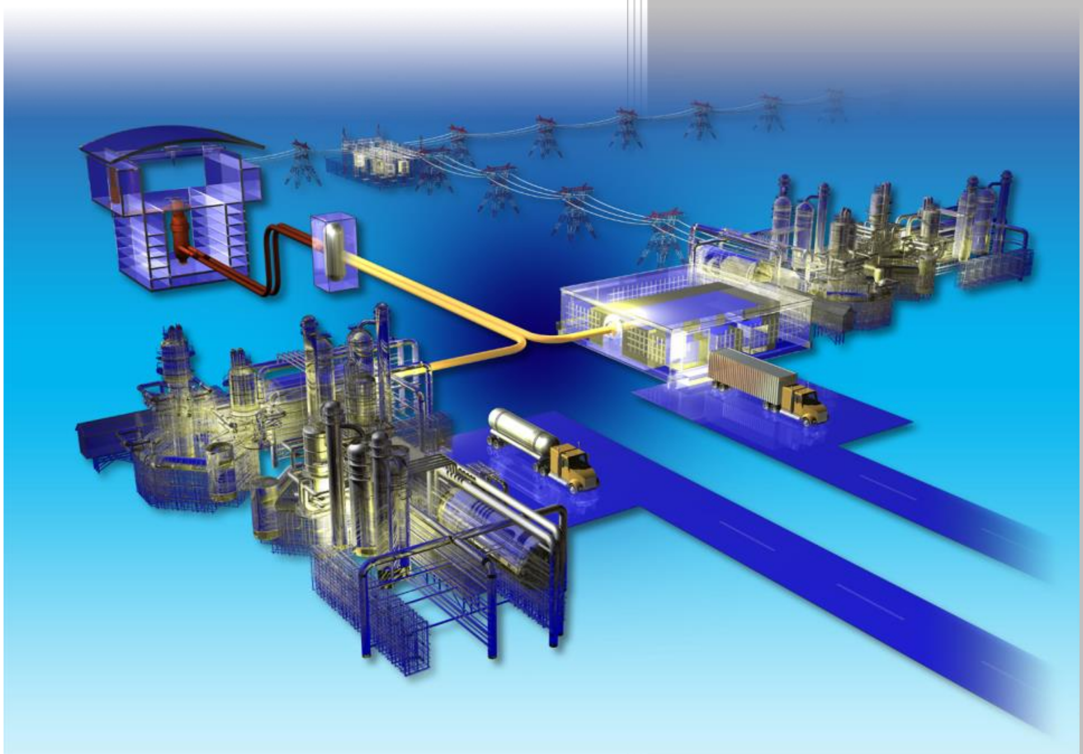
ORNL/TM-2016/678 Rev.1

The Fracture Toughness of Nuclear Graphite Grades



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July 2022

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Advanced Reactor Technology Program

THE FRACTURE TOUGHNESS OF NUCLEAR GRAPHITE GRADES

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ABBREVIATION AND ACRONYMS

AE	acoustic emission
AG	against grain
ASME	American Society for Mechanical Engineers
ASTM	American Society for Testing of Materials
B&PV	Boiler & Pressure Vessel
CNSR	Chevron Notched Short Rod
DENC	Double Edge Notched Compression
FEM	Finite Element Analysis
K_{Ic}	critical stress intensity factor, or facture toughness
K_{IIc}	critical shear stress intensity factor, or shear facture toughness
SENB	Single Edge Notched Beam
SINAP	Shanghai Institute of Applied Physics
PZ	Process Zone
WG	with grain

SUMMARY OF REVISIONS

1. Revision 1 of this report is being released because of two errors discovered in Table 3.
    a. The first error was that the tensile strength values for PCEA were switched. The tensile strength of PCEA is quoted by the manufacturer as larger in the WG direction. The error has been corrected in Table 3 of this revision.
        i. This error was also propagated into Table 6, where the r_c values calculated with the switched strengths were reported and the proposed V_m values were also incorrect. The original values of r_c and V_m from Rev.0 are retained in Table 6 (struck through) but have been updated, with calculation error, to maintain consistency. A footnote to this effect has been added to Table 6.
    b. The second error was in calculating the process zone size (r_c) using Equation 3:

$$r_c = \frac{1}{2\pi}\left[\frac{K_{Ic}}{\sigma_t}\right]^2,$$

    the 2π term was not contained within a set of parentheses, resulting in the spreadsheet calculating values with π in the numerator, resulting in the following equation being used:

$$r_c = \frac{\pi}{2}\left[\frac{K_{Ic}}{\sigma_t}\right]^2.$$

    This resulted in the values for r_c reported in Table 3 bring a factor of π^2 too large. The values in Table 3 have been corrected accordingly.
2. The calculation error in #1 was propagated through the report. A summary of changes include:
    a. Updating Figure 18 to use correct process zone sizes
        i. Note the R^2 value in Figure 18 did not change because this data used the correct values of tensile strength for PCEA rather than the switched values discussed in Revision 1 above.
    b. Update Table 6 to use correct process zone sizes. Two columns added to the right side of Table 6 that list the correct values of r_c and Proposed V_m. Heading reads "Proposed New Rule Rev.1"
        i. It is important to note that since these calculation errors were consistent, the comment after Table 6 "**The proposed new integration volume, V_m, varies by only ~x 10 between IG-110 to NBG-18, rather than the ~x1000000 variation of the existing ASME definition of V_m.**" is still correct.
    c. Paragraph following Equation 3, process zone values
3. In the text before Equation 3, the process zone is referred to as the radius, but the definition in Reference 12, and per Griffith theory is that r_c is the diameter of the process zone (i.e. distance from crack tip to process zone boundary). This means the proposed V_m in Table 6, while still using the volume of a sphere, should be:

$$V_m = \frac{4\pi}{3}\left(\frac{r_c}{2}\right)^3.$$

    A new column has been added to the right side of Table 6 that shows this V_m value, and has the heading "Proposed V_m Rev.1"

The error in this report was discovered by A.A. Campbell, who then led the revision, review, and issuing of Revision 1 of this report. Findings and revisions were confirmed via independent review by Glenn Romanoski and Ryan Paul.

ABSTRACT

New measurements of graphite mode I critical stress intensity factor, K_{Ic} (commonly referred to as the fracture toughness) and the mode II critical shear stress intensity, K_{IIc}, are reported and compared with prior data for K_{Ic} and K_{IIc}. The new data are for graphite grades PCEA, IG-110 and 2114. Variations of K_{Ic} and acoustic emission (AE) data with graphite texture are reported and discussed. The Codes and Standards applications of fracture toughness, K_{Ic}, data are also discussed. A specified minimum value for nuclear graphite K_{Ic} is recommended.

1. INTRODUCTION

Quantitative measures of graphite fracture are not widely used in nuclear graphite technology, perhaps because representative toughness values vary with specimen geometry/measurement method[1] and with the specimen size[2], this despite the fact that the critical stress intensity factor, K_{Ic}, can vary by ~50% from grade to grade. For example, the critical stress intensity factor for grade IG-110 was reported[1] with values from 0.83 to 1.16 MPa√m, when measured on six different specimen geometries. Romanoski and Burchell[2], using just the chevron notched short rod geometry (CNSR), reported an increase in K_{Ic} of >20% when the CNSR specimen diameter increased from 12.7 mm to 25.4 mm for the three graphite grades they tested (H-451, S-2020 and IG-110).

The recent adoption of an ASTM Standard Test Method for the Determination of Fracture Toughness of Graphite at Ambient Temperature[3] has allowed for the use of standard values and consequently the adoption of K_{Ic} minimums in ASTM Standard Specifications for nuclear graphite[4,5]. The proposed use of fracture toughness in codes and standards is discussed in section 4 General Discussion.

The standard method[3] prescribes the use of the single edge notched beam (SENB) specimen and test geometry. It mandates the specimen minimum size and loading conditions, and gives details of the notch sharpening methodology and required notch dimensions. As noted in the experimental section (2.1) all K_{Ic} testing reported here was in accordance with the ASTM standard for graphite fracture toughness[3] and all testing was performed on identical geometry specimen and test conditions. Thus, the variations in the K_{Ic} data reported and discussed here can only be attributed to changes of the grade (i.e., to the texture changes between different grades).

In prior work Burchell and Strizak[6,7] studied nuclear graphite grade PCEA to determine the effect of neutron irradiation on the critical stress intensity factor, K_{Ic}. Although the SENB-type specimen was used and the specimen was compliant with ASTM D7779[3] a smaller volume sample was required for the irradiations. The K_{Ic} value of 0.97 MPa√m for these small specimens is significantly smaller than the 1.33 MPa√m reported in the current work, suggesting the SENB geometry suffers significantly from a specimen size effect.

Yang et al[8] reported a study of graphite SENB specimen size on the absolute value of K_{Ic} measured. They tested a fine-grain (20μm), isostatically pressed graphite (grade SNG742) and obtained K_{Ic} = 1.12 from specimens of identical geometry and size as tested here. However, a reduced value of K_{Ic} = 0.76 MPa√m was measured for smaller volume samples measuring 23 x 2 x 1.5 mm, confirming the observation that the value of K_{Ic} derived from an SENB specimen is subject to a significant size effect.

Additionally, Burchell and Strizak[6,7] reported toughness was increased for specimens oriented in a with-grain direction (yielding an against-grain crack plane). Similar toughness change with changes to the sample orientation was also noted in the current study.

If the derived K_{Ic} value is to be used for the purposes of grade comparison, quality control, or codes and standards activities the specimen geometry and size should be held constant.

The K_{Ic} and K_{IIc} data reported here were taken over a two year period. Table 1 reports the testing chronology for the data reported here.

