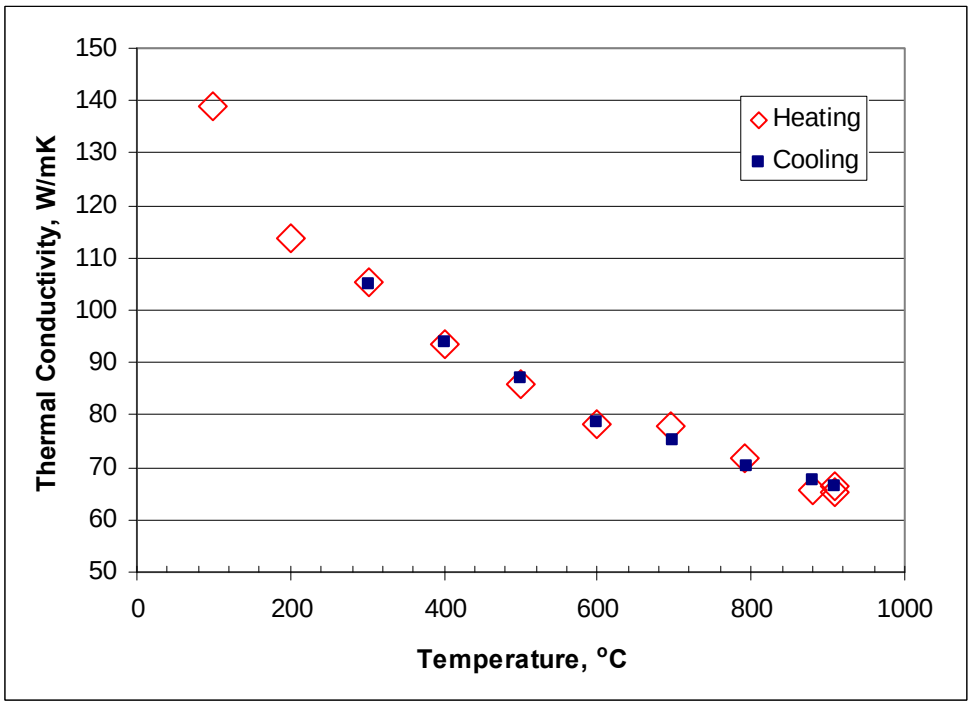

Figure 115. With-grain elevated temperature thermal conductivity for grade IG-430 (specimen F7-4-3)

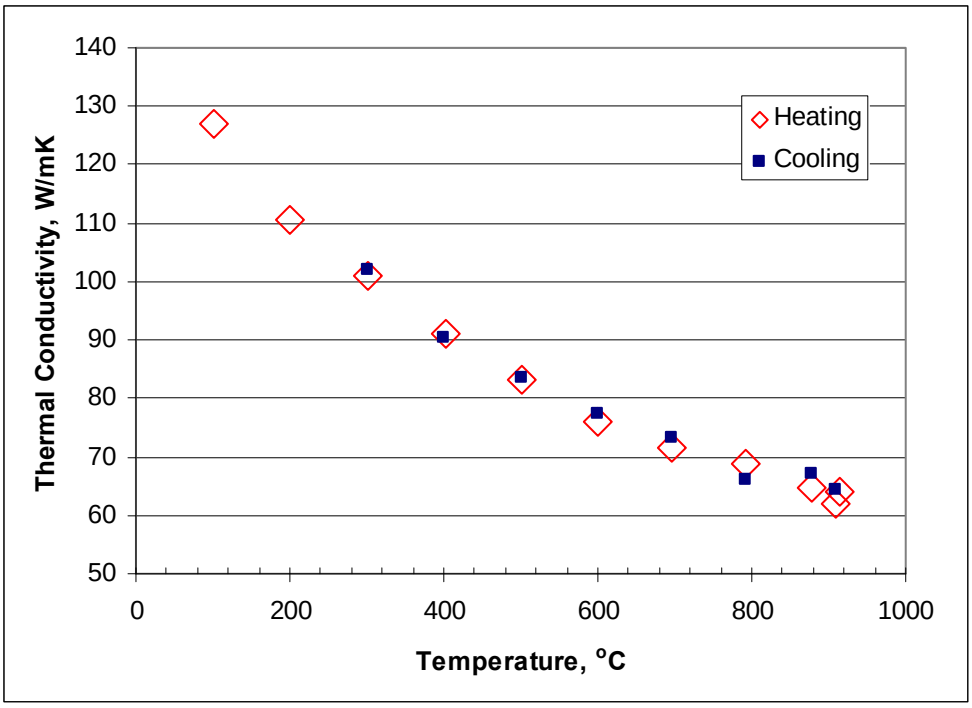

Figure 116. With-grain elevated temperature thermal conductivity for grade IG-430 (specimen F9-4-3)

3.7.6. PCEA thermal conductivity

Elevated temperature thermal diffusivity and thermal conductivity data for grade PCEA in the with-grain direction are reported in Tables 32-34 and for the against-grain direction in Tables 35-37. The reported thermal diffusivity values represent the mean of three measurements taken at each temperature. The mensuration data used to determine the specimen density is given in Appendix 40.

Table 32. Elevated temperature thermal diffusivity and conductivity data for grade PCEA (with grain) specimen DA1-4-3

Thermal Conductivity, PCEA (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm2/sec	Specific Heat J/kg.K	Density Kg/m3	Thermal Conductivity W/m.K
DA1-4-3	WG	101	374	0.9952	932.8	1805.39	167.6
DA1-4-3	WG	202	475	0.6788	1159.6	1805.39	142.1
DA1-4-3	WG	302	575	0.5319	1341.5	1805.39	128.8
DA1-4-3	WG	401	674	0.4468	1485.8	1805.39	119.9
DA1-4-3	WG	500	773	0.3665	1601.7	1805.39	106.0
DA1-4-3	WG	599	872	0.3228	1695.1	1805.39	98.8
DA1-4-3	WG	697	970	0.279	1770.3	1805.39	89.2
DA1-4-3	WG	793	1066	0.2649	1830.8	1805.39	87.6
DA1-4-3	WG	879	1152	0.2484	1876.2	1805.39	84.1
DA1-4-3	WG	912	1185	0.2409	1891.8	1805.39	82.3
DA1-4-3	WG	913	1186	0.2421	1892.2	1805.39	82.7
DA1-4-3	WG	910	1183	0.2377	1890.9	1805.39	81.1
DA1-4-3	WG	879	1152	0.2477	1876.2	1805.39	83.9
DA1-4-3	WG	794	1067	0.2635	1831.4	1805.39	87.1
DA1-4-3	WG	697	970	0.2885	1770.3	1805.39	92.2
DA1-4-3	WG	600	873	0.3154	1695.9	1805.39	96.6
DA1-4-3	WG	500	773	0.3674	1601.7	1805.39	106.2
DA1-4-3	WG	401	674	0.4268	1485.8	1805.39	114.5
DA1-4-3	WG	301	574	0.5294	1339.9	1805.39	128.1
DA1-4-3	WG	301	574	0.5229	1339.9	1805.39	126.5
DA1-4-3	WG	101	374	1.0794	932.8	1805.39	181.8

Table 33. Elevated temperature thermal diffusivity and conductivity data for grade PCEA (with grain) specimen DA5-4-3

Thermal Conductivity, PCEA (3 mm thick specimens)							
Specimen	Orientation	Temperature	Temperature	Mean Thermal Diffusivity	Specific Heat	Density	Thermal Conductivity
		C	K	cm2/sec	J/kg.K	Kg/m3	W/m.K
DA5-4-3	WG	101	374	1.0356	932.8	1804.87	174.3
DA5-4-3	WG	202	475	0.6716	1159.6	1804.87	140.6
DA5-4-3	WG	302	575	0.5231	1341.5	1804.87	126.7
DA5-4-3	WG	400	673	0.4264	1484.5	1804.87	114.3
DA5-4-3	WG	500	773	0.3583	1601.7	1804.87	103.6
DA5-4-3	WG	599	872	0.3194	1695.1	1804.87	97.7
DA5-4-3	WG	696	969	0.2812	1769.6	1804.87	89.8
DA5-4-3	WG	793	1066	0.2567	1830.8	1804.87	84.8
DA5-4-3	WG	878	1151	0.2397	1875.7	1804.87	81.1
DA5-4-3	WG	910	1183	0.2359	1890.9	1804.87	80.5
DA5-4-3	WG	911	1184	0.2343	1891.3	1804.87	80.0
DA5-4-3	WG	880	1153	0.2397	1876.7	1804.87	81.2
DA5-4-3	WG	792	1065	0.2619	1830.2	1804.87	86.5
DA5-4-3	WG	697	970	0.2817	1770.3	1804.87	90.0
DA5-4-3	WG	599	872	0.3141	1695.1	1804.87	96.1
DA5-4-3	WG	500	773	0.35	1601.7	1804.87	101.2
DA5-4-3	WG	401	674	0.4253	1485.8	1804.87	114.1
DA5-4-3	WG	301	574	0.5194	1339.9	1804.87	125.6
DA5-4-3	WG	301	574	0.5523	1339.9	1804.87	133.6
DA5-4-3	WG	101	374	0.9291	932.8	1804.87	156.4

Table 34. Elevated temperature thermal diffusivity and conductivity data for grade PCEA (with grain) specimen DA9-4-3

Thermal Conductivity, PCEA (3 mm thick specimens)							
Specimen	Orientation	Temperature	Temperature	Mean Thermal Diffusivity	Specific Heat	Density	Thermal Conductivity
		C	K	cm2/sec	J/kg.K	Kg/m3	W/m.K
DA9-4-3	WG	101	374	0.9958	932.8	1803.89	167.6
DA9-4-3	WG	202	475	0.7026	1159.6	1803.89	147.0
DA9-4-3	WG	301	574	0.5235	1339.9	1803.89	126.5
DA9-4-3	WG	400	673	0.4469	1484.5	1803.89	119.7
DA9-4-3	WG	500	773	0.3591	1601.7	1803.89	103.8
DA9-4-3	WG	599	872	0.319	1695.1	1803.89	97.5
DA9-4-3	WG	697	970	0.2819	1770.3	1803.89	90.0
DA9-4-3	WG	793	1066	0.2605	1830.8	1803.89	86.0
DA9-4-3	WG	879	1152	0.2387	1876.2	1803.89	80.8
DA9-4-3	WG	911	1184	0.2256	1891.3	1803.89	77.0
DA9-4-3	WG	912	1185	0.2376	1891.8	1803.89	81.1
DA9-4-3	WG	909	1182	0.2375	1890.4	1803.89	81.0
DA9-4-3	WG	879	1152	0.2383	1876.2	1803.89	80.7
DA9-4-3	WG	793	1066	0.2582	1830.8	1803.89	85.3
DA9-4-3	WG	696	969	0.2858	1769.6	1803.89	91.2
DA9-4-3	WG	599	872	0.3175	1695.1	1803.89	97.1
DA9-4-3	WG	500	773	0.355	1601.7	1803.89	102.6
DA9-4-3	WG	400	673	0.4295	1484.5	1803.89	115.0
DA9-4-3	WG	301	574	0.5261	1339.9	1803.89	127.2
DA9-4-3	WG	301	574	0.527	1339.9	1803.89	127.4
DA9-4-3	WG	101	374	1.0427	932.8	1803.89	175.4

Figs. 117-119 report the thermal conductivity data as a function of temperature. The two curves on each plot show the heating and cooling thermal conductivity data. There is good agreement between the heating and cooling curves for all of the PCEA WG data.

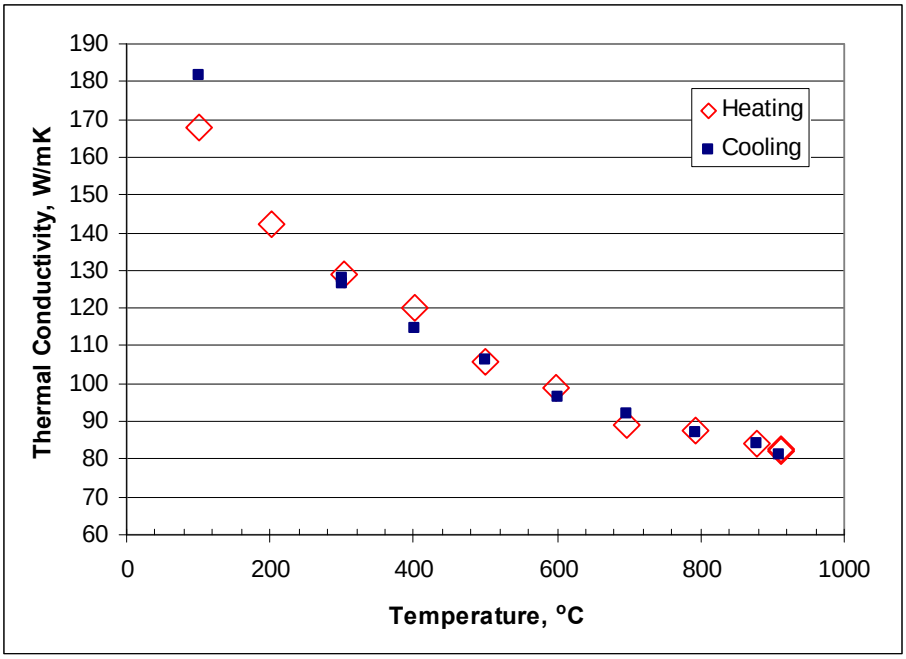

Figure 117. With-grain elevated temperature thermal conductivity for grade PCEA (specimen DA1-4-3)

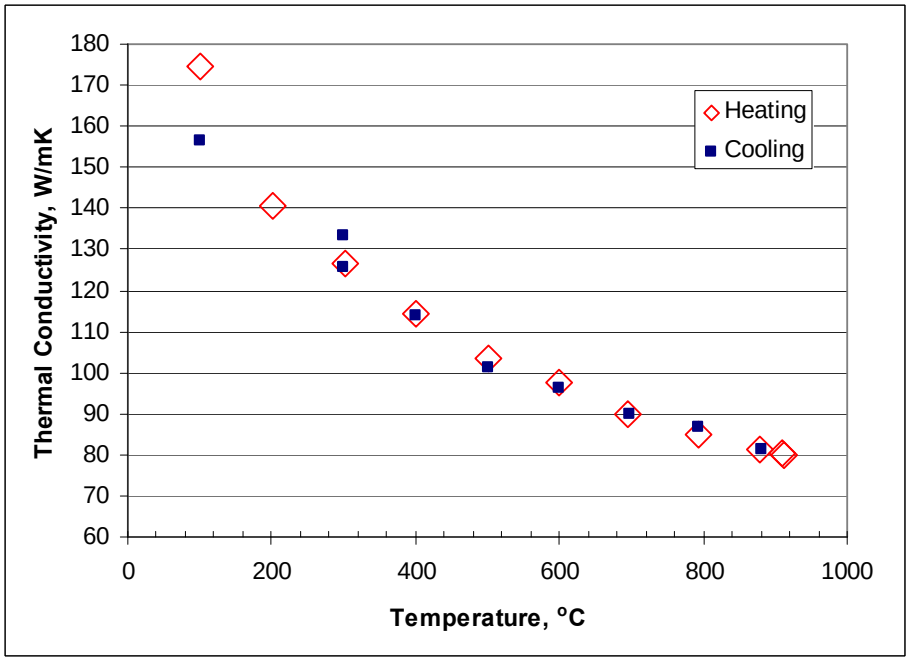

Figure 118. With-grain elevated temperature thermal conductivity for grade PCEA (specimen DA5-4-3)

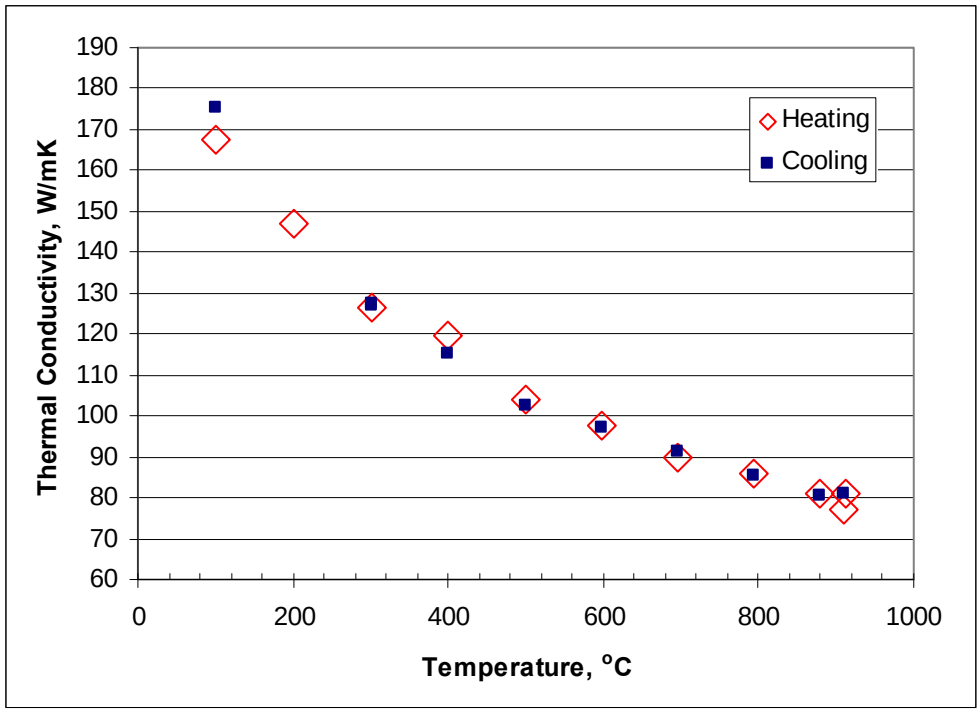

Figure 119. With-grain elevated temperature thermal conductivity for grade PCEA (specimen DA9-4-3)

Elevated temperature thermal diffusivity and thermal conductivity data for grade PCEA in the against-grain direction are reported in Tables 35-37.

Table 35. Elevated temperature thermal diffusivity and conductivity data for grade PCEA (against-grain) specimen DB1-4-3

Thermal Conductivity, PCEA (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm2/sec	Specific Heat J/kg.K	Density Kg/m3	Thermal Conductivity W/m.K
DB1-4-3	AG	101	374	0.9924	932.8	1783.85	165.1
DB1-4-3	AG	201	474	0.6482	1157.6	1783.85	133.9
DB1-4-3	AG	302	575	0.5222	1341.5	1783.85	125.0
DB1-4-3	AG	401	674	0.4131	1485.8	1783.85	109.5
DB1-4-3	AG	501	774	0.3458	1602.7	1783.85	98.9
DB1-4-3	AG	599	872	0.3068	1695.1	1783.85	92.8
DB1-4-3	AG	697	970	0.2704	1770.3	1783.85	85.4
DB1-4-3	AG	792	1065	0.2522	1830.2	1783.85	82.3
DB1-4-3	AG	879	1152	0.2234	1876.2	1783.85	74.8
DB1-4-3	AG	912	1185	0.2223	1891.8	1783.85	75.0
DB1-4-3	AG	914	1187	0.2204	1892.7	1783.85	74.4
DB1-4-3	AG	912	1185	0.2261	1891.8	1783.85	76.3
DB1-4-3	AG	880	1153	0.2239	1876.7	1783.85	75.0
DB1-4-3	AG	793	1066	0.2513	1830.8	1783.85	82.1
DB1-4-3	AG	697	970	0.2697	1770.3	1783.85	85.2
DB1-4-3	AG	600	873	0.3077	1695.9	1783.85	93.1
DB1-4-3	AG	501	774	0.3447	1602.7	1783.85	98.6
DB1-4-3	AG	401	674	0.4045	1485.8	1783.85	107.2
DB1-4-3	AG	302	575	0.5224	1341.5	1783.85	125.0
DB1-4-3	AG	301	574	0.5043	1339.9	1783.85	120.5
DB1-4-3	AG	201	474	0.6299	1157.6	1783.85	130.1
DB1-4-3	AG	101	374	0.8225	932.8	1783.85	136.9

Table 36. Elevated temperature thermal diffusivity and conductivity data for grade PCEA (against-grain) specimen DB5-4-3

Thermal Conductivity, PCEA (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm2/sec	Specific Heat J/kg.K	Density Kg/m3	Thermal Conductivity W/m.K
DB5-4-3	AG	101	374	0.9231	932.8	1791.45	154.3
DB5-4-3	AG	201	474	0.6198	1157.6	1791.45	128.5
DB5-4-3	AG	301	574	0.5	1339.9	1791.45	120.0
DB5-4-3	AG	401	674	0.4154	1485.8	1791.45	110.6
DB5-4-3	AG	499	772	0.3384	1600.6	1791.45	97.0
DB5-4-3	AG	599	872	0.2949	1695.1	1791.45	89.6
DB5-4-3	AG	697	970	0.2693	1770.3	1791.45	85.4
DB5-4-3	AG	793	1066	0.2455	1830.8	1791.45	80.5
DB5-4-3	AG	880	1153	0.225	1876.7	1791.45	75.6
DB5-4-3	AG	914	1187	0.2167	1892.7	1791.45	73.5
DB5-4-3	AG	917	1190	0.2219	1894.1	1791.45	75.3
DB5-4-3	AG	913	1186	0.2225	1892.2	1791.45	75.4
DB5-4-3	AG	881	1154	0.2305	1877.2	1791.45	77.5
DB5-4-3	AG	793	1066	0.2463	1830.8	1791.45	80.8
DB5-4-3	AG	697	970	0.2685	1770.3	1791.45	85.2
DB5-4-3	AG	600	873	0.2985	1695.9	1791.45	90.7
DB5-4-3	AG	501	774	0.3482	1602.7	1791.45	100.0
DB5-4-3	AG	401	674	0.4096	1485.8	1791.45	109.0
DB5-4-3	AG	302	575	0.4939	1341.5	1791.45	118.7
DB5-4-3	AG	301	574	0.4879	1339.9	1791.45	117.1
DB5-4-3	AG	201	474	0.6285	1157.6	1791.45	130.3
DB5-4-3	AG	100	373	0.874	930.3	1791.45	145.7

Table 37. Elevated temperature thermal diffusivity and conductivity data for grade PCEA (against-grain) specimen DB9-4-3

Thermal Conductivity, PCEA (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm2/sec	Specific Heat J/kg.K	Density Kg/m3	Thermal Conductivity W/m.K
DB9-4-3	AG	100	373	0.9379	930.3	1803.08	157.3
DB9-4-3	AG	201	474	0.6336	1157.6	1803.08	132.2
DB9-4-3	AG	302	575	0.489	1341.5	1803.08	118.3
DB9-4-3	AG	400	673	0.4039	1484.5	1803.08	108.1
DB9-4-3	AG	500	773	0.3425	1601.7	1803.08	98.9
DB9-4-3	AG	599	872	0.3011	1695.1	1803.08	92.0
DB9-4-3	AG	696	969	0.2653	1769.6	1803.08	84.6
DB9-4-3	AG	792	1065	0.2405	1830.2	1803.08	79.4
DB9-4-3	AG	878	1151	0.2279	1875.7	1803.08	77.1
DB9-4-3	AG	911	1184	0.2178	1891.3	1803.08	74.3
DB9-4-3	AG	914	1187	0.2171	1892.7	1803.08	74.1
DB9-4-3	AG	912	1185	0.2234	1891.8	1803.08	76.2
DB9-4-3	AG	879	1152	0.2258	1876.2	1803.08	76.4
DB9-4-3	AG	792	1065	0.2396	1830.2	1803.08	79.1
DB9-4-3	AG	697	970	0.2626	1770.3	1803.08	83.8
DB9-4-3	AG	599	872	0.2968	1695.1	1803.08	90.7
DB9-4-3	AG	500	773	0.3464	1601.7	1803.08	100.0
DB9-4-3	AG	401	674	0.3994	1485.8	1803.08	107.0
DB9-4-3	AG	301	574	0.485	1339.9	1803.08	117.2
DB9-4-3	AG	301	574	0.4858	1339.9	1803.08	117.4
DB9-4-3	AG	201	474	0.6104	1157.6	1803.08	127.4
DB9-4-3	AG	100	373	0.9077	930.3	1803.08	152.3

Figs 120-122 report the thermal conductivity data as a function of temperature. The two curves on each plot show the heating and cooling thermal conductivity data. Again, there is good agreement between the heating and cooling curves for all of the PCEA AG data.

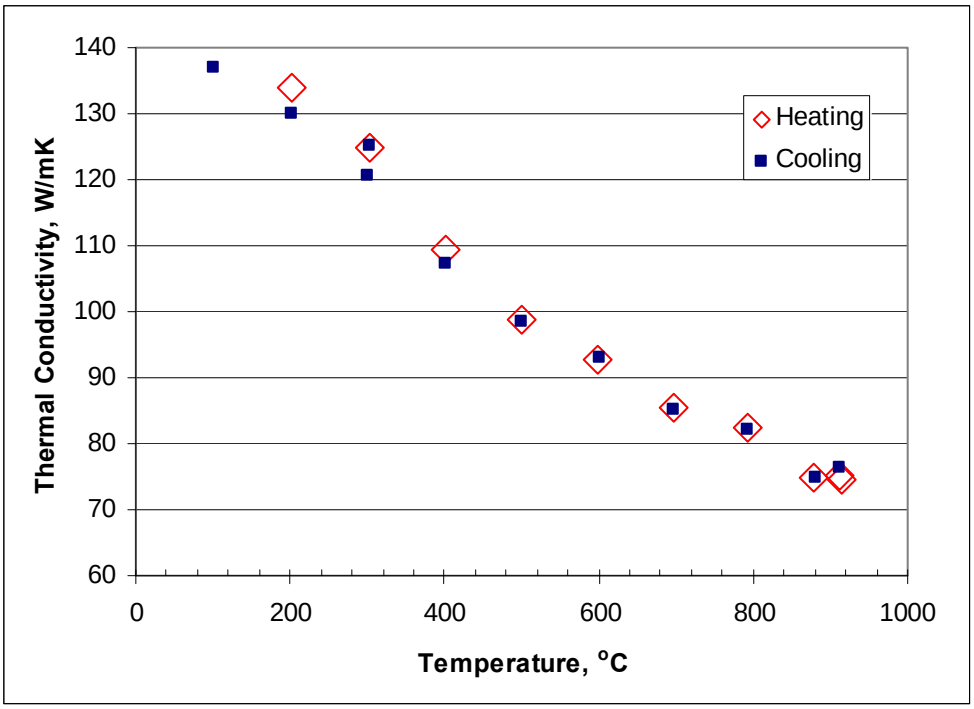

Figure 120. Against-grain elevated temperature thermal conductivity for grade PCEA (specimen DB1-4-3)

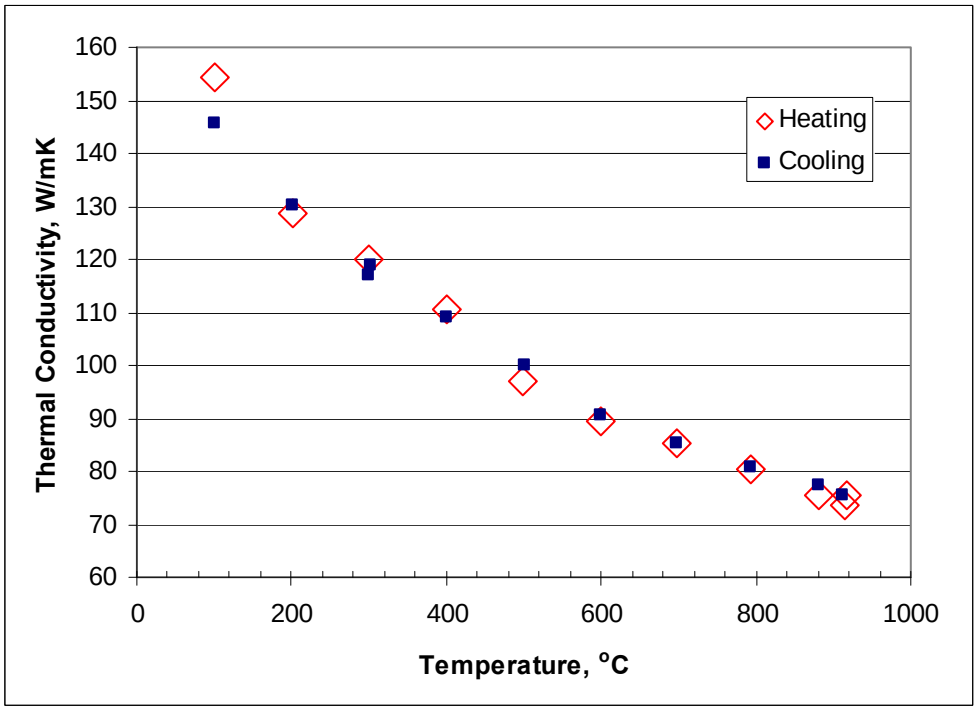

Figure 121. Against-grain elevated temperature thermal conductivity for grade PCEA (specimen DB5-4-3)

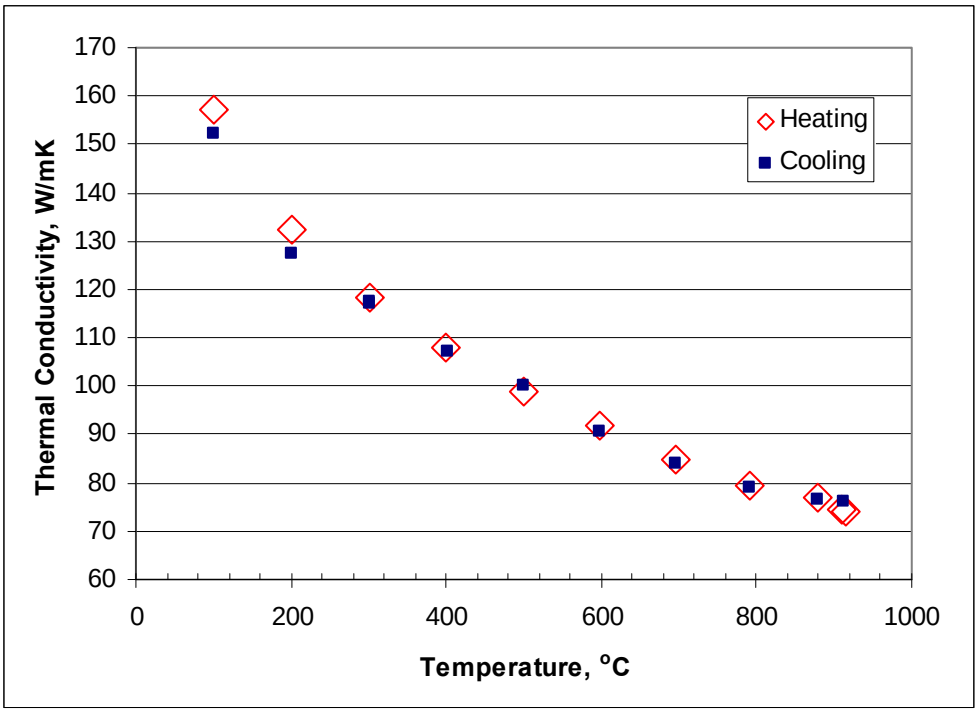

Figure 122. Against-grain elevated temperature thermal conductivity for grade PCEA (specimen DB9-4-3)

Figs. 123-125 compare the with- and against-grain orientations and indicate PCEA is nearly isotropic. However, the graphite appears to be marginally less isotropic than either NGB-17 or NBG-18. This is probably because of the different forming techniques employed. The NBG grades are vibrationally-molded, whereas PCEA is extruded graphite.