Table 1 Fracture testing chronology for the test data reported here

Year Tested	Fracture Measurement type	specimen Geometry	Grade/Crack Orientation	No. specimens Tested	Total No. of Specimens for grade and Orientation
			K_{Ic} (SENB)		
2016	K_{Ic}	SENB	2114 (AG)	54	54
2016	K_{Ic}	SENB	2114 (WG)	55	55
2016	K_{Ic}	SENB	IG-110	32	32
2015	K_{Ic}	SENB	PCEA (AG)	20	
2016	K_{Ic}	SENB	PCEA (AG)	98	118
2015	K_{Ic}	SENB	PCEA (WG)	37	
2016	K_{Ic}	SENB	PCEA (WG)	36	73
2015	K_{Ic}	SENB	NBG-18WG (spec. PERP*)	25	25
2015	K_{Ic}	SENB	NBG-18 AG (spec. PAR*)	25	25
			K_{IIc} (DENC)		
2016	K_{IIc}	DENC	IG-110	26	26
2015	K_{IIc}	DENC	PCEA (PAR)	8	
2016	K_{IIc}	DENC	PCEA (PAR)	51	59
2015	K_{IIc}	DENC	PCEA (PERP)	0	
2016	K_{IIc}	DENC	PCEA (PERP)	24	24
2015	K_{IIc}	DENC	NBG-18 WG (spec. PERP*)	10	10
2015/16	K_{IIc}	DENC	NBG-18 AG (spec. PAR*)	0	0

*orientation w.r.t. long axis of billet

2. CRITICAL STRESS INTENSITY FACTOR, K_{Ic}

2.1 EXPERIMENMTAL

The “Fracture Toughness” or Critical Stress Intensity Factor, K_{Ic}, was determined using the single edge notched beam (SENB) with the ASTM recommended size and geomtry[3]. The critical stress intensity factor, K_{Ic}, was calculated for three-point flexure with $5 \leq S/W \leq 10$, and $0.35 \leq a/W \leq 0.60$ using equation (1):

$$K_{Ic} = g\left[\frac{P_{max} S 10^{-6}}{BW^{3/2}}\right]\left[\frac{3[a/W]^{1/2}}{2[1-a/W]^{3/2}}\right] \tag{1}$$

Where:

$$g = g(a/W)$$
$$g = A_o + A_1(a/W) + A_2(a/W)^2 + A_3(a/W)^3 + A_4(a/W)^4 + A_5(a/W)^5 \tag{2}$$

The coefficients for the factor, g, are shown in Table 1 of the ASTM standard or calculated from equation 2.

Where:

K_{Ic}	=	fracture toughness (MPa√m),
g = g(a/W)	=	function of the ratio a/W,
P_{max}	=	maximum force (N),
S	=	support span (m)
B	=	breadth (width) of the specimen (m),
W	=	specimen depth (m), and
a	=	notch depth (m)

A typical sample is shown being notched in Figure 2. The ASTM specified[3] geometry used here was the centrally slotted single edge notched beam (SENB) with dimensions of length 200 x depth 20 x width 15-mm nominal.

The notch was sharpened with a scalpel (Figure 2), and had a nominal ligament length and notch depth of 12-mm and 8-mm, respectively. The notch was first cut to width 0.38-0.51-mm with a machine tool slitting saw. The specimen utilized here thus had an (a/W) ratio of ~0.4

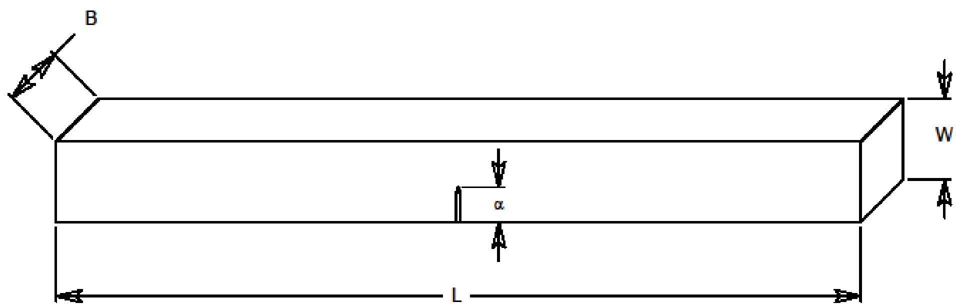

Figure 1 Specimen configuration showing dimensions L, W, B, and a.

Figure 2 Typical SENB specimen showing the notching process

The specimens were each subjected to dimensional inspection after notching using calipers, micrometer, and shadowgraph profilometry (Figure 3) to ensure they conformed to the dimensions adopted here.

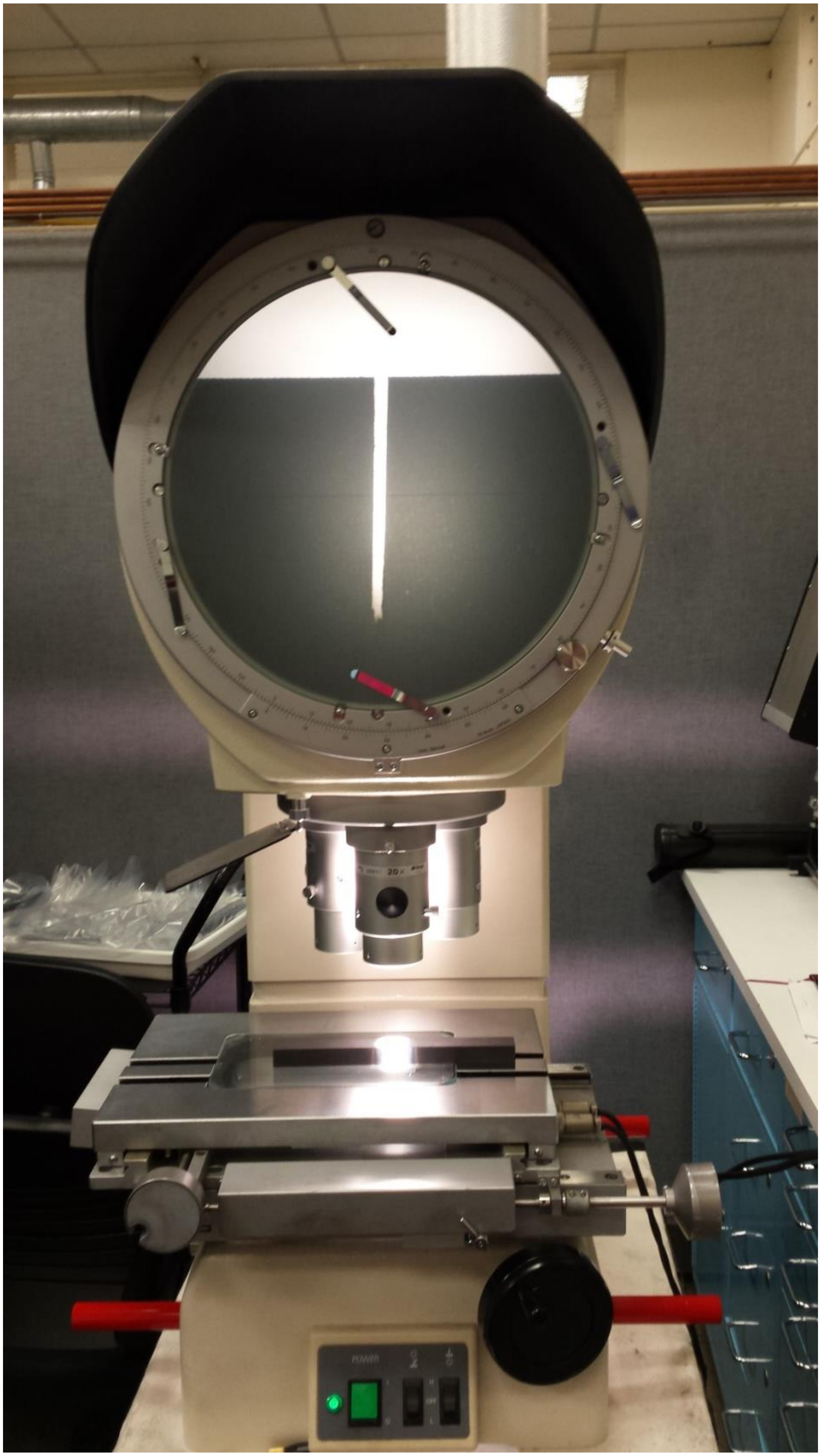

Figure 3 Profilometry technique used to determine notch dimensions and standard conformity

Fracture testing was performed in 3-point bending, with the support span set to 160 mm. Thus, the S/W ratio was ~8 for this work (Figure 4). A uniform crosshead speed of 7.6 μm/sec or 0.46 mm/min (0.0003 in/sec) was used for all testing.

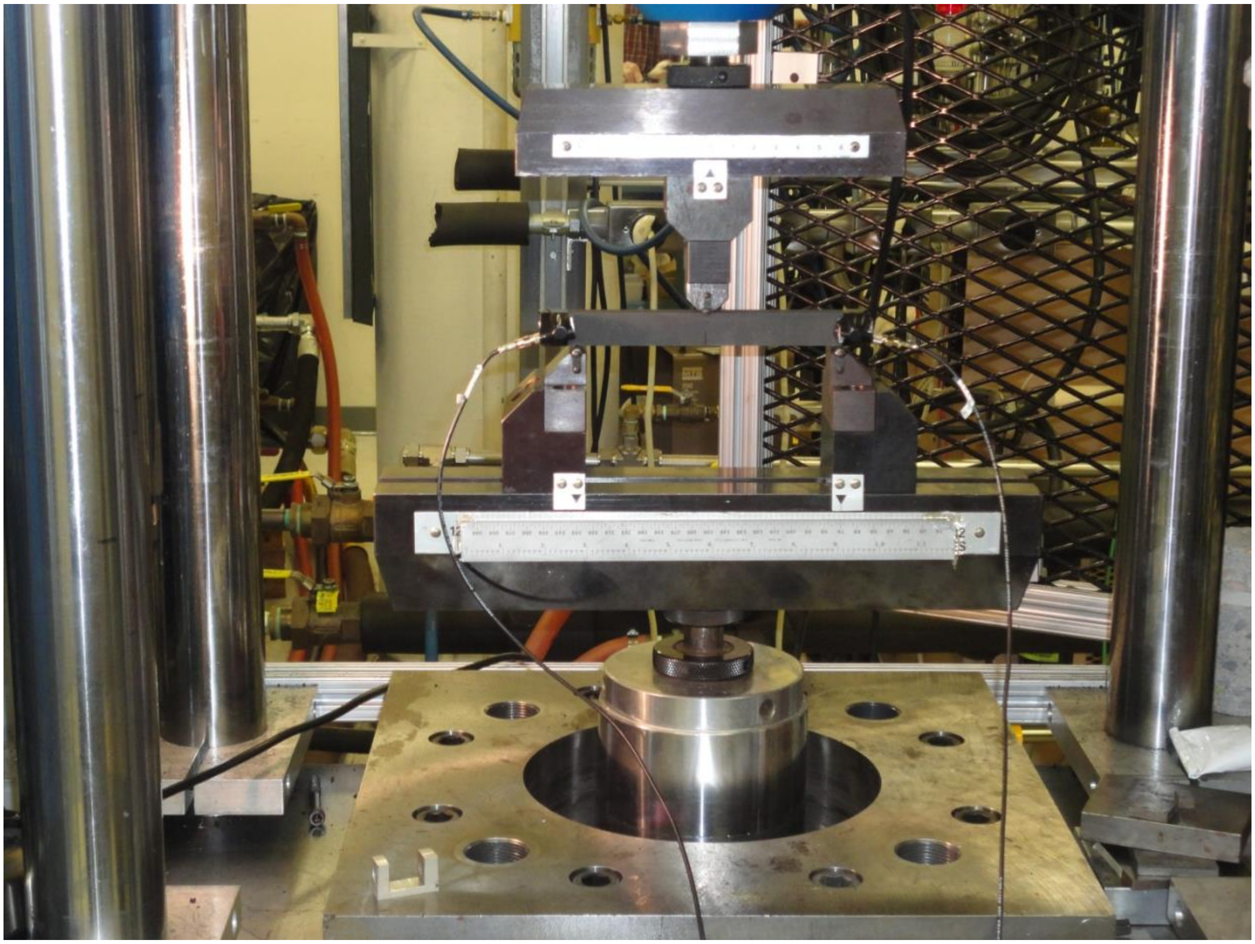

Figure 4 SENB - specimen under test showing the test configuration and AE probe locations

Acoustic Emission (AE) was monitored during specimen loading using a Vallen AMSY-6 multi-channel system, running two channels with type AE105A high frequency probes[9]. The 8 mm dia. X 8 mm height, ceramic faced, stainless steel mini-probes had a frequency range from 450 to 1150 kHz with a peak response frequency of 800 kHz. A representative probe frequency response is given in Figure 5.

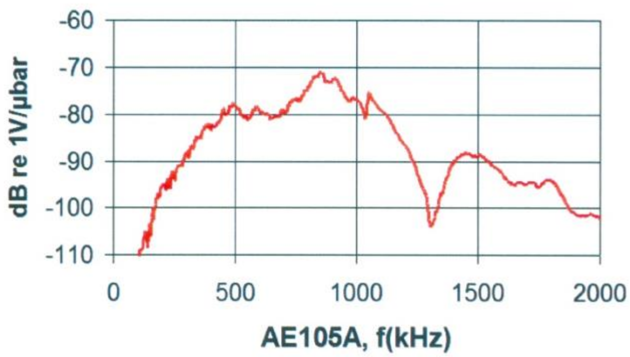

Figure 5 AE Probe frequency response curve[9]

The two AE probes were placed equidistance from the notch on the center of the front face of the SENB specimen (Figure 4). Sonotrace 40 Ultrasonic Couplant was used between the specimen and the probes. The acoustic emission was recorded as the cumulative total of AE events at P, the peak load used in the calculation of K_{Ic}, and the cumulative total of AE events at the facture load (this was arbitrarily taken to be at a load 50N where a fracture end point was ill-defined).

2.2 RESULTS

The results of individual tests are given by grade in Appendix A along with the mean and standard deviations of the experimental values determined. The test data means are summarized in Table 2. Typical load-time plots for the graphite grades examined here are in Figure 6 to Figure 12. The load and cumulative AE counts are obtained from the digital data at the time intervals for P and the fracture end point was arbitrarily taken to be 50N bending load (Figure 6 to Figure 12).

Table 2 Summary of mean and St.Dev. for K_{Ic} and AE data for the grades examined here

FRACTURE TOGHNESS DATA FROM SENB TESTING												
Grade/notch orientation	Manufacturer	Forming method	Filler Particle Size, mm	Number of specimens, n	Mean failure load (N)	S.D. failure load (N)	Mean Fracture Toughness, KIc (MPa√m)	S.D. Fracture Toughness, KIc (MPa√m)	Mean cumulative AE counts at failure (P)	S.D. cumulative AE counts at failure (P)	Mean cumulative AE counts at 50N	S.D. cumulative AE counts at 50N
2114 (AG)*	Mercen	Isostatically molded	0.013	54	149.62	4.62	1.15	0.04	1532	723	16813	8992
2114 (WG)*	Mercen	Isostatically molded	0.013	55	148.77	3.05	1.15	0.02	1503	171	15713	10229
IG-110	Toyo Tanso	Isostatically molded	0.02	32	138.7	3.9	1.07	0.03	585	446	17138	1738
PCEA (WG)	GrafTech	Extruded	0.8	73	168.62	3.82	1.33	0.06	2101	1113	21845	5672
PCEA (AG)	GrafTech	Extruded	0.8	118	186.17	5.14	1.48	0.06	2797	1419	27864	6273
NBG-18 (WG)	SGL Carbon	Vibrationally molded	1.6	25	176.1	12.8	1.36	0.1	3578	2806	41693	16115
NBG-18 (AG)	SGL Carbon	Vibrationally molded	1.6	25	182.7	6.6	1.41	0.05	4210	2174	54092	10826
*molded vertically so WG perp to molding direction and WG specimens have AG notch												

Table 3 provides calculated values of the fracture process zone[12] (from equation 3) for the graphite grades examined. Manufacturer's data was used in some instances for this calculation.

Table 3 K_{Ic} and calculated process zone size, PZ, (radius) for the graphite grades examined here

Grade/notch orientation	Manufacturer	Forming method	Filler Particle Size, mm	TS (Manufact data) MPa	KIc (MPa√m)	PZ r_c (m)	PZ r_c (mm)
2114 (WG)*	Mercen	Isostsically molded	0.013	34.7	1.15	0.00017	0.17
2114 (AG)*	Mercen	Isostsically molded	0.013	34.7	1.15	0.00017	0.17
IG-110	Toyo Tanso	Isostsically molded	0.02	24.5	1.07	0.00030	0.30
PCEA (WG)	GrafTech	Extruded	0.8	20	1.33	0.00070	0.70
PCEA (AG)	GrafTech	Extruded	0.8	16	1.48	0.00136	1.36
NBG-18 (WG)**	SGL Carbon	Vibrationally molded	1.6	21	1.36	0.00067	0.67
NBG-18 (AG)**	SGL Carbon	Vibrationally molded	1.6	20	1.41	0.00079	0.79
*	Tensile strength taken as 2/3 of bend strength						
**	Tensile Strength from ORNL/TM-2010/219 Billet 6022 635 6						

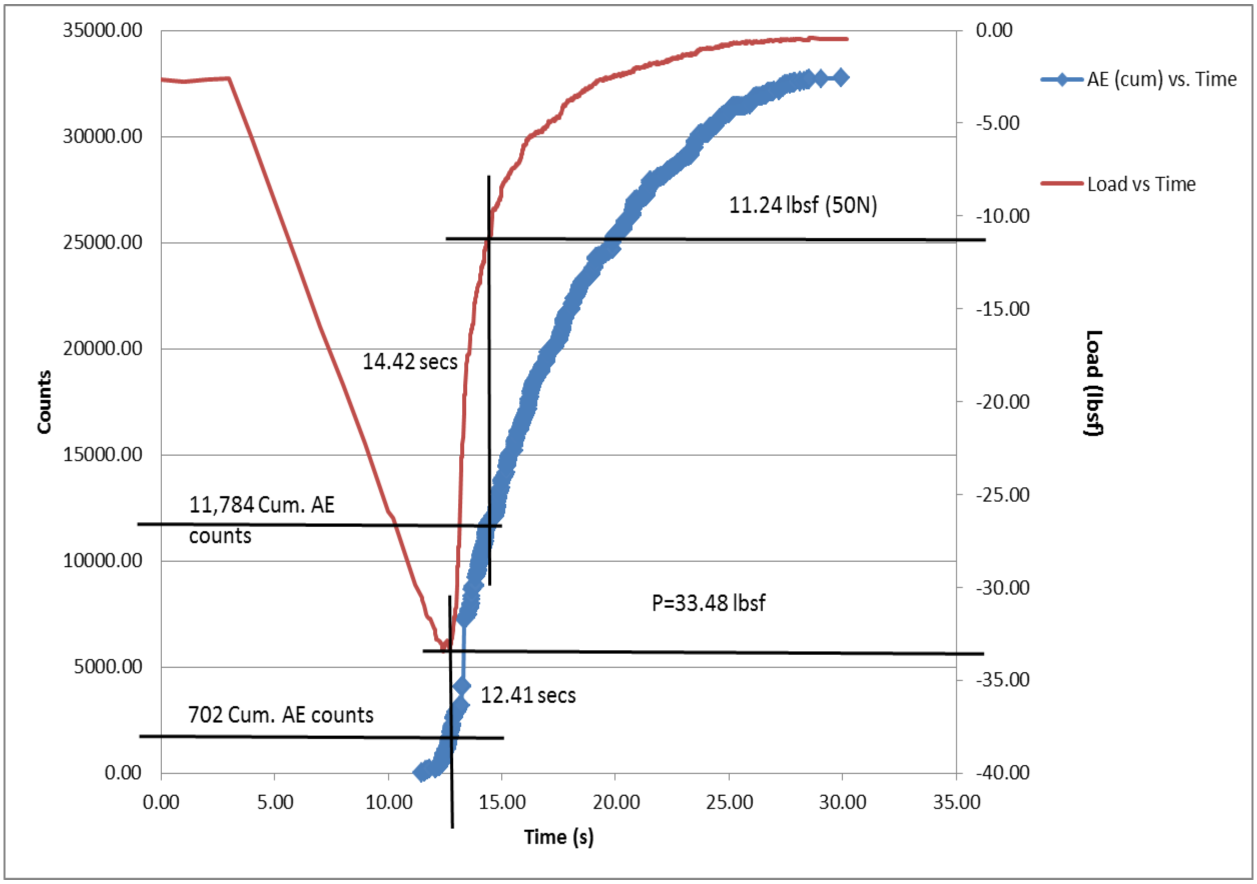

Figure 6 Load-time and cumulative AE counts-time curves for grade 2114 Block 2 specimen WG 31