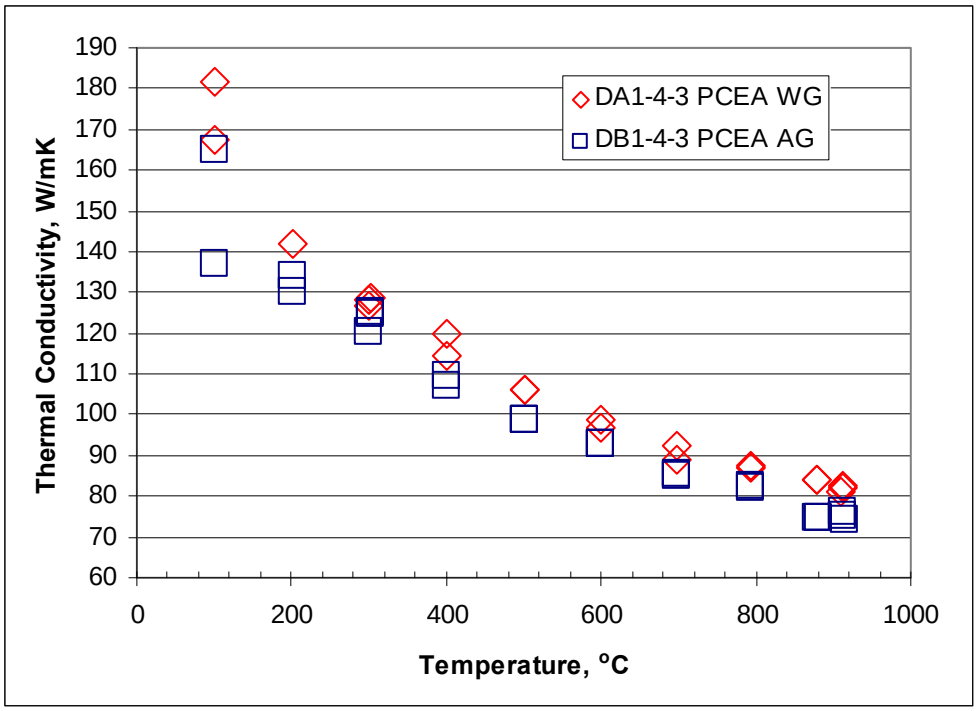

Figure 123. Comparison of with- and against-grain elevated temperature thermal conductivity for grade PCEA

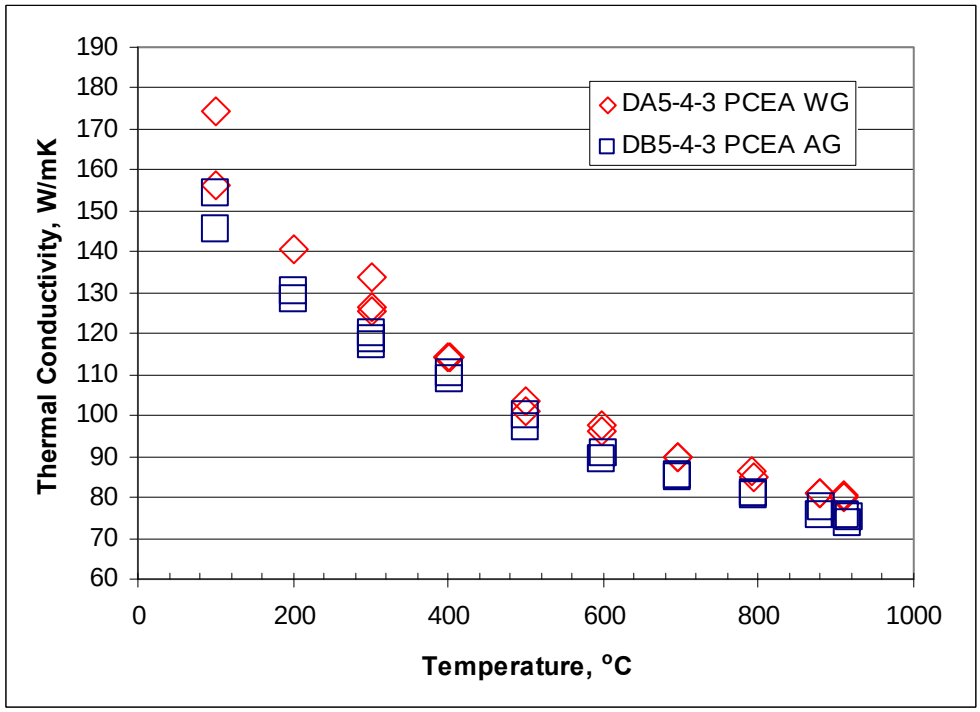

Figure 124. Comparison of with- and against-grain elevated temperature thermal conductivity for grade PCEA

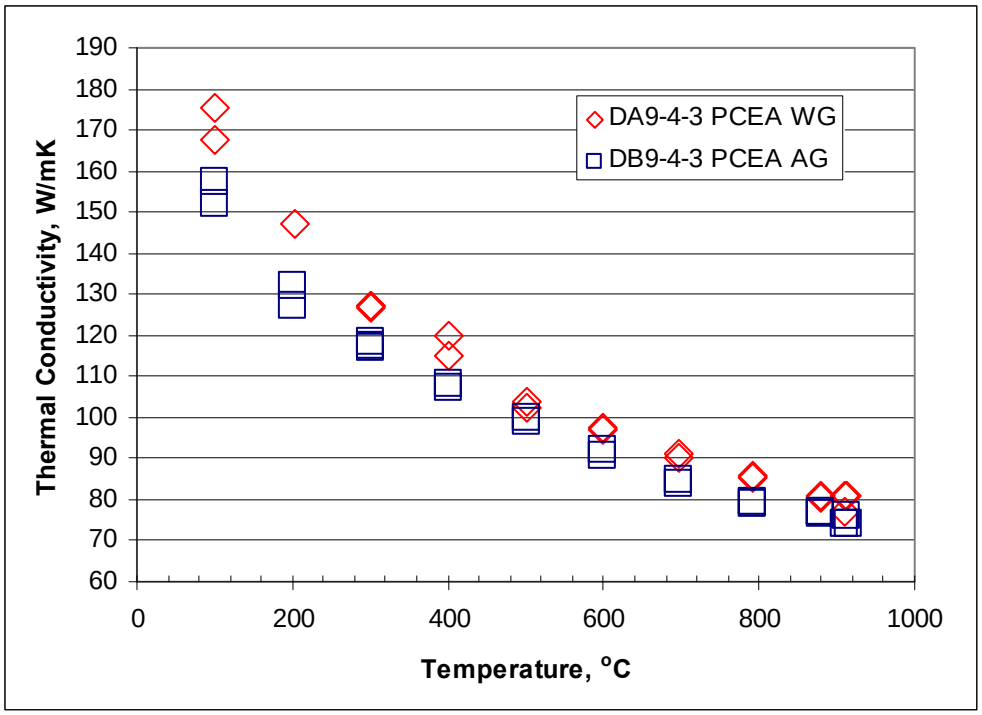

Figure 125. Comparison of with- and against-grain elevated temperature thermal conductivity for grade PCEA

3.7.7. H-451 thermal conductivity

Elevated temperature thermal diffusivity and thermal conductivity data for grade H-451 in the with-grain direction are reported in Tables 38-40. Against-grain thermal conductivity was not determined for grade H-451 since it is included in the AGC-1 as creep-reference materials in the WG orientation only. The reported thermal diffusivity values represent the mean of three measurements taken at each temperature. The mensuration data used to determine the specimen density is given in Appendix 40.

Table 38. Elevated temperature thermal diffusivity and conductivity data for grade H-451 (with grain) specimen C1-4-3

Thermal Conductivity, H-451 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm2/sec	Specific Heat J/kg.K	Density Kg/m3	Thermal Conductivity W/m.K
C1-4-3	WG	100	373	0.9707	930.3	1721.82	155.5
C1-4-3	WG	201	474	0.6536	1157.6	1721.82	130.3
C1-4-3	WG	301	574	0.4969	1339.9	1721.82	114.6
C1-4-3	WG	400	673	0.4014	1484.5	1721.82	102.6
C1-4-3	WG	500	773	0.3584	1601.7	1721.82	98.8
C1-4-3	WG	599	872	0.3152	1695.1	1721.82	92.0
C1-4-3	WG	697	970	0.2792	1770.3	1721.82	85.1
C1-4-3	WG	792	1065	0.2394	1830.2	1721.82	75.4
C1-4-3	WG	877	1150	0.221	1875.2	1721.82	71.4
C1-4-3	WG	907	1180	0.2208	1889.5	1721.82	71.8
C1-4-3	WG	910	1183	0.2248	1890.9	1721.82	73.2
C1-4-3	WG	910	1183	0.2246	1890.9	1721.82	73.1
C1-4-3	WG	878	1151	0.2193	1875.7	1721.82	70.8
C1-4-3	WG	792	1065	0.2399	1830.2	1721.82	75.6
C1-4-3	WG	696	969	0.2696	1769.6	1721.82	82.1
C1-4-3	WG	599	872	0.2948	1695.1	1721.82	86.0
C1-4-3	WG	500	773	0.3475	1601.7	1721.82	95.8
C1-4-3	WG	401	674	0.4111	1485.8	1721.82	105.2
C1-4-3	WG	301	574	0.4934	1339.9	1721.82	113.8
C1-4-3	WG	302	575	0.5271	1341.5	1721.82	121.7
C1-4-3	WG	202	475	0.6469	1159.6	1721.82	129.2
C1-4-3	WG	102	375	0.9706	935.2	1721.82	156.3

Table 39. Elevated temperature thermal diffusivity and conductivity data for grade H-451 (with grain) specimen C5-4-3

Thermal Conductivity, H-451 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm2/sec	Specific Heat J/kg.K	Density Kg/m3	Thermal Conductivity W/m.K
C5-4-3	WG	100	373	1.0276	930.3	1736.24	166.0
C5-4-3	WG	201	474	0.6494	1157.6	1736.24	130.5
C5-4-3	WG	301	574	0.5354	1339.9	1736.24	124.6
C5-4-3	WG	400	673	0.4163	1484.5	1736.24	107.3
C5-4-3	WG	500	773	0.3576	1601.7	1736.24	99.4
C5-4-3	WG	599	872	0.325	1695.1	1736.24	95.7
C5-4-3	WG	696	969	0.2823	1769.6	1736.24	86.7
C5-4-3	WG	792	1065	0.2493	1830.2	1736.24	79.2
C5-4-3	WG	877	1150	0.2303	1875.2	1736.24	75.0
C5-4-3	WG	907	1180	0.2201	1889.5	1736.24	72.2
C5-4-3	WG	909	1182	0.2257	1890.4	1736.24	74.1
C5-4-3	WG	910	1183	0.2258	1890.9	1736.24	74.1
C5-4-3	WG	877	1150	0.225	1875.2	1736.24	73.3
C5-4-3	WG	792	1065	0.2479	1830.2	1736.24	78.8
C5-4-3	WG	696	969	0.2666	1769.6	1736.24	81.9
C5-4-3	WG	599	872	0.315	1695.1	1736.24	92.7
C5-4-3	WG	500	773	0.36	1601.7	1736.24	100.1
C5-4-3	WG	400	673	0.4287	1484.5	1736.24	110.5
C5-4-3	WG	301	574	0.4975	1339.9	1736.24	115.7
C5-4-3	WG	302	575	0.5155	1341.5	1736.24	120.1
C5-4-3	WG	202	475	0.6423	1159.6	1736.24	129.3
C5-4-3	WG	102	375	1.0754	935.2	1736.24	174.6

Table 40. Elevated temperature thermal diffusivity and conductivity data for grade PCEA (with grain) specimen C9-4-3

Thermal Conductivity, H-451 (3 mm thick specimens)							
Specimen	Orientation	Temperature C	Temperature K	Mean Thermal Diffusivity cm2/sec	Specific Heat J/kg.K	Density Kg/m3	Thermal Conductivity W/m.K
C9-4-3	WG	100	373	0.9548	930.3	1720.47	152.8
C9-4-3	WG	201	474	0.6453	1157.6	1720.47	128.5
C9-4-3	WG	301	574	0.4999	1339.9	1720.47	115.2
C9-4-3	WG	400	673	0.4048	1484.5	1720.47	103.4
C9-4-3	WG	500	773	0.358	1601.7	1720.47	98.7
C9-4-3	WG	599	872	0.2954	1695.1	1720.47	86.1
C9-4-3	WG	696	969	0.2638	1769.6	1720.47	80.3
C9-4-3	WG	792	1065	0.2489	1830.2	1720.47	78.4
C9-4-3	WG	878	1151	0.2139	1875.7	1720.47	69.0
C9-4-3	WG	908	1181	0.223	1890.0	1720.47	72.5
C9-4-3	WG	909	1182	0.2193	1890.4	1720.47	71.3
C9-4-3	WG	908	1181	0.2142	1890.0	1720.47	69.6
C9-4-3	WG	877	1150	0.2259	1875.2	1720.47	72.9
C9-4-3	WG	792	1065	0.2364	1830.2	1720.47	74.4
C9-4-3	WG	696	969	0.2788	1769.6	1720.47	84.9
C9-4-3	WG	599	872	0.2785	1695.1	1720.47	81.2
C9-4-3	WG	500	773	0.3477	1601.7	1720.47	95.8
C9-4-3	WG	400	673	0.4121	1484.5	1720.47	105.3
C9-4-3	WG	301	574	0.5068	1339.9	1720.47	116.8
C9-4-3	WG	302	575	0.5051	1341.5	1720.47	116.6
C9-4-3	WG	202	475	0.6576	1159.6	1720.47	131.2
C9-4-3	WG	101	374	0.9887	932.8	1720.47	158.7

Figs. 126-128 report the thermal conductivity data as a function of temperature. The two curves on each plot show the heating and cooling thermal conductivity data. There is good agreement between the heating and cooling curves for all of the H-451 WG data.

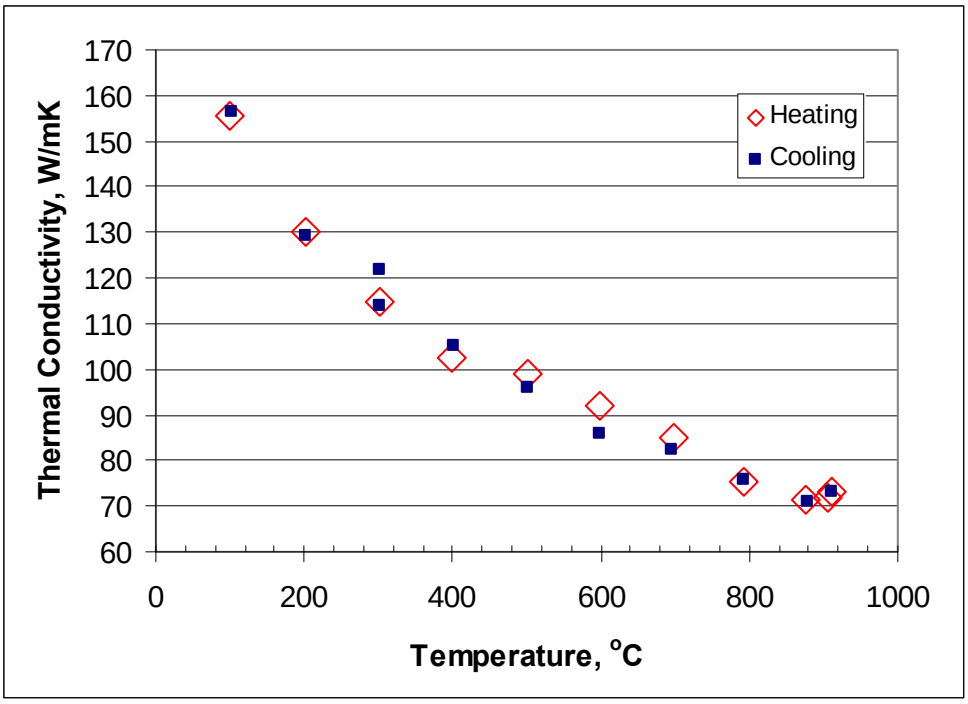

Figure 126. With-grain elevated temperature thermal conductivity for grade H-451 (specimen C1-4-3)

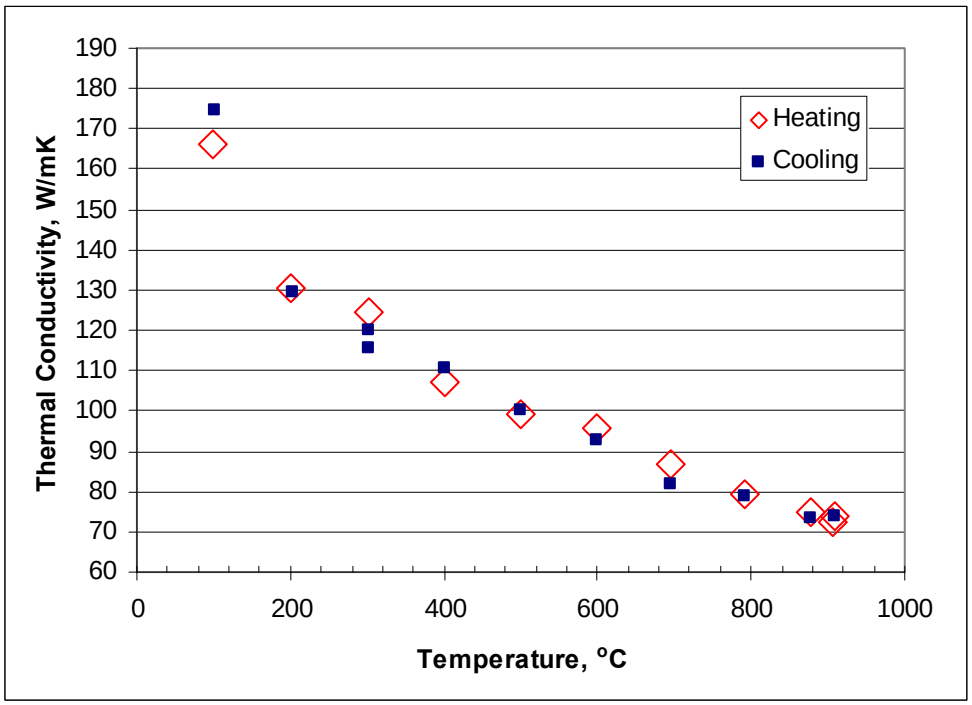

Figure 127. With-grain elevated temperature thermal conductivity for grade H-451 (specimen C5-4-3)

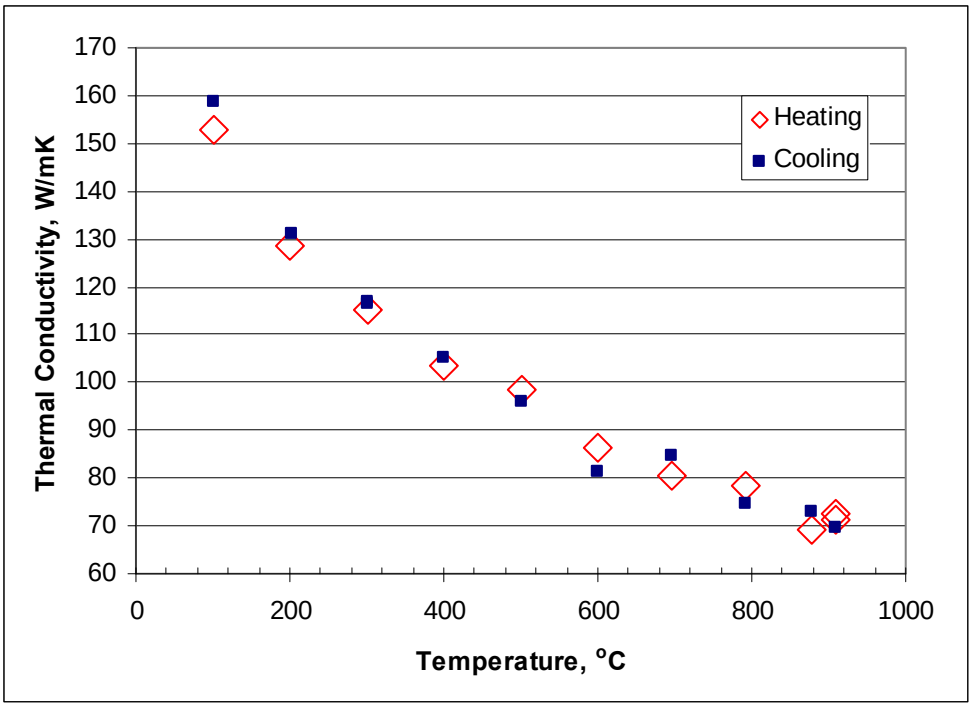

Figure 128. With-grain elevated temperature thermal conductivity for grade H-451 (specimen C9-4-3)

3.7.8. Thermal Conductivity General Discussion

The thermal conductivity data reported here for the major grades follows the expected trend of decreasing thermal conductivity with increasing temperature. This behavior is attributed to increased phonon-phonon scattering with increasing temperature (Umklapp scattering). For the grades examined the heating and cooling curves were very similar. The fine-grained, isostatically pressed grades (IG-110 and IG-430) have lower thermal conductivities that the coarser grained vibrationally-molded and extruded grades. The thermal conductivity was determined in the with-grain and against-grain directions for three of the grades (PCEA, NBG-17, and NBG-18). All three grades exhibited slight anisotropy, as would be expected for near-isotropic graphite. The extruded grade, PCEA, exhibited more anisotropy than the two vibrationally-molded grades.

3.8 Tensile (Static) Young's Modulus and Strain to Failure

The tensile (static) Young's modulus was determined from the initial slope of the stress-strain curve (Figs. 23-31) determined in accordance with ASTM C 749 [5]. The modulus was calculated from the slope over the range 0-0.05% strain. The strain to failure was determined as defined in C 749 [5] as the strain at the maximum stress (i.e., at failure). The mean Young's modulus and strain-to-failure data for the graphite grades examined here are reported in Table 41.

Table 41. Mean Young's modulus and strain-to-failure data for the graphite grades examined here

Results for Glued-end Tensile Specimens							
	Grain Orientation						
Graphite Grade	With (WG)	Against (AG)	Modulus GPa	Standard Deviation GPa	Maximum Strain %	Standard Deviation %	Number of Specimens
NBG-17 (wg)	x		13.27	4.66	0.208	0.074	12
NBG-17(ag)		x	11.05	2.76	0.214	0.042	9
NBG-18 (wg)	x		13.99	5.53	0.200	0.074	12
NBG-18 (ag)		x	10.73	3.41	0.265	0.054	11
H-451	x		10.89	3.16	0.167	0.063	10
PCEA (wg)	x		8.87	2.34	0.274	0.061	12
PCEA (ag)		x	9.30	1.99	0.255	0.056	11
IG-110	Isotropic		10.83	4.72	0.224	0.073	12
IG-430	Isotropic		8.48	2.42	0.331	0.052	12

The mean modulus data are displayed in graphical form as bar-chart in Fig. 129. All of the mean static Young's modulus values fall within the specified ASTM C 7219 [11] range of 8-15 GPa. However, the standard deviations of the means are very large, indicating the modulus data populations were very scattered. This scatter is a reflection of the difficulty of accurately measuring strain over a small gauge-length, and of using the clip style strain gauges on a small specimen. Moreover, in many cases the specimen used is too small to yield satisfactory data (absolute values), but is acceptable for comparative measurements, i.e., pre- and post-irradiation measurements to yield a "fractional change". As previously discussed, the stress concentration effect of the glue joint also affects the consistency of the stress-strain data.

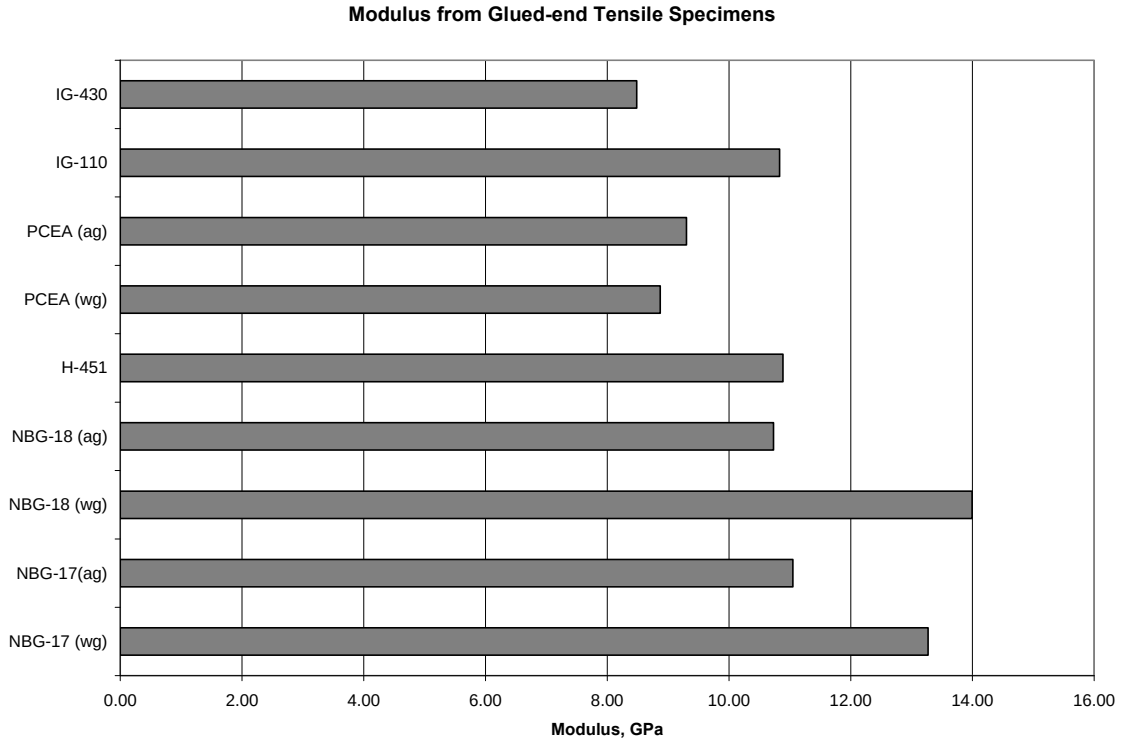

Figure 129. Mean static Young's modulus data from glued-end tensile stress-strain curves for the grades examined here

The trends observed in the Fig. 129 static moduli data are similar to those observed in the dynamic and sonic moduli data, i.e., the NBG grades exhibit the greatest moduli (probably because of the greater density), and grade H-451 exhibits the lowest moduli.

The mean maximum strain (strain-to-failure) data for the grades examined here are shown summarized in the bar-chart in Fig. 130. The vibrationally-molded, NBG grades, exhibited smaller strains-to-failure than the other grades (except H-451). The standard deviations of the strain-to-failure data samples were large, indicating considerable scatter in the data populations, for the reasons discussed above.

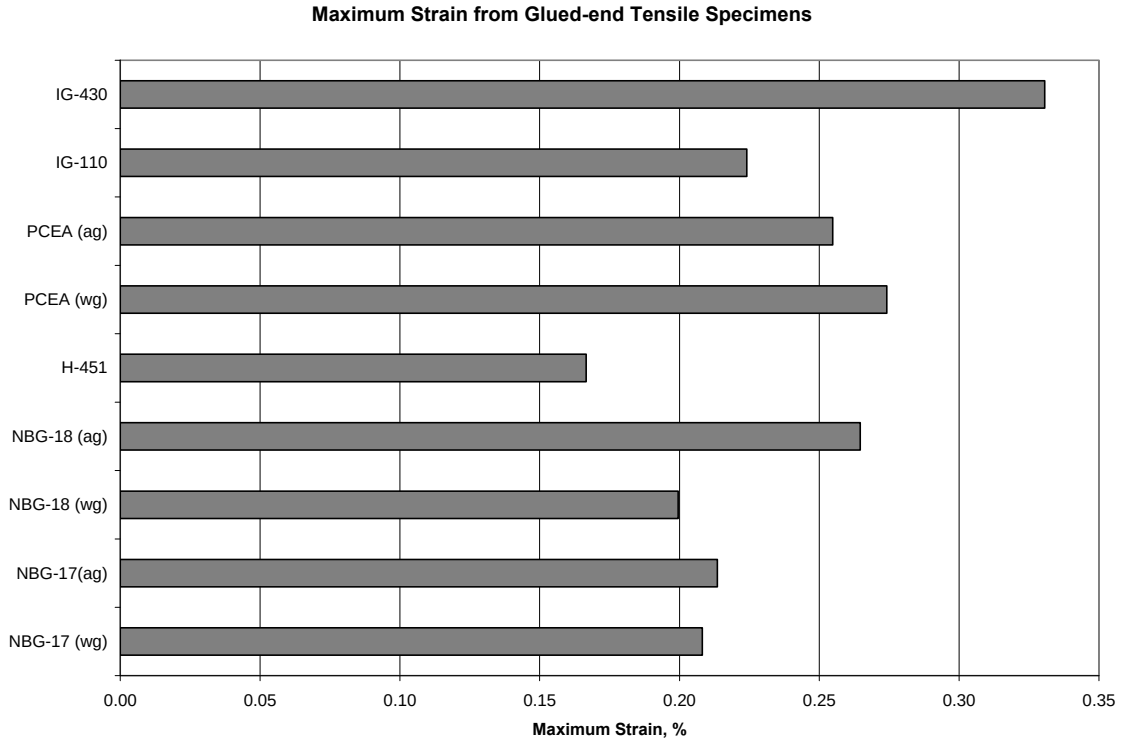

Figure 130. Mean maximum strain (strain-to-failure) data from glued-end tensile stress-strain curves for the grades examined here

3.9 Compressive Modulus and Strain to Failure

The compressive modulus was determined from the initial slope of the compressive stress-strain curve (see Figs. 34-42 for typical compressive stress-strain curves) and the strain to failure was determined as the strain at the maximum stress. The mean compressive modulus and strain-to-failure data for the graphite grades examined here are reported in Table 42.

Table 42. Mean compressive modulus and strain-to-failure data for the graphite grades examined here

Results for Compression Specimens							
	Grain Orientation						
Graphite Grade	With (WG)	Against (AG)	Modulus GPa	Standard Deviation GPa	Maximum Strain %	Standard Deviation %	Number of Specimens
NBG-17 (wg)	x		16.67	2.04	2.384	0.134	11
NBG-17(ag)		x	17.25	1.89	2.213	0.173	12
NBG-18 (wg)	x		17.91	1.67	2.529	0.246	12
NBG-18 (ag)		x	19.97	1.58	2.040	0.371	12
H-451	x		13.30	3.65	1.555	0.267	12
PCEA (wg)	x		16.30	2.64	2.216	0.283	12
PCEA (ag)		x	13.24	2.87	3.385	0.304	12
IG-110	Isotropic		14.41	1.61	2.918	0.221	12
IG-430	Isotropic		16.87	3.26	3.331	0.489	11

The mean compressive modulus data are displayed in graphical form in a bar chart in Fig. 131. The compressive moduli ranged from ~13 to 20 GPa and is typically twice the value of the respective tensile (Young's) modulus values. The vibrationally-molded grades (NBG-17 and -18) exhibited the greatest compressive moduli values (in common with their tensile moduli). The compressive strain to failure data are displayed in graphical form in a bar chart in Fig. 132. The compressive strains to failure varied from ~1.5% to ~3.5%, with grade H-451 exhibiting the lowest strain to failure and PCEA (AG) exhibiting the greatest strain to failure. Interestingly, the isostatically pressed grades exhibited quite high compressive strains to failure.

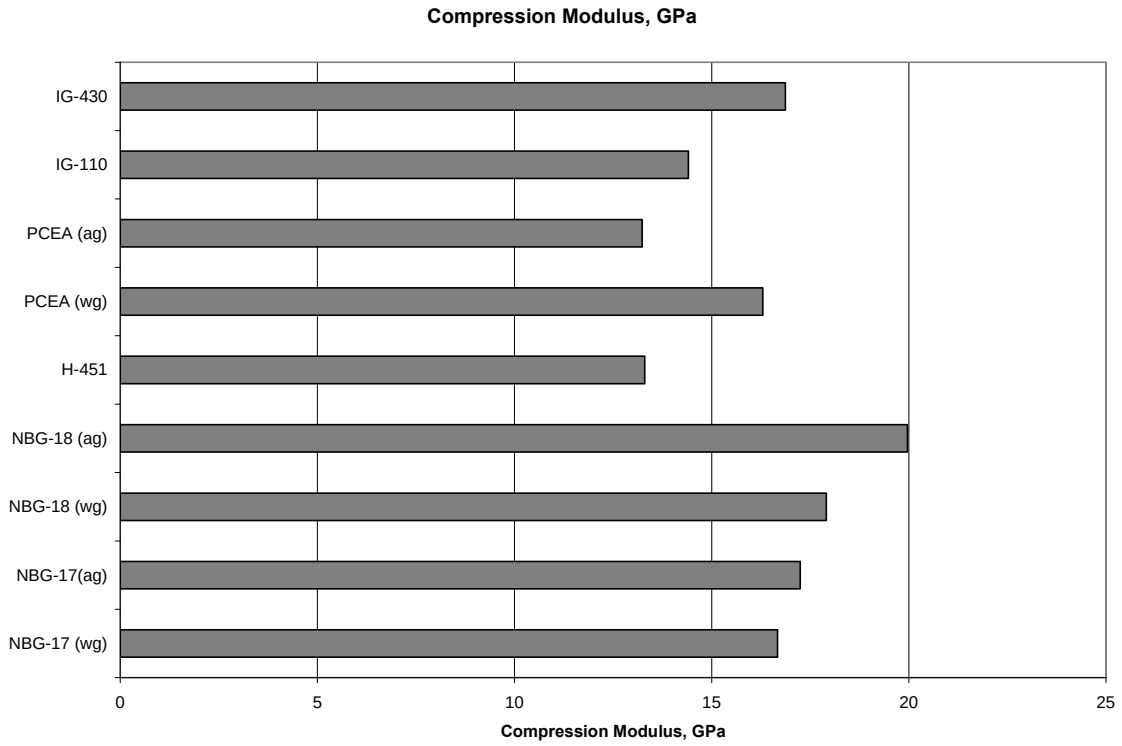

Figure 131. Mean static compressive modulus data from compressive stress-strain curves for the grades examined here

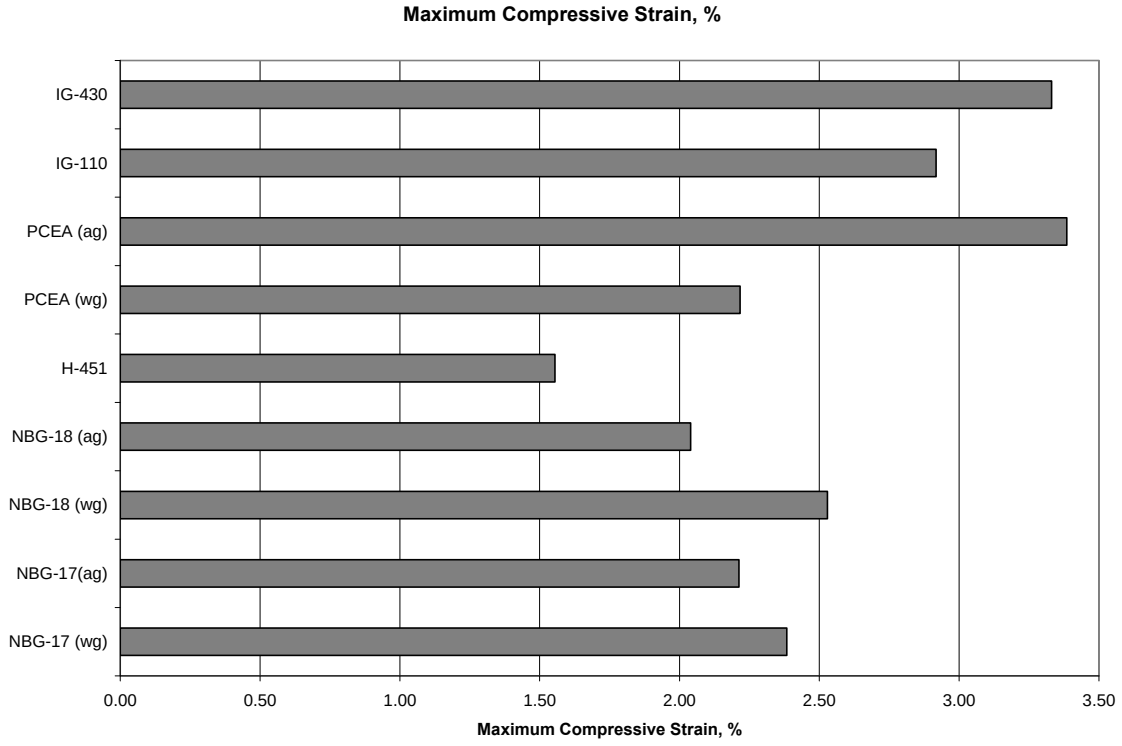

Figure 132. Mean maximum strain (strain-to-failure) data from compressive stress-strain curves for the grades examined here

4 Conclusions

The characterization, both non-destructively and destructively, of AGC-1 creep "sister" specimens is reported for the major grades, i.e., NBG-17, NBG-18, H-451, PCEA, IG-110, and IG-430. The properties measured were:

- Bulk density
  - Mensuration
  - Hg-immersions
- Tensile Properties
  - Strength
  - Stress-strain behavior
  - Static Young's modulus
  - Strain to failure
- Compressive Properties
  - Strength
  - Stress-strain behavior
  - Static elastic modulus
  - Strain to failure
- Elastic Constants
  - Dynamic Young's modulus (fundamental frequency method)
  - Sonic elastic constants
    - Young's modulus
    - Shear modulus
    - Poisson's ratio
- Pore Size Distribution (by Hg-intrusion)
- Crystal Structure (by XRD)
- Specific Heat (elevated temperature)
- Thermal Conductivity (elevated temperature)

Some of the methods used for characterization are difficult to apply to the small specimens geometries adopted of necessity for AGC-1. However, within the scope of ASTM C 781, these methods are modified to accommodate the smaller sample sizes specifically for irradiation experiments. Consequently, some of the data should not be considered representative of the absolute properties for the graphite, but should allow for relative effects (or fractional property changes) to be established post-irradiation. This was particularly evident for the tensile properties, where the stress concentration of the glued-end was problematic in the fine grain materials and other grain/pore size – specimen volume effects were evident. The need for further work in understanding these effects with representative specimen volume (as part of our larger characterization program) is indicated. Based upon the tensile data reported here H-451 would not meet the ASTM D 7219 (2008) "Standard Specification for Isotropic and Near-Isotropic Nuclear Graphites" specified minimum tensile strength. However, for the reasons discussed above, the absolute value of strength reported here cannot be interpreted as an accurate assessment.

The compressive strength showed the anticipated dependency on graphite structure, which illustrates the need to characterize the structure (grain and pore size distributions, crystallinity, etc.). Vibrationally molded grades showed the highest strength which was attributed to their greater density. The isostatically pressed grades also exhibited high strength (uniform grain and pore structure). The extruded grades displayed the lowest strengths. Based on the compressive strength data reported here H-451 would not meet the ASTM D 7219 (2008) specified minimum compressive strength. However, the sub-size specimen used here of necessity would not be acceptable for quality acceptance purposes. For compressive specimens, ten times the maximum grain size is recommended, requiring for H-451 a specimen > 12mm diameter (as used here). The AGC-1 specimen geometry is however permitted for irradiation specimens per ASTM C 781. The low strength determined for H-451 reinforces the conclusion that detailed characterization is need for the NGNP candidate grades using representative specimen volumes.

Pore structure characterization was performed via Hg-intrusion. It was determined that surface roughness (machining marks) can introduce spurious indications into the pore size distributions, and the distributions must be modified accordingly. Hg-porosimetry revealed details of the pore

sizes and their distribution. The fine-grain isotropic (isostatically pressed) grades exhibited unimodal distributions, whereas the extruded and vibrationally molded grades exhibited bimodal pore size distributions. Baseline characterization of the pore structure using Hg-intrusion will allow assessment of the effects of irradiation induced dimensional changes and creep strain on the pore structure. A detailed knowledge of pore structure changes with irradiation induced dimensional change and creep are essential if physically sound models are to be developed from the experimental creep data flowing from the AGC irradiation experiments.

XRD analysis was performed on all the major grades and selected other graphites (BAN and HOPG) from the AGC-1 experiment. A "tentative" ranking system was proposed based upon the crystallinity of the graphite. The XRD data shows H-451 to be particularly well-ordered graphite. Similarly, grade IG-430 displayed a high degree of overall crystallinity. Disruption of the graphite crystal structure during irradiation is a fundamental damage mechanism and drives the build up of irradiation induced crystal strain and polycrystalline dimensional change. Consequently, establishing baseline XRD spectra for the major grades is required so that post-irradiation assessment is meaningful. Samples of HOPG were examined and crystal pole figures determined for specified crystallographic directions. The pole figures show the HOPG to have a "fiber-like" texture with very strong preferred orientation of the crystal basal planes in the material. HOPG irradiation behavior provides a good analog for the graphite single crystal behavior. Hence, HOPG was included in the AGC-1 capsule.

Bulk density was determined by mensuration and by Hg-immersion (on selected samples). Bulk density determined by mensuration and by Hg immersion, showed remarkable agreement, and all the grades examined here met the requirements of the ASTM standard specification for nuclear graphites, D 7219-08.

Young's modulus was determined non-destructively by the fundamental frequency method (dynamic modulus) and sonically from the longitudinal wave velocity. There was good agreement between the moduli determined from the two methods, although the dynamic moduli values were slightly greater for most of the grades examined here. Based upon the non-

destructive evaluations of Young's modulus all of the grades meet the ASTM D 7219 (2008) nuclear graphite specification requirement for Young's modulus. Other elastic constants were determined sonically, including shear modulus and Poisson's ratio. A large difference was observed in the Poisson's ratio between the isostatically pressed grades ($\mu \approx 0.15$) and the other grades ($\mu \approx 0.3$). The large Poisson's ratio of some of the grades may have been a contributory factor in the difficulties encountered with the "glued-end" tensile testing.

The specific heat of graphite was determined for grade NBG-18 and found to be well predicted by the equation provided by the National Institute of Standards and Technology, and incorporated into ASTM C 781 (2008), for all graphites.

A study of specimen thickness on the measurement of elevated temperature thermal conductivity of graphite by the thermal pulse technique conducted on NBG-18 (the coarsest textured materials studied here) showed that 3 mm thickness was the best compromise given the conflicting needs to have the thinnest specimen for ease of post-irradiation examination (when thermal conductivity will be greatly diminished) and the desire to have thick specimens that are representative of the materials structure. The heating and cooling thermal conductivity curves were in good agreement for all of the grades studied. Moreover, the anticipated behavior (for all the grades examined) of reducing thermal conductivity with increasing temperature was observed and is attributed to Umklapp phonon scattering. The thermal conductivity was determined in the with-grain and against-grain directions for three of the grades (PCEA, NBG-17, and NBG-18). All three grades exhibited slight anisotropy, as would be expected for near-isotropic graphite. The extruded grade, PCEA, exhibited more anisotropy than the two vibrationally-molded grades.

Tensile modulus and strain to failure were determined from the tensile stress-strain curves. The moduli values agreed well with the values determined non-destructively, although the scatter for the static moduli was quite large. This was attributed to problems with the small specimen size and the nature of the extensometer used. The graphite grades examined here all exhibited static Young's moduli within the range allowed by the ASTM D 7219 (2008) nuclear graphite specification.

The compressive moduli ranged from ~13 to 20 GPa, typically twice the value of the respective tensile (Young's) modulus values. The vibrationally-molded grades (NBG-17 and -18) exhibited the greatest compressive moduli values (in common with their tensile moduli). The compressive strains to failure varied from ~1.5% to ~3.5%, with grade H-451 exhibiting the lowest strain to failure and PCEA-(AG) exhibiting the greatest strain to failure.

Finally, a sufficient body of experimental data has been acquired from the AGC-1 creep "sister" specimens to fully characterize the properties of interest for the major grades included in the AGC-1 capsule. These data, in combination with the pre-irradiation characterization data packages for the actual AGC-1 creep and control specimens provide a sound and sufficient pre-irradiation data set for determination of the effects of irradiation induced dimensional change and creep strain of the physical properties of the nuclear graphite grades in the AGC-1 capsule.

5 References

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6. Acknowledgments

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Appendix 1. "Glued-end" tensile strength data for NBG-17 specimens (WG and AG)

Orientation	Specimen Number	Average Diameter in.	Maximum Load lb.	Tensile Strength MPa	*Failure within ext. G.L.
wg	**A1-5**	0.50096	541.99	18.96	No
wg	**A1-6**	0.50121	532.23	18.60	No
wg	**A1-7**	0.50126	390.66	13.65	No
wg	**A3-5**	0.50114	581.05	20.31	No
wg	**A3-6**	0.50113	561.52	19.63	No
wg	**A3-7**	0.50120	605.47	21.16	No
wg	**A7-5**	0.50098	590.82	20.67	No
wg	**A7-6**	0.50086	463.87	16.23	No
wg	**A7-7**	0.50107	439.45	15.37	No
wg	**A9-5**	0.50110	419.92	14.68	No
wg	**A9-6**	0.50074	429.69	15.04	No
wg	**A9-7**	0.50092	546.87	19.13	Yes
			Average	17.79	
			Std Dev	2.51	
ag	**AB1-5**	0.50085	551.76	19.31	Yes
ag	**AB1-6**	0.50121	366.21	12.80	No
ag	**AB1-7**	0.50103	483.40	16.90	No
ag	**AB3-5**	0.50112	458.98	16.05	No
ag	**AB3-6**	0.50114	424.80	14.85	No
ag	**AB3-7**	0.50113	546.87	19.12	No
ag	**AB7-5**	0.50104	512.70	17.93	No
ag	**AB7-6**	0.50038	541.99	19.00	No
ag	**AB7-7**	0.50094	415.04	14.52	No
ag	**AB9-5**	0.50104	522.46	18.27	No
ag	**AB9-6**	0.50098	478.52	16.74	No
ag	**AB9-7**	0.50109	571.29	19.97	No
			Average	17.12	
			Std Dev	2.13	

Appendix 2. "Glued-end" tensile strength data for NBG-18 specimens (WG and AG)

Orientation	Specimen Number	Average Diameter in.	Maximum Load lb.	Tensile Strength MPa	*Failure within ext. G.L.
wg	**B3-5**	0.50148	512.70	17.90	No
wg	**B3-6**	0.50089	444.34	15.55	No
wg	**B3-7**	0.50109	512.70	17.92	No
wg	**B5-5**	0.50162	434.57	15.16	Yes
wg	**B5-6**	0.50158	620.12	21.64	No
wg	**B5-7**	0.50151	639.65	22.33	No
wg	**B7-5**	0.50144	463.87	16.20	No
wg	**B7-6**	0.50118	620.12	21.67	No
wg	**B7-7**	0.50173	581.05	20.26	Yes
wg	**B9-5**	0.50168	454.10	15.84	Yes
wg	**B9-6**	0.50137	468.75	16.37	Yes
wg	**B9-7**	0.50154	527.34	18.40	No
			Average	18.27	
			Std Dev	2.49	
ag	**BB3-5**	0.50051	488.28	17.11	No
ag	**BB3-6**	0.50111	512.70	17.92	Yes
ag	**BB3-7**	0.50094	434.57	15.20	Yes
ag	**BB5-5**	0.50131	668.95	23.37	No
ag	**BB5-6**	0.50113	585.94	20.48	Yes
ag	**BB5-7**	0.50128	478.52	16.72	No
ag	**BB7-5**	0.50138	585.94	20.46	No
ag	**BB7-6**	0.50096	615.23	21.52	No
ag	**BB7-7**	0.50118	419.92	14.68	Yes
ag	**BB9-5**	0.50125	629.88	22.01	No
ag	**BB9-6**	0.50133	527.34	18.42	Yes
ag	**BB9-7**	0.50127	629.88	22.01	Yes
			Average	19.16	
			Std Dev	2.75	

Appendix 3. "Glued-end" tensile strength data for H-451 (WG) specimens

Specimen Number	Average Diameter in.	Maximum Load lb.	Tensile Strength MPa	*Failure within ext. G.L.
C11-1	0.50126	297.85	10.41	Yes
C11-2	0.50134	307.62	10.74	No
C11-3	0.50038	234.37	8.22	No
C13-1	0.50103	322.27	11.27	Yes
C13-2	0.50153	346.68	12.10	Yes
C13-3	0.50130	312.50	10.92	Yes
C15-1	0.50124	380.86	13.31	Yes
C15-2	0.50113	419.92	14.68	No
C15-3	0.50123	449.22	15.70	Yes
C19-1	0.50099	395.51	13.83	Yes
C19-2	0.50129	380.86	13.30	Yes
C19-3	0.50129	302.73	10.58	Yes
		Average	12.09	
		Std Dev	2.04	

Appendix 4. "Glued-end" tensile strength data for PCEA specimens (WG and AG)

Orientation	Specimen Number	Average Diameter in.	Maximum Load lb.	Tensile Strength MPa	*Failure within ext. G.L.
wg	**DA2-4**	0.50139	454.10	15.86	No
wg	**DA2-5**	0.50146	478.52	16.71	No
wg	**DA2-6**	0.50134	541.99	18.93	No
wg	**DA4-4**	0.50151	546.87	19.09	No
wg	**DA4-5**	0.50161	449.22	15.67	No
wg	**DA4-6**	0.50161	605.47	21.13	No
wg	**DA8-4**	0.50144	615.23	21.48	No
wg	**DA8-5**	0.50136	522.46	18.25	No
wg	**DA8-6**	0.50162	605.47	21.12	No
wg	**DA10-4**	0.50179	366.21	12.77	No
wg	**DA10-5**	0.50157	581.05	20.28	No
wg	**DA10-6**	0.50167	581.05	20.27	No
			Average	18.46	
			Std Dev	2.59	
ag	**DB2-4**	0.50158	541.99	18.91	No
ag	**DB2-5**	0.50183	527.34	18.38	No
ag	**DB2-6**	0.50161	478.52	16.70	Yes
ag	**DB4-4**	0.50176	444.34	15.49	No
ag	**DB4-5**	0.50157	434.57	15.16	Yes
ag	**DB4-6**	0.50166	502.93	17.54	No
ag	**DB8-4**	0.50119	572.46	20.01	No
ag	**DB8-5**	0.50129	361.33	12.62	Yes
ag	**DB8-6**	0.50130	488.28	17.06	No
ag	**DB10-4**	0.50098	483.40	16.91	No
ag	**DB10-5**	0.50141	541.99	18.92	No
ag	**DB10-6**	0.50111	478.52	16.73	Yes
			Average	17.04	
			Std Dev	1.91	

Appendix 5. "Glued-end" tensile strength data for IG-110 specimens

Specimen Number	Average Diameter in.	Maximum Load lb.	Tensile Strength MPa	*Failure within ext. G.L.
E2-4	0.50158	419.92	14.65	No
E2-5	0.50166	415.04	14.48	No
E2-6	0.50140	385.74	13.47	No
E4-4	0.50142	473.63	16.54	No
E4-5	0.50116	444.34	15.53	No
E4-6	0.50126	434.57	15.18	No
E8-4	0.50176	380.86	13.28	No
E8-5	0.50190	454.10	15.83	No
E8-6	0.50160	454.10	15.84	No
E10-4	0.50145	454.10	15.85	No
E10-5	0.50136	375.98	13.13	No
E10-6	0.50127	429.69	15.01	No
		Average	14.90	
		Std Dev	1.08	

Appendix 6. "Glued-end" tensile strength data for IG-430 specimens

Specimen Number	Average Diameter in.	Maximum Load lb.	Tensile Strength MPa	*Failure within ext. G.L.
F2-4	0.50135	571.29	19.95	No
F2-5	0.50118	537.11	18.77	No
F2-6	0.50126	605.47	21.15	No
F4-4	0.50121	507.81	17.75	No
F4-5	0.50061	551.76	19.33	No
F4-6	0.50157	668.95	23.34	No
F8-4	0.50098	478.52	16.74	No
F8-5	0.50147	541.99	18.92	No
F8-6	0.50078	512.70	17.95	No
F10-4	0.50109	581.05	20.32	No
F10-5	0.50130	595.70	20.81	No
F10-6	0.50154	522.46	18.23	No
		Average	19.44	
		Std Dev	1.72	

Appendix 7. Dimensions, volume, mass, and density data for compressive specimens NBG-17 (WG) sheet 1

Specimen	Thickness Measurements, in.					Outside Diameter Measurements			
Number	Allowable: 0.998 - 1.000					Allowable: 0.500 - 0.502			
	T1	T2	T3	T4		D1	D2	D3	D4
A2-1	0.99935	0.99935	0.99890	0.99895		0.50120	0.50105	0.50100	0.50150
A2-2	0.99920	0.99895	0.99905	0.99940		0.50145	0.50140	0.50125	0.50140
A2-3	0.99900	0.99915	0.99925	0.99910		0.50120	0.50120	0.50090	0.50085
A4-1	0.99930	0.99925	0.99920	0.99920		0.50095	0.50120	0.50100	0.50090
A4-2	0.99975	0.99960	0.99955	0.99975		0.50120	0.50125	0.50140	0.50130
A4-3	0.99895	0.99885	0.99900	0.99920		0.50100	0.50130	0.50130	0.50170
A6-1	0.99950	0.99960	0.99960	0.99945		0.50105	0.50085	0.50070	0.50075
A6-2	0.99955	0.99965	0.99985	0.99960		0.50150	0.50145	0.50150	0.50145
A6-3	0.99935	0.99920	0.99925	0.99935		0.50130	0.50140	0.50150	0.50140
A8-1	0.99975	0.99965	0.99970	0.99980		0.50115	0.50105	0.50115	0.50105
A8-2	0.99945	0.99945	0.99940	0.99940		0.50095	0.50125	0.50100	0.50090
A8-3	0.99935	0.99960	0.99945	0.99935		0.50120	0.50130	0.50140	0.50120
A10-1	0.99930	0.99930	0.99935	0.99940		0.50130	0.50120	0.50120	0.50125
A10-2	0.99950	0.99955	0.99940	0.99940		0.50145	0.50110	0.50115	0.50135
A10-3	0.99930	0.99900	0.99910	0.99920		0.50130	0.50080	0.50115	0.50115

Appendix 7. Dimensions, volume, mass, and density data for compressive specimens NBG-17 (WG) sheet 2

Specimen	Outside Diameter Measurements					Hole Diameter, in.			
Number	Allowable: 0.500 - 0.502					Allowable: 0.124 - 0.128			
	$D1^{90}$	$D2^{90}$	$D3^{90}$	$D4^{90}$		H1	H2	H1'	H2'
A2-1	0.50120	0.50105	0.50105	0.50100		0.12780	0.12770	0.12790	0.12780
A2-2	0.50150	0.50145	0.50120	0.50125		0.12780	0.12770	0.12790	0.12790
A2-3	0.50115	0.50120	0.50080	0.50085		0.12790	0.12790	0.12790	0.12790
A4-1	0.50070	0.50090	0.50090	0.50095		0.12780	0.12770	0.12770	0.12760
A4-2	0.50125	0.50130	0.50145	0.50135		0.12790	0.12770	0.12790	0.12810
A4-3	0.50130	0.50115	0.50115	0.50155		0.12770	0.12780	0.12770	0.12770
A6-1	0.50090	0.50090	0.50080	0.50060		0.12780	0.12780	0.12780	0.12760
A6-2	0.50140	0.50130	0.50150	0.50165		0.12790	0.12770	0.12770	0.12790
A6-3	0.50100	0.50125	0.50160	0.50160		0.12800	0.12800	0.12810	0.12770
A8-1	0.50065	0.50100	0.50100	0.50125		0.12800	0.12790	0.12780	0.12780
A8-2	0.50100	0.50115	0.50100	0.50085		0.12780	0.12780	0.12770	0.12780
A8-3	0.50130	0.50140	0.50130	0.50125		0.12810	0.12790	0.12800	0.12790
A10-1	0.50110	0.50100	0.50110	0.50115		0.12790	0.12800	0.12800	0.12800
A10-2	0.50135	0.50125	0.50125	0.50135		0.12800	0.12810	0.12820	0.12790
A10-3	0.50110	0.50085	0.50125	0.50135		0.12800	0.12800	0.12800	0.12790

Appendix 7. Dimensions, volume, mass, and density data for compressive specimens NBG-17 (WG) sheet 3

Specimen Number	Weight, g		Average Thickness	Average Diameter	Hole Volume	Mass	Density	Density
			m	m	m^3	kg	kg/m^3	g/cm^3
A2-1	5.9104		0.025378	0.012729	5.4655E-08	0.00591	1861.6995	1.8617
A2-2	5.9107		0.025378	0.012735	5.4676E-08	0.005911	1860.0362	1.8600
A2-3	5.8864		0.025378	0.012726	5.4740E-08	0.005886	1855.0605	1.8551
A4-1	5.8977		0.025381	0.012724	5.4569E-08	0.005898	1858.9219	1.8589
A4-2	5.9135		0.025391	0.012733	5.4740E-08	0.005914	1860.3618	1.8604
A4-3	5.8941		0.025375	0.012733	5.4591E-08	0.005894	1855.4692	1.8555
A6-1	5.8939		0.025388	0.012721	5.4612E-08	0.005894	1858.0779	1.8581
A6-2	5.9163		0.025391	0.012737	5.4655E-08	0.005916	1860.0130	1.8600
A6-3	5.8952		0.025382	0.012735	5.4783E-08	0.005895	1854.8201	1.8548
A8-1	5.9095		0.025393	0.012726	5.4719E-08	0.00591	1861.0491	1.8610
A8-2	5.8965		0.025385	0.012726	5.4633E-08	0.005897	1857.6606	1.8577
A8-3	5.8955		0.025386	0.012733	5.4804E-08	0.005896	1855.3025	1.8553
A10-1	5.9006		0.025383	0.01273	5.4804E-08	0.005901	1858.0861	1.8581
A10-2	5.9016		0.025386	0.012733	5.4869E-08	0.005902	1857.3067	1.8573
A10-3	5.8913		0.025378	0.012728	5.4804E-08	0.005891	1855.8413	1.8558

Appendix 8. Dimensions, volume, mass, and density data for compressive specimens NBG-18 (AG) sheet 1

Specimen	Thickness Measurements, in.					Outside Diameter Measurements			
Number	Allowable: 0.998 - 1.000					Allowable: 0.500 - 0.502			
	T1	T2	T3	T4		D1	D2	D3	D4
AB2-1	0.99940	0.99965	0.99955	0.99930		0.50115	0.50115	0.50110	0.50120
AB2-2	0.99955	0.99935	0.99940	0.99950		0.50110	0.50080	0.50105	0.50110
AB2-3	0.99930	0.99940	0.99940	0.99935		0.50140	0.50110	0.50135	0.50135
AB4-1	0.99920	0.99945	0.99925	0.99920		0.50130	0.50110	0.50110	0.50100
AB4-2	0.99890	0.99910	0.99935	0.99910		0.50090	0.50090	0.50100	0.50105
AB4-3	0.99905	0.99935	0.99950	0.99930		0.50150	0.50120	0.50130	0.50140
AB6-1	0.99905	0.99925	0.99920	0.99900		0.50115	0.50120	0.50100	0.50080
AB6-2	0.99930	0.99945	0.99960	0.99955		0.50115	0.50115	0.50130	0.50125
AB6-3	0.99930	0.99920	0.99925	0.99945		0.50145	0.50145	0.50135	0.50120
AB8-1	0.99955	0.99965	0.99965	0.99955		0.50050	0.50045	0.50045	0.50055
AB8-2	0.99910	0.99925	0.99945	0.99935		0.50105	0.50105	0.50100	0.50105
AB8-3	0.99940	0.99940	0.99955	0.99945		0.50135	0.50135	0.50130	0.50110
AB10-1	0.99875	0.99885	0.99940	0.99905		0.50050	0.50050	0.50065	0.50050
AB10-2	0.99965	0.99945	0.99940	0.99960		0.50110	0.50090	0.50110	0.50110
AB10-3	0.99965	0.99960	0.99950	0.99955		0.50105	0.50100	0.50100	0.50110

Appendix 8. Dimensions, volume, mass, and density data for compressive specimens NBG-18 (AG) sheet 2

Specimen	Outside Diameter Measurements					Hole Diameter, in.			
Number	Allowable: 0.500 - 0.502					Allowable: 0.124 - 0.128			
	$D1^{90}$	$D2^{90}$	$D3^{90}$	$D4^{90}$		H1	H2	H1'	H2'
AB2-1	0.50120	0.50105	0.50120	0.50110		0.12790	0.12790	0.12790	0.12790
AB2-2	0.50100	0.50090	0.50100	0.50110		0.12780	0.12800	0.12780	0.12800
AB2-3	0.50125	0.50125	0.50130	0.50125		0.12800	0.12790	0.12790	0.12790
AB4-1	0.50140	0.50115	0.50100	0.50110		0.12800	0.12790	0.12800	0.12790
AB4-2	0.50075	0.50075	0.50100	0.50100		0.12800	0.12790	0.12790	0.12790
AB4-3	0.50090	0.50110	0.50140	0.50135		0.12810	0.12790	0.12790	0.12800
AB6-1	0.50130	0.50105	0.50100	0.50110		0.12790	0.12790	0.12800	0.12790
AB6-2	0.50125	0.50125	0.50125	0.50125		0.12820	0.12800	0.12800	0.12810
AB6-3	0.50150	0.50130	0.50145	0.50135		0.12800	0.12800	0.12790	0.12790
AB8-1	0.50070	0.50070	0.50070	0.50055		0.12790	0.12790	0.12800	0.12790
AB8-2	0.50095	0.50105	0.50100	0.50100		0.12790	0.12790	0.12780	0.12790
AB8-3	0.50125	0.50140	0.50160	0.50125		0.12790	0.12790	0.12790	0.12790
AB10-1	0.50030	0.50040	0.50065	0.50050		0.12790	0.12790	0.12800	0.12790
AB10-2	0.50125	0.50110	0.50120	0.50120		0.12810	0.12790	0.12800	0.12800
AB10-3	0.50095	0.50070	0.50110	0.50100		0.12800	0.12790	0.12790	0.12790

Appendix 8. Dimensions, volume, mass, and density data for compressive specimens NBG-17 (AG) sheet 3

Specimen Number	Weight, g		Average Thickness	Average Diameter	Hole Volume	Mass	Density	Density
			m	m	m^3	kg	kg/m^3	g/cm^3
AB2-1	5.8993		0.025387	0.012729	5.4740E-08	0.005899	1857.5206	1.8575
AB2-2	5.8939		0.025386	0.012726	5.4740E-08	0.005894	1856.9039	1.8569
AB2-3	5.8975		0.025384	0.012733	5.4762E-08	0.005898	1856.1427	1.8561
AB4-1	5.8978		0.025382	0.012729	5.4783E-08	0.005898	1857.4514	1.8575
AB4-2	5.8884		0.025377	0.012723	5.4762E-08	0.005888	1856.4807	1.8565
AB4-3	5.9101		0.025382	0.012732	5.4804E-08	0.00591	1860.3462	1.8603
AB6-1	5.8945		0.025378	0.012727	5.4762E-08	0.005895	1857.2014	1.8572
AB6-2	5.8981		0.025387	0.012731	5.4890E-08	0.005898	1856.5708	1.8566
AB6-3	5.9091		0.025382	0.012735	5.4783E-08	0.005909	1859.1699	1.8592
AB8-1	5.8914		0.025390	0.012715	5.4762E-08	0.005891	1859.0998	1.8591
AB8-2	5.9031		0.025382	0.012726	5.4719E-08	0.005903	1860.0031	1.8600
AB8-3	5.9036		0.025386	0.012734	5.4740E-08	0.005904	1857.5548	1.8576
AB10-1	5.8873		0.025375	0.012713	5.4762E-08	0.005887	1859.4842	1.8595
AB10-2	5.9047		0.025388	0.012728	5.4826E-08	0.005905	1859.3652	1.8594
AB10-3	5.9049		0.025389	0.012725	5.4762E-08	0.005905	1860.2870	1.8603

Appendix 9. Dimensions, volume, mass, and density data for compressive specimens NBG-18 (WG) sheet 1

Specimen	Thickness Measurements, in.					Outside Diameter Measurements			
Number	Allowable: 0.998 - 1.000					Allowable: 0.500 - 0.502			
	T1	T2	T3	T4		D1	D2	D3	D4
B2-1	0.99930	0.99920	0.99925	0.99915		0.50125	0.50125	0.50130	0.50130
B2-2	0.99925	0.99915	0.99925	0.99935		0.50115	0.50115	0.50100	0.50125
B2-3	0.99890	0.99910	0.99900	0.99890		0.50165	0.50165	0.50165	0.50155
B4-1	0.99895	0.99905	0.99895	0.99885		0.50130	0.50085	0.50125	0.50135
B4-2	0.99910	0.99900	0.99910	0.99910		0.50160	0.50155	0.50160	0.50160
B4-3	0.99900	0.99915	0.99895	0.99875		0.50140	0.50150	0.50130	0.50165
B6-1	0.99955	0.99955	0.99935	0.99945		0.50090	0.50105	0.50070	0.50140
B6-2	0.99910	0.99900	0.99890	0.99910		0.50175	0.50165	0.50170	0.50155
B6-3	0.99925	0.99925	0.99905	0.99900		0.50160	0.50150	0.50160	0.50175
B8-1	0.99875	0.99875	0.99890	0.99895		0.50160	0.50145	0.50155	0.50140
B8-2	0.99905	0.99915	0.99890	0.99875		0.50120	0.50140	0.50100	0.50120
B8-3	0.99910	0.99920	0.99940	0.99925		0.50170	0.50180	0.50190	0.50190
B10-1	0.99870	0.99875	0.99865	0.99870		0.50165	0.50150	0.50150	0.50170
B10-2	0.99875	0.99880	0.99895	0.99885		0.50175	0.50150	0.50160	0.50150
B10-3	0.99905	0.99920	0.99925	0.99895		0.50165	0.50170	0.50160	0.50165

Appendix 9. Dimensions, volume, mass, and density data for compressive specimens NBG-18 (WG) sheet 2

Specimen	Outside Diameter Measurements					Hole Diameter, in.			
Number	Allowable: 0.500 - 0.502					Allowable: 0.124 - 0.128			
	$D1^{90}$	$D2^{90}$	$D3^{90}$	$D4^{90}$		H1	H2	H1'	H2'
B2-1	0.50125	0.50120	0.50125	0.50125		0.12800	0.12780	0.12790	0.12780
B2-2	0.50115	0.50095	0.50090	0.50120		0.12800	0.12780	0.12800	0.12800
B2-3	0.50175	0.50165	0.50165	0.50155		0.12780	0.12790	0.12780	0.12770
B4-1	0.50125	0.50055	0.50115	0.50130		0.12760	0.12770	0.12770	0.12760
B4-2	0.50165	0.50155	0.50150	0.50150		0.12780	0.12770	0.12780	0.12780
B4-3	0.50135	0.50145	0.50125	0.50170		0.12800	0.12780	0.12790	0.12780
B6-1	0.50090	0.50100	0.50065	0.50130		0.12780	0.12780	0.12780	0.12780
B6-2	0.50170	0.50170	0.50160	0.50165		0.12770	0.12770	0.12780	0.12780
B6-3	0.50150	0.50150	0.50160	0.50170		0.12790	0.12780	0.12790	0.12780
B8-1	0.50140	0.50145	0.50140	0.50145		0.12790	0.12780	0.12770	0.12770
B8-2	0.50125	0.50145	0.50110	0.50120		0.12770	0.12770	0.12810	0.12790
B8-3	0.50180	0.50185	0.50190	0.50195		0.12790	0.12780	0.12790	0.12770
B10-1	0.50160	0.50150	0.50155	0.50175		0.12790	0.12800	0.12800	0.12790
B10-2	0.50155	0.50165	0.50165	0.50155		0.12780	0.12780	0.12770	0.12780
B10-3	0.50175	0.50170	0.50170	0.50175		0.12780	0.12780	0.12780	0.12780

Appendix 9. Dimensions, volume, mass, and density data for compressive specimens NBG-18 (WG) sheet 3

Specimen Number	Weight, g		Average * Length	Average * Diameter	2-Hole Volume	Mass	Density	Density
			m	m	m^3	kg	kg/m^3	g/cm^3
B2-1	5.9450		0.02538	0.01273	5.4719E-08	0.005945	1871.5192	1.8715
B2-2	5.9358		0.02538	0.01273	5.4783E-08	0.005936	1869.8462	1.8698
B2-3	5.9328		0.02537	0.01274	5.4655E-08	0.005933	1865.2290	1.8652
B4-1	5.9621		0.02537	0.01273	5.4526E-08	0.005962	1878.3146	1.8783
B4-2	5.9444		0.02538	0.01274	5.4633E-08	0.005944	1869.1942	1.8692
B4-3	5.9415		0.02537	0.01274	5.4719E-08	0.005942	1869.4469	1.8694
B6-1	5.9514		0.02539	0.01273	5.4655E-08	0.005951	1875.0641	1.8751
B6-2	5.9392		0.02538	0.01274	5.4612E-08	0.005939	1866.9317	1.8669
B6-3	5.9436		0.02538	0.01274	5.4697E-08	0.005944	1868.6719	1.8687
B8-1	5.9594		0.02537	0.01274	5.4633E-08	0.005959	1875.1722	1.8752
B8-2	5.9497		0.02537	0.01273	5.4697E-08	0.005950	1873.7245	1.8737
B8-3	5.9538		0.02538	0.01275	5.4676E-08	0.005954	1869.7320	1.8697
B10-1	5.9612		0.02537	0.01274	5.4783E-08	0.005961	1875.0910	1.8751
B10-2	5.9545		0.02537	0.01274	5.4633E-08	0.005955	1872.6331	1.8726
B10-3	5.9473		0.02538	0.01274	5.4655E-08	0.005947	1869.1469	1.8691

Appendix 10. Dimensions, volume, mass, and density data for compressive specimens NBG-18 (AG) sheet 1

Specimen	Thickness Measurements, in.					Outside Diameter Measurements			
Number	Allowable: 0.998 - 1.000					Allowable: 0.500 - 0.502			
	T1	T2	T3	T4		D1	D2	D3	D4
BB2-1	0.99940	0.99940	0.99945	0.99940		0.50080	0.50080	0.50080	0.50075
BB2-2	0.99945	0.99955	0.99940	0.99925		0.50130	0.50105	0.50105	0.50125
BB2-3	0.99945	0.99960	0.99960	0.99950		0.50105	0.50095	0.50105	0.50085
BB4-1	0.99945	0.99940	0.99940	0.99940		0.50080	0.50080	0.50100	0.50105
BB4-2	0.99905	0.99925	0.99925	0.99920		0.50100	0.50105	0.50105	0.50110
BB4-3	0.99915	0.99925	0.99925	0.99910		0.50115	0.50120	0.50135	0.50100
BB6-1	0.99955	0.99960	0.99960	0.99960		0.50075	0.50080	0.50060	0.50095
BB6-2	0.99950	0.99940	0.99940	0.99945		0.50130	0.50120	0.50090	0.50100
BB6-3	0.99930	0.99905	0.99910	0.99940		0.50165	0.50160	0.50145	0.50160
BB8-1	0.99880	0.99880	0.99875	0.99875		0.50130	0.50115	0.50115	0.50135
BB8-2	0.99915	0.99940	0.99925	0.99905		0.50120	0.50100	0.50120	0.50105
BB8-3	0.99915	0.99910	0.99905	0.99905		0.50140	0.50155	0.50120	0.50180
BB10-1	0.99910	0.99910	0.99895	0.99910		0.50110	0.50115	0.50105	0.50110
BB10-2	0.99980	0.99975	0.99985	0.99995		0.50130	0.50125	0.50125	0.50130
BB10-3	0.99930	0.99945	0.99925	0.99920		0.50170	0.50180	0.50170	0.50170

Appendix 10. Dimensions, volume, mass, and density data for compressive specimens NBG-18 (AG) sheet 2