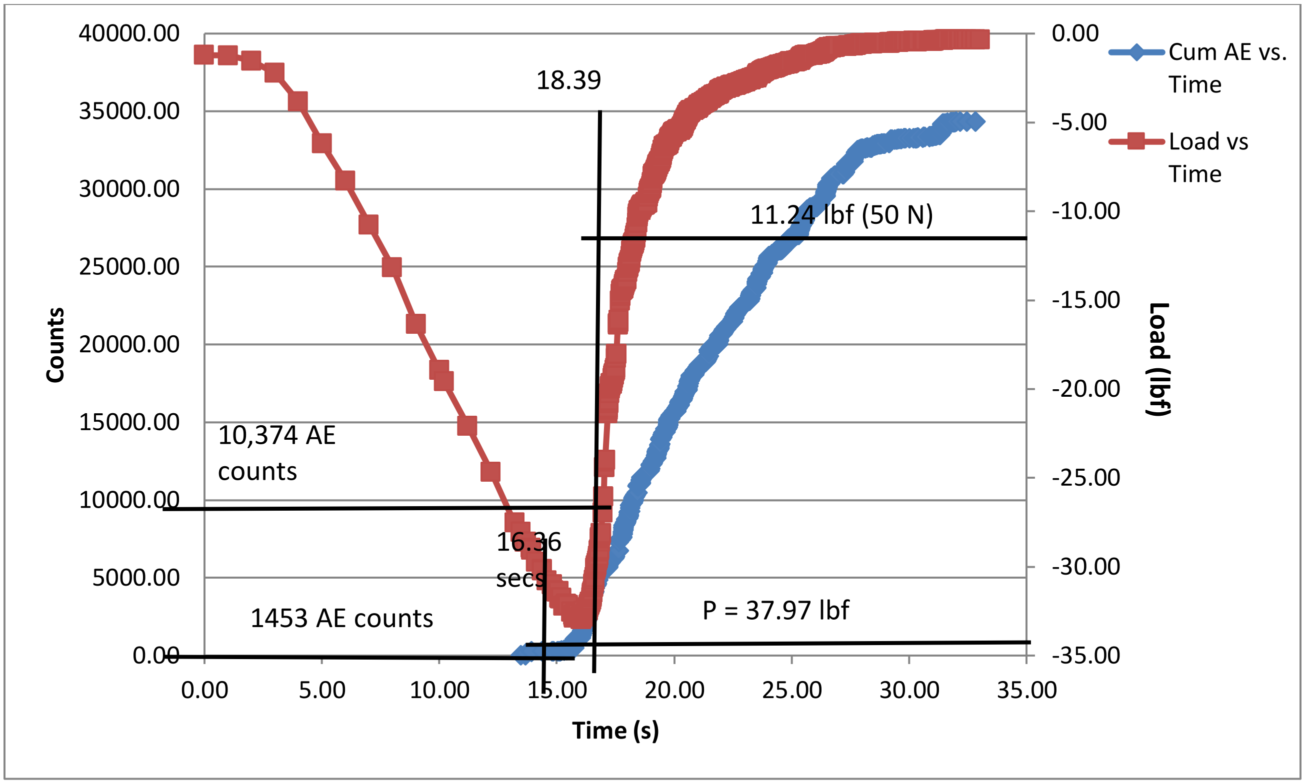

Figure 7 Load-time and cumulative AE counts-time curves for grade 2114 Block 2 specimen AG 23

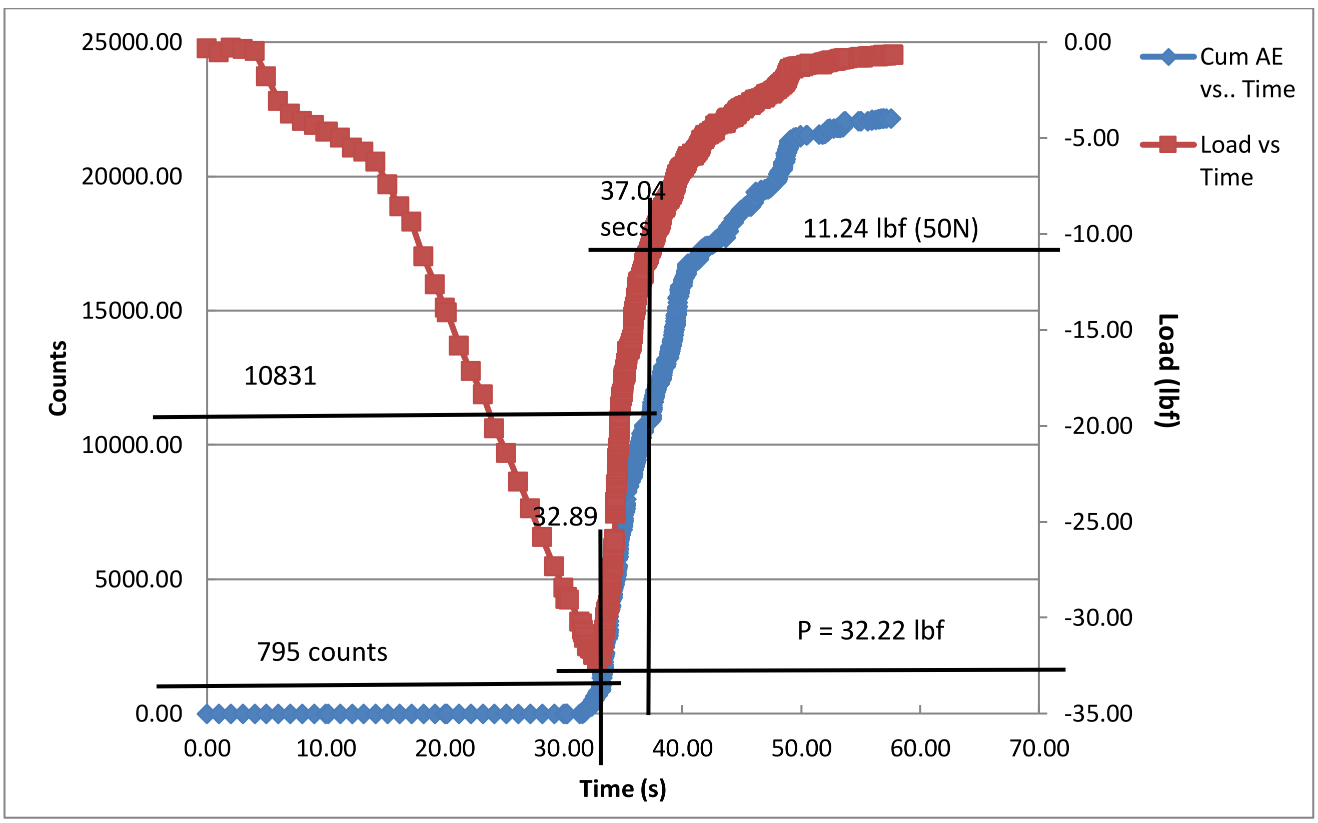

Figure 8 Load-time and cumulative AE counts-time curves for grade IG-110 specimen 22

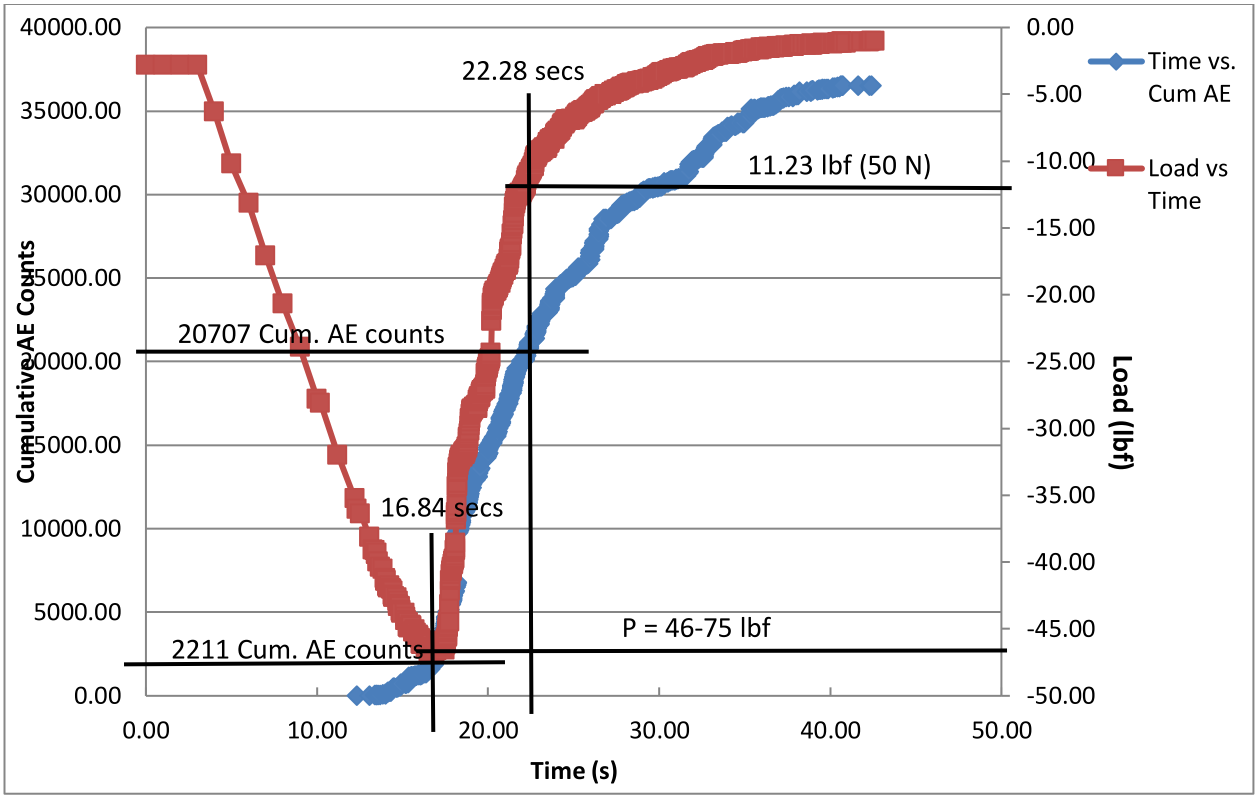

Figure 9 Load-time and cumulative AE counts-time curves for grade PCEA specimen WG K_{Ic} 118