Specimen	Outside Diameter Measurements					Hole Diameter, in.			
Number	Allowable: 0.500 - 0.502					Allowable: 0.124 - 0.128			
	$D1^{90}$	$D2^{90}$	$D3^{90}$	$D4^{90}$		H1	H2	H1'	H2'
BB2-1	0.50095	0.50070	0.50110	0.50090		0.12780	0.12780	0.12790	0.12790
BB2-2	0.50105	0.50100	0.50105	0.50105		0.12790	0.12780	0.12790	0.12790
BB2-3	0.50120	0.50100	0.50085	0.50090		0.12780	0.12780	0.12790	0.12780
BB4-1	0.50100	0.50095	0.50070	0.50070		0.12810	0.12800	0.12810	0.12800
BB4-2	0.50120	0.50110	0.50110	0.50115		0.12810	0.12810	0.12800	0.12800
BB4-3	0.50115	0.50090	0.50120	0.50120		0.12800	0.12790	0.12800	0.12790
BB6-1	0.50105	0.50090	0.50070	0.50075		0.12780	0.12780	0.12790	0.12790
BB6-2	0.50100	0.50120	0.50095	0.50080		0.12790	0.12790	0.12780	0.12780
BB6-3	0.50175	0.50165	0.50150	0.50170		0.12780	0.12790	0.12780	0.12770
BB8-1	0.50130	0.50105	0.50130	0.50130		0.12800	0.12790	0.12790	0.12800
BB8-2	0.50120	0.50105	0.50115	0.50140		0.12800	0.12800	0.12780	0.12780
BB8-3	0.50125	0.50160	0.50125	0.50175		0.12800	0.12800	0.12800	0.12790
BB10-1	0.50130	0.50115	0.50105	0.50110		0.12820	0.12800	0.12810	0.12790
BB10-2	0.50120	0.50135	0.50135	0.50130		0.12810	0.12810	0.12820	0.12820
BB10-3	0.50180	0.50180	0.50160	0.50175		0.12810	0.12810	0.12810	0.12810

Appendix 10. Dimensions, volume, mass, and density data for compressive specimens NBG-18 (AG) sheet 3

Specimen Number	Weight, g		Average * Length	Average * Diameter	2-Hole Volume	Mass	Density	Density
			m	m	m^3	kg	kg/m^3	g/cm^3
BB2-1	5.9174		0.02539	0.01272	5.4697E-08	0.005917	1865.5372	1.8655
BB2-2	5.9187		0.02539	0.01273	5.4719E-08	0.005919	1864.0662	1.8641
BB2-3	5.9296		0.02539	0.01272	5.4676E-08	0.005930	1868.1369	1.8681
BB4-1	5.9055		0.02539	0.01272	5.4869E-08	0.005906	1861.6970	1.8617
BB4-2	5.9172		0.02538	0.01273	5.4869E-08	0.005917	1864.1560	1.8642
BB4-3	5.9289		0.02538	0.01273	5.4783E-08	0.005929	1867.4124	1.8674
BB6-1	5.9144		0.02539	0.01272	5.4697E-08	0.005914	1864.5434	1.8645
BB6-2	5.9170		0.02539	0.01273	5.4697E-08	0.005917	1863.8964	1.8639
BB6-3	5.9510		0.02538	0.01274	5.4655E-08	0.005951	1870.6883	1.8707
BB8-1	5.9165		0.02537	0.01273	5.4783E-08	0.005917	1863.5804	1.8636
BB8-2	5.9278		0.02538	0.01273	5.4740E-08	0.005928	1866.8985	1.8669
BB8-3	5.9533		0.02538	0.01274	5.4804E-08	0.005953	1872.7818	1.8728
BB10-1	5.9185		0.02538	0.01273	5.4869E-08	0.005919	1864.5662	1.8646
BB10-2	5.9241		0.02540	0.01273	5.4954E-08	0.005924	1863.6794	1.8637
BB10-3	5.9411		0.02538	0.01274	5.4912E-08	0.005941	1866.6615	1.8667

Appendix 11. Dimensions, volume, mass, and density data for compressive specimens H-451 (WG) sheet 1

Specimen	Thickness Measurements, in.					Outside Diameter Measurements			
Number	Allowable: 0.998 - 1.000					Allowable: 0.500 - 0.502			
	T1	T2	T3	T4		D1	D2	D3	D4
C2-1	0.99960	0.99965	0.99950	0.99960		0.50100	0.50070	0.50065	0.50065
C2-2	0.99970	0.99965	0.99940	0.99960		0.50170	0.50180	0.50170	0.50135
C2-3	0.99965	0.99965	0.99965	0.99975		0.50195	0.50195	0.50185	0.50175
C4-1	0.99960	0.99950	0.99960	0.99970		0.50145	0.50140	0.50125	0.50165
C4-2	0.99965	0.99970	0.99975	0.99970		0.50145	0.50160	0.50155	0.50165
C4-3	1.00005	1.00015	1.00015	1.00010		0.50200	0.50175	0.50165	0.50150
C6-1	0.99975	0.99975	0.99965	0.99960		0.50155	0.50165	0.50165	0.50195
C6-2	0.99955	0.99960	0.99955	0.99945		0.50110	0.50115	0.50105	0.50115
C6-3	0.99955	0.99960	0.99955	0.99955		0.50110	0.50025	0.50055	0.50040
C8-1	0.99925	0.99930	0.99930	0.99910		0.50155	0.50130	0.50125	0.50100
C8-2	0.99910	0.99940	0.99975	0.99950		0.50125	0.50010	0.50105	0.50100
C8-3	0.99935	0.99935	0.99910	0.99940		0.50155	0.50150	0.50155	0.50145
C10-1	0.99895	0.99910	0.99890	0.99895		0.50100	0.50095	0.50120	0.50125
C10-2	0.99950	0.99925	0.99925	0.99935		0.50125	0.50120	0.50135	0.50130
C10-3	0.99915	0.99915	0.99910	0.99930		0.50145	0.50140	0.50115	0.50090

Appendix 11. Dimensions, volume, mass, and density data for compressive specimens H-451 (WG) sheet 2

Specimen	Outside Diameter Measurements					Hole Diameter, in.			
Number	Allowable: 0.500 - 0.502					Allowable: 0.124 - 0.128			
	$D1^{90}$	$D2^{90}$	$D3^{90}$	$D4^{90}$		H1	H2	H1'	H2'
C2-1	0.50090	0.50050	0.50060	0.50065		0.12770	0.12780	0.12770	0.12770
C2-2	0.50175	0.50165	0.50170	0.50135		0.12780	0.12760	0.12780	0.12770
C2-3	0.50185	0.50185	0.50175	0.50165		0.12760	0.12780	0.12770	0.12760
C4-1	0.50115	0.50150	0.50140	0.50165		0.12760	0.12760	0.12770	0.12770
C4-2	0.50135	0.50165	0.50155	0.50170		0.12770	0.12760	0.12760	0.12770
C4-3	0.50175	0.50175	0.50170	0.50160		0.12760	0.12760	0.12760	0.12750
C6-1	0.50150	0.50165	0.50165	0.50200		0.12760	0.12750	0.12760	0.12770
C6-2	0.50110	0.50115	0.50105	0.50095		0.12750	0.12770	0.12800	0.12800
C6-3	0.50120	0.50010	0.50085	0.50040		0.12760	0.12760	0.12750	0.12750
C8-1	0.50145	0.50120	0.50110	0.50115		0.12780	0.12780	0.12800	0.12800
C8-2	0.50120	0.50080	0.50080	0.50110		0.12750	0.12740	0.12810	0.12820
C8-3	0.50135	0.50150	0.50150	0.50145		0.12750	0.12730	0.12750	0.12750
C10-1	0.50095	0.50100	0.50110	0.50140		0.12790	0.12790	0.12790	0.12770
C10-2	0.50100	0.50125	0.50130	0.50140		0.12780	0.12770	0.12790	0.12770
C10-3	0.50130	0.50130	0.50080	0.50080		0.12780	0.12780	0.12770	0.12780

Appendix 11. Dimensions, volume, mass, and density data for compressive specimens H-451 (WG) sheet 3

Specimen Number	Weight, g		Average Thickness	Average Diameter	2-Hole Volume	Mass	Density	Density
			m	m	mm^3	kg	kg/m^3	g/cm^3
C2-1	5.42780		0.025390	0.012718	5.45905E-08	0.005428	1711.8215	1.7118
C2-2	5.44620		0.025390	0.012741	5.45905E-08	0.005446	1711.2306	1.7112
C2-3	5.45750		0.025392	0.012746	5.45478E-08	0.005458	1713.2156	1.7132
C4-1	5.45610		0.025390	0.012736	5.45264E-08	0.005456	1715.6326	1.7156
C4-2	5.46250		0.025392	0.012740	5.45264E-08	0.005463	1716.5562	1.7166
C4-3	5.48340		0.025403	0.012743	5.44624E-08	0.005483	1721.3190	1.7213
C6-1	5.45270		0.025392	0.012743	5.44837E-08	0.005453	1712.5202	1.7125
C6-2	5.42110		0.025388	0.012728	5.46548E-08	0.005421	1707.1844	1.7072
C6-3	5.39930		0.025389	0.012715	5.4441E-08	0.005399	1703.4882	1.7035
C8-1	5.39700		0.025381	0.012732	5.47402E-08	0.005397	1699.0387	1.6990
C8-2	5.39850		0.025386	0.012723	5.4655E-08	0.005399	1701.4492	1.7014
C8-3	5.38340		0.025382	0.012738	5.43557E-08	0.005383	1692.8552	1.6929
C10-1	5.44540		0.025374	0.012728	5.46974E-08	0.005445	1715.7115	1.7157
C10-2	5.45090		0.025383	0.012732	5.46332E-08	0.005451	1715.7310	1.7157
C10-3	5.46740		0.025379	0.012729	5.46333E-08	0.005467	1722.0392	1.7220

Appendix 12. Dimensions, volume, mass, and density data for compressive specimens PCEA (WG) sheet 1

Specimen	Thickness Measurements, in.					Outside Diameter Measurements			
Number	Allowable: 0.998 - 1.000					Allowable: 0.500 - 0.502			
	T1	T2	T3	T4		D1	D2	D3	D4
DA2-1	0.99865	0.99885	0.99890	0.99880		0.50135	0.50130	0.50150	0.50135
DA2-2	0.99900	0.99890	0.99895	0.99905		0.50180	0.50160	0.50155	0.50155
DA2-3	0.99885	0.99895	0.99905	0.99905		0.50160	0.50145	0.50145	0.50115
DA4-1	0.99930	0.99940	0.99925	0.99930		0.50190	0.50175	0.50165	0.50140
DA4-2	0.99930	0.99925	0.99925	0.99925		0.50160	0.50150	0.50135	0.50135
DA4-3	0.99860	0.99870	0.99885	0.99885		0.50150	0.50155	0.50165	0.50180
DA6-1	0.99920	0.99930	0.99930	0.99905		0.50160	0.50145	0.50145	0.50135
DA6-2	0.99920	0.99945	0.99930	0.99920		0.50165	0.50180	0.50180	0.50145
DA6-3	0.99860	0.99860	0.99855	0.99855		0.50140	0.50165	0.50175	0.50165
DA8-1	0.99915	0.99940	0.99925	0.99910		0.50170	0.50160	0.50145	0.50130
DA8-2	0.99925	0.99915	0.99925	0.99925		0.50120	0.50140	0.50145	0.50165
DA8-3	0.99905	0.99925	0.99925	0.99915		0.50170	0.50155	0.50155	0.50125
DA10-1	0.99905	0.99915	0.99900	0.99900		0.50180	0.50160	0.50165	0.50130
DA10-2	0.99880	0.99890	0.99900	0.99890		0.50135	0.50155	0.50160	0.50170
DA10-3	0.99930	0.99915	0.99920	0.99935		0.50165	0.50155	0.50145	0.50130

Appendix 12. Dimensions, volume, mass, and density data for compressive specimens PCEA (WG) sheet 2

Specimen	Outside Diameter Measurements					Hole Diameter, in.			
Number	Allowable: 0.500 - 0.502					Allowable: 0.124 - 0.128			
	$D1^{90}$	$D2^{90}$	$D3^{90}$	$D4^{90}$		H1	H2	H1'	H2'
DA2-1	0.50125	0.50130	0.50130	0.50150		0.1277	0.1277	0.1278	0.1278
DA2-2	0.50150	0.50145	0.50145	0.50145		0.1278	0.1278	0.1278	0.1277
DA2-3	0.50140	0.50130	0.50120	0.50125		0.1279	0.1279	0.1279	0.1278
DA4-1	0.50190	0.50170	0.50160	0.50155		0.1279	0.1277	0.1278	0.1278
DA4-2	0.50150	0.50145	0.50145	0.50130		0.1279	0.1277	0.1277	0.1277
DA4-3	0.50165	0.50150	0.50170	0.50180		0.1278	0.1279	0.1279	0.1279
DA6-1	0.50165	0.50135	0.50145	0.50130		0.1276	0.1275	0.1276	0.1278
DA6-2	0.50175	0.50170	0.50180	0.50145		0.1276	0.1276	0.1277	0.1276
DA6-3	0.50150	0.50145	0.50170	0.50175		0.1275	0.1276	0.1277	0.1277
DA8-1	0.50165	0.50150	0.50150	0.50140		0.1277	0.1277	0.1276	0.1276
DA8-2	0.50115	0.50140	0.50145	0.50155		0.1277	0.1277	0.1275	0.1274
DA8-3	0.50170	0.50155	0.50145	0.50120		0.1276	0.1275	0.1277	0.1276
DA10-1	0.50175	0.50165	0.50160	0.50135		0.1276	0.1276	0.1277	0.1275
DA10-2	0.50125	0.50150	0.50155	0.50165		0.1276	0.1276	0.1277	0.1278
DA10-3	0.50160	0.50150	0.50140	0.50130		0.1278	0.1277	0.1276	0.1280

Appendix 12. Dimensions, volume, mass, and density data for compressive specimens PCEA (WG) sheet 3

Specimen Number	Weight, g		Average * Thickness	Average * Diameter	Mass	2-Hole Volume	Density	Density
			m	m	kg	m^3	kg/m^3	g/cm^3
DA2-1	5.6695		0.02537	0.01273	0.00567	5.46119E-08	1784.7782	1.7848
DA2-2	5.6673		0.02537	0.01274	0.00567	5.46333E-08	1782.4234	1.7824
DA2-3	5.6753		0.02537	0.01273	0.00568	5.47188E-08	1786.3912	1.7864
DA4-1	5.6963		0.02538	0.01274	0.00570	5.46546E-08	1789.9423	1.7899
DA4-2	5.6905		0.02538	0.01274	0.00569	5.46119E-08	1789.9555	1.7900
DA4-3	5.7004		0.02537	0.01274	0.00570	5.47188E-08	1792.5655	1.7926
DA6-1	5.7194		0.02538	0.01274	0.00572	5.45051E-08	1798.9859	1.7990
DA6-2	5.7154		0.02538	0.01274	0.00572	5.45051E-08	1795.9509	1.7960
DA6-3	5.7173		0.02536	0.01274	0.00572	5.45051E-08	1798.3531	1.7984
DA8-1	5.7132		0.02538	0.01274	0.00571	5.45264E-08	1796.5694	1.7966
DA8-2	5.7113		0.02538	0.01274	0.00571	5.44624E-08	1796.7101	1.7967
DA8-3	5.7194		0.02538	0.01274	0.00572	5.44837E-08	1798.7233	1.7987
DA10-1	5.7189		0.02538	0.01274	0.00572	5.44837E-08	1798.1110	1.7981
DA10-2	5.7177		0.02537	0.01274	0.00572	5.45478E-08	1798.5460	1.7985
DA10-3	5.7211		0.02538	0.01274	0.00572	5.46332E-08	1799.3876	1.7994

Appendix 13. Dimensions, volume, mass, and density data for compressive specimens PCEA (AG) sheet 1

Specimen	Thickness Measurements, in.					Outside Diameter Measurements			
Number	Allowable: 0.998 - 1.000					Allowable: 0.500 - 0.502			
	T1	T2	T3	T4		D1	D2	D3	D4
DB2-1	0.99915	0.99920	0.99925	0.99920		0.50150	0.50155	0.50155	0.50175
DB2-2	0.99895	0.99875	0.99890	0.99910		0.50180	0.50165	0.50155	0.50185
DB2-3	0.99910	0.99910	0.99920	0.99915		0.50155	0.50140	0.50140	0.50155
DB4-1	0.99910	0.99915	0.99925	0.99905		0.50170	0.50165	0.50165	0.50160
DB4-2	0.99910	0.99900	0.99890	0.99910		0.50150	0.50125	0.50135	0.50165
DB4-3	0.99905	0.99905	0.99925	0.99925		0.50175	0.50160	0.50150	0.50155
DB6-1	0.99915	0.99915	0.99930	0.99925		0.50130	0.50145	0.50145	0.50175
DB6-2	0.99935	0.99935	0.99940	0.99945		0.50170	0.50175	0.50165	0.50160
DB6-3	0.99955	0.99955	0.99955	0.99945		0.50135	0.50085	0.50100	0.50135
DB8-1	0.99930	0.99920	0.99925	0.99935		0.50165	0.50145	0.50125	0.50135
DB8-2	0.99905	0.99920	0.99910	0.99895		0.50160	0.50175	0.50100	0.50160
DB8-3	0.99960	0.99955	0.99955	0.99945		0.50160	0.50135	0.50125	0.50155
DB10-1	0.99915	0.99915	0.99900	0.99905		0.50150	0.50135	0.50140	0.50135
DB10-2	0.99875	0.99890	0.99870	0.99870		0.50160	0.50130	0.50160	0.50150
DB10-3	0.99925	0.99905	0.99895	0.99925		0.50165	0.50145	0.50125	0.50145

Appendix 13. Dimensions, volume, mass, and density data for compressive specimens PCEA (AG) sheet 2

Specimen	Outside Diameter Measurements					Hole Diameter, in.			
Number	Allowable: 0.500 - 0.502					Allowable: 0.124 - 0.128			
	$D1^{90}$	$D2^{90}$	$D3^{90}$	$D4^{90}$		H1	H2	H1'	H2'
DB2-1	0.50155	0.50155	0.50160	0.50180		0.1279	0.1279	0.1281	0.1280
DB2-2	0.50165	0.50155	0.50150	0.50175		0.1280	0.1280	0.1281	0.1279
DB2-3	0.50135	0.50135	0.50135	0.50145		0.1280	0.1279	0.1278	0.1279
DB4-1	0.50165	0.50170	0.50165	0.50160		0.1280	0.1279	0.1278	0.1279
DB4-2	0.50165	0.50125	0.50145	0.50165		0.1278	0.1277	0.1279	0.1280
DB4-3	0.50160	0.50150	0.50150	0.50150		0.1278	0.1280	0.1279	0.1279
DB6-1	0.50135	0.50130	0.50130	0.50175		0.1277	0.1278	0.1278	0.1277
DB6-2	0.50160	0.50165	0.50150	0.50150		0.1276	0.1278	0.1279	0.1277
DB6-3	0.50130	0.50110	0.50100	0.50130		0.1277	0.1278	0.1277	0.1277
DB8-1	0.50165	0.50130	0.50130	0.50145		0.1275	0.1278	0.1275	0.1275
DB8-2	0.50155	0.50140	0.50100	0.50130		0.1275	0.1278	0.1276	0.1275
DB8-3	0.50155	0.50130	0.50125	0.50145		0.1278	0.1276	0.1278	0.1276
DB10-1	0.50145	0.50125	0.50135	0.50130		0.1280	0.1278	0.1277	0.1277
DB10-2	0.50180	0.50145	0.50145	0.50175		0.1278	0.1277	0.1277	0.1277
DB10-3	0.50150	0.50125	0.50120	0.50125		0.1279	0.1279	0.1277	0.1278

Appendix 13. Dimensions, volume, mass, and density data for compressive specimens PCEA (AG) sheet 3

Specimen Number	Weight, g		Average * Thickness	Average * Diameter	Mass	2-Hole Volume	Density	Density
			m	m	kg	m^3	kg/m^3	g/cm^3
DB2-1	5.7015		0.02538	0.01274	0.00570	5.48044E-08	1792.4109	1.7924
DB2-2	5.6883		0.02537	0.01274	0.00569	5.48258E-08	1788.3660	1.7884
DB2-3	5.6825		0.02538	0.01274	0.00568	5.47402E-08	1787.8294	1.7878
DB4-1	5.6959		0.02538	0.01274	0.00570	5.47402E-08	1790.4105	1.7904
DB4-2	5.6895		0.02538	0.01274	0.00569	5.46974E-08	1789.8950	1.7899
DB4-3	5.6803		0.02538	0.01274	0.00568	5.47402E-08	1786.1179	1.7861
DB6-1	5.6809		0.02538	0.01274	0.00568	5.46119E-08	1786.8909	1.7869
DB6-2	5.6972		0.02538	0.01274	0.00570	5.46119E-08	1790.5182	1.7905
DB6-3	5.7189		0.02539	0.01273	0.00572	5.45905E-08	1800.4499	1.8004
DB8-1	5.6797		0.02538	0.01274	0.00568	5.44624E-08	1786.5422	1.7865
DB8-2	5.6844		0.02538	0.01274	0.00568	5.44837E-08	1788.5781	1.7886
DB8-3	5.7063		0.02539	0.01274	0.00571	5.45691E-08	1794.5810	1.7946
DB10-1	5.6778		0.02538	0.01273	0.00568	5.46547E-08	1786.8013	1.7868
DB10-2	5.7054		0.02537	0.01274	0.00571	5.45905E-08	1794.6794	1.7947
DB10-3	5.6968		0.02538	0.01273	0.00570	5.46760E-08	1792.6788	1.7927

Appendix 14. Dimensions, volume, mass, and density data for compressive specimens IG-110 sheet 1

Specimen	Thickness Measurements, in.					Outside Diameter Measurements			
Number	Allowable: 0.998 - 1.000					Allowable: 0.500 - 0.502			
	T1	T2	T3	T4		D1	D2	D3	D4
E2-1	0.99895	0.99925	0.99925	0.99910		0.50175	0.50175	0.50165	0.50190
E2-2	0.99945	0.99925	0.99930	0.99950		0.50160	0.50155	0.50155	0.50155
E2-3	0.99930	0.99930	0.99910	0.99915		0.50165	0.50150	0.50175	0.50185
E4-1	0.99900	0.99920	0.99920	0.99905		0.50175	0.50175	0.50150	0.50155
E4-2	0.99935	0.99920	0.99945	0.99955		0.50165	0.50150	0.50170	0.50170
E4-3	0.99940	0.99940	0.99910	0.99910		0.50170	0.50165	0.50160	0.50155
E6-1	0.99910	0.99940	0.99945	0.99930		0.50160	0.50150	0.50150	0.50150
E6-2	0.99915	0.99920	0.99915	0.99920		0.50170	0.50170	0.50175	0.50185
E6-3	0.99915	0.99900	0.99885	0.99905		0.50185	0.50175	0.50165	0.50180
E8-1	0.99870	0.99900	0.99885	0.99860		0.50175	0.50180	0.50170	0.50195
E8-2	0.99925	0.99940	0.99930	0.99910		0.50170	0.50160	0.50166	0.50185
E8-3	0.99885	0.99885	0.99910	0.99905		0.50175	0.50190	0.50180	0.50170
E10-1	0.99940	0.99930	0.99930	0.99945		0.50150	0.50145	0.50140	0.50155
E10-2	0.99905	0.99905	0.99885	0.99885		0.50145	0.50145	0.50140	0.50180
E10-3	0.99895	0.99880	0.99895	0.99900		0.50155	0.50155	0.50155	0.50185

Appendix 14. Dimensions, volume, mass, and density data for compressive specimens IG-110 sheet 2

Specimen	Outside Diameter Measurements					Hole Diameter, in.			
Number	Allowable: 0.500 - 0.502					Allowable: 0.124 - 0.128			
	$D1^{90}$	$D2^{90}$	$D3^{90}$	$D4^{90}$		H1	H2	H1'	H2'
E2-1	0.50170	0.50170	0.50170	0.50185		0.1277	0.1277	0.1278	0.1275
E2-2	0.50155	0.50150	0.50145	0.50160		0.1278	0.1276	0.1277	0.1277
E2-3	0.50160	0.50165	0.50160	0.50185		0.1277	0.1276	0.1278	0.1277
E4-1	0.50165	0.50170	0.50145	0.50160		0.1275	0.1276	0.1277	0.1277
E4-2	0.50165	0.50170	0.50175	0.50465		0.1277	0.1278	0.1276	0.1278
E4-3	0.50165	0.50165	0.50160	0.50165		0.1279	0.1278	0.1280	0.1278
E6-1	0.50155	0.50140	0.50150	0.50150		0.1278	0.1279	0.1277	0.1275
E6-2	0.50170	0.50170	0.50180	0.50180		0.1279	0.1279	0.1279	0.1279
E6-3	0.50185	0.50160	0.50170	0.50175		0.1276	0.1276	0.1278	0.1277
E8-1	0.50180	0.50175	0.50175	0.50185		0.1277	0.1276	0.1274	0.1276
E8-2	0.50160	0.50170	0.50170	0.50190		0.1277	0.1279	0.1276	0.1278
E8-3	0.50170	0.50190	0.50185	0.50160		0.1278	0.1277	0.1278	0.1277
E10-1	0.50150	0.50150	0.50150	0.50155		0.1276	0.1275	0.1279	0.1277
E10-2	0.50145	0.50140	0.50130	0.50165		0.1275	0.1276	0.1277	0.1279
E10-3	0.50150	0.50150	0.50155	0.50185		0.1276	0.1279	0.1277	0.1276

Appendix 14. Dimensions, volume, mass, and density data for compressive specimens IG-110 sheet 3

Specimen Number	Weight, g		Average Thickness	Average Diameter	2-Hole Volume	Mass	Density	Density
			m	m	m^3	kg	kg/m^3	g/cm^3
E2-1	5.6316		0.02538	0.01274	5.4548E-08	0.00563	1769.3742	1.7694
E2-2	5.6119		0.02538	0.01911	5.4569E-08	0.00561	1764.2453	1.7642
E2-3	5.6127		0.02538	0.01911	5.4569E-08	0.00561	1763.8049	1.7638
E4-1	5.6101		0.02538	0.01911	5.4505E-08	0.00561	1763.5787	1.7636
E4-2	5.6012		0.02538	0.01912	5.4590E-08	0.00560	1757.3509	1.7574
E4-3	5.5628		0.02538	0.01912	5.4719E-08	0.00556	1748.4937	1.7485
E6-1	5.6350		0.02538	0.01911	5.4591E-08	0.00564	1771.9016	1.7719
E6-2	5.6321		0.02538	0.01911	5.4740E-08	0.00563	1769.5707	1.7696
E6-3	5.6306		0.02537	0.01912	5.4548E-08	0.00563	1769.3300	1.7693
E8-1	5.5829		0.02537	0.01912	5.4462E-08	0.00558	1754.3402	1.7543
E8-2	5.5812		0.02538	0.01912	5.4612E-08	0.00558	1753.6127	1.7536
E8-3	5.5949		0.02537	0.01912	5.4612E-08	0.00559	1758.0140	1.7580
E10-1	5.6110		0.02538	0.01911	5.4548E-08	0.00561	1764.3308	1.7643
E10-2	5.5871		0.02537	0.01911	5.4548E-08	0.00559	1757.5981	1.7576
E10-3	5.5948		0.02537	0.01911	5.4569E-08	0.00559	1759.1849	1.7592

Appendix 15. Dimensions, volume, mass, and density data for compressive specimens IG-430 sheet 1

Specimen	Thickness Measurements, in.					Outside Diameter Measurements			
Number	Allowable: 0.998 - 1.000					Allowable: 0.500 - 0.502			
	T1	T2	T3	T4		D1	D2	D3	D4
F2-1	0.99900	0.99895	0.99905	0.99920		0.50095	0.50080	0.50080	0.50080
F2-2	0.99935	0.99930	0.99925	0.99935		0.50125	0.50110	0.50095	0.50100
F2-3	0.99925	0.99910	0.99925	0.99935		0.50145	0.50135	0.50130	0.50150
F4-1	0.99920	0.99925	0.99915	0.99910		0.50110	0.50105	0.50120	0.50120
F4-2	0.99880	0.99880	0.99890	0.99880		0.50155	0.50150	0.50160	0.50145
F4-3	0.99915	0.99915	0.99900	0.99895		0.50135	0.50120	0.50125	0.50120
F6-1	0.99960	0.99940	0.99950	0.99940		0.50100	0.50090	0.50090	0.50125
F6-2	0.99915	0.99930	0.99915	0.99910		0.50150	0.50150	0.50145	0.50135
F6-3	0.99915	0.99900	0.99895	0.99915		0.50130	0.50125	0.50120	0.50135
F8-1	0.99935	0.99925	0.99910	0.99925		0.50120	0.50125	0.50130	0.50115
F8-2	0.99920	0.99930	0.99950	0.99955		0.50095	0.50110	0.50095	0.50095
F8-3	0.99890	0.99905	0.99900	0.99895		0.50145	0.50135	0.50135	0.50155
F10-1	0.99925	0.99925	0.99905	0.99925		0.50140	0.50135	0.50150	0.50130
F10-2	0.99890	0.99900	0.99900	0.99875		0.50115	0.50115	0.50130	0.50120
F10-3	0.99930	0.99935	0.99925	0.99920		0.50125	0.50125	0.50135	0.50145

Appendix 15. Dimensions, volume, mass, and density data for compressive specimens IG-430 sheet 2

Specimen	Outside Diameter Measurements					Hole Diameter, in.			
Number	Allowable: 0.500 - 0.502					Allowable: 0.124 - 0.128			
	$D1^{90}$	$D2^{90}$	$D3^{90}$	$D4^{90}$		H1	H2	H1'	H2'
F2-1	0.50100	0.50085	0.50085	0.50085		0.1275	0.1275	0.1280	0.1280
F2-2	0.50100	0.50100	0.50100	0.50100		0.1278	0.1278	0.1276	0.1276
F2-3	0.50125	0.50135	0.50125	0.50135		0.1278	0.1277	0.1279	0.1279
F4-1	0.50100	0.50105	0.50105	0.50125		0.1279	0.1279	0.1276	0.1274
F4-2	0.50150	0.50150	0.50155	0.50155		0.1279	0.1279	0.1279	0.1279
F4-3	0.50125	0.50135	0.50110	0.50120		0.1278	0.1280	0.1279	0.1280
F6-1	0.50110	0.50105	0.50120	0.50115		0.1277	0.1277	0.1277	0.1278
F6-2	0.50135	0.50145	0.50135	0.50125		0.1278	0.1276	0.1279	0.1278
F6-3	0.50135	0.50125	0.50120	0.50135		0.1278	0.1277	0.1279	0.1277
F8-1	0.50110	0.50125	0.50130	0.50125		0.1278	0.1277	0.1276	0.1276
F8-2	0.50115	0.50090	0.50110	0.50110		0.1277	0.1277	0.1277	0.1278
F8-3	0.50160	0.50150	0.50145	0.50140		0.1278	0.1278	0.1276	0.1277
F10-1	0.50140	0.50135	0.50140	0.50125		0.1276	0.1277	0.1277	0.1277
F10-2	0.50100	0.50095	0.50110	0.50120		0.1277	0.1278	0.1277	0.1278
F10-3	0.50115	0.50130	0.50135	0.50150		0.1279	0.1277	0.1279	0.1278

Appendix 15. Dimensions, volume, mass, and density data for compressive specimens IG-430 sheet 3

Specimen Number	Weight, g		Average Thickness	Average Diameter	2-Hole Volume	Mass	Density	Density
			m	m	m^3	kg	kg/m^3	g/cm^3
F2-1	5.7020		0.02538	0.01272	5.4612E-08	0.00570	1798.1534	1.7982
F2-2	5.7166		0.02538	0.01273	5.4569E-08	0.00572	1800.9711	1.8010
F2-3	5.7274		0.02538	0.01273	5.4676E-08	0.00573	1802.2845	1.8023
F4-1	5.7251		0.02538	0.01273	5.4569E-08	0.00573	1803.3523	1.8034
F4-2	5.7434		0.02537	0.01274	5.4740E-08	0.00574	1806.8317	1.8068
F4-3	5.7394		0.02538	0.01273	5.4762E-08	0.00574	1807.2560	1.8073
F6-1	5.7360		0.02539	0.01273	5.4591E-08	0.00574	1806.5670	1.8066
F6-2	5.7084		0.02538	0.01274	5.4633E-08	0.00571	1796.0313	1.7960
F6-3	5.7220		0.02538	0.01273	5.4633E-08	0.00572	1801.3842	1.8014
F8-1	5.7231		0.02538	0.01273	5.4548E-08	0.00572	1801.7724	1.8018
F8-2	5.7444		0.02538	0.01273	5.4591E-08	0.00574	1809.6951	1.8097
F8-3	5.6910		0.02537	0.01274	5.4591E-08	0.00569	1790.4886	1.7905
F10-1	5.7192		0.02538	0.01273	5.4548E-08	0.00572	1799.5632	1.7996
F10-2	5.7490		0.02537	0.01273	5.4612E-08	0.00575	1811.2511	1.8113
F10-3	5.7300		0.02538	0.01273	5.4676E-08	0.00573	1803.2167	1.8032

Appendix 16. Compressive strength data for NBG-17 specimens

Compression Strength				
Orientation	Specimen Number	Average Diameter in.	Maximum Load lb.	Compression Strength MPa
wg	**A2-1**	0.5011	2402.34	83.98
wg	**A2-2**	0.5014	2333.98	81.51
wg	**A2-3**	0.5010	2285.16	79.92
wg	**A4-1**	0.5009	2343.75	81.99
wg	**A4-2**	0.5013	2319.34	81.02
wg	**A4-3**	0.5013	2294.92	80.17
wg	**A6-1**	0.5008	2324.22	81.35
wg	**A6-2**	0.5015	2294.04	80.08
wg	**A6-3**	0.5014	2270.51	79.29
wg	**A8-1**	0.5010	2358.40	82.47
wg	**A8-2**	0.5010	2285.16	79.92
wg	**A8-3**	0.5013	2290.04	80.00

Mean	80.97
Standard Deviation	1.32

ag	**AB2-1**	0.5011	2319.34	81.07
ag	**AB2-2**	0.5010	2241.21	78.38
ag	**AB2-3**	0.5013	2314.45	80.86
ag	**AB4-1**	0.5011	2290.04	80.05
ag	**AB4-2**	0.5009	2255.86	78.92
ag	**AB4-3**	0.5013	2343.75	81.88
ag	**AB6-1**	0.5011	2319.34	81.09
ag	**AB6-2**	0.5012	2299.80	80.36
ag	**AB6-3**	0.5014	2343.75	81.85
ag	**AB8-1**	0.5006	2343.75	82.11
ag	**AB8-2**	0.5010	2338.87	81.80
ag	**AB8-3**	0.5013	2255.86	78.80