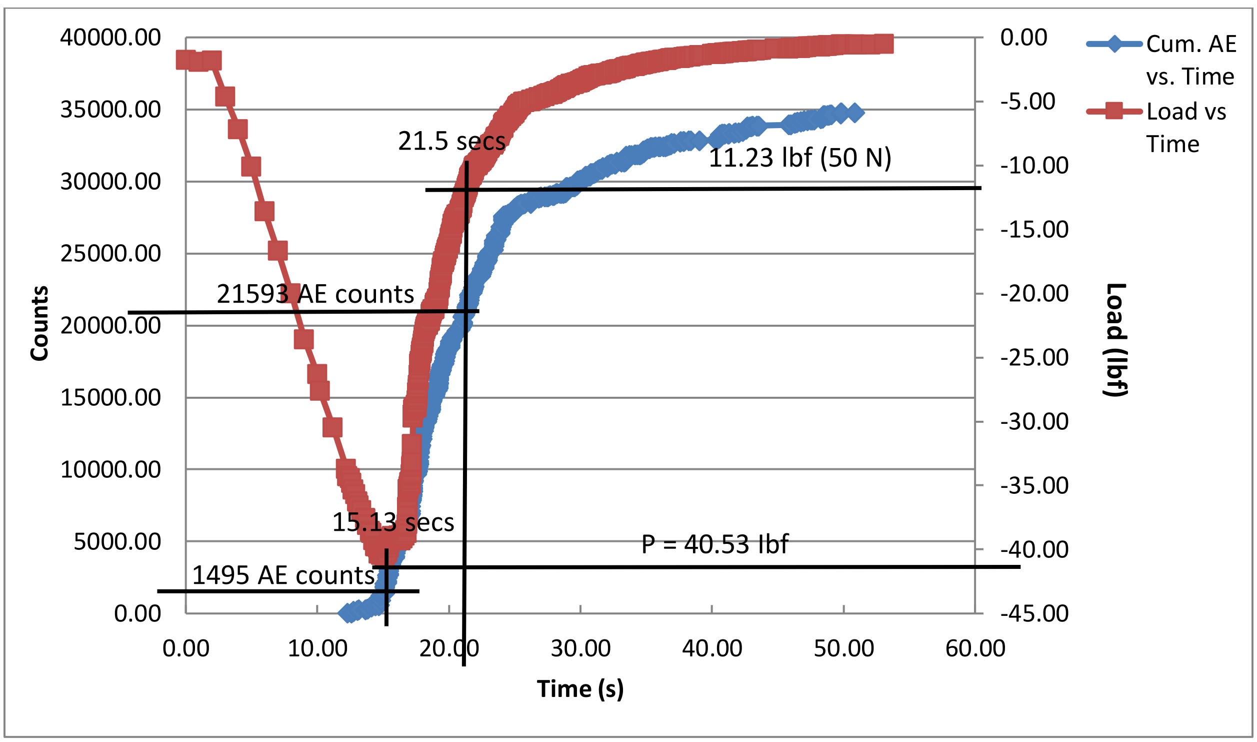

Figure 10 Load-time and cumulative AE counts-time curves for grade PCEA specimen AG KIc 75

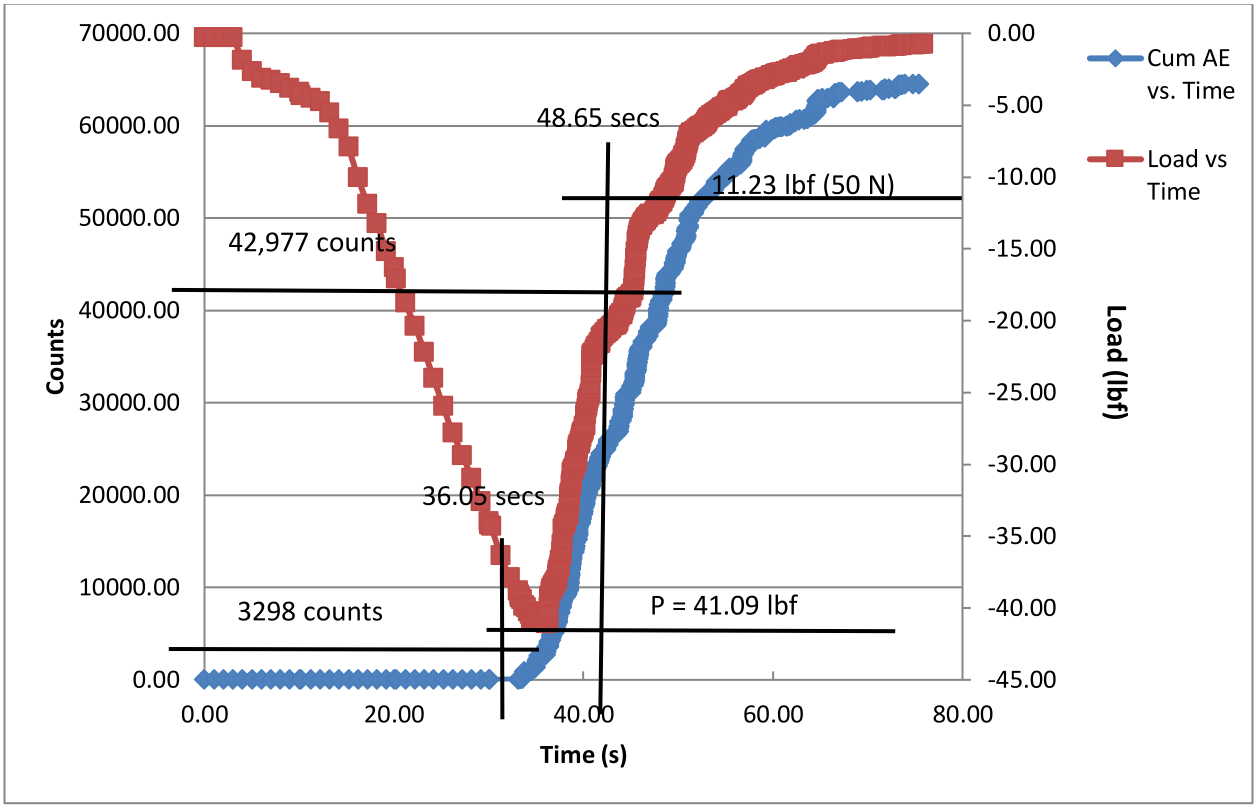

Figure 11 Load-time and cumulative AE counts-time curves for grade NBG-18 specimen 3B perp 10

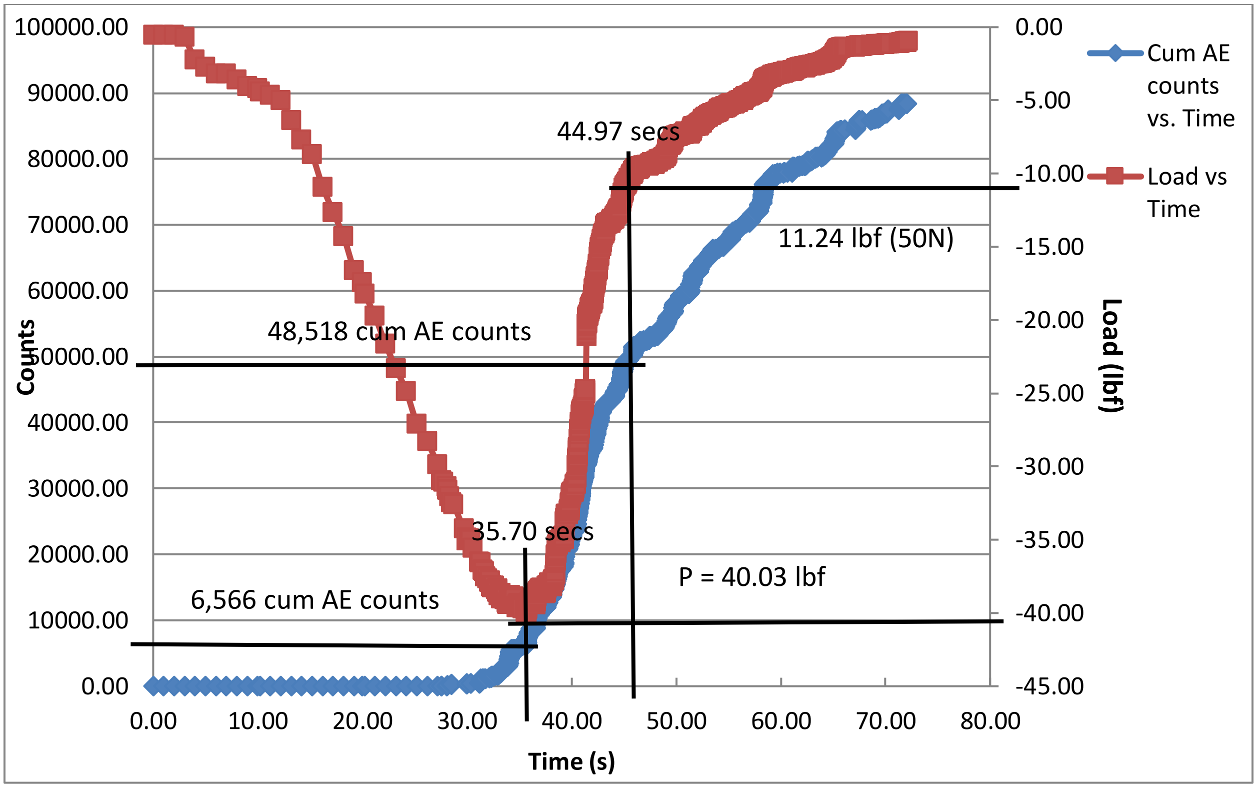

Figure 12 Load-time and cumulative AE counts-time curves for grade NBG-18 specimen 3B Par 15

2.3 DISCUSSION

The summarized K_{Ic} data from Table **3** are plotted against graphite texture (described by the manufacturers reported filler particle size) in Figure 13. Coarser textured graphite grades are seen to exhibit a larger K_{Ic} value, i.e., the fine grain graphite grades tend to be more brittle. This trend is well established from previous studies in literature. In addition, the AE data shows that the coarser textured grades exhibit more acoustic emissions prior to sustaining their maximum load (Figure 14), or upon reaching their notional failure load of 50N (Figure 15). Anisotropy in K_{Ic} was observed for grades PCEA and NBG-18. These were the medium grained graphite grades that were respectively extruded or vibrationally molded.

The fine grained, isostatically pressed grade MERCEN 2114 was isotropic with respect to K_{Ic}. Both the 2114(WG) and 2114(AG) returned a K_{Ic} value of 1.15 MPa√m. Although the standard deviation in the 2114(AG) specimens, (i.e., WG crack propagation orientation) was twice that of the standard deviation of the 2114(WG) specimens (i.e., AG crack propagation orientation). Given the direction of crack propagation in 2114 a more variable K_{Ic} result from the 2114(WG) specimens might be expected. Graphite grade Toyo-Tanso IG-110 was assumed to be isotropic with respect to K_{Ic}.

Increasing AE with increasing K_{Ic} is anticipated (Figure 16) since the "toughening" mechanisms in graphite, such as slip, shear, cleavage, and particularly micro-cracking, give rise to the acoustic emissions.[10,11.] Thus, coarser textured graphite grades, which exhibit more micro-cracking, are tougher than the fine textured graphite grades, even though they may well possess a lower strength than finer textured graphite.

The relationship between the cumulative AE and texture should be very apparent for sub-critical fracture events, i.e., those occurring prior to the graphite specimen sustaining its peak load, P. Indeed, inspection of Figure 14 shows a correlation coefficient better than 0.89 for the linear relationship between graphite filler particle size and cumulative AE. These data are replotted in Figure 17 with the filler particle size plotted on a logarithmic scale since the correlation apparently holds across four orders of magnitude in filler particle size. However, the filler particle size may not be the best descriptor of the graphite texture relevant to fracture toughness variations.

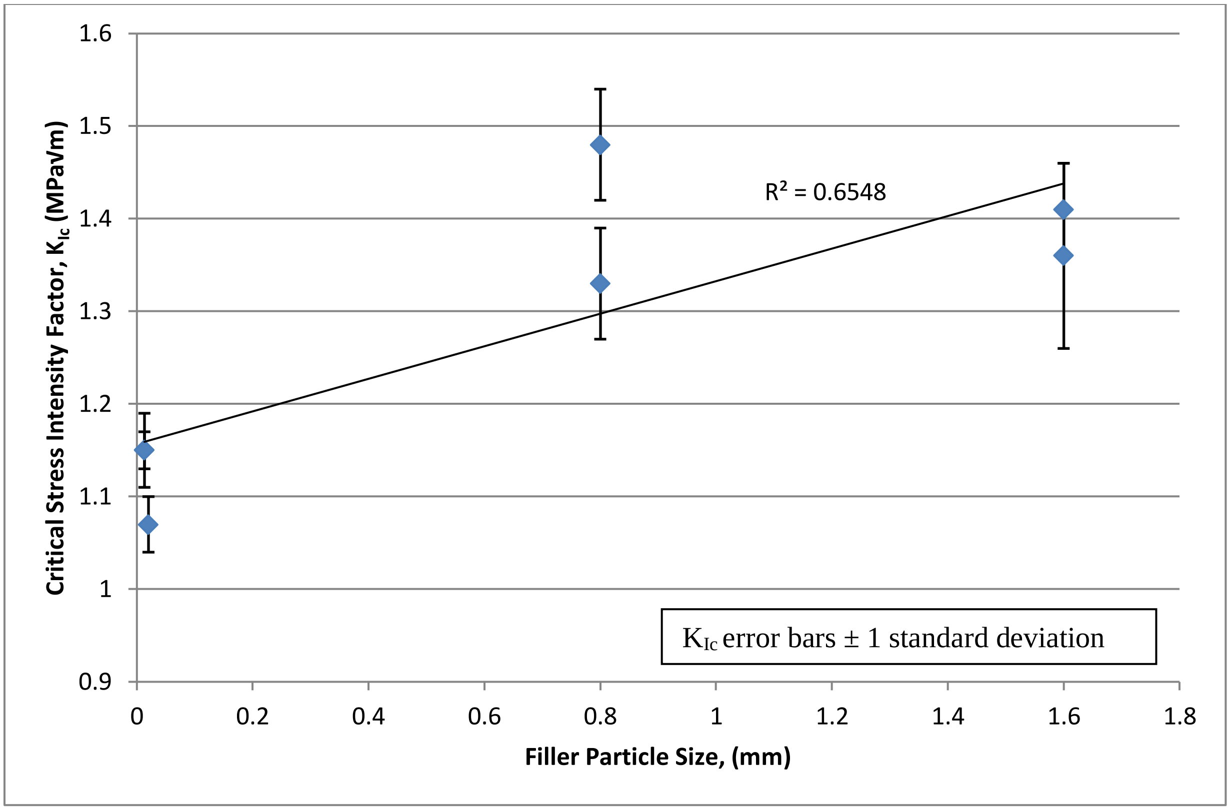

Figure 13 Variation of Critical Stress Intensity Factor with the graphite filler particle size

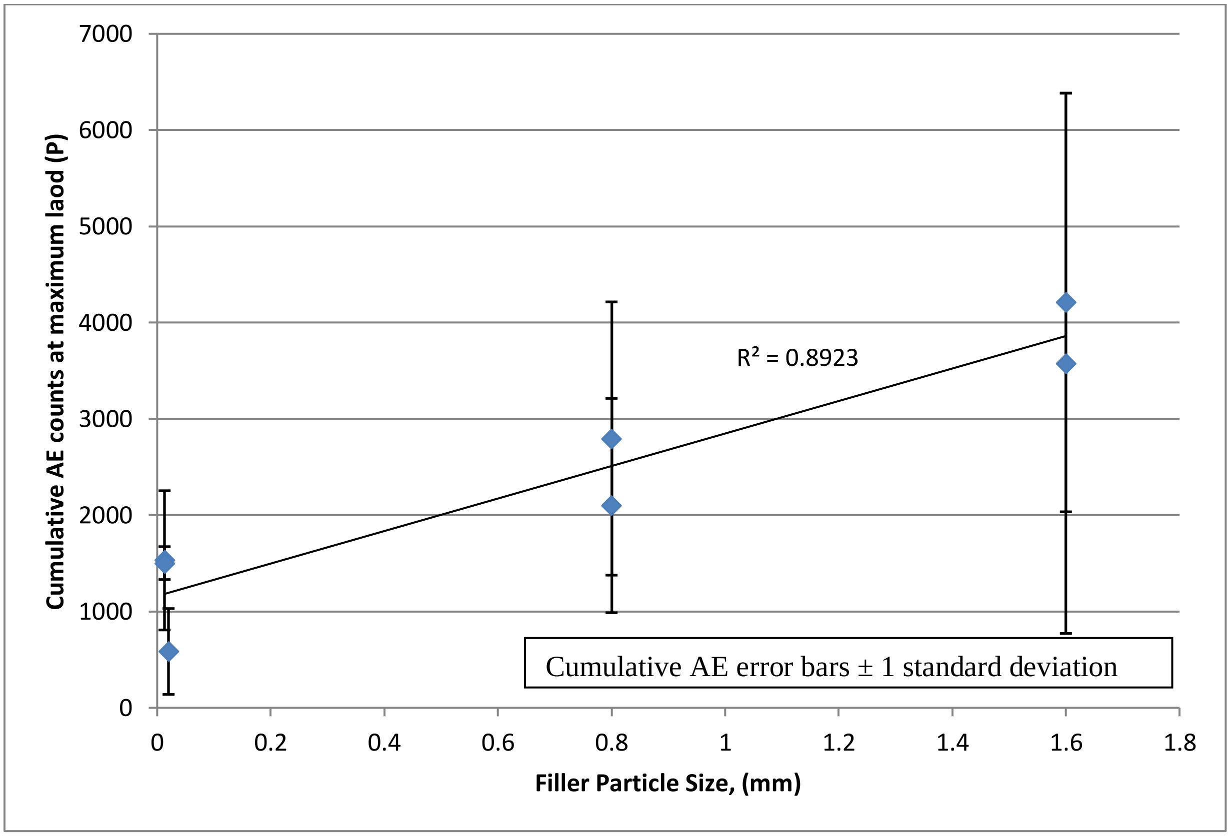

Figure 14 Variation of cumulative AE counts at maximum load, P, with the graphite filler particle size (mm)

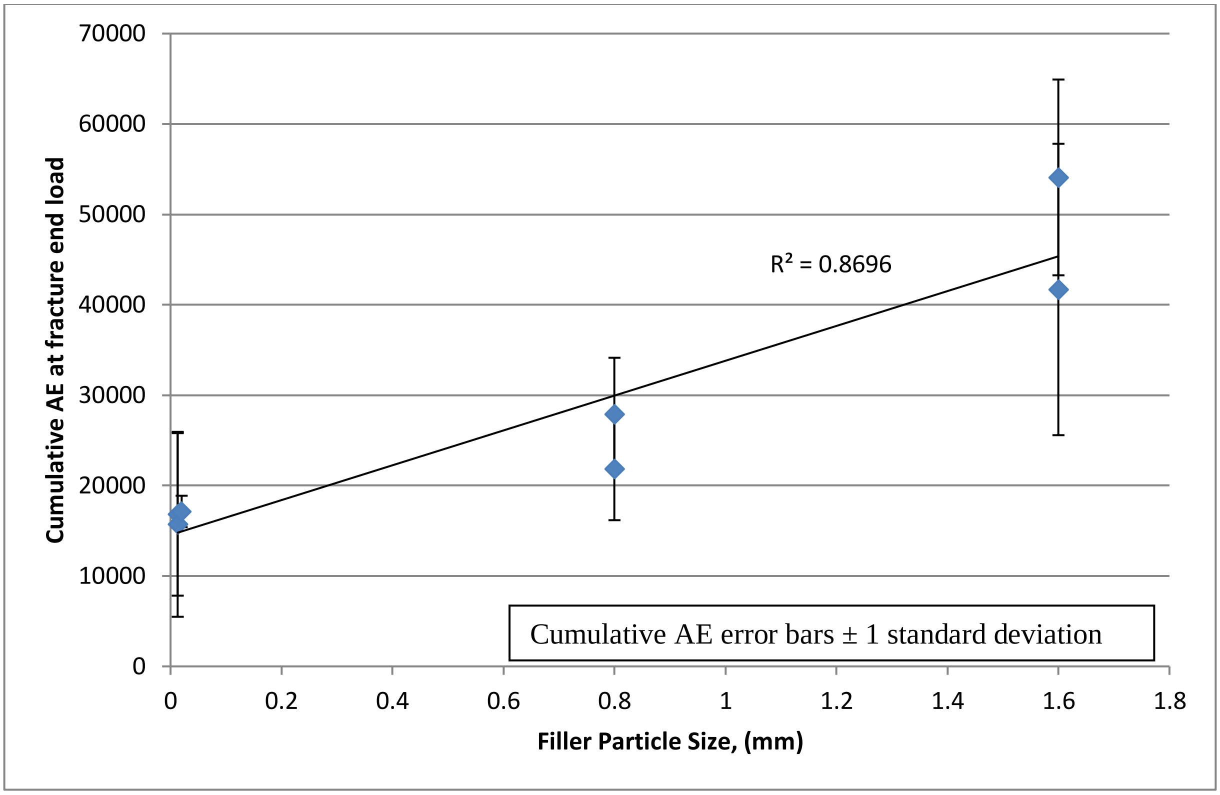

Figure 15 Variation of cumulative AE counts at fracture end load with the graphite filler particle size (mm)