Mean	80.60
Standard Deviation	1.18

Appendix 17. Compressive strength data for NBG-18 specimens

Compression Strength				
Orientation	Specimen Number	Average Diameter in.	Maximum Load lb.	Compression Strength MPa
wg	**B2-1**	0.5013	2255.86	78.82
wg	**B2-2**	0.5011	2241.21	78.36
wg	**B2-3**	0.5016	2343.75	81.76
wg	**B4-1**	0.5011	2197.27	76.81
wg	**B4-2**	0.5016	2280.27	79.57
wg	**B4-3**	0.5015	2280.27	79.61
wg	**B6-1**	0.5010	2353.52	82.32
wg	**B6-2**	0.5017	2304.69	80.39
wg	**B6-3**	0.5016	2260.74	78.88
wg	**B8-1**	0.5015	2353.52	82.16
wg	**B8-2**	0.5012	2382.81	83.26
wg	**B8-3**	0.5019	2423.76	84.48
			Mean	80.54
			Standard Deviation	2.17
ag	**BB2-1**	0.5009	2387.70	83.56
ag	**BB2-2**	0.5011	2368.16	82.79
ag	**BB2-3**	0.5010	2377.93	83.17
ag	**BB4-1**	0.5009	2358.40	82.53
ag	**BB4-2**	0.5011	2373.05	82.97
ag	**BB4-3**	0.5011	2377.93	83.12
ag	**BB6-1**	0.5008	2270.51	79.47
ag	**BB6-2**	0.5010	1904.30	66.59
ag	**BB6-3**	0.5016	2294.92	80.07
ag	**BB8-1**	0.5012	2250.98	78.65
ag	**BB8-2**	0.5012	2016.60	70.49
ag	**BB8-3**	0.5015	2231.45	77.90
			Mean	79.28
			Standard Deviation	5.21

Appendix 18. Compressive strength data for H-451 specimens

Compression Strength			
Specimen Number	Average Diameter in.	Maximum Load lb.	Compression Strength MPa
C2-1	0.5007	1220.70	42.74
C2-2	0.5016	1323.24	46.16
C2-3	0.5018	1372.07	47.83
C4-1	0.5014	1337.89	46.71
C4-2	0.5016	1401.37	48.90
C4-3	0.5017	1474.61	51.43
C6-1	0.5017	1206.05	42.06
C6-2	0.5011	1191.41	41.65
C6-3	0.5006	1201.17	42.08
C8-1	0.5013	1171.87	40.95
C8-2	0.5009	1152.34	40.32
C8-3	0.5015	1083.98	37.84

Mean	44.06
Standard Deviation	3.89

Appendix 19. Compressive strength data for PCEA specimens

Compression Strength				
Orientation	Specimen Number	Average Diameter in.	Maximum Load lb.	Compression Strength Mpa
wg	**DA2-1**	0.5014	1396.48	48.77
wg	**DA2-2**	0.5015	1695.51	59.17
wg	**DA2-3**	0.5014	1625.98	56.79
wg	**DA4-1**	0.5017	1577.15	55.01
wg	**DA4-2**	0.5014	1601.56	55.92
wg	**DA4-3**	0.5016	1586.91	55.36
wg	**DA6-1**	0.5015	1757.81	61.37
wg	**DA6-2**	0.5017	1733.40	60.46
wg	**DA6-3**	0.5016	1738.28	60.65
wg	**DA8-1**	0.5015	1689.95	58.98
wg	**DA8-2**	0.5014	1757.81	61.38
wg	**DA8-3**	0.5015	1757.81	61.36
			Mean	57.94
			Standard Deviation	3.61
ag	**DB2-1**	0.5016	1679.80	58.61
ag	**DB2-2**	0.5017	1748.05	60.98
ag	**DB2-3**	0.5014	1743.16	60.86
ag	**DB4-1**	0.5017	1704.10	59.45
ag	**DB4-2**	0.5015	1743.16	60.85
ag	**DB4-3**	0.5016	1791.99	62.53
ag	**DB6-1**	0.5015	1762.70	61.54
ag	**DB6-2**	0.5016	1777.34	62.01
ag	**DB6-3**	0.5012	1840.82	64.34
ag	**DB8-1**	0.5014	1787.11	62.40
ag	**DB8-2**	0.5014	1757.81	61.38
ag	**DB8-3**	0.5014	1826.17	63.76
			Mean	61.56
			Standard Deviation	1.55

Appendix 20. Compressive strength data for IG-110 specimens

Compression Strength			
Specimen Number	Average Diameter in.	Maximum Load lb.	Compression Strength MPa
E2-1	0.5018	2177.73	75.94
E2-2	0.5015	2128.10	74.27
E2-3	0.5017	2119.14	73.92
E4-1	0.5016	2045.90	71.38
E4-2	0.5020	2104.73	73.31
E4-3	0.5016	2026.48	70.70
E6-1	0.5015	2187.50	76.35
E6-2	0.5018	2153.32	75.09
E6-3	0.5017	2182.62	76.11
E8-1	0.5018	1972.66	68.78
E8-2	0.5017	2021.48	70.50
E8-3	0.5018	2148.44	74.91

Mean	73.44
Standard Deviation	2.41

Appendix 21. Compressive strength data for IG-430 specimens

Compression Strength			
Specimen Number	Average Diameter in.	Maximum Load lb.	Compression Strength MPa
F2-1	0.5009	2,275.39	79.63
F2-2	0.5010	2,329.10	81.45
F2-3	0.5014	2,285.16	79.81
F4-1	0.5011	2,348.63	82.11
F4-2	0.5015	2,231.45	77.88
F4-3	0.5012	2,236.33	78.14
F6-1	0.5011	2,333.98	81.61
F6-2	0.5014	2,153.32	75.19
F6-3	0.5013	2,290.04	80.00
F8-1	0.5012	2,319.34	81.05
F8-2	0.5010	2,343.75	81.96
F8-3	0.5015	2,275.39	79.44

Mean	79.86
Standard Deviation	1.94

Appendix 22. Hg porosimetry specimen dimensions, mass, and density data by grade

Graphite Grade	Specimen Number	Average Thickness		Average Diameter		Density	Thickness Measurements, in. Allowable: 0.393 - 0.397			
		in	mm	in	mm	kg/m^3	T1	T2	T3	T4
NBG-17	**A1-2**	0.39643	10.06920	0.31545	8.01243	1849.37	0.39645	0.39645	0.39640	0.39640
NBG-17	**A3-2**	0.39645	10.06983	0.31543	8.01180	1855.05	0.39675	0.39655	0.39620	0.39630
NBG-17	**A7-2**	0.39675	10.07745	0.31495	7.99973	1855.70	0.39710	0.39645	0.39645	0.39700
NBG-17	**A9-2**	0.39679	10.07840	0.31496	8.00005	1854.00	0.39665	0.39675	0.39700	0.39675
NBG-17	**AB1-1**	0.39714	10.08729	0.31558	8.01561	1852.82	0.39730	0.39695	0.39705	0.39725
NBG-17	**AB3-1**	0.39666	10.07523	0.31554	8.01465	1857.24	0.39645	0.39650	0.39685	0.39685
NBG-18	**B3-2**	0.39598	10.05777	0.31258	7.93941	1855.46	0.39610	0.39620	0.39575	0.39585
NBG-18	**B7-2**	0.39630	10.06602	0.31506	8.00259	1871.44	0.39635	0.39635	0.39625	0.39625
NBG-18	**B9-2**	0.39596	10.05745	0.31478	7.99529	1866.39	0.39610	0.39600	0.39585	0.39590
NBG-18	**BB1-1**	0.39623	10.06412	0.31551	8.01402	1869.21	0.39625	0.39615	0.39615	0.39635
NBG-18	**BB3-1**	0.39633	10.06666	0.31569	8.01846	1857.26	0.39655	0.39630	0.39600	0.39645
NBG-18	**BB5-1**	0.39615	10.06221	0.31535	8.00989	1863.83	0.39610	0.39630	0.39620	0.39600
H-451	**C1-2**	0.31545	8.01243	0.31468	7.99275	1715.91	0.31510	0.31550	0.31555	0.31565
H-451	**C3-2**	0.39463	10.02348	0.31438	7.98513	1712.26	0.39470	0.39460	0.39460	0.39460
H-451	**C7-2**	0.39463	10.02348	0.31436	7.98481	1716.37	0.39460	0.39445	0.39475	0.39470
H-451	**C9-2**	0.39336	9.99141	0.31410	7.97814	1715.58	0.39350	0.39320	0.39330	0.39345
PCEA	**DA1-2**	0.39516	10.03713	0.31476	7.99497	1791.98	0.39520	0.39510	0.39510	0.39525
PCEA	**DA3-2**	0.39660	10.07364	0.31471	7.99370	1799.06	0.39680	0.39665	0.39640	0.39655
PCEA	**DA7-2**	0.39624	10.06443	0.31466	7.99243	1798.52	0.39630	0.39620	0.39620	0.39625
PCEA	**DA9-2**	0.39621	10.06380	0.31476	7.99497	1800.45	0.39635	0.39610	0.39605	0.39635
PCEA	**DB3-1**	0.39603	10.05904	0.31401	7.97592	1795.64	0.39605	0.39595	0.39595	0.39615
PCEA	**DB5-1**	0.39605	10.05967	0.31505	8.00227	1789.82	0.39585	0.39635	0.39620	0.39580
IG-110	**E1-2**	0.39688	10.08063	0.31373	7.96862	1770.88	0.39690	0.39675	0.39690	0.39695
IG-110	**E3-2**	0.39684	10.07967	0.31310	7.95274	1753.44	0.39690	0.39700	0.39670	0.39675

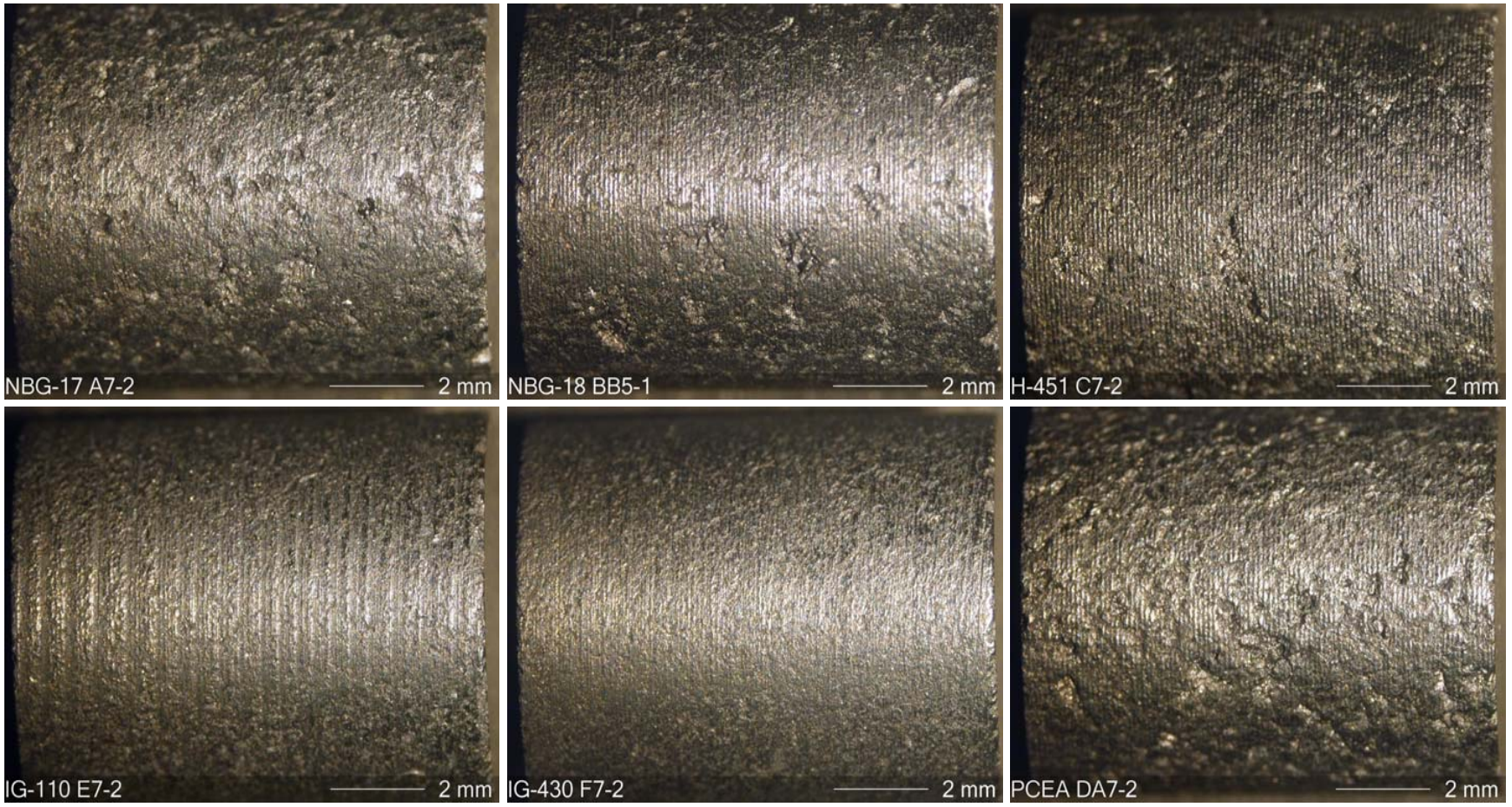
IG-110	**E7-2**	0.39606	10.05999	0.31520	8.00608	1766.81	0.39585	0.39600	0.39625	0.39615
IG-110	**E9-2**	0.39645	10.06983	0.31548	8.01307	1751.99	0.39650	0.39620	0.39640	0.39670
IG-430	**F1-1**	0.39698	10.08317	0.31448	7.98767	1801.66	0.39675	0.39690	0.39725	0.39700
IG-430	**F3-2**	0.39516	10.03713	0.31479	7.99560	1793.67	0.39510	0.39490	0.39520	0.39545
IG-430	**F7-2**	0.39598	10.05777	0.31525	8.00735	1796.95	0.39625	0.39615	0.39575	0.39575
IG-430	**F9-2**	0.39631	10.06634	0.31555	8.01497	1819.48	0.39630	0.39610	0.39640	0.39645

Appendix 22. Hg porosimetry specimen dimensions, mass, and density data by grade (sheet 2)

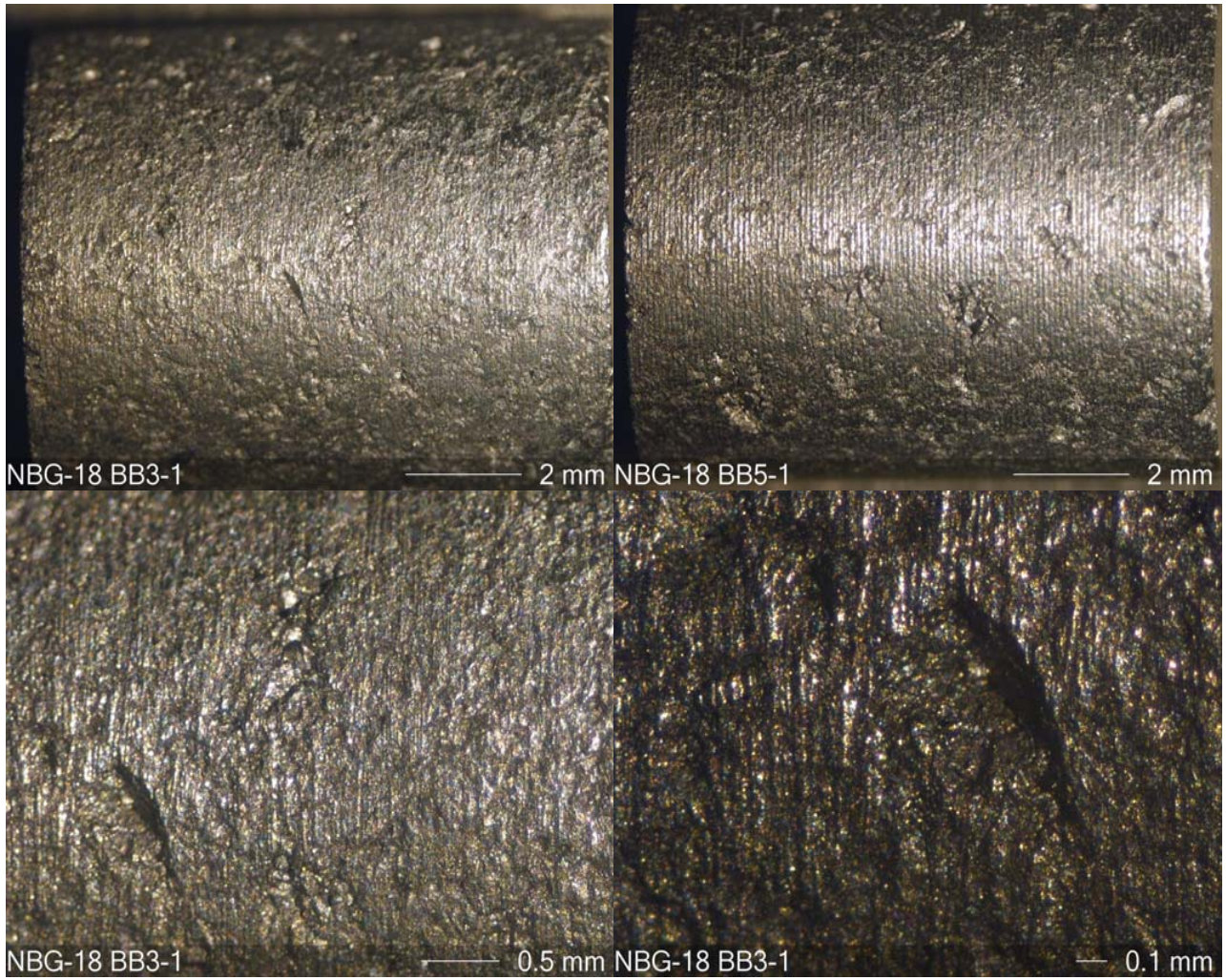
Diameter Measurements, in.					Specimen	Measured by:	Date:		Weight, g	Weighed by:	Date:
Allowable: 0.313 - 0.317					Number		mm/dd/yr				mm/dd/yr
D1	D2		$D1^{90}$	$D2^{90}$							
0.31555	0.31555		0.31535	0.31535	**A1-2**	CCD	6/25/2008		0.9419	CCD	6/25/2008
0.31520	0.31530		0.31535	0.31585	**A3-2**	CCD	6/25/2008		0.9447	CCD	6/25/2008
0.31500	0.31515		0.31470	0.31495	**A7-2**	CCD	6/25/2008		0.9429	CCD	6/25/2008
0.31525	0.31515		0.31490	0.31455	**A9-2**	CCD	6/25/2008		0.9422	CCD	6/25/2008
0.31570	0.31550		0.31550	0.31560	**AB1-1**	CCD	6/25/2008		0.9461	CCD	6/25/2008
0.31560	0.31570		0.31555	0.31530	**AB3-1**	CCD	6/25/2008		0.9470	CCD	6/25/2008
0.31235	0.31255		0.31265	0.31275	**B3-2**	CCD	6/25/2008		0.9268	CCD	6/25/2008
0.31500	0.31475		0.31545	0.31505	**B7-2**	CCD	6/25/2008		0.9505	CCD	6/25/2008
0.31420	0.31480		0.31470	0.31540	**B9-2**	CCD	6/25/2008		0.9454	CCD	6/25/2008
0.31570	0.31560		0.31535	0.31540	**BB1-1**	CCD	6/25/2008		0.9519	CCD	6/25/2008
0.31540	0.31565		0.31585	0.31585	**BB3-1**	CCD	6/25/2008		0.9471	CCD	6/25/2008
0.31560	0.31535		0.31520	0.31525	**BB5-1**	CCD	6/25/2008		0.9480	CCD	6/25/2008
0.31480	0.31470		0.31445	0.31475	**C1-2**	CCD	6/25/2008		0.6920	CCD	6/25/2008
0.31450	0.31445		0.31430	0.31425	**C3-2**	CCD	6/25/2008		0.8622	CCD	6/25/2008
0.31490	0.31460		0.31395	0.31400	**C7-2**	CCD	6/25/2008		0.8642	CCD	6/25/2008
0.31410	0.31425		0.31335	0.31470	**C9-2**	CCD	6/25/2008		0.8596	CCD	6/25/2008
0.31465	0.31490		0.31445	0.31505	**DA1-2**	CCD	6/25/2008		0.9058	CCD	6/25/2008
0.31460	0.31515		0.31435	0.31475	**DA3-2**	CCD	6/25/2008		0.9124	CCD	6/25/2008
0.31480	0.31510		0.31500	0.31375	**DA7-2**	CCD	6/25/2008		0.9110	CCD	6/25/2008
0.31480	0.31475		0.31475	0.31475	**DA9-2**	CCD	6/25/2008		0.9125	CCD	6/25/2008
0.31395	0.31415		0.31400	0.31395	**DB3-1**	CCD	6/25/2008		0.9053	CCD	6/25/2008
0.31530	0.31520		0.31475	0.31495	**DB5-1**	CCD	6/25/2008		0.9084	CCD	6/25/2008
0.31355	0.31395		0.31355	0.31385	**E1-2**	CCD	6/25/2008		0.8931	CCD	6/25/2008
0.31310	0.31300		0.31320	0.31310	**E3-2**	CCD	6/25/2008		0.8807	CCD	6/25/2008
0.31530	0.31505		0.31540	0.31505	**E7-2**	CCD	6/25/2008		0.8976	CCD	6/25/2008

0.31560	0.31560		0.31540	0.31530	**E9-2**	CCD	6/25/2008		0.8925	CCD	6/25/2008
0.31440	0.31480		0.31435	0.31435	**F1-1**	CCD	6/25/2008		0.9132	CCD	6/25/2008
0.31460	0.31490		0.31485	0.31480	**F3-2**	CCD	6/25/2008		0.9068	CCD	6/25/2008
0.31520	0.31535		0.31505	0.31540	**F7-2**	CCD	6/25/2008		0.9130	CCD	6/25/2008
0.31550	0.31565		0.31540	0.31565	**F9-2**	CCD	6/25/2008		0.9270	CCD	6/25/2008

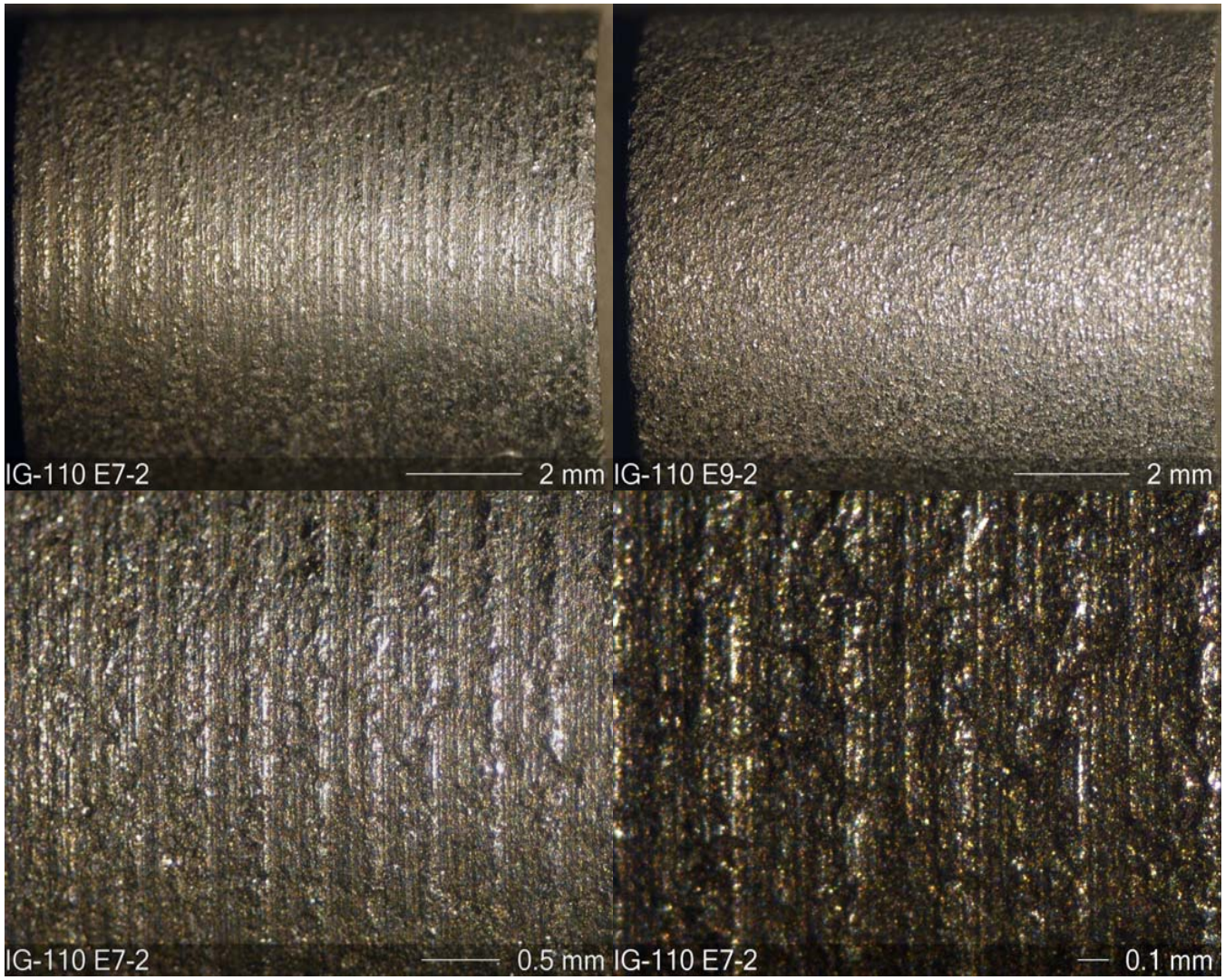
Appendix 23. Photo macrograph gallery of Hg porosimetry samples showing surface roughness and machining marks



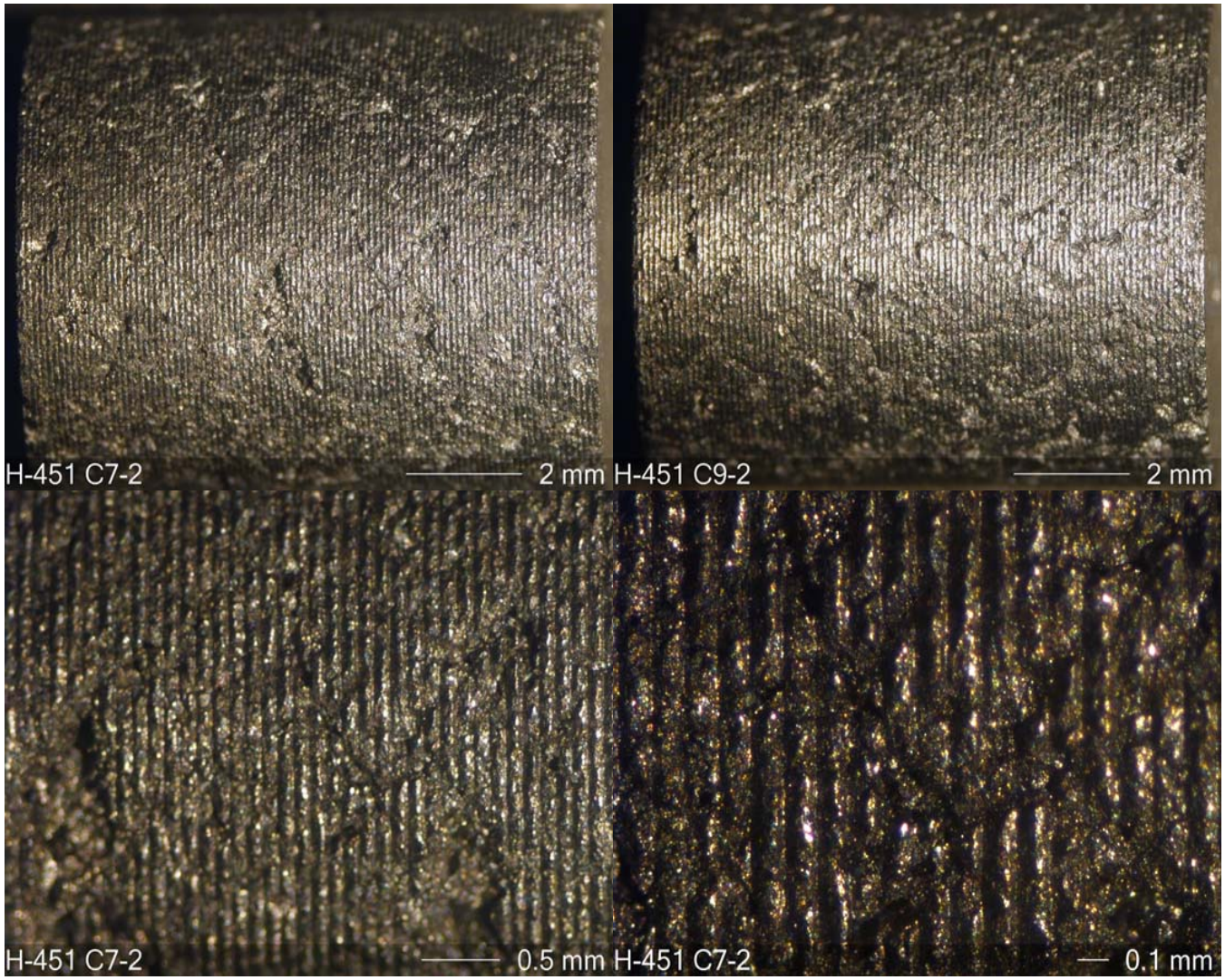
Appendix 23. Photo macrograph gallery of Hg porosimetry samples showing surface roughness and machining marks (continued)



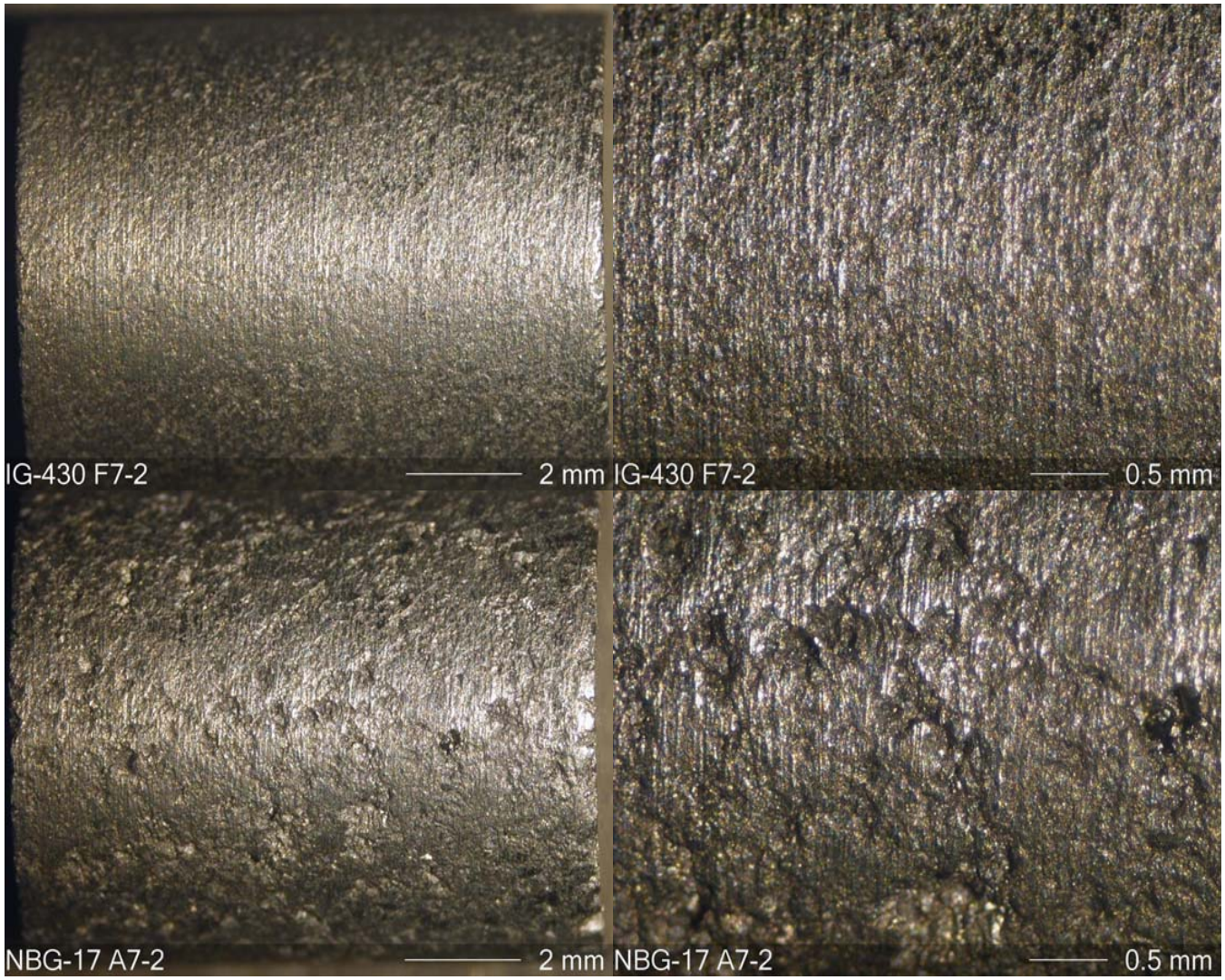
Appendix 23. Photo macrograph gallery of Hg porosimetry samples showing surface roughness and machining marks (continued)



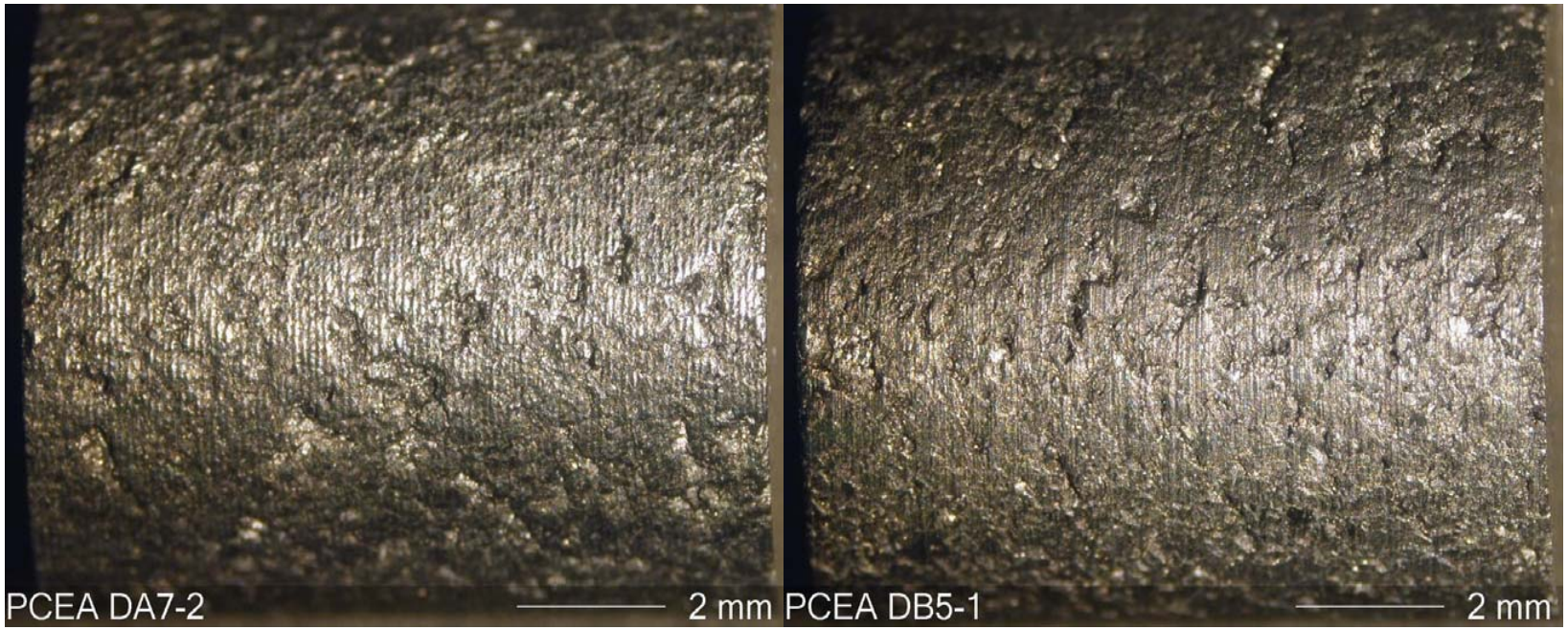
Appendix 23. Photo macrograph gallery of Hg porosimetry samples showing surface roughness and machining marks (continued)