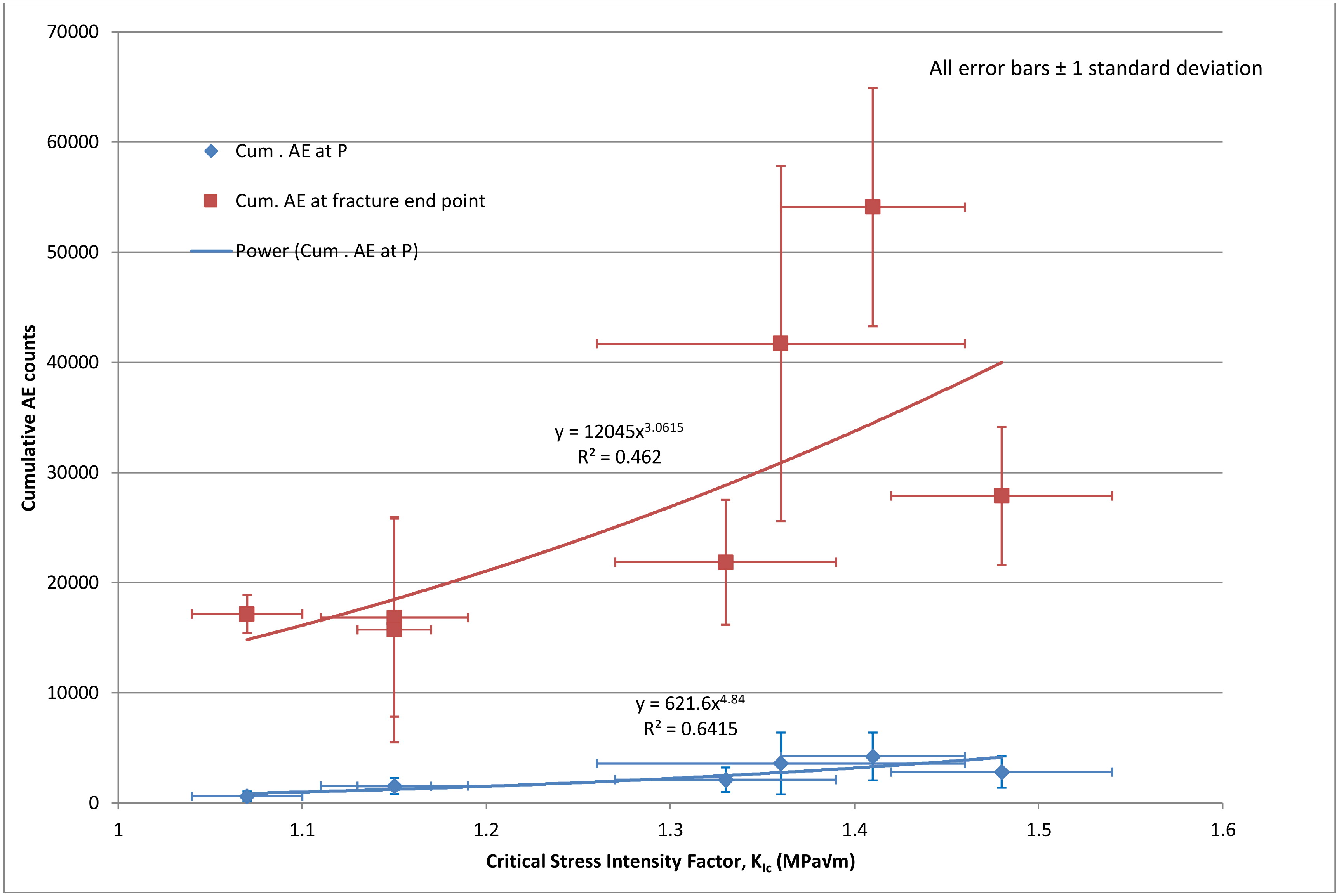

Figure 16 Variation of cumulative AE counts (i) at max load P, and (ii) at fracture end load with Critical Stress Intensity Factor

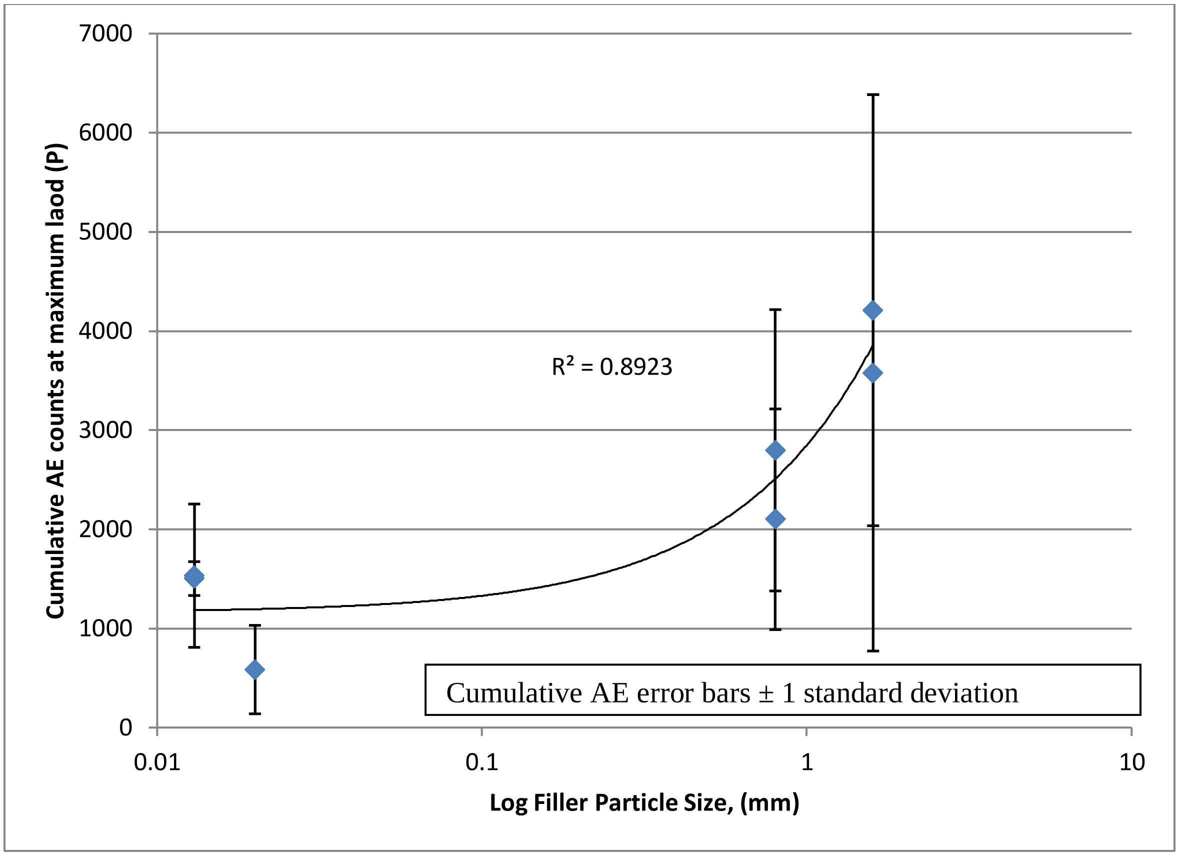

Figure 17 Variation of cumulative AE counts at maximum load, P, with the Log of graphite filler particle size (mm)

It is possible to define a volume of material in which the sub-critical, microcracking events of fracture occur i.e., those events giving rise to AE. The size of this "Process Zone[12]" is defined by its radius, r, and is given as a function of the material's tensile strength and its critical stress intensity factor (tensile strength orthogonal to the fracture propagation direction).

$$\textit{Process Zone Size,} \qquad r_c = \frac{1}{2\pi}\left[\frac{K_{Ic}}{\sigma_t}\right]^2 \tag{3}$$

Where K_{Ic} is the critical stress intensity factor (MPa√m) and σ_t is the tensile strength (MPa).

Thus, graphite grades with smaller K_{Ic} and higher tensile strength (such as fine-grained graphite grades) would exhibit smaller process zone size. The "process zone" sizes for the six graphite grade/orientation combinations reported in this study are given in Table 3. As the texture coarsens the process zone increases (Table 3). However, the increase of Process Zone size is from r_c = 0.17 mm to 1.36 mm, i.e., approximately one order of magnitude compared to two orders of magnitude when describing the texture with the filler particle size. The variation of K_{Ic} with the Process Zone size is shown in Figure 18.