Appendix 23. Photo macrograph gallery of Hg porosimetry samples showing surface roughness and machining marks (continued)



Appendix 23. Photo macrograph gallery of Hg porosimetry samples showing surface roughness and machining marks (continued)



Appendix 24. Sister specimens bulk density and skeletal density data from Hg porosimetry

Graphite Porosity Measurement								
		Weight	Weight	Retained	Bulk	Bulk	Skeletal	Skeletal
Sample ID	Date	Before	After	Hg Weight	Volume	Density	Volume	Density
		g	g	g	cm^3	g/cm^3	cm^3	g/cm^3
H-451 C1-2	7/17/2008	0.692			0.3993	1.7330	error	error
H-451 C3-2	8/11/2008	0.862	2.193	1.331	0.5000	1.7240	0.4060	2.1230
H-451 C7-2	11/6/2008	0.865	2.187	1.322	0.4989	1.7338	0.4032	2.1453
H-451 C9-2	11/6/2008	0.858	2.130	1.272	0.4986	1.7208	0.3821	2.2455
Mean						1.7279		2.1713
Std. Dev.						0.0065		0.0652
IG-110 E1-2	7/18/2008	0.893	1.947	1.054	0.4983	1.7921	0.4338	2.0585
IG-110 E3-2	7/21/2008	0.880	1.977	1.097	0.4990	1.7635	0.4465	1.9709
IG-110 E7-2	10/10/2008	0.896	1.990	1.094	0.5051	1.7739	0.4468	2.0055
IG-110 E9-2	10/10/2008	0.891	2.023	1.132	0.5051	1.7640	0.4469	1.9938
Mean						1.7734		2.0072
Std. Dev.						0.0134		0.0371
IG-430 F1-1	8/11/2008	0.912	1.882	0.970	0.5058	1.8031	0.4559	2.0004
IG-430 F3-2	8/14/2008	0.906	1.905	0.999	0.5010	1.8084	0.4533	1.9988
IG-430 F7-2	11/6/2008	0.911	1.915	1.004	0.5070	1.7968	0.4611	1.9757
IG-430 F9-2	11/6/2008	0.928	1.854	0.926	0.5099	1.8200	0.4652	1.9948
Mean						1.8071		1.9924
Std. Dev.						0.0098		0.0114
NBG-17 A1-2	7/31/2008	0.942	1.555	0.613	0.5026	1.8743	0.4242	2.2205
NBG-17 A3-2	8/14/2008	0.945	1.546	0.601	0.5022	1.8817	0.4238	2.2297
NBG-17 A7-2	11/7/2008	0.943	1.549	0.606	0.5074	1.8585	0.4384	2.1510
NBG-17 A9-2	11/7/2008	0.939	1.544	0.605	0.5038	1.8638	0.4260	2.2042
NBG-17 AB1-1	11/10/2008	0.942	1.557	0.615	0.5062	1.8609	0.4264	2.2092
NBG-17 AB3-1	11/10/2008	0.946	1.554	0.608	0.5087	1.8596	0.4334	2.1827
Mean						1.8665		2.1996
Std. Dev.						0.0094		0.0286
NBG-18 B3-2	8/27/2008	0.927	1.529	0.602	0.4930	1.8803	0.4169	2.2236
NBG-18 B7-2	8/27/2008	0.950	1.527	0.577	0.5023	1.8913	0.4330	2.1938
NBG-18 B9-2	8/27/2008	0.944	1.534	0.590	0.4983	1.8944	0.4306	2.1925
NBG-18 BB1-1	7/31/2008	0.953	1.573	0.620	0.5074	1.8782	0.4405	2.1632
NBG-18 BB3-1	9/24/2008	0.947	1.613	0.666	0.5086	1.8620	0.4770	1.9853
NBG-18 BB5-1	10/2/2008	0.950	1.597	0.647	0.5027	1.8898	0.4289	2.2150
Mean						1.8827		2.1622
Std. Dev.						0.0120		0.0892
PCEA DA1-2	7/18/2008	0.905	1.731	0.826	0.5000	1.8100	0.4049	2.2353
PCEA DA3-2	10/1/2008	0.912	1.746	0.834	0.5039	1.8099	0.4061	2.2458
PCEA DA7-2	11/11/2008	0.910	1.736	0.826	0.5057	1.7995	0.4076	2.2326
PCEA DA9-2	11/11/2008	0.913	1.726	0.813	0.5045	1.8097	0.4139	2.2058
PCEA DB3-1	8/11/2008	0.907	1.750	0.843	0.5025	1.8050	0.4157	2.1819
PCEA DB5-1	11/11/2008	0.908	1.740	0.832	0.5065	1.7927	0.4139	2.1938
Mean						1.8045		2.2159
Std. Dev.						0.0071		0.0257

Appendix 25. NBG-17 (WG) Fundamental frequency and Young's modulus data (sheet 1)

Modulus by Resonant Frequency

Specimen number			A2-1	A2-2	A2-3	A4-1	A4-2	A4-3	A6-1	A6-2
mass of bar	m	[g]	5.9104	5.9107	5.8864	5.8977	5.9135	5.8941	5.8939	5.9163
length of bar	L	[mm]	25.3781	25.3784	25.3778	25.3806	25.3914	25.3746	25.3883	25.3914
diameter of bar	D	[mm]	12.7287	12.7346	12.7259	12.7238	12.7333	12.7332	12.7208	12.7373
Poisson's ratio	μ		0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
average resonant frequency	f_{avg}	[Hz]	29659	29526	29395	29580	29464	29368	29544	29531
frequency data	f_i	1	29664	29512	29398	29588	29463	29370	29570	29528
(specimen number		2	29658	29532	29403	29584	29464	29366	29576	29538
oriented up in fixture)		3	29659	29535	29388	29581	29463	29371	29569	29530
		4	29657	29524	29394	29579	29464	29371	29547	29529
		5	29655	29526	29398	29574	29462	29366	29544	29529
		6	29664	29549	29393	29584	29462	29365	29550	29529
		7	29653	29502	29391	29579	29463	29371	29497	29532
		8	29659	29524	29392	29576	29467	29368	29545	29530
		9	29660	29520	29401	29579	29465	29361	29550	29533
		10	29658	29533	29396	29579	29467	29370	29496	29533
$T_{1'}$ correction factor			2.28604541	2.2872	2.2855	2.284794	2.285624	2.287298	2.283414	2.286426
calculation of individual			0.03090236	0.030958	0.030876	0.030842	0.030882	0.030963	0.030776	0.030921
terms			0.32480188	0.325386	0.324527	0.32417	0.324589	0.325435	0.323474	0.324994
			2.27503807	2.276183	2.274498	2.273797	2.274621	2.27628	2.272429	2.275415
resultant $T_{1'}$		$T_{1'}$	2.11237539	2.11329	2.111944	2.111384	2.112042	2.113368	2.110291	2.112677
modulus of elasticity **	E	[Pa]	1.10E+10	1.09E+10	1.08E+10	1.09E+10	1.08E+10	1.07E+10	1.09E+10	1.09E+10
Average Modulus for specimen group			1.0828E+10							
Standard deviation			9.6701E+07							

Appendix 25. NBG-17 (WG) Fundamental frequency and Young's modulus data (sheet 2)

A6-3	A6-4	A6-5	A6-6	A6-7	A6-8	A6-9	A6-10	A6-11	A6-12
5.8952	5.8952	5.8952	5.8952	5.8952	5.8952	5.8952	5.8952	5.8952	5.8952
25.3819	25.3819	25.3819	25.3819	25.3819	25.3819	25.3819	25.3819	25.3819	25.3819
12.7351	12.7351	12.7351	12.7351	12.7351	12.7351	12.7351	12.7351	12.7351	12.7351
0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
29377	29377	29377	29377	29377	29377	29377	29377	29377	29377
29380	29380	29380	29380	29380	29380	29380	29380	29380	29380
29376	29376	29376	29376	29376	29376	29376	29376	29376	29376
29370	29370	29370	29370	29370	29370	29370	29370	29370	29370
29376	29376	29376	29376	29376	29376	29376	29376	29376	29376
29380	29380	29380	29380	29380	29380	29380	29380	29380	29380
29381	29381	29381	29381	29381	29381	29381	29381	29381	29381
29380	29380	29380	29380	29380	29380	29380	29380	29380	29380
29369	29369	29369	29369	29369	29369	29369	29369	29369	29369
29380	29380	29380	29380	29380	29380	29380	29380	29380	29380
29380	29380	29380	29380	29380	29380	29380	29380	29380	29380
2.286942	2.286942	2.286942	2.286942	2.286942	2.286942	2.286942	2.286942	2.286942	2.286942
0.030945	0.030945	0.030945	0.030945	0.030945	0.030945	0.030945	0.030945	0.030945	0.030945
0.325255	0.325255	0.325255	0.325255	0.325255	0.325255	0.325255	0.325255	0.325255	0.325255
2.275927	2.275927	2.275927	2.275927	2.275927	2.275927	2.275927	2.275927	2.275927	2.275927
2.113086	2.113086	2.113086	2.113086	2.113086	2.113086	2.113086	2.113086	2.113086	2.113086
1.07E+10	1.07E+10	1.07E+10	1.07E+10	1.07E+10	1.07E+10	1.07E+10	1.07E+10	1.07E+10	1.07E+10

Appendix 25. NBG-17 (WG) Fundamental frequency and Young's modulus data (sheet 3)

A6-13	A6-14	A6-15	A7-5	A7-6	A7-7	A9-5	A9-6	A9-7
5.8952	5.8952	5.8952	5.8904	5.9014	5.8995	5.8921	5.8840	5.8811
25.3819	25.3819	25.3819	25.3771	25.3917	25.3797	25.3790	25.3841	25.3787
12.7351	12.7351	12.7351	12.7248	12.7219	12.7271	12.7279	12.7187	12.7233
0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
29377	29377	29377	29569	29232	29475	29459	29192	29381
29380	29380	29380	29575	29238	29480	29462	29189	29402
29376	29376	29376	29574	29237	29474	29460	29211	29377
29370	29370	29370	29568	29235	29476	29461	29198	29383
29376	29376	29376	29572	29231	29474	29458	29185	29367
29380	29380	29380	29567	29227	29477	29459	29184	29378
29381	29381	29381	29572	29247	29478	29462	29186	29374
29380	29380	29380	29568	29228	29477	29461	29193	29394
29369	29369	29369	29565	29217	29471	29453	29192	29391
29380	29380	29380	29561	29235	29474	29454	29195	29373
29380	29380	29380	29564	29227	29466	29460	29184	29373
2.286942	2.286942	2.286942	2.28534	2.283285	2.285564	2.285789	2.283415	2.284891
0.030945	0.030945	0.030945	0.030868	0.03077	0.030879	0.03089	0.030776	0.030847
0.325255	0.325255	0.325255	0.324446	0.323409	0.324559	0.324672	0.323475	0.324219
2.275927	2.275927	2.275927	2.274339	2.272302	2.274561	2.274783	2.27243	2.273893
2.113086	2.113086	2.113086	2.111817	2.110189	2.111994	2.112172	2.110292	2.111461
1.07E+10	1.07E+10	1.07E+10	1.09E+10	1.07E+10	1.08E+10	1.08E+10	1.06E+10	1.07E+10

Appendix 26. NBG-17 (AG) Fundamental frequency and Young's modulus data (sheet 1)

Modulus by Resonant Frequency

Specimen number			AB2-1	AB2-2	AB2-3	AB4-1	AB4-2	AB4-3	AB6-1	AB6-2
mass of bar	m	[g]	5.8993	5.8939	5.8975	5.8978	5.8884	5.9101	5.8945	5.8981
length of bar	L	[mm]	25.3867	25.3860	25.3838	25.3816	25.3775	25.3822	25.3778	25.3867
diameter of bar	D	[mm]	12.7291	12.7256	12.7325	12.7291	12.7233	12.7322	12.7273	12.7313
Poisson's ratio	μ		0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
average resonant frequency	f_{avg}	[Hz]	30182	30108	30119	30204	30151	30033	30214	30232
frequency data	f_i	1	30204	30136	30149	30201	30141	30054	30181	30236
(specimen number		2	30204	30141	30043	30215	30151	30016	30212	30233
oriented up in fixture)		3	30199	29834	30109	30203	30155	30026	30234	30231
		4	30210	30117	30097	30201	30149	30047	30186	30231
		5	29973	30168	30105	30209	30154	30026	30214	30233
		6	30211	30139	30137	30202	30156	30038	30306	30232
		7	30207	30137	30140	30201	30154	30028	30204	30233
		8	30200	30133	30140	30202	30148	30042	30222	30226
		9	30203	30141	30135	30203	30153	30028	30198	30230
		10	30208	30137	30136	30201	30150	30024	30178	30236
$T_{1'}$ correction factor			2.28524114	2.2846	2.286236	2.285756	2.285019	2.286333	2.285789	2.28569
calculation of individual			0.03086372	0.030833	0.030912	0.030888	0.030853	0.030916	0.03089	0.030885
terms			0.32439575	0.324072	0.324898	0.324656	0.324284	0.324947	0.324672	0.324622
			2.27424068	2.273605	2.275227	2.274751	2.274021	2.275323	2.274784	2.274686
resultant $T_{1'}$		$T_{1'}$	2.11173827	2.111231	2.112526	2.112146	2.111563	2.112603	2.112172	2.112094
modulus of elasticity *	E	[Pa]	1.14E+10	1.13E+10	1.13E+10	1.14E+10	1.13E+10	1.13E+10	1.14E+10	1.14E+10
Average Modulus for specimen group			1.1372E+10							
Standard deviation			7.2583E+07							

Appendix 26. NBG-17 (AG) Fundamental frequency and Young's modulus data (sheet 2)

AB6-3	AB8-1	AB8-2	AB8-3	AB10-1	AB10-2	AB10-3	AB1-5	AB1-6	AB1-7
5.9091	5.8914	5.9031	5.9036	5.8873	5.9047	5.9049	5.9018	5.9072	5.9007
25.3822	25.3898	25.3819	25.3860	25.3749	25.3879	25.3892	25.3810	25.3848	25.3797
12.7351	12.7146	12.7259	12.7337	12.7127	12.7284	12.7251	12.7216	12.7308	12.7262
0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
30215	30245	30302	30272	30314	30215	30227	30137	30260	30138
30221	30198	30305	30269	30344	30206	30205	30162	30260	30191
30217	30223	30300	30271	30315	30216	30229	30152	30269	30224
30218	30238	30305	30278	30322	30222	30245	30143	30284	30113
30215	30315	30303	30261	30325	30221	30229	30144	30258	30123
30217	30254	30306	30268	30200	30215	30237	30132	30301	30117
30215	30285	30300	30282	30328	30219	30227	30141	30270	30118
30212	30232	30300	30267	30328	30212	30216	30125	30292	30119
30212	30228	30300	30277	30323	30203	30237	30120	30249	30131
30211	30224	30301	30264	30326	30215	30221	30128	30244	30120
30208	30256	30295	30279	30325	30217	30222	30123	30173	30125
2.28691	2.282005	2.285082	2.286235	2.283129	2.284984	2.284183	2.284313	2.285787	2.285371
0.030944	0.030708	0.030856	0.030911	0.030762	0.030851	0.030813	0.030819	0.03089	0.03087
0.325239	0.322764	0.324316	0.324898	0.32333	0.324266	0.323862	0.323927	0.324671	0.324462
2.275895	2.271032	2.274083	2.275226	2.272146	2.273986	2.273191	2.273321	2.274782	2.27437
2.11306	2.109174	2.111612	2.112526	2.110065	2.111535	2.1109	2.111003	2.11217	2.111841
1.14E+10	1.14E+10	1.15E+10	1.14E+10	1.15E+10	1.14E+10	1.14E+10	1.13E+10	1.14E+10	1.13E+10

Appendix 26. NBG-17 (AG) Fundamental frequency and Young's modulus data (sheet 3)

AB3-5	AB3-6	AB3-7	AB7-5	AB7-6	AB7-7	AB9-5	AB9-6	AB9-7
5.9107	5.9126	5.9146	5.9085	5.8947	5.9030	5.9125	5.9078	5.9121
25.3860	25.3870	25.3863	25.3876	25.3835	25.3762	25.3883	25.3829	25.3921
12.7284	12.7291	12.7286	12.7265	12.7097	12.7238	12.7265	12.7248	12.7276
0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
30297	30035	30117	30221	30159	30330	30017	29904	30160
30297	30071	30115	30219	30173	30343	30002	29884	30166
30298	30070	30133	30206	30162	30334	30020	29901	30165
30296	30067	30154	30223	30168	30321	30017	29993	30163
30293	30072	30113	30224	30158	30324	30023	29894	30166
30300	30133	30108	30215	30157	30324	30022	29895	30159
30304	30086	30107	30226	30155	30332	30016	29894	30162
30300	30082	30103	30228	30154	30325	30018	29895	30155
30291	30001	30114	30217	30159	30330	30017	29905	30157
30295	29884	30110	30223	30151	30336	30017	29894	30154
30300	29885	30108	30225	30152	30329	30021	29883	30149
2.285177	2.285209	2.285177	2.284632	2.281654	2.285244	2.284568	2.284761	2.284406
0.030861	0.030862	0.030861	0.030834	0.030692	0.030864	0.030831	0.030841	0.030824
0.324363	0.32438	0.324363	0.324088	0.322587	0.324397	0.324056	0.324154	0.323975
2.274177	2.274209	2.274177	2.273637	2.270684	2.274244	2.273573	2.273765	2.273413
2.111688	2.111713	2.111688	2.111256	2.108896	2.111741	2.111205	2.111358	2.111077
1.15E+10	1.13E+10	1.13E+10	1.14E+10	1.14E+10	1.15E+10	1.13E+10	1.12E+10	1.14E+10

Appendix 27. NBG-18 (WG) Fundamental frequency and Young's modulus data (sheet 1)

Modulus by Resonant Frequency

Specimen number				B2-1	B2-2	B2-3	B4-1	B4-2	B4-3	B6-1
mass of bar	m	[g]		5.9450	5.9358	5.9328	5.9621	5.9444	5.9415	5.9514
length of bar	L	[mm]		25.3803	25.3810	25.3740	25.3733	25.3765	25.3736	25.3867
diameter of bar	D	[mm]		12.7319	12.7278	12.7416	12.7286	12.7398	12.7368	12.7251
Poisson's ratio	μ			0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667
average resonant frequency	f_{avg}	[Hz]		29977	29766	29953	29929	29734	30080	30525
frequency data	f_i		1	29982	29771	29949	29927	29735	30076	30667
(specimen number			2	29986	29774	29953	29934	29740	30081	30594
oriented up in fixture)			3	29998	29765	29962	29926	29734	30084	30520
			4	29984	29768	29951	29923	29736	30078	30492
			5	29969	29765	29953	29935	29734	30077	30496
			6	29965	29762	29953	29923	29729	30066	30500
			7	29981	29767	29950	29928	29734	30082	30489
			8	29972	29763	29950	29936	29735	30081	30496
			9	29965	29761	29953	29931	29736	30087	30499
			10	29972	29764	29956	29924	29731	30086	30498
$T_{1'}$ correction factor				2.28646173	2.28556343	2.28906436	2.28649614	2.28845308	2.28813314	2.28443982
calculation of individual				0.03092237	0.0308792	0.03104761	0.03092402	0.03101817	0.03100277	0.03082525
terms				0.3250122	0.32455847	0.32632859	0.32502959	0.32601917	0.32585728	0.32399137
				2.27545082	2.27456021	2.27803118	2.27548494	2.27742513	2.27710792	2.27344622
resultant $T_{1'}$		$T_{1'}$		2.11270516	2.11199358	2.11476647	2.11273242	2.11428238	2.11402899	2.11110345
modulus of elasticity **	E	[Pa]		1.13E+10	1.11E+10	1.12E+10	1.13E+10	1.11E+10	1.13E+10	1.17E+10
Average Modulus for specimen group				1.165E+10						
Standard deviation				2.603E+08						

Appendix 27. NBG-18 (WG) Fundamental frequency and Young's modulus data (sheet 2)

B6-2	B6-3	B8-1	B8-2	B8-3	B10-1	B10-2	B10-3	B3-5	B3-6
5.9392	5.9436	5.9594	5.9497	5.9538	5.9612	5.9545	5.9473	5.9398	5.9176
25.3752	25.3781	25.3705	25.3736	25.3806	25.3670	25.3705	25.3775	25.3721	25.3797
12.7422	12.7405	12.7371	12.7311	12.7470	12.7405	12.7405	12.7429	12.7376	12.7225
0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667
30592	30703	30545	30598	30743	30593	30603	30565	30359	30540
30596	30703	30556	30622	30741	30620	30578	30569	30359	30537
30574	30699	30563	30627	30740	30624	30602	30558	30362	30541
30581	30703	30536	30627	30750	30624	30585	30564	30360	30542
30589	30701	30558	30636	30738	30623	30599	30570	30355	30539
30584	30707	30497	30626	30740	30328	30595	30565	30378	30544
30610	30704	30555	30628	30744	30624	30605	30567	30354	30541
30602	30707	30530	30630	30745	30624	30598	30561	30356	30538
30582	30703	30537	30625	30740	30621	30597	30568	30357	30532
30590	30699	30529	30329	30747	30621	30629	30564	30344	30532
30610	30704	30586	30631	30746	30621	30640	30566	30360	30551
2.28906381	2.28842032	2.2885198	2.28697743	2.28947896	2.28954941	2.28919439	2.28896649	2.28845491	2.28463393
0.03104759	0.0310166	0.03102139	0.03094717	0.03106759	0.03107098	0.03105388	0.0310429	0.03101826	0.03083456
0.32632831	0.3260026	0.32605294	0.32527283	0.32653854	0.32657422	0.32639443	0.32627904	0.3260201	0.32408931
2.27803063	2.27739265	2.27749128	2.27596211	2.27844223	2.27851207	2.27816009	2.27793415	2.27742695	2.27363867
2.11476604	2.11425643	2.11433522	2.11311364	2.1150948	2.11515058	2.11486945	2.11468897	2.11428382	2.11125723
1.17E+10	1.18E+10	1.17E+10	1.18E+10	1.18E+10	1.17E+10	1.17E+10	1.17E+10	1.15E+10	1.17E+10

Appendix 27. NBG-18 (WG) Fundamental frequency and Young's modulus data (sheet 3)

B3-7	B5-5	B5-6	B5-7	B7-5	B7-6	B7-7	B9-5	B9-6	B9-7
5.9253	5.9419	5.9395	5.9304	5.9461	5.9383	5.9513	5.9465	5.9319	5.9491
25.3717	25.3778	25.3670	25.3825	25.3762	25.3921	25.3768	25.3825	25.3867	25.3721
12.7278	12.7411	12.7402	12.7384	12.7367	12.7300	12.7438	12.7425	12.7348	12.7391
0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667
30824	30323	30696	30761	30752	30844	30995	30672	30419	30887
30836	30409	30703	30765	30727	30885	30999	30657	30438	30978
30837	30389	30703	30769	30727	30881	30982	30739	30420	30927
30843	30366	30705	30758	30767	30860	30997	30666	30428	30864
30829	30370	30700	30762	30763	30851	30997	30677	30424	30936
30823	30299	30682	30765	30763	30817	30997	30676	30417	30919
30830	30277	30711	30758	30757	30848	30996	30661	30413	30847
30825	30286	30695	30760	30756	30830	30996	30659	30413	30846
30828	30283	30701	30762	30756	30828	30994	30657	30412	30846
30811	30277	30660	30759	30755	30823	30999	30663	30414	30848
30774	30278	30696	30755	30753	30821	30991	30664	30414	30856
2.28649667	2.288581	2.28948513	2.287552	2.287843	2.284887	2.289224	2.288386	2.286395	2.288744
0.03092405	0.03102433	0.03106789	0.030975	0.030989	0.030847	0.031055	0.031015	0.030919	0.031032
0.32502986	0.32608391	0.32654167	0.325563	0.325711	0.324217	0.326409	0.325985	0.324979	0.326166
2.27548547	2.27755195	2.27844835	2.276532	2.27682	2.27389	2.278189	2.277359	2.275385	2.277714
2.11273284	2.11438368	2.11509968	2.113569	2.113799	2.111458	2.114893	2.11423	2.112653	2.114513
1.19E+10	1.15E+10	1.18E+10	1.18E+10	1.19E+10	1.19E+10	1.20E+10	1.18E+10	1.16E+10	1.20E+10

Appendix 28. NBG-18 (AG) Fundamental frequency and Young's modulus data (sheet 1)

Modulus by Resonant Frequency

Specimen number			BB2-1	BB2-2	BB2-3	BB4-1	BB4-2	BB4-3	BB6-1
mass of bar	m	[g]	5.9174	5.9187	5.9296	5.9055	5.9172	5.9289	5.9144
length of bar	L	[mm]	25.3851	25.3851	25.3883	25.3851	25.3794	25.3794	25.3895
diameter of bar	D	[mm]	12.7216	12.7279	12.7249	12.7222	12.7278	12.7291	12.7206
Poisson's ratio	μ		0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667
average resonant frequency	f_{avg}	[Hz]	31159	31102	31075	31124	31100	31127	31162
frequency data	f_i	1	31154	31136	31066	31110	31103	31128	31162
(specimen number		2	31164	31113	31075	31115	31095	31115	31164
oriented up in fixture)		3	31162	31112	31078	31133	31099	31118	31169
		4	31169	31078	31075	31127	31097	31122	31166
		5	31163	31114	31079	31149	31106	31129	31152
		6	31166	31148	31077	31142	31098	31135	31161
		7	31175	31112	31075	31136	31101	31131	31148
		8	31147	31041	31071	31123	31096	31130	31162
		9	31145	31053	31078	31106	31101	31129	31166
		10	31144	31110	31072	31103	31100	31129	31170
$T_{1'}$ correction factor			2.28389543	2.28517747	2.28424715	2.28402361	2.28572426	2.28598086	2.28325374
calculation of individual			0.03079912	0.03086066	0.030816	0.03080527	0.03088693	0.03089926	0.03076834
terms			0.3237168	0.32436362	0.32389418	0.32378144	0.32463968	0.32476927	0.32339329
			2.27290649	2.27417756	2.2732552	2.27303357	2.27471967	2.27497407	2.27227029
resultant $T_{1'}$		$T_{1'}$	2.11067215	2.11168783	2.11095081	2.1107737	2.11212099	2.11232425	2.11016374
modulus of elasticity **	E	[Pa]	1.22E+10	1.21E+10	1.21E+10	1.21E+10	1.21E+10	1.21E+10	1.22E+10
Average Modulus for specimen group			1.2108E+10						
Standard deviation			8.7047E+07						

Appendix 28. NBG-18 (AG) Fundamental frequency and Young's modulus data (sheet 2)

BB6-2	BB6-3	BB8-1	BB8-2	BB8-3	BB10-1	BB10-2	BB10-3	BB3-5	BB3-6
5.9170	5.9510	5.9165	5.9278	5.9533	5.9185	5.9241	5.9411	5.9354	5.9450
25.3857	25.3800	25.3689	25.3800	25.3768	25.3762	25.3959	25.3822	25.3813	25.3838
12.7265	12.7410	12.7314	12.7294	12.7375	12.7286	12.7327	12.7440	12.7129	12.7283
0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667
31051	31071	30995	31032	31072	31113	31086	30701	31178	31053
31058	31086	30995	31042	31083	31118	31076	30666	31238	31063
31048	31071	30990	31024	31008	31112	31093	30667	31216	31069
31041	31005	30991	31035	31075	31108	31081	30675	31189	31066
31053	31079	30999	31025	31086	31111	31088	30888	31173	31044
31046	31080	31005	31040	31081	31114	31083	30685	31204	31053
31052	31102	30994	31027	31080	31106	31082	30673	31150	31055
31053	31073	30987	31041	31080	31124	31086	30674	31156	31039
31049	31053	30993	31031	31079	31116	31082	30671	31151	31048
31049	31082	30995	31026	31077	31113	31113	30695	31148	31052
31056	31074	30999	31029	31069	31106	31079	30713	31155	31040
2.28482468	2.28832323	2.2875249	2.28598066	2.28793924	2.28620643	2.28504625	2.28870757	2.282519	2.28537
0.03084372	0.03101192	0.0309735	0.03089925	0.03099344	0.0309101	0.03085436	0.03103043	0.030733	0.03087
0.32418556	0.32595346	0.32554962	0.32476917	0.32575919	0.32488322	0.32429738	0.32614798	0.323023	0.324461
2.27382778	2.27729639	2.27650489	2.27497387	2.27691569	2.2751977	2.27404746	2.27767744	2.271541	2.274369
2.11140835	2.11417953	2.11354726	2.11232409	2.11387542	2.11250293	2.11158388	2.11448392	2.109581	2.111841
1.21E+10	1.21E+10	1.20E+10	1.21E+10	1.21E+10	1.21E+10	1.21E+10	1.18E+10	1.22E+10	1.21E+10

Appendix 28. NBG-18 (AG) Fundamental frequency and Young's modulus data (sheet 3)

BB3-7	BB5-5	BB5-6	BB5-7	BB7-5	BB7-6	BB7-7	BB9-5	BB9-6	BB9-7
5.9411	5.9380	5.9493	5.9474	5.9559	5.9589	5.9561	5.9559	5.9609	5.9523
25.3781	25.3771	25.3886	25.3787	25.3756	25.3705	25.3825	25.3702	25.3816	25.3822
12.7240	12.7333	12.7286	12.7325	12.7349	12.7243	12.7298	12.7318	12.7337	12.7322
0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667
31062	31075	30943	30838	31180	31117	31063	31111	31117	31065
31096	31120	30989	30847	31236	31091	31051	31069	31120	31067
31092	31133	30902	30891	31168	31090	31053	31111	31120	31088
31072	31139	30902	30826	31218	31117	31050	31123	31119	31065
31096	31074	30910	30814	31156	31195	31054	31108	31112	31055
31134	31114	30904	30833	31176	31085	31056	31137	31119	31065
31133	31095	30900	30835	31169	31081	31065	31112	31114	31059
31131	31030	30951	30838	31168	31094	31114	31116	31124	31056
30947	31037	30941	30833	31164	31094	31060	31114	31118	31051
30950	30994	31077	30833	31171	31134	31077	31110	31115	31065
30973	31012	30957	30833	31174	31185	31051	31108	31113	31075
2.285083	2.287072	2.284952	2.286751	2.287555	2.285919	2.28582	2.28746	2.286686	2.286333
0.030856	0.030952	0.03085	0.030936	0.030975	0.030896	0.030892	0.03097	0.030933	0.030916
0.324316	0.325321	0.32425	0.325158	0.325565	0.324738	0.324688	0.325517	0.325125	0.324947
2.274084	2.276056	2.273954	2.275738	2.276534	2.274913	2.274814	2.276441	2.275673	2.275323
2.111613	2.113189	2.111509	2.112934	2.113571	2.112276	2.112196	2.113496	2.112883	2.112603
1.21E+10	1.21E+10	1.20E+10	1.19E+10	1.22E+10	1.22E+10	1.21E+10	1.22E+10	1.22E+10	1.21E+10

Appendix 29. H-451 (WG) Fundamental frequency and Young's modulus data (sheet 1)

Modulus by Resonant Frequency

Specimen number			C2-1	C2-2	C2-3	C4-1	C4-2	C4-3	C6-1	C6-2
mass of bar	m	[g]	5.4278	5.4462	5.4575	5.4561	5.4625	5.4834	5.4527	5.4211
length of bar	L	[mm]	25.3895	25.3895	25.3917	25.3898	25.3924	25.4029	25.3921	25.3883
diameter of bar	D	[mm]	12.7179	12.7413	12.7464	12.7364	12.7397	12.7435	12.7432	12.7276
Poisson's ratio	μ		0.1666667	0.166667	0.166667	0.166667	0.166667	0.166667	0.166667	0.166667
average resonant frequency	f_{avg}	[Hz]	28620	28409	28816	28556	28765	28864	28267	27894
frequency data	f_i	1	28618	28419	28818	28538	28732	28862	28278	27915
(specimen number		2	28556	28416	28821	28563	28735	28857	28192	27891
oriented up in fixture)		3	28740	28411	28822	28553	28726	28857	28283	27888
		4	28595	28400	28826	28580	28726	28862	28234	27896
		5	28591	28437	28814	28566	28718	28868	28265	27892
		6	28599	28403	28814	28561	28722	28861	28293	27895
		7	28655	28392	28805	28554	28823	28864	28289	27892
		8	28595	28395	28814	28552	28869	28876	28251	27891
		9	28669	28408	28807	28550	28768	28872	28308	27891
		10	28586	28404	28816	28545	28834	28862	28280	27892
$T_{1'}$ correction factor			2.2827093	2.287421	2.288222	2.286394	2.28681	2.286518	2.287548	2.284792
calculation of individual			0.0307422	0.030968	0.031007	0.030919	0.030939	0.030925	0.030975	0.030842
terms			0.3231189	0.325497	0.325902	0.324978	0.325188	0.325041	0.325561	0.324169
			2.2717305	2.276402	2.277196	2.275384	2.275797	2.275507	2.276528	2.273795
resultant $T_{1'}$		$T_{1'}$	2.1097323	2.113465	2.1141	2.112652	2.112981	2.11275	2.113566	2.111382
modulus of elasticity **	E	[Pa]	9.43E+09	9.27E+09	9.55E+09	9.39E+09	9.54E+09	9.64E+09	9.19E+09	8.92E+09
Average Modulus for specimen group			9.18E+09							
Standard deviation			3.20E+08							

Appendix 29. H-451 (WG) Fundamental frequency and Young's modulus data (sheet 2)

C6-3	C8-1	C8-2	C8-3	C10-1	C10-2	C10-3	C11-1	C11-2	C11-3
5.3993	5.3970	5.3985	5.3834	5.4454	5.4509	5.4674	5.4269	5.4212	5.4124
25.3889	25.3806	25.3857	25.3822	25.3740	25.3832	25.3790	25.3819	25.3816	25.3787
12.7154	12.7318	12.7232	12.7376	12.7281	12.7319	12.7289	12.7321	12.7341	12.7095
0.166667	0.166667	0.166667	0.166667	0.166667	0.166667	0.166667	0.166667	0.166667	0.166667
27812	27767	27899	27618	28787	28708	29039	28160	27535	27449
27818	27777	27911	27612	28786	28730	29038	28188	27535	27453
27816	27775	27909	27632	28786	28724	29050	28137	27537	27458
27816	27777	27906	27630	28796	28704	29052	28147	27537	27448
27812	27762	27897	27613	28795	28703	29034	28115	27542	27453
27819	27761	27891	27628	28767	28716	29039	28220	27535	27447
27815	27757	27890	27606	28786	28703	29039	28179	27533	27448
27806	27765	27891	27618	28792	28702	29030	28209	27538	27451
27810	27764	27897	27625	28788	28704	29039	28119	27528	27443
27797	27770	27890	27608	28785	28693	29034	28111	27531	27451
27812	27762	27909	27609	28784	28700	29037	28174	27531	27442
2.282261	2.286397	2.284152	2.287424	2.286335	2.286172	2.285981	2.286333	2.286782	2.282103
0.030721	0.030919	0.030811	0.030969	0.030916	0.030908	0.030899	0.030916	0.030938	0.030713
0.322893	0.32498	0.323846	0.325498	0.324948	0.324866	0.324769	0.324947	0.325174	0.322813
2.271286	2.275387	2.273161	2.276404	2.275326	2.275164	2.274974	2.275323	2.275768	2.271129
2.109377	2.112654	2.110875	2.113467	2.112605	2.112476	2.112324	2.112603	2.112959	2.109252
8.86E+09	8.79E+09	8.90E+09	8.66E+09	9.53E+09	9.49E+09	9.74E+09	9.09E+09	8.68E+09	8.66E+09

Appendix 29. H-451 (WG) Fundamental frequency and Young's modulus data (sheet 3)

C13-1	C13-2	C13-3	C15-1	C15-2	C15-3	C19-1	C19-2	C19-3
5.4445	5.4538	5.4419	5.4635	5.4594	5.4459	5.4323	5.4281	5.4263
25.3781	25.3819	25.3717	25.3768	25.3778	25.3749	25.3851	25.3790	25.3768
12.7262	12.7387	12.7330	12.7316	12.7286	12.7313	12.7251	12.7329	12.7327
0.166667	0.166667	0.166667	0.166667	0.166667	0.166667	0.166667	0.166667	0.166667
28326	28152	28066	28790	28516	28378	28316	27792	27789
28339	28151	28071	28807	28518	28371	28320	27787	27795
28332	28155	28068	28813	28515	28384	28311	27790	27727
28319	28151	28063	28800	28520	28373	28318	27805	27782
28324	28148	28062	28818	28515	28376	28314	27792	27803
28328	28149	28066	28806	28510	28390	28319	27799	27796
28337	28154	28068	28816	28511	28374	28311	27788	27788
28328	28154	28066	28807	28514	28378	28316	27795	27809
28317	28149	28069	28610	28520	28391	28316	27771	27796
28317	28152	28065	28805	28516	28371	28319	27791	27797
28323	28152	28066	28816	28517	28367	28315	27800	27797
2.285532	2.28768	2.287556	2.286752	2.286046	2.286881	2.2846	2.286783	2.286976
0.030878	0.030981	0.030975	0.030936	0.030902	0.030943	0.030833	0.030938	0.030947
0.324543	0.325628	0.325565	0.325159	0.324802	0.325224	0.324072	0.325175	0.325272
2.274529	2.276659	2.276536	2.275738	2.275038	2.275866	2.273605	2.275769	2.275961
2.111969	2.11367	2.113572	2.112935	2.112375	2.113037	2.111231	2.11296	2.113113
9.24E+09	9.11E+09	9.04E+09	9.56E+09	9.38E+09	9.26E+09	9.22E+09	8.85E+09	8.85E+09

Appendix 30. PCEA (WG) Fundamental frequency and Young's modulus data (sheet 1)

Modulus by Resonant Frequency

Specimen number				DA2-1	DA2-2	DA2-3	DA4-1	DA4-2	DA4-3	DA6-1	DA6-2
mass of bar	m	[g]		5.6695	5.6673	5.6753	5.6963	5.6905	5.7004	5.7194	5.7154
length of bar	L	[mm]		25.3695	25.3740	25.3740	25.3825	25.3813	25.3683	25.3800	25.3819
diameter of bar	D	[mm]		12.7344	12.7392	12.7343	12.7427	12.7365	12.7418	12.7368	12.7425
Poisson's ratio	μ			0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
average resonant frequency	f_{avg}	[Hz]		28749	28838	29012	28643	28907	29006	29275	29230
frequency data	f_i		1	28764	28849	29021	28643	28844	29011	29285	29239
(specimen number			2	28765	28837	29015	28647	28832	29012	29298	29228
oriented up in fixture)			3	28732	28859	29016	28641	28851	29002	29292	29240
			4	28745	28840	29009	28635	28824	29005	29272	29222
			5	28733	28838	29009	28650	28813	29006	29274	29233
			6	28780	28830	29018	28632	28938	29004	29256	29237
			7	28739	28830	29008	28645	28948	29006	29262	29232
			8	28748	28829	29005	28643	29004	29000	29261	29218
			9	28745	28828	29009	28652	29004	29001	29272	29225
			10	28737	28839	29014	28643	29013	29013	29279	29225
$T_{1'}$ correction factor				2.2880706	2.288583	2.287587	2.288419	2.287296	2.289677	2.287489	2.288451
calculation of individual				0.0309998	0.031024	0.030976	0.031017	0.030962	0.031077	0.030972	0.031018
terms				0.3258256	0.326085	0.325581	0.326002	0.325434	0.326639	0.325531	0.326018
				2.2770459	2.277554	2.276567	2.277391	2.276278	2.278639	2.276469	2.277423
resultant $T_{1'}$		$T_{1'}$		2.1139794	2.114385	2.113597	2.114255	2.113366	2.115252	2.113519	2.114281
modulus of elasticity **	E	[Pa]		9.88E+09	9.93E+09	1.01E+10	9.85E+09	1.00E+10	1.01E+10	1.03E+10	1.03E+10
Average Modulus for specimen group				1.023E+10							
Standard deviation				2.153E+08							

Appendix 30. PCEA (WG) Fundamental frequency and Young's modulus data (sheet 2)

DA6-3	DA8-1	DA8-2	DA8-3	DA10-1	DA10-2	DA10-3	DA2-4	DA2-5	DA2-6
5.7173	5.7132	5.7113	5.7194	5.7189	5.7177	5.7211	5.6889	5.7090	5.7224
25.3638	25.3803	25.3803	25.3790	25.3759	25.3721	25.3810	25.3689	25.3683	25.3733
12.7408	12.7384	12.7357	12.7379	12.7403	12.7386	12.7373	12.7352	12.7371	12.7340
0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
29350	28997	29154	29518	29007	29233	29415	29031	29068	29376
29365	28995	29246	29525	29047	29236	29428	29065	29082	29301
29349	29030	29149	29456	28945	29239	29414	29103	29078	29323
29336	28998	29045	29548	28984	29227	29410	29058	29049	29314
29352	28994	29131	29565	29001	29240	29415	29114	29066	29367
29342	28995	29111	29505	29028	29236	29414	29039	29066	29373
29353	28995	29144	29536	29022	29226	29418	29005	29074	29399
29357	28990	29145	29522	28996	29230	29414	29034	29072	29423
29341	28992	29255	29526	29029	29230	29414	28953	29061	29395
29347	28988	29145	29506	29025	29229	29414	28970	29072	29431
29353	28995	29166	29491	28990	29236	29404	28966	29060	29433
2.289937	2.287777	2.287232	2.28781	2.288614	2.288648	2.287488	2.288296	2.288746	2.287587
0.03109	0.030986	0.030959	0.030987	0.031026	0.031028	0.030972	0.031011	0.031032	0.030977
0.32677	0.325677	0.325401	0.325694	0.326101	0.326118	0.325531	0.325939	0.326167	0.325581
2.278896	2.276755	2.276214	2.276788	2.277585	2.277618	2.276469	2.277269	2.277715	2.276567
2.115457	2.113747	2.113315	2.113773	2.11441	2.114436	2.113518	2.114158	2.114514	2.113597
1.04E+10	1.01E+10	1.02E+10	1.05E+10	1.01E+10	1.03E+10	1.04E+10	1.01E+10	1.02E+10	1.04E+10

Appendix 30. PCEA (WG) Fundamental frequency and Young's modulus data (sheet 3)

DA4-4	DA4-5	DA4-6	DA8-4	DA8-5	DA8-6	DA10-4	DA10-5	DA10-6
5.6892	5.6686	5.6658	5.7245	5.7264	5.7453	5.7387	5.7394	5.7433
25.3771	25.3695	25.3657	25.3784	25.3784	25.3781	25.3736	25.3746	25.3819
12.7384	12.7410	12.7408	12.7365	12.7346	12.7411	12.7454	12.7398	12.7424
0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
29054	28869	28937	29384	29355	29546	29552	29467	29455
28959	28866	28942	29401	29420	29556	29555	29481	29471
28962	28879	28948	29389	29347	29557	29556	29474	29455
28952	28882	28948	29388	29370	29550	29555	29467	29458
29943	28875	28934	29379	29352	29543	29547	29464	29454
28957	28863	28935	29386	29335	29536	29549	29469	29444
28951	28867	28931	29379	29370	29556	29548	29461	29459
28950	28867	28930	29375	29389	29540	29557	29464	29452
28957	28862	28948	29379	29333	29539	29562	29465	29450
28956	28864	28935	29381	29307	29539	29553	29462	29457
28948	28862	28922	29381	29327	29542	29542	29464	29450
2.2881	2.289388	2.289743	2.287586	2.2872	2.288549	2.289868	2.288647	2.288419
0.031001	0.031063	0.03108	0.030976	0.030958	0.031023	0.031086	0.031027	0.031017
0.32584	0.326492	0.326672	0.32558	0.325386	0.326068	0.326735	0.326117	0.326002
2.277075	2.278352	2.278704	2.276565	2.276183	2.27752	2.278828	2.277617	2.277391
2.114002	2.115022	2.115304	2.113595	2.11329	2.114358	2.115403	2.114436	2.114255
1.01E+10	9.95E+09	9.99E+09	1.04E+10	1.04E+10	1.06E+10	1.05E+10	1.05E+10	1.05E+10

Appendix 31. PCEA (AG) Fundamental frequency and Young's modulus data (sheet 1)

Modulus by Resonant Frequency

Specimen number			DB2-1	DB2-2	DB2-3	DB4-1	DB4-2	DB4-3	DB6-1	DB6-2
mass of bar	m	[g]	5.7015	5.6883	5.6825	5.6959	5.6895	5.6803	5.6809	5.6972
length of bar	L	[mm]	25.3797	25.3727	25.3781	25.3781	25.3752	25.3784	25.3800	25.3844
diameter of bar	D	[mm]	12.7408	12.7422	12.7362	12.7419	12.7373	12.7397	12.7370	12.7411
Poisson's ratio	μ		0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
average resonant frequency	f_{avg}	[Hz]	27839	27952	27927	27735	27756	28079	27920	28039
frequency data	f_i	1	27832	27963	27929	27749	27758	28086	27923	28036
(specimen number		2	27839	27956	27919	27546	27764	28081	27911	28056
oriented up in fixture)		3	27846	27948	27925	27769	27757	28089	27925	28035
		4	27846	27949	27927	27753	27755	28091	27917	28040
		5	27839	27954	27929	27761	27752	28079	27912	28052
		6	27846	27950	27926	27755	27746	28074	27925	28040
		7	27836	27952	27935	27743	27758	28068	27921	28040
		8	27837	27951	27922	27758	27752	28077	27927	28033
		9	27833	27945	27932	27761	27762	28074	27917	28039
		10	27831	27956	27927	27758	27755	28071	27921	28022
$T_{1'}$ correction factor			2.2883234	2.289322	2.287554	2.288709	2.288068	2.288228	2.287521	2.287904
calculation of individual			0.0310119	0.03106	0.030975	0.031031	0.031	0.031007	0.030973	0.030992
terms			0.3259535	0.326459	0.325564	0.326149	0.325824	0.325905	0.325548	0.325741
			2.2772965	2.278287	2.276533	2.277679	2.277044	2.277202	2.276501	2.276881
resultant $T_{1'}$		$T_{1'}$	2.1141796	2.11497	2.11357	2.114485	2.113978	2.114104	2.113544	2.113848
modulus of elasticity *	E	[Pa]	9.31E+09	9.36E+09	9.35E+09	9.23E+09	9.24E+09	9.44E+09	9.34E+09	9.44E+09
Average Modulus for specimen group			9.40E+09							
Standard deviation			114755092							

Appendix 31. PCEA (AG) Fundamental frequency and Young's modulus data (sheet 2)

DB6-3	DB8-1	DB8-2	DB8-3	DB10-1	DB10-2	DB10-3	DB2-4	DB2-5	DB2-6
5.7189	5.6797	5.6844	5.7063	5.6778	5.7054	5.6968	5.7095	5.7226	5.7014
25.3879	25.3816	25.3765	25.3883	25.3768	25.3686	25.3778	25.3724	25.3695	25.3721
12.7294	12.7362	12.7356	12.7359	12.7348	12.7395	12.7349	12.7402	12.7464	12.7410
0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
27740	27800	27838	27856	27906	27906	27789	28201	28311	28069
27745	27803	27843	27868	27922	27920	27784	28147	28377	28065
27738	27809	27844	27862	27908	27904	27782	28190	28317	28068
27744	27785	27845	27854	27917	27898	27787	28229	28216	28078
27736	27813	27834	27855	27902	27909	27788	28193	28299	28067
27746	27799	27845	27860	27907	27908	27784	28247	28307	28071
27740	27796	27838	27850	27895	27900	27786	28213	28325	28063
27740	27806	27820	27852	27924	27906	27783	28210	28319	28069
27739	27798	27839	27854	27902	27904	27791	28188	28318	28072
27737	27798	27835	27857	27892	27909	27783	28205	28316	28067
27734	27795	27835	27843	27894	27899	27820	28188	28314	28069
2.285177	2.287199	2.287586	2.286459	2.287394	2.289195	2.287329	2.288937	2.29048	2.289129
0.030861	0.030958	0.030976	0.030922	0.030967	0.031054	0.030964	0.031041	0.031116	0.031051
0.324363	0.325385	0.325581	0.325011	0.325483	0.326395	0.325451	0.326264	0.327046	0.326362
2.274177	2.276182	2.276566	2.275448	2.276375	2.278161	2.276311	2.277904	2.279435	2.278096
2.111687	2.113289	2.113596	2.112703	2.113443	2.11487	2.113392	2.114665	2.115888	2.114818
9.31E+09	9.26E+09	9.29E+09	9.35E+09	9.33E+09	9.36E+09	9.28E+09	9.57E+09	9.65E+09	9.46E+09

Appendix 31. PCEA (AG) Fundamental frequency and Young's modulus data (sheet 3)

DB4-4	DB4-5	DB4-6	DB8-4	DB8-5	DB8-6	DB10-4	DB10-5	DB10-6
5.7102	5.7215	5.7012	5.7157	5.6878	5.6956	5.7272	5.6974	5.6867
25.3756	25.3775	25.3781	25.3832	25.3822	25.3813	25.3822	25.3781	25.3794
12.7446	12.7398	12.7421	12.7303	12.7329	12.7330	12.7248	12.7359	12.7283
0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
28256	28177	28295	27863	27859	27957	27942	27892	28029
28259	28179	28290	27864	27858	27960	27925	27905	28067
28252	28170	28303	27870	27858	27959	27991	27883	28017
28254	28180	28288	27866	27875	27964	27923	27901	28030
28265	28171	28294	27862	27856	27949	27938	27887	28054
28254	28181	28298	27859	27834	27956	27935	27883	28021
28257	28181	28293	27868	27842	27955	27954	27895	28020
28262	28172	28298	27860	27853	27965	27937	27896	28015
28254	28178	28296	27862	27877	27953	27935	27896	28019
28252	28177	28292	27854	27868	27951	27953	27883	28026
28253	28182	28293	27867	27868	27958	27924	27887	28016
2.289513	2.288356	2.288741	2.285851	2.286461	2.28659	2.284826	2.287489	2.28582
0.031069	0.031014	0.031032	0.030893	0.030922	0.030929	0.030844	0.030972	0.030892
0.326556	0.32597	0.326165	0.324704	0.325012	0.325077	0.324186	0.325532	0.324688
2.278476	2.277329	2.277711	2.274846	2.27545	2.275578	2.273829	2.27647	2.274815
2.115122	2.114206	2.114511	2.112222	2.112705	2.112807	2.111409	2.113519	2.112197
9.60E+09	9.57E+09	9.61E+09	9.38E+09	9.32E+09	9.40E+09	9.46E+09	9.35E+09	9.44E+09

Appendix 32. IG-110 Fundamental frequency and Young's modulus data (sheet 1)

Modulus by Resonant Frequency

Specimen number			E2-1	E2-2	E2-3	E4-1	E4-2	E4-3	E6-1	E6-2
mass of bar	m	[g]	5.6316	5.6119	5.6127	5.6101	5.6012	5.5628	5.6350	5.6321
length of bar	L	[mm]	25.3781	25.3841	25.3800	25.3775	25.3844	25.3810	25.3825	25.3790
diameter of bar	D	[mm]	12.7445	12.7392	12.7427	12.7411	12.7518	12.7414	12.7383	12.7445
Poisson's ratio	μ		0.1666667	0.166667	0.166667	0.166667	0.166667	0.166667	0.166667	0.166667
average resonant frequency	f_{avg}	[Hz]	27363	27077	27718	27383	26810	27342	27522	27746
frequency data	f_i	1	27363	27083	27725	27392	26808	27344	27520	27743
(specimen number		2	27370	27082	27726	27383	26802	27348	27528	27756
oriented up in fixture)		3	27369	27081	27722	27384	26815	27340	27522	27747
		4	27364	27075	27722	27386	26813	27349	27523	27744
		5	27355	27077	27722	27376	26799	27347	27521	27744
		6	27348	27076	27708	27391	26814	27331	27525	27742
		7	27364	27076	27712	27380	26820	27341	27522	27740
		8	27366	27081	27716	27392	26815	27340	27522	27747
		9	27368	27062	27714	27375	26810	27336	27512	27748
		10	27358	27076	27716	27369	26808	27341	27522	27744
$T_{1'}$ correction factor			2.28922	2.28755	2.28868	2.28861	2.29006	2.28832	2.28752	2.28913
calculation of individual			0.03106	0.03097	0.03103	0.03103	0.03110	0.03101	0.03097	0.03105
terms			0.32641	0.32556	0.32613	0.32610	0.32683	0.32595	0.32555	0.32636
			2.27819	2.27653	2.27765	2.27758	2.27901	2.27730	2.27650	2.27809
resultant $T_{1'}$		$T_{1'}$	2.11489	2.11357	2.11446	2.11441	2.11555	2.11418	2.11354	2.11482
modulus of elasticity **	E	[Pa]	8.88E+09	8.68E+09	9.08E+09	8.86E+09	8.47E+09	8.76E+09	9.00E+09	9.13E+09
Average Modulus for specimen group			8.68E+09							
Standard deviation			2.32E+08							

Appendix 32. IG-110 Fundamental frequency and Young's modulus data (sheet 2)

E6-3	E8-1	E8-2	E8-3	E10-1	E10-2	E10-3	E2-4	E2-5	E2-6
5.6306	5.5829	5.5812	5.5949	5.6110	5.5871	5.5948	5.6138	5.5716	5.5906
25.3749	25.3692	25.3813	25.3736	25.3838	25.3733	25.3727	25.3746	25.3765	25.3768
12.7443	12.7456	12.7435	12.7451	12.7379	12.7378	12.7410	12.7400	12.7421	12.7356
0.166667	0.166667	0.166667	0.166667	0.166667	0.166667	0.166667	0.166667	0.166667	0.166667
27747	26892	26789	26957	27142	26995	27070	27354	26921	27306
27747	26890	26760	26925	27144	26993	27078	27343	26929	27307
27752	26895	26762	26931	27145	27002	27073	27353	26932	27309
27750	26895	26814	26959	27138	26994	27071	27368	26919	27307
27745	26890	26778	26961	27139	26966	27071	27344	26925	27306
27746	26894	26773	26942	27141	26994	27062	27346	26919	27307
27751	26896	26787	26970	27138	26991	27067	27358	26922	27305
27747	26885	26799	26955	27139	27003	27069	27352	26914	27301
27742	26888	26802	26969	27160	27004	27069	27352	26926	27304
27746	26895	26811	26978	27138	27001	27071	27352	26912	27302
27748	26892	26799	26975	27138	26997	27070	27368	26915	27310
2.28951	2.29035	2.28871	2.28980	2.28733	2.28836	2.28906	2.28868	2.28890	2.28755
0.03107	0.03111	0.03103	0.03108	0.03096	0.03101	0.03105	0.03103	0.03104	0.03097
0.32656	0.32698	0.32615	0.32670	0.32545	0.32597	0.32633	0.32613	0.32625	0.32556
2.27848	2.27931	2.27768	2.27876	2.27631	2.27733	2.27803	2.27765	2.27787	2.27653
2.11512	2.11579	2.11449	2.11535	2.11339	2.11421	2.11477	2.11446	2.11464	2.11357
9.12E+09	8.49E+09	8.44E+09	8.55E+09	8.72E+09	8.58E+09	8.63E+09	8.85E+09	8.51E+09	8.79E+09

Appendix 32. IG-110 Fundamental frequency and Young's modulus data (sheet 3)

E4-4	E4-5	E4-6	E8-4	E8-5	E8-6	E10-4	E10-5	E10-6
5.5855	5.5849	5.5878	5.5799	5.5676	5.5612	5.5983	5.5899	5.5757
25.3781	25.3790	25.3787	25.3721	25.3816	25.3714	25.3759	25.3733	25.3844
12.7360	12.7294	12.7319	12.7448	12.7483	12.7406	12.7368	12.7346	12.7322
0.166667	0.166667	0.166667	0.16666667	0.166667	0.166667	0.166667	0.166667	0.166667
26608	26834	26961	26968	26701	26716	27088	27447	26838
26607	26833	26974	26963	26705	26726	27089	27445	26840
26613	26831	26981	26969	26696	26659	27092	27453	26829
26627	26835	26827	26974	26697	26727	27089	27455	26850
26598	26878	26977	26977	26702	26692	27089	27447	26839
26625	26834	26976	26973	26703	26699	27092	27441	26821
26615	26834	26977	26967	26711	26735	27082	27442	26850
26608	26798	26985	26969	26704	26732	27091	27448	26833
26617	26835	26970	26964	26736	26719	27089	27446	26844
26592	26829	26976	26962	26660	26734	27082	27447	26841
26582	26829	26967	26961	26695	26732	27080	27448	26834
2.28752	2.28608	2.28662	2.28990	2.28964	2.28913	2.28791	2.28772	2.28611
0.03097	0.03090	0.03093	0.03109	0.03108	0.03105	0.03099	0.03098	0.03091
0.32555	0.32482	0.32509	0.32675	0.32662	0.32636	0.32574	0.32565	0.32483
2.27650	2.27507	2.27561	2.27886	2.27860	2.27810	2.27688	2.27669	2.27510
2.11354	2.11240	2.11283	2.11543	2.11522	2.11482	2.11385	2.11370	2.11242
8.34E+09	8.50E+09	8.58E+09	8.54E+09	8.35E+09	8.36E+09	8.66E+09	8.88E+09	8.48E+09

Appendix 33. IG-430 Fundamental frequency and Young's modulus data (sheet 1)

Modulus by Resonant Frequency

Specimen number				F2-1	F2-2	F2-3	F4-1	F4-2	F4-3	F6-1	F6-2
mass of bar	m	[g]		5.7020	5.7166	5.7274	5.7251	5.7434	5.7394	5.7360	5.7084
length of bar	L	[mm]		25.3759	25.3825	25.3806	25.3790	25.3702	25.3762	25.3867	25.3790
diameter of bar	D	[mm]		12.7219	12.7264	12.7343	12.7283	12.7387	12.7314	12.7271	12.7356
Poisson's ratio	μ			0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667
average resonant frequency	f_{avg}	[Hz]		28065	27549	27586	27670	27786	28217	28327	27930
frequency data	f_i		1	28080	27559	27618	27667	27784	28214	28333	27931
(specimen number			2	28075	27545	27564	27669	27785	28214	28328	27930
oriented up in fixture)			3	28064	27549	27594	27680	27778	28221	28329	27928
			4	28061	27547	27596	27673	27785	28220	28324	27937
			5	28061	27546	27583	27664	27783	28216	28327	27929
			6	28058	27545	27581	27667	27792	28217	28326	27929
			7	28062	27544	27575	27667	27794	28216	28326	27932
			8	28062	27545	27576	27670	27791	28218	28326	27929
			9	28062	27545	27582	27676	27784	28217	28327	27926
			10	28062	27564	27591	27670	27779	28219	28325	27932
$T_{1'}$ correction factor				2.2848914	2.285114	2.286911	2.285853	2.288873	2.286784	2.284856	2.287329
calculation of individual				0.0308469	0.030858	0.030944	0.030893	0.031038	0.030938	0.030845	0.030964
terms				0.3242193	0.324332	0.325239	0.324705	0.326232	0.325175	0.324202	0.32545
				2.273894	2.274115	2.275896	2.274847	2.277842	2.27577	2.273859	2.27631
resultant $T_{1'}$		$T_{1'}$		2.1114612	2.111638	2.113061	2.112223	2.114615	2.11296	2.111434	2.113392
modulus of elasticity **	E	[Pa]		9.50E+09	9.18E+09	9.20E+09	9.26E+09	9.34E+09	9.65E+09	9.74E+09	9.40E+09
Average Modulus for specimen group				9.38E+09							
Standard deviation				1.85E+08							

Appendix 33. IG-430 Fundamental frequency and Young's modulus data (sheet 2)

F6-3	F8-1	F8-2	F8-3	F10-1	F10-2	F10-3	F2-4	F2-5	F2-6
5.7220	5.7231	5.7444	5.6910	5.7192	5.7490	5.7300	5.7526	5.7248	5.7179
25.3762	25.3806	25.3844	25.3740	25.3797	25.3724	25.3816	25.3813	25.3794	25.3730
12.7325	12.7311	12.7260	12.7370	12.7348	12.7287	12.7337	12.7343	12.7300	12.7319
0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667
27703	27799	28049	28252	28088	27958	28133	27330	27964	27353
27703	27692	28054	28241	28095	27953	28121	27333	27970	27360
27700	27696	28063	28252	28103	27964	28133	27336	27969	27363
27713	27728	28041	28258	28094	27961	28143	27333	27967	27351
27682	27747	28049	28254	28101	27967	28127	27327	27962	27347
27718	27633	28039	28253	28087	27953	28145	27332	27973	27359
27718	27848	28046	28251	28077	27968	28134	27334	27970	27347
27689	27892	28049	28250	28084	27952	28144	27331	27948	27332
27709	27849	28045	28254	28078	27952	28116	27327	27974	27332
27700	27860	28050	28250	28079	27957	28122	27325	27916	27369
27697	28042	28050	28255	28081	27955	28145	27324	27989	27368
2.287009	2.286269	2.284857	2.288133	2.287104	2.286625	2.286686	2.286846	2.286173	2.287202
0.030949	0.030913	0.030845	0.031003	0.030953	0.03093	0.030933	0.030941	0.030909	0.030958
0.325289	0.324915	0.324202	0.325857	0.325337	0.325095	0.325125	0.325207	0.324866	0.325387
2.275993	2.27526	2.27386	2.277108	2.276087	2.275613	2.275673	2.275832	2.275165	2.276185
2.113138	2.112553	2.111434	2.114029	2.113214	2.112834	2.112883	2.11301	2.112477	2.113292
9.27E+09	9.34E+09	9.56E+09	9.58E+09	9.52E+09	9.49E+09	9.58E+09	9.07E+09	9.46E+09	9.03E+09

Appendix 33. IG-430 Fundamental frequency and Young's modulus data (sheet 3)

F4-4	F4-5	F4-6	F8-4	F8-5	F8-6	F10-4	F10-5	F10-6
5.7431	5.7244	5.7521	5.6924	5.7305	5.7133	5.7644	5.7526	5.7552
25.3790	25.3898	25.3711	25.3857	25.3778	25.3778	25.3797	25.3816	25.3727
12.7308	12.7154	12.7398	12.7249	12.7373	12.7198	12.7276	12.7330	12.7391
0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667
28186	28064	27881	27765	27434	27602	27794	27693	27616
28183	28069	27881	27769	27479	27608	27789	27695	27619
28183	28063	27885	27766	27431	27611	27792	27705	27618
28189	28070	27884	27766	27422	27605	27793	27692	27617
28185	28066	27881	27767	27427	27609	27796	27711	27614
28186	28069	27885	27756	27428	27599	27787	27687	27621
28187	28057	27880	27762	27427	27597	27792	27689	27619
28188	28057	27888	27772	27432	27592	27792	27688	27607
28189	28061	27886	27757	27430	27598	27797	27691	27617
28187	28064	27866	27767	27430	27598	27802	27684	27613
28186	28060	27876	27766	27438	27600	27796	27685	27612
2.286366	2.282165	2.289001	2.284504	2.28781	2.284282	2.28566	2.286558	2.288679
0.030918	0.030716	0.031045	0.030828	0.030987	0.030818	0.030884	0.030927	0.031029
0.324964	0.322845	0.326297	0.324024	0.325694	0.323912	0.324607	0.325061	0.326134
2.275356	2.271191	2.277969	2.27351	2.276788	2.27329	2.274656	2.275546	2.27765
2.112629	2.109301	2.114717	2.111154	2.113773	2.110978	2.11207	2.112781	2.114462
9.64E+09	9.57E+09	9.42E+09	9.29E+09	9.10E+09	9.22E+09	9.41E+09	9.32E+09	9.25E+09

Appendix 34. Sonic elastic constants data for NBG-17 (Sheet 1)

Young's Modulus, Shear Modulus and Poisson's Ratio by Sonic Velocity											
								Elastic	Shear	Poisson's Ratio	
Orientation	Specimen	Density, ρ	Sonic Velocities, υ [m/s]			Average Shear		Modulus, [Pa]	Modulus, [Pa]		Elastic Modulus, [Pa]
	Number	kg/m^3	Longitudinal	Shear 0^o	Shear 90^o			$E=\rho\upsilon_l^2$	$G=\rho\upsilon_s^2$	$\mu=(1-[2(\upsilon_s/\upsilon_l)^2])/(2-[2(\upsilon_s/\upsilon_l)^2])$	$E=\rho\upsilon_l^2[(1+\mu)(1-2\mu)/(1-\mu)]$
	AW1-01	1843.91	2.766E+03	1.416E+03	1.420E+03	1.418E+03		1.41028E+10	3.709E+09	3.216E-01	9.803E+09
wg	**A2-1**	1861.70	2674	1439	1430	1.435E+03		1.33117E+10	3.831E+09	2.980E-01	9.945E+09
wg	**A2-2**	1860.04	2732	1412	1434	1.423E+03		1.38830E+10	3.766E+09	3.138E-01	9.897E+09
wg	**A2-3**	1855.06	2732	1423	1416	1.420E+03		1.38458E+10	3.738E+09	3.151E-01	9.831E+09
wg	**A4-1**	1858.92	2732	1416	1432	1.424E+03		1.38747E+10	3.769E+09	3.135E-01	9.902E+09
wg	**A4-2**	1860.36	2733	1433	1416	1.425E+03		1.38956E+10	3.775E+09	3.135E-01	9.917E+09
wg	**A4-3**	1855.47	2731	1415	1414	1.415E+03		1.38388E+10	3.712E+09	3.167E-01	9.776E+09
wg	**A6-1**	1858.08	2733	1448	1426	1.437E+03		1.38785E+10	3.837E+09	3.090E-01	1.004E+10
wg	**A6-2**	1860.01	2733	1410	1429	1.420E+03		1.38930E+10	3.748E+09	3.153E-01	9.859E+09
wg	**A6-3**	1854.82	2732	1419	1422	1.421E+03		1.38441E+10	3.743E+09	3.147E-01	9.841E+09
wg	**A8-1**	1861.05	2733	1417	1415	1.416E+03		1.39007E+10	3.732E+09	3.165E-01	9.825E+09
wg	**A8-2**	1857.66	2733	1421	1421	1.421E+03		1.38754E+10	3.751E+09	3.148E-01	9.863E+09
wg	**A8-3**	1855.30	2733	1413	1412	1.413E+03		1.38578E+10	3.702E+09	3.178E-01	9.756E+09
wg	**A10-1**	1858.09	2732	1401	1403	1.402E+03		1.38684E+10	3.652E+09	3.213E-01	9.651E+09
wg	**A10-2**	1857.31	2733	1436	1419	1.428E+03		1.38728E+10	3.785E+09	3.124E-01	9.934E+09
wg	**A10-3**	1855.84	2733	1434	1455	1.445E+03		1.38618E+10	3.872E+09	3.062E-01	1.012E+10
	Average	1857.98	2728.60			1422.70		1.383E+10	3.761E+09	3.132E-01	9.877E+09
	Std Dev	2.24	14.61			10.07		1.406E+08	5.394E+07	5.308E-03	1.090E+08

Annex 34. Sonic elastic constants data for NBG-17 (Sheet 2)

ag	**AB2-1**	1857.52	2802	1449	1466	1.458E+03		1.45838E+10	3.946E+09	3.145E-01	1.037E+10
ag	**AB2-2**	1856.90	2802	1453	1436	1.445E+03		1.45789E+10	3.875E+09	3.190E-01	1.022E+10
ag	**AB2-3**	1856.14	2801	1413	1439	1.426E+03		1.45626E+10	3.774E+09	3.251E-01	1.000E+10
ag	**AB4-1**	1857.45	2802	1406	1428	1.417E+03		1.45832E+10	3.730E+09	3.282E-01	9.907E+09
ag	**AB4-2**	1856.48	2801	1415	1438	1.427E+03		1.45652E+10	3.778E+09	3.249E-01	1.001E+10
ag	**AB4-3**	1860.35	2802	1425	1422	1.424E+03		1.46060E+10	3.770E+09	3.261E-01	9.998E+09
ag	**AB6-1**	1857.20	2801	1435	1464	1.450E+03		1.45709E+10	3.902E+09	3.171E-01	1.028E+10
ag	**AB6-2**	1856.57	2802	1429	1440	1.435E+03		1.45763E+10	3.820E+09	3.224E-01	1.010E+10
ag	**AB6-3**	1859.17	2802	1419	1420	1.420E+03		1.45967E+10	3.746E+09	3.274E-01	9.945E+09
ag	**AB8-1**	1859.10	2809	1429	1442	1.436E+03		1.46692E+10	3.831E+09	3.233E-01	1.014E+10
ag	**AB8-2**	1860.00	2808	1429	1418	1.424E+03		1.46659E+10	3.769E+09	3.271E-01	1.000E+10
ag	**AB8-3**	1857.55	2808	1436	1437	1.437E+03		1.46466E+10	3.833E+09	3.228E-01	1.014E+10
ag	**AB10-1**	1859.48	2807	1437	1429	1.433E+03		1.46513E+10	3.818E+09	3.238E-01	1.011E+10
ag	**AB10-2**	1859.37	2808	1418	1430	1.424E+03		1.46608E+10	3.770E+09	3.269E-01	1.001E+10
ag	**AB10-3**	1860.29	2809	1430	1418	1.424E+03		1.46786E+10	3.772E+09	3.271E-01	1.001E+10
	Average	1858.29	2804.43			1429.82		1.462E+10	3.799E+09	3.244E-01	1.006E+10
	Std Dev	1.47	3.29			9.09		4.258E+07	4.730E+07	3.131E-03	1.020E+08

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Measurements and calculations by Joe Strizak

Appendix 35. Sonic elastic constants data for NBG-18 (Sheet 1)

Young's Modulus, Shear Modulus and Poisson's Ratio by Sonic Velocity											
								Elastic	Shear		Elastic
Orientation	Specimen	Density, ρ	Sonic Velocities, υ [m/s}			Average Shear		Modulus, [Pa]	Modulus, [Pa]	Poisson's Ratio	Modulus, [Pa]
	Number	kg/m^3	Longitudinal	Shear 0^o	Shear 90^o			$E=\rho\upsilon_l^2$	$G=\rho\upsilon_s^2$	$\mu=(1-[2(\upsilon_s/\upsilon_l)^2])/(2-[2(\upsilon_s/\upsilon_l)^2])$	$E=\rho\upsilon_l^2[(1+\mu)(1-2\mu)/(1-\mu)]$
	BL6-01	1872.85	2903	1474	1582	1528.00		1.57833E+10	4.373E+09	3.084E-01	1.144E+10
wg	**B2-1**	1871.52	2792	1416	1414	1415.00		1.45890E+10	3.747E+09	3.272E-01	9.946E+09
wg	**B2-2**	1869.85	2792	1437	1429	1433.00		1.45759E+10	3.840E+09	3.212E-01	1.015E+10
wg	**B2-3**	1865.23	2791	1426	1437	1431.50		1.45295E+10	3.822E+09	3.215E-01	1.010E+10
wg	**B4-1**	1878.31	2791	1437	1447	1442.00		1.46315E+10	3.906E+09	3.179E-01	1.029E+10
wg	**B4-2**	1869.19	2792	1458	1576	1517.00		1.45709E+10	4.302E+09	2.906E-01	1.110E+10
wg	**B4-3**	1869.45	2801	1470	1447	1458.50		1.46669E+10	3.977E+09	3.140E-01	1.045E+10
wg	**B6-1**	1875.06	2824	1441	1482	1461.50		1.49536E+10	4.005E+09	3.171E-01	1.055E+10
wg	**B6-2**	1866.93	2823	1467	1473	1470.00		1.48782E+10	4.034E+09	3.140E-01	1.060E+10
wg	**B6-3**	1868.67	2839	1453	1463	1458.00		1.50613E+10	3.972E+09	3.209E-01	1.049E+10
wg	**B8-1**	1875.17	2838	1456	1484	1470.00		1.51031E+10	4.052E+09	3.167E-01	1.067E+10
wg	**B8-2**	1873.72	2835	1461	1468	1464.50		1.50595E+10	4.019E+09	3.180E-01	1.059E+10
wg	**B8-3**	1869.73	2836	1447	1454	1450.50		1.50381E+10	3.934E+09	3.229E-01	1.041E+10
wg	**B10-1**	1875.09	2834	1450	1461	1455.50		1.50599E+10	3.972E+09	3.209E-01	1.049E+10
wg	**B10-2**	1872.63	2835	1467	1478	1472.50		1.50508E+10	4.060E+09	3.153E-01	1.068E+10
wg	**B10-3**	1869.15	2835	1456	1495	1475.50		1.50228E+10	4.069E+09	3.142E-01	1.070E+10
	Average	1871.31	2817.20			1458.33		1.485E+10	3.981E+09	3.168E-01	1.048E+10
	Std Dev	3.38	28.52			27.82		3.093E+08	1.538E+08	7.913E-03	3.525E+08

Appendix 35. Sonic elastic constants data for NBG-18 (Sheet 2)

ag	**BB2-1**	1865.54	2895	1479	1491	1485.00	1.56351E+10	4.114E+09	3.215E-01	1.087E+10
ag	**BB2-2**	1864.07	2895	1499	1507	1503.00	1.56228E+10	4.211E+09	3.155E-01	1.108E+10
ag	**BB2-3**	1868.14	2895	1473	1484	1478.50	1.56569E+10	4.084E+09	3.236E-01	1.081E+10
ag	**BB4-1**	1861.70	2895	1467	1466	1466.50	1.56029E+10	4.004E+09	3.274E-01	1.063E+10
ag	**BB4-2**	1864.16	2894	1480	1478	1479.00	1.56127E+10	4.078E+09	3.232E-01	1.079E+10
ag	**BB4-3**	1867.41	2894	1452	1492	1472.00	1.56400E+10	4.046E+09	3.255E-01	1.073E+10
ag	**BB6-1**	1864.54	2895	1463	1499	1481.00	1.56268E+10	4.090E+09	3.228E-01	1.082E+10
ag	**BB6-2**	1863.90	2895	1451	1486	1468.50	1.56214E+10	4.019E+09	3.268E-01	1.067E+10
ag	**BB6-3**	1870.69	2884	1468	1482	1475.00	1.55594E+10	4.070E+09	3.229E-01	1.077E+10
ag	**BB8-1**	1863.58	2883	1481	1491	1486.00	1.54895E+10	4.115E+09	3.191E-01	1.086E+10
ag	**BB8-2**	1866.90	2884	1470	1496	1483.00	1.55278E+10	4.106E+09	3.203E-01	1.084E+10
ag	**BB8-3**	1872.78	2884	1462	1482	1472.00	1.55768E+10	4.058E+09	3.239E-01	1.074E+10
ag	**BB10-1**	1864.57	2903	1484	1484	1484.00	1.57135E+10	4.106E+09	3.231E-01	1.087E+10
ag	**BB10-2**	1863.68	2876	1494	1458	1476.00	1.54152E+10	4.060E+09	3.212E-01	1.073E+10
ag	**BB10-3**	1866.66	2875	1457	1495	1476.00	1.54291E+10	4.067E+09	3.210E-01	1.074E+10
	Average	1865.89	2889.80			1479.03	1.558E+10	4.082E+09	3.225E-01	1.080E+10
	Std Dev	2.84	7.87			8.58	8.120E+07	4.670E+07	2.896E-03	1.025E+08

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Measurements and calculations by Joe Strizak

Appendix 36. Sonic elastic constants data for H-451

Young's Modulus, Shear Modulus and Poisson's Ratio by Sonic Velocity

Specimen Number	Density, ρ kg/m^3	Sonic Velocities, υ [m/s] Longitudinal	Shear 0°	Shear 90°	Average Shear	Elastic Modulus, [Pa] $E=\rho\upsilon_l^2$	Shear Modulus, [Pa] $G=\rho\upsilon_s^2$	Poisson's Ratio $\mu=(1-[2(\upsilon_s/\upsilon_l)^2])/(2-[2(\upsilon_s/\upsilon_l)^2])$	Elastic Modulus, [Pa] $E=\rho\upsilon_l^2[(1+\mu)(1-2\mu)/(1-\mu)]$
C2-1	1711.82	2524	1357	1364	1360.50	1.09053E+10	3.169E+09	2.952E-01	8.208E+09
C2-2	1711.23	2494	1342	1331	1336.50	1.06439E+10	3.057E+09	2.986E-01	7.939E+09
C2-3	1713.22	2594	1336	1344	1340.00	1.15279E+10	3.076E+09	3.180E-01	8.109E+09
C4-1	1715.63	2575	1366	1372	1369.00	1.13757E+10	3.215E+09	3.030E-01	8.379E+09
C4-2	1716.56	2575	1360	1370	1365.00	1.13818E+10	3.198E+09	3.046E-01	8.345E+09
C4-3	1721.32	2576	1352	1372	1362.00	1.14223E+10	3.193E+09	3.060E-01	8.340E+09
C6-1	1712.52	2578	1372	1341	1356.50	1.13816E+10	3.151E+09	3.086E-01	8.247E+09
C6-2	1707.18	2559	1340	1326	1333.00	1.11795E+10	3.033E+09	3.138E-01	7.971E+09
C6-3	1703.49	2544	1326	1315	1320.50	1.10249E+10	2.970E+09	3.156E-01	7.816E+09
C8-1	1699.04	2543	1314	1340	1327.00	1.09874E+10	2.992E+09	3.129E-01	7.856E+09
C8-2	1701.45	2541	1325	1328	1326.50	1.09857E+10	2.994E+09	3.127E-01	7.860E+09
C8-3	1692.86	2523	1335	1326	1330.50	1.07759E+10	2.997E+09	3.074E-01	7.836E+09
C10-1	1715.71	2571	1348	1358	1353.00	1.13409E+10	3.141E+09	3.085E-01	8.219E+09
C10-2	1715.73	2572	1359	1351	1355.00	1.13499E+10	3.150E+09	3.079E-01	8.240E+09
C10-3	1722.04	2580	1379	1351	1365.00	1.14626E+10	3.209E+09	3.056E-01	8.378E+09
Average	1710.65	2556.60			1346.67	1.118E+10	3.103E+09	3.079E-01	8.116E+09
Std Dev	8.02	26.59			16.08	2.657E+08	8.643E+07	5.983E-03	2.077E+08

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Measurements and calculations by Joe Strizak

Appendix 37. Sonic elastic constants data for PCEA (Sheet 1)

Young's Modulus, Shear Modulus and Poisson's Ratio by Sonic Velocity											
								Elastic	Shear		Elastic
Orientation	Specimen	Density, ρ	Sonic Velocities, υ [m/s}			Average Shear		Modulus, [Pa]	Modulus, [Pa]	Poisson's Ratio	Modulus, [Pa]
	Number	kg/m^3	Longitudinal	Shear 0^o	Shear 90^o			$E=\rho\upsilon_l^2$	$G=\rho\upsilon_s^2$	$\mu=(1-[2(\upsilon_s/\upsilon_l)^2])/(2-[2(\upsilon_s/\upsilon_l)^2])$	$E=\rho\upsilon_l^2[(1+\mu)(1-2\mu)/(1-\mu)]$
wg	**DA2-1**	1784.78	2581	1377	1372	1374.50		1.18894E+10	3.372E+09	3.021E-01	8.781E+09
wg	**DA2-2**	1782.42	2581	1384	1366	1375.00		1.18737E+10	3.370E+09	3.019E-01	8.774E+09
wg	**DA2-3**	1786.39	2616	1384	1391	1387.50		1.22251E+10	3.439E+09	3.043E-01	8.971E+09
wg	**DA4-1**	1789.94	2577	1374	1376	1375.00		1.18869E+10	3.384E+09	3.010E-01	8.805E+09
wg	**DA4-2**	1789.96	2609	1368	1395	1381.50		1.21840E+10	3.416E+09	3.052E-01	8.918E+09
wg	**DA4-3**	1792.57	2621	1384	1391	1387.50		1.23143E+10	3.451E+09	3.053E-01	9.009E+09
wg	**DA6-1**	1798.99	2638	1392	1385	1388.50		1.25192E+10	3.468E+09	3.084E-01	9.076E+09
wg	**DA6-2**	1795.95	2652	1385	1376	1380.50		1.26311E+10	3.423E+09	3.142E-01	8.996E+09
wg	**DA6-3**	1798.35	2623	1389	1387	1388.00		1.23729E+10	3.465E+09	3.055E-01	9.046E+09
wg	**DA8-1**	1796.57	2625	1381	1379	1380.00		1.23795E+10	3.421E+09	3.090E-01	8.957E+09
wg	**DA8-2**	1796.71	2644	1389	1386	1387.50		1.25603E+10	3.459E+09	3.100E-01	9.062E+09
wg	**DA8-3**	1798.72	2644	1386	1405	1395.50		1.25744E+10	3.503E+09	3.069E-01	9.156E+09
wg	**DA10-1**	1798.11	2621	1372	1382	1377.00		1.23524E+10	3.409E+09	3.094E-01	8.929E+09
wg	**DA10-2**	1798.55	2621	1382	1390	1386.00		1.23554E+10	3.455E+09	3.059E-01	9.024E+09
wg	**DA10-3**	1799.39	2636	1402	1390	1396.00		1.25030E+10	3.507E+09	3.051E-01	9.153E+09
	Average	1793.83	2619.27			1384.00		1.231E+10	3.436E+09	3.063E-01	8.977E+09
	Std Dev	5.55	22.82			6.78		2.448E+08	4.091E+07	3.378E-03	1.166E+08

Appendix 37. Sonic elastic constants data for PCEA (Sheet 2)

ag	**DB2-1**	1792.41	2474	1361	1385	1373.00		1.09708E+10	3.379E+09	2.775E-01	8.633E+09
ag	**DB2-2**	1788.37	2473	1370	1362	1366.00		1.09372E+10	3.337E+09	2.805E-01	8.546E+09
ag	**DB2-3**	1787.83	2473	1378	1391	1384.50		1.09339E+10	3.427E+09	2.717E-01	8.716E+09
ag	**DB4-1**	1790.41	2486	1391	1371	1381.00		1.10651E+10	3.415E+09	2.768E-01	8.720E+09
ag	**DB4-2**	1789.89	2485	1363	1378	1370.50		1.10530E+10	3.362E+09	2.814E-01	8.616E+09
ag	**DB4-3**	1786.12	2476	1378	1358	1368.00		1.09499E+10	3.343E+09	2.803E-01	8.559E+09
ag	**DB6-1**	1786.89	2476	1358	1405	1381.50		1.09547E+10	3.410E+09	2.740E-01	8.689E+09
ag	**DB6-2**	1790.52	2476	1377	1372	1374.50		1.09769E+10	3.383E+09	2.773E-01	8.641E+09
ag	**DB6-3**	1800.45	2465	1387	1379	1383.00		1.09399E+10	3.444E+09	2.703E-01	8.749E+09
ag	**DB8-1**	1786.54	2464	1371	1388	1379.50		1.08466E+10	3.400E+09	2.717E-01	8.647E+09
ag	**DB8-2**	1788.58	2463	1358	1378	1368.00		1.08502E+10	3.347E+09	2.769E-01	8.548E+09
ag	**DB8-3**	1794.58	2477	1387	1351	1369.00		1.10107E+10	3.363E+09	2.801E-01	8.611E+09
ag	**DB10-1**	1786.80	2476	1387	1353	1370.00		1.09541E+10	3.354E+09	2.794E-01	8.581E+09
ag	**DB10-2**	1794.68	2435	1353	1352	1352.50		1.06411E+10	3.283E+09	2.769E-01	8.384E+09
ag	**DB10-3**	1792.68	2436	1341	1341	1341.00		1.06379E+10	3.224E+09	2.826E-01	8.270E+09
	Average	1790.45	2469.00			1370.80		1.091E+10	3.365E+09	2.772E-01	8.594E+09
	Std Dev	3.82	14.57			11.30		1.222E+08	5.459E+07	3.638E-03	1.229E+08

ASTM C 769 - 98 (Reapproved 2005)
Measurements and calculations by Joe Strizak

Appendix 38. Sonic elastic constants data for IG-110

Young's Modulus, Shear Modulus and Poisson's Ratio by Sonic Velocity

Specimen Number	Density, ρ kg/m^3	Sonic Velocities, υ [m/s] Longitudinal	Shear 0°	Shear 90°	Average Shear	Elastic Modulus, [Pa] $E=\rho\upsilon_l^2$	Shear Modulus, [Pa] $G=\rho\upsilon_s^2$	Poisson's Ratio $\mu=(1-[2(\upsilon_s/\upsilon_l)^2])/(2-[2(\upsilon_s/\upsilon_l)^2])$	Elastic Modulus, [Pa] $E=\rho\upsilon_l^2[(1+\mu)(1-2\mu)/(1-\mu)]$
E2-1	1769.37	2337	1488	1492	1490.00	9.66356E+09	3.928E+09	0.1575	9.094E+09
E2-2	1764.25	2320	1480	1464	1472.00	9.49587E+09	3.823E+09	0.1631	8.892E+09
E2-3	1763.80	2341	1484	1487	1485.50	9.66615E+09	3.892E+09	0.1630	9.053E+09
E4-1	1763.58	2324	1481	1485	1483.00	9.52505E+09	3.879E+09	0.1565	8.972E+09
E4-2	1757.35	2287	1476	1477	1476.50	9.19159E+09	3.831E+09	0.1427	8.755E+09
E4-3	1748.49	2326	1478	1473	1475.50	9.45983E+09	3.807E+09	0.1633	8.857E+09
E6-1	1771.90	2361	1467	1506	1486.50	9.87715E+09	3.915E+09	0.1716	9.175E+09
E6-2	1769.57	2383	1504	1487	1495.50	1.00488E+10	3.958E+09	0.1751	9.302E+09
E6-3	1769.33	2383	1525	1537	1531.00	1.00475E+10	4.147E+09	0.1486	9.527E+09
E8-1	1754.34	2285	1481	1457	1469.00	9.15981E+09	3.786E+09	0.1478	8.690E+09
E8-2	1753.61	2268	1473	1455	1464.00	9.02027E+09	3.759E+09	0.1428	8.591E+09
E8-3	1758.01	2296	1471	1480	1475.50	9.26757E+09	3.827E+09	0.1482	8.789E+09
E10-1	1764.33	2327	1471	1476	1473.50	9.55373E+09	3.831E+09	0.1653	8.928E+09
E10-2	1757.60	2309	1475	1483	1479.00	9.37060E+09	3.845E+09	0.1521	8.859E+09
E10-3	1759.18	2319	1482	1469	1475.50	9.46048E+09	3.830E+09	0.1599	8.885E+09
Average	1761.65	2324.40			1482.13	9.521E+09	3.870E+09	1.572E-01	8.958E+09
Std Dev	6.60	32.53			15.30	2.955E+08	9.072E+07	9.648E-03	2.342E+08

ASTM C 769 - 98 (Reapproved 2005)
Measurements and calculations by Joe Strizak

Appendix 39. Sonic elastic constants data for IG-430

Young's Modulus, Shear Modulus and Poisson's Ratio by Sonic Velocity										
							Elastic	Shear		Elastic
Specimen	Density, ρ	Sonic Velocities, υ [m/s}			Average Shear		Modulus, [Pa]	Modulus, [Pa]	Poisson's Ratio	Modulus, [Pa]
Number	kg/m^3	Longitudinal	Shear 0^o	Shear 90^o			$E=\rho\upsilon_l^2$	$G=\rho\upsilon_s^2$	$\mu=(1-[2(\upsilon_s/\upsilon_l)^2])/(2-[2(\upsilon_s/\upsilon_l)^2])$	$E=\rho\upsilon_l^2[(1+\mu)(1-2\mu)/(1-\mu)]$
F2-1	1798.15	2401	1648	1697	1672.50		1.037E+10	5.030E+09	2.869E-02	1.035E+10
F2-2	1800.97	2366	1511	1515	1513.00		1.008E+10	4.123E+09	1.541E-01	9.516E+09
F2-3	1802.28	2341	1494	1501	1497.50		9.877E+09	4.042E+09	1.537E-01	9.326E+09
F4-1	1803.35	2403	1526	1505	1515.50		1.041E+10	4.142E+09	1.698E-01	9.690E+09
F4-2	1806.83	2384	1516	1484	1500.00		1.027E+10	4.065E+09	1.723E-01	9.532E+09
F4-3	1807.26	2421	1526	1510	1518.00		1.059E+10	4.165E+09	1.761E-01	9.796E+09
F6-1	1806.57	2450	1499	1530	1514.50		1.084E+10	4.144E+09	1.908E-01	9.869E+09
F6-2	1796.03	2424	1533	1517	1525.00		1.055E+10	4.177E+09	1.725E-01	9.794E+09
F6-3	1801.38	2380	1517	1516	1516.50		1.020E+10	4.143E+09	1.582E-01	9.597E+09
F8-1	1801.77	2381	1489	1527	1508.00		1.021E+10	4.097E+09	1.651E-01	9.548E+09
F8-2	1809.70	2415	1528	1491	1509.50		1.055E+10	4.124E+09	1.794E-01	9.727E+09
F8-3	1790.49	2433	1497	1556	1526.50		1.060E+10	4.172E+09	1.754E-01	9.808E+09
F10-1	1799.56	2408	1508	1553	1530.50		1.043E+10	4.215E+09	1.611E-01	9.789E+09
F10-2	1811.25	2387	1542	1525	1533.50		1.032E+10	4.259E+09	1.486E-01	9.785E+09
F10-3	1803.22	2401	1518	1529	1523.50		1.040E+10	4.185E+09	1.630E-01	9.735E+09
Average	1802.59	2399.57			1516.54		1.038E+10	4.147E+09	1.671E-01	9.679E+09
Std Dev	5.20	27.68			10.28		2.374E+08	5.479E+07	1.118E-02	1.477E+08
ASTM C 769 - 98 (Reapproved 2005)										
Measurements and calculations by Joe Strizak										

Appendix 40. Mensuration data for the thermal diffusivity specimens (Sheet 1)

Graphite	Specimen	Orientation		Thickness, mm					Diameter, mm			Weight, mg	
Grade	Number			T1	T2	T3	T4		D_0	D_{90}			
NBG-17	**A1-4-2**	wg		2.000	2.001	2.001	2.001		12.736	12.735		474.67	
NBG-17	**A1-4-3**	wg		3.022	3.024	3.021	3.023		12.735	12.736		717.32	
NBG-17	**A5-4-2**	wg		1.994	1.995	1.992	1.993		12.732	12.735		470.52	
NBG-17	**A5-4-3**	wg		3.015	3.011	3.015	3.015		12.736	12.736		713.09	
NBG-17	**A9-4-2**	wg		1.991	1.996	1.993	1.993		12.732	12.731		469.54	
NBG-17	**A9-4-3**	wg		3.020	3.019	3.019	3.018		12.732	12.732		712.02	
NBG-17	**AB1-4-2**	ag		2.003	2.002	2.004	2.002		12.740	12.744		473.90	
NBG-17	**AB1-4-3**	ag		3.022	3.021	3.021	3.022		12.738	12.736		717.97	
NBG-17	**AB5-4-2**	ag		1.989	1.989	1.989	1.990		12.731	12.733		472.10	
NBG-17	**AB5-4-3**	ag		3.017	3.020	3.020	3.020		12.730	12.727		716.31	
NBG-17	**AB9-4-2**	ag		1.992	1.995	1.995	1.994		12.731	12.731		474.47	
NBG-17	**AB9-4-3**	ag		3.023	3.021	3.019	3.021		12.733	12.731		720.55	
NBG-18	**B1-4-2**	wg		1.995	1.993	1.994	1.995		12.732	12.732		474.98	
NBG-18	**B1-4-3**	wg		3.024	3.023	3.024	3.024		12.729	12.725		719.44	
NBG-18	**B5-4-2**	wg		1.990	1.991	1.991	1.992		12.726	12.731		473.93	
NBG-18	**B5-4-3**	wg		3.019	3.016	3.016	3.018		12.738	12.738		724.86	
NBG-18	**B9-4-2**	wg		1.989	1.991	1.996	1.989		12.747	12.747		476.57	
NBG-18	**B9-4-3**	wg		3.013	3.009	3.012	3.011		12.749	12.749		720.42	
NBG-18	**BB1-4-2**	ag		1.999	2.004	2.001	2.001		12.746	12.744		476.59	
NBG-18	**BB1-4-3**	ag		3.018	3.021	3.023	3.020		12.743	12.749		720.86	
NBG-18	**BB5-4-2**	ag		2.114	2.057	2.064	2.127		12.737	12.734		495.16	
NBG-18	**BB5-4-3**	ag		3.025	3.023	3.024	3.022		12.734	12.734		718.31	
NBG-18	**BB9-4-2**	ag		2.001	2.006	2.003	2.002		12.738	12.736		478.26	
NBG-18	**BB9-4-3**	ag		3.021	3.023	3.021	3.021		12.739	12.741		724.84	

Appendix 40. Mensuration data for the thermal diffusivity specimens (sheet 2)

Graphite Grade	Specimen Number	Orientation	Technician	Date Weighed	Date Measured		Average thickness, mm	Density kg/m^3
NBG-17	**A1-4-2**	wg	JPS	11/25/2008	11/25/2008		2.001	1862.41
NBG-17	**A1-4-3**	wg	JPS	11/25/2008	11/25/2008		3.023	1863.05
NBG-17	**A5-4-2**	wg	JPS	11/25/2008	11/25/2008		1.994	1853.43
NBG-17	**A5-4-3**	wg	JPS	11/25/2008	11/25/2008		3.014	1857.14
NBG-17	**A9-4-2**	wg	JPS	11/25/2008	11/25/2008		1.993	1850.38
NBG-17	**A9-4-3**	wg	JPS	11/25/2008	11/25/2008		3.019	1852.44
NBG-17	**AB1-4-2**	ag	JPS	11/25/2008	11/25/2008		2.003	1855.64
NBG-17	**AB1-4-3**	ag	JPS	11/25/2008	11/25/2008		3.022	1864.91
NBG-17	**AB5-4-2**	ag	JPS	11/25/2008	11/25/2008		1.989	1864.06
NBG-17	**AB5-4-3**	ag	JPS	11/25/2008	11/25/2008		3.019	1864.48
NBG-17	**AB9-4-2**	ag	JPS	11/25/2008	11/25/2008		1.994	1869.25
NBG-17	**AB9-4-3**	ag	JPS	11/25/2008	11/25/2008		3.021	1873.39
NBG-18	**B1-4-2**	wg	JPS	11/25/2008	11/25/2008		1.994	1870.73
NBG-18	**B1-4-3**	wg	JPS	11/25/2008	11/25/2008		3.024	1870.28
NBG-18	**B5-4-2**	wg	JPS	11/25/2008	11/25/2008		1.991	1870.67
NBG-18	**B5-4-3**	wg	JPS	11/25/2008	11/25/2008		3.017	1885.17
NBG-18	**B9-4-2**	wg	JPS	11/25/2008	11/25/2008		1.991	1875.40
NBG-18	**B9-4-3**	wg	JPS	11/25/2008	11/25/2008		3.011	1874.11
NBG-18	**BB1-4-2**	ag	JPS	11/25/2008	11/25/2008		2.001	1866.69
NBG-18	**BB1-4-3**	ag	JPS	11/25/2008	11/25/2008		3.021	1870.40
NBG-18	**BB5-4-2**	ag	JPS	11/25/2008	11/25/2008		2.091	1859.40
NBG-18	**BB5-4-3**	ag	JPS	11/25/2008	11/25/2008		3.024	1865.44
NBG-18	**BB9-4-2**	ag	JPS	11/25/2008	11/25/2008		2.003	1873.95
NBG-18	**BB9-4-3**	ag	JPS	11/25/2008	11/25/2008		3.022	1881.87

Appendix 40. Mensuration data for the thermal diffusivity specimens (sheet 3)

Graphite	Specimen	Orientation		Thickness, mm					Diameter, mm			Weight, mg
Grade	Number			T1	T2	T3	T4		D_0	D_{90}		
H-451	**C1-4-2**	wg		1.994	1.992	1.992	1.993		12.745	12.745		437.49
H-451	**C1-4-3**	wg		3.019	3.015	3.016	3.019		12.732	12.738		661.74
H-451	**C5-4-2**	wg		1.993	2.000	2.000	2.002		12.735	12.734		441.81
H-451	**C5-4-3**	wg		3.018	3.016	3.019	3.015		12.735	12.736		667.28
H-451	**C9-4-2**	wg		1.986	1.988	1.987	1.983		12.714	12.715		435.32
H-451	**C9-4-3**	wg		3.011	3.016	3.015	3.013		12.721	12.724		659.16
PCEA	**DA1-4-2**	wg		1.996	1.996	1.995	1.999		12.747	12.737		458.34
PCEA	**DA1-4-3**	wg		3.010	3.014	3.015	3.014		12.740	12.739		693.43
PCEA	**DA5-4-2**	wg		2.002	2.000	2.000	1.993		12.749	12.759		459.92
PCEA	**DA5-4-3**	wg		3.024	3.020	3.022	3.022		12.738	12.738		695.08
PCEA	**DA9-4-2**	wg		1.989	1.987	1.984	1.985		12.739	12.741		457.77
PCEA	**DA9-4-3**	wg		3.016	3.010	3.011	3.014		12.751	12.738		693.28
PCEA	**DB1-4-2**	ag		2.000	2.000	2.001	1.999		12.745	12.745		459.52
PCEA	**DB1-4-3**	ag		3.120	3.003	3.008	3.010		12.744	12.747		690.81
PCEA	**DB5-4-2**	ag		1.993	1.992	1.993	1.992		12.716	12.722		452.44
PCEA	**DB5-4-3**	ag		3.012	3.016	3.012	3.018		12.740	12.734		688.09
PCEA	**DB9-4-2**	ag		1.986	1.990	1.991	1.987		12.740	12.740		456.39
PCEA	**DB9-4-3**	ag		3.015	3.005	3.010	3.009		12.737	12.740		691.63
IG-110	**E1-4-2**	wg		1.991	1.998	1.997	1.992		12.746	12.744		451.38
IG-110	**E1-4-3**	wg		3.007	3.009	3.008	3.004		12.744	12.742		678.16
IG-110	**E7-4-2**	wg		1.984	1.988	1.987	1.986		12.731	12.734		447.53
IG-110	**E7-4-3**	wg		3.011	3.017	3.016	3.015		12.740	12.746		681.46
IG-110	**E9-4-2**	wg		1.987	1.990	1.989	1.985		12.748	12.749		444.52
IG-110	**E9-4-3**	wg		3.016	3.017	3.016	3.018		12.746	12.746		678.51

Appendix 40. Mensuration data for the thermal diffusivity specimens (sheet 4)

Graphite Grade	Specimen Number	Orientation	Technician	Date Weighed	Date Measured		Average thickness, mm	Density kg/m^3
H-451	**C1-4-2**	wg	JPS	11/25/2008	11/25/2008		1.993	1720.86
H-451	**C1-4-3**	wg	JPS	11/25/2008	11/25/2008		3.017	1721.82
H-451	**C5-4-2**	wg	JPS	11/25/2008	11/25/2008		1.999	1735.49
H-451	**C5-4-3**	wg	JPS	11/25/2008	11/25/2008		3.017	1736.24
H-451	**C9-4-2**	wg	JPS	11/25/2008	11/25/2008		1.986	1726.39
H-451	**C9-4-3**	wg	JPS	11/25/2008	11/25/2008		3.014	1720.47
PCEA	**DA1-4-2**	wg	JPS	11/25/2008	11/25/2008		1.997	1800.33
PCEA	**DA1-4-3**	wg	JPS	11/25/2008	11/25/2008		3.013	1805.39
PCEA	**DA5-4-2**	wg	JPS	11/25/2008	11/25/2008		1.999	1801.11
PCEA	**DA5-4-3**	wg	JPS	11/25/2008	11/25/2008		3.022	1804.87
PCEA	**DA9-4-2**	wg	JPS	11/25/2008	11/25/2008		1.986	1807.94
PCEA	**DA9-4-3**	wg	JPS	11/25/2008	11/25/2008		3.013	1803.89
PCEA	**DB1-4-2**	ag	JPS	11/25/2008	11/25/2008		2.000	1800.96
PCEA	**DB1-4-3**	ag	JPS	11/25/2008	11/25/2008		3.035	1783.85
PCEA	**DB5-4-2**	ag	JPS	11/25/2008	11/25/2008		1.993	1787.17
PCEA	**DB5-4-3**	ag	JPS	11/25/2008	11/25/2008		3.015	1791.45
PCEA	**DB9-4-2**	ag	JPS	11/25/2008	11/25/2008		1.989	1800.45
PCEA	**DB9-4-3**	ag	JPS	11/25/2008	11/25/2008		3.010	1803.08
IG-110	**E1-4-2**	wg	JPS	11/25/2008	11/25/2008		1.995	1773.93
IG-110	**E1-4-3**	wg	JPS	11/25/2008	11/25/2008		3.007	1768.33
IG-110	**E7-4-2**	wg	JPS	11/25/2008	11/25/2008		1.986	1769.58
IG-110	**E7-4-3**	wg	JPS	11/25/2008	11/25/2008		3.015	1772.37
IG-110	**E9-4-2**	wg	JPS	11/25/2008	11/25/2008		1.988	1751.95
IG-110	**E9-4-3**	wg	JPS	11/25/2008	11/25/2008		3.017	1762.70

Appendix 40. Mensuration data for the thermal diffusivity specimens (sheet 5)

Graphite	Specimen	Orientation		Thickness, mm					Diameter, mm			Weight, mg
Grade	Number			T1	T2	T3	T4		D_0	D_{90}		
IG-430	**F1-4-2**	wg		1.996	1.995	1.994	1.996		12.733	12.737		459.17
IG-430	**F1-4-3**	wg		3.016	3.016	3.018	3.011		12.744	12.743		695.71
IG-430	**F7-4-2**	wg		1.992	1.991	1.993	1.993		12.740	12.750		462.80
IG-430	**F7-4-3**	wg		3.022	3.022	3.023	3.020		12.747	12.739		696.03
IG-430	**F9-4-2**	wg		1.995	1.996	1.997	1.994		12.743	12.746		461.89
IG-430	**F9-4-3**	wg		3.003	3.011	3.001	3.016		12.741	12.746		697.59

Appendix 40. Mensuration data for the thermal diffusivity specimens (sheet 6)

Graphite Grade	Specimen Number	Orientation	Technician	Date Weighed	Date Measured		Average thickness, mm	Density kg/m^3
IG-430	**F1-4-2**	wg	JPS	11/25/2008	11/25/2008		1.995	1806.71
IG-430	**F1-4-3**	wg	JPS	11/25/2008	11/25/2008		3.015	1808.99
IG-430	**F7-4-2**	wg	JPS	11/25/2008	11/25/2008		1.992	1820.87
IG-430	**F7-4-3**	wg	JPS	11/25/2008	11/25/2008		3.022	1806.07
IG-430	**F9-4-2**	wg	JPS	11/25/2008	11/25/2008		1.996	1814.47
IG-430	**F9-4-3**	wg	JPS	11/25/2008	11/25/2008		3.008	1818.40

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