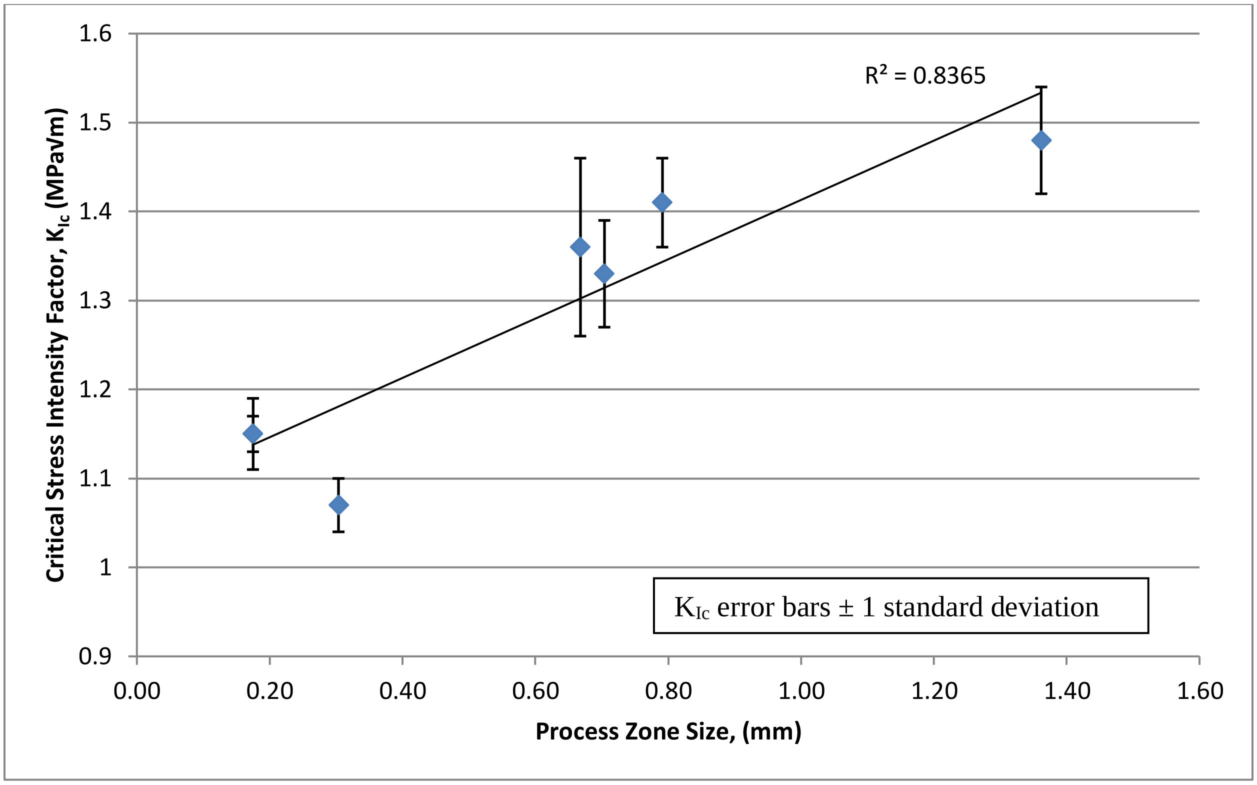

Figure 18 Variation of Critical Stress Intensity Factor with the graphite fracture process zone size

As expected, the correlation between K_{Ic} and texture (i.e., PZ) is improved with a linear fit to the data from Table **3** (Figure 18). The data suggests that PZ is a more useful description of the graphite texture (than is filler particle size) when trying to define the structure for the purpose of analysis or test. Later, in section 4, General Discussion, it will be shown how the PZ can be used to define the finite element mesh cell volume as prescribed by the American Society of Mechanical Engineers (ASME) design code.

3. SHEAR STRESS INTENSITY FACTOR, K_{IIc}

3.1 EXPERIMENTAL

The experimental method used to test the Double Edge Notch Compression (DENC) specimens was the same as that used in our previous testing[13,14] of identical geometry DENC specimens.

3.2 RESULTS

The additional K_{IIc} testing reported here was of graphite grades PCEA (both orientations) and IG-110, which was assumed to be isotropic with respect to K_{IIc}. The results of the new measurements are reported in Table 14, Table 15 and Table 16 (see Appendix A, Experimental Data),

The K_{IIc} data means from this work are summarized in Table 4 along with prior data for NBG-18(WG) specimens. Also reported are the ratio values of K_{IIc}/K_{Ic} for the grade/orientations were we have both K_{Ic} and K_{IIc} values (PCEA (PAR), PCEA (PER), NBG-18 (WG) and IG-110). This ratio is clearly greater than 1.0 for all graphite grades examined here.

Table 4 Summary K_{Ic} and K_{IIc} data for the specimens tested here (note, in the case of the PCEA (PAR) specimens and the NBG-18 (WG) specimens our prior data is included or reported[13,14])

K_{IIC} Graphite specimen and Notch Orientation	K_{Ic}		K_{IIc}		RATIO K_{IIc}/K_{Ic}
	MPa√m	n (K_{Ic})	MPa√m	n (K_{IIc})	
PCEA (PAR SPEC)(AG notch)	1.48 ± 0.06	57	2.41 ± 0.28*	57 [8 in 2015)	1.63
PCEA (PERP SPEC)(WG notch)	1.33±0.06	24	2.21 ± 0.19	24	1.66
NBG-18 (AG)	1.41±0.05	25			
NBG-18 (WG)	1.36 ± 0.1	25	2.2 ± 0.53**	10 [from 2015 testing]	1.62
IG-110	1.07 ± 0.03	32	2.87 ± 0.14	26	2.68

*includes the additional specimens (type 4's) tested in 2015 [see Carbon 98 (2016) 267-279]

**from type 4 specimens tested in 2015 [see Carbon 98 (2016) 267-279]

3.3 DISCUSSION

The prior PCEA (PAR) K_{IIc} value was 2.26 ± 0.37 MPa√m, and the new data for PCEA (PAR) is reported as K_{IIc} = 2.44±0.26 (with PCEA (PER) K_{IIc} = 2.21 ± 0.19). The K_{IIc} values obtained here for PCEA (PAR) and PCEA (PER) are in good agreement with the values obtain previously for PCEA (PAR). Interestingly, the K_{IIc} value obtained for the isostatically pressed, fine grain graphite, IG-110 was substantially larger than that measured for the medium grained PCEA or NBG-18 graphite grades (2.87±0.14 for IG-110 cf. 2.2 -2.4 K_{IIc}) suggesting that IG-110 is more shear resistant than the medium grain graphite grades PCEA or NBG-18.

Previously, Shetty[15] had speculated that K_{IIc} was not a unique materials property, i.e., there is a different value of K_{IIc} and hence a different Shetty coefficient, c, for each specimen geometry and loading condition. Moreover, from the results of the current study it appears the K_{IIc} values derived from the DENC geometry specimens may not be conservative and are seen to be artificially high. With these negative results for K_{IIc} testing on other graphite grades, we have not tested the grade 2114 graphite for its shear toughness and will not pursue this line of research further.

4. GENERAL DISCUSSION

4.1 APPLICATION OF FRACTURE MECHNICS IN ASTM STANDARDS AND SPECIFICATIONS

ASTM Standards specifications for nuclear graphite[4,5] do not currently require a minimum Critical Stress Intensity Factor (K_{Ic}) value. The specified minimum value was removed during the past balloting process because there was no accepted standard test method available to determine a viable K_{Ic} value for graphite. An approved standard test method[3] now exists and is used to report the results in this comprehensive study with a fixed specimen size. Thus, we may confidently specify a minimum K_{Ic} and ASTM test method to the nuclear graphite ASTM Standard specifications (D7219 and D7301).

Table 5 gives the mean value minus three standard deviations (mean – 3*St. Dev.) for the seven graphite grade/orientation combinations studied here. If the value of the lowest reported mean – 3*St. Dev. are taken from Table 5 a value of 0.98 would be obtained for the minimum K_{Ic}. For ASTM standard specification purposes a minimum K_{Ic} of 0.95 MPa√m (determined on a 200 x 20 x 15 – mm SENB) should be required for any graphite grade considered for nuclear component applications. At this level, none of the grades in Table 5 (or other current grades being considered for nuclear applications such as Sino-Steel's grade SNG742[8]) would be excluded.

Table 5 Mean values, Standard deviation and [mean-(3*St. Dev.)] values

	K_{Ic} (MPa√m)		
Grade	mean	st dev	mean-3 st. dev.
2114 (WG)	1.15	0.04	1.03
2114 (AG)	1.15	0.02	1.09
IG-110	1.07	0.03	0.98
PCEA (WG)	1.33	0.06	1.15
PCEA (AG)	1.48	0.06	1.3
NBG-18 (WG)	1.36	0.1	1.06
NBG-18 (AG)	1.41	0.05	1.26

Revisions to ASTM Standard Specifications D7219 and D7301 shall be introduced at the ASTM DO2.F Committee on Manufactured Carbons and Graphite.

4.2 APPLICATION IN ASME GRAPHITE CORE DESIGN CODE

The ASME B&PV Code (2013 edition) in Section III, Division 5, sub-part A: Graphite materials, Article 3: Design, requires in paragraph HHA-3217 the calculation of the probability of component failure. This calculation is achieved through the application of a Finite Element Model (FEM) stress analysis to assess the stresses in a graphite core component. The code defines the FEM integration volume with two conditions (see HHA 3000).

Condition 1: group volume $V_{I, II, III,\ldots} > V_m$

Condition 2: group stress range as follows: $\frac{\max(X_{I,II,III\ldots}) - \min(X_{I,II,III\ldots})}{\min(X_{I,II,III\ldots})} \geq \Delta$

Where,

Vm = a process zone volume, which is the volume described by the cube of 10 times the maximum grain size, and

Δ = the stress range parameter, 7%.

The integration volume defines the integration points at which, using the FEM analysis and the equations given in the ASME B&PV code (sub part A: Graphite, Article HHA 3000 Design), an equivalent stress is defined and compared to the materials strength. Thus, the probability of survival is calculated.

For medium grained nuclear graphite such as NBG-18, with a maximum grain size of 1.6 mm, V_m is $(10 \times 1.6)^3 = (16\ \text{mm})^3$ or a volume or 4096 mm^3. For a fine grained graphite such as IG-110, with a grain size of 20 µm, the integration volume $V_m = (10 \times 20)^3 = (200\ \mu\text{m})^3$ or a volume of 0.008 mm^3, a variation in V_m of some 6 orders of magnitude!

Unfortunately, this ASME methodology places a huge computational analysis (and financial) burden on the designer of a fine grain graphite core component or assembly. Moreover, as is shown in Figure 19 this methodology places unrealistic constraints on the use of a fine grained graphite because the computed probabilities of failure are extremely conservative, if not untenable.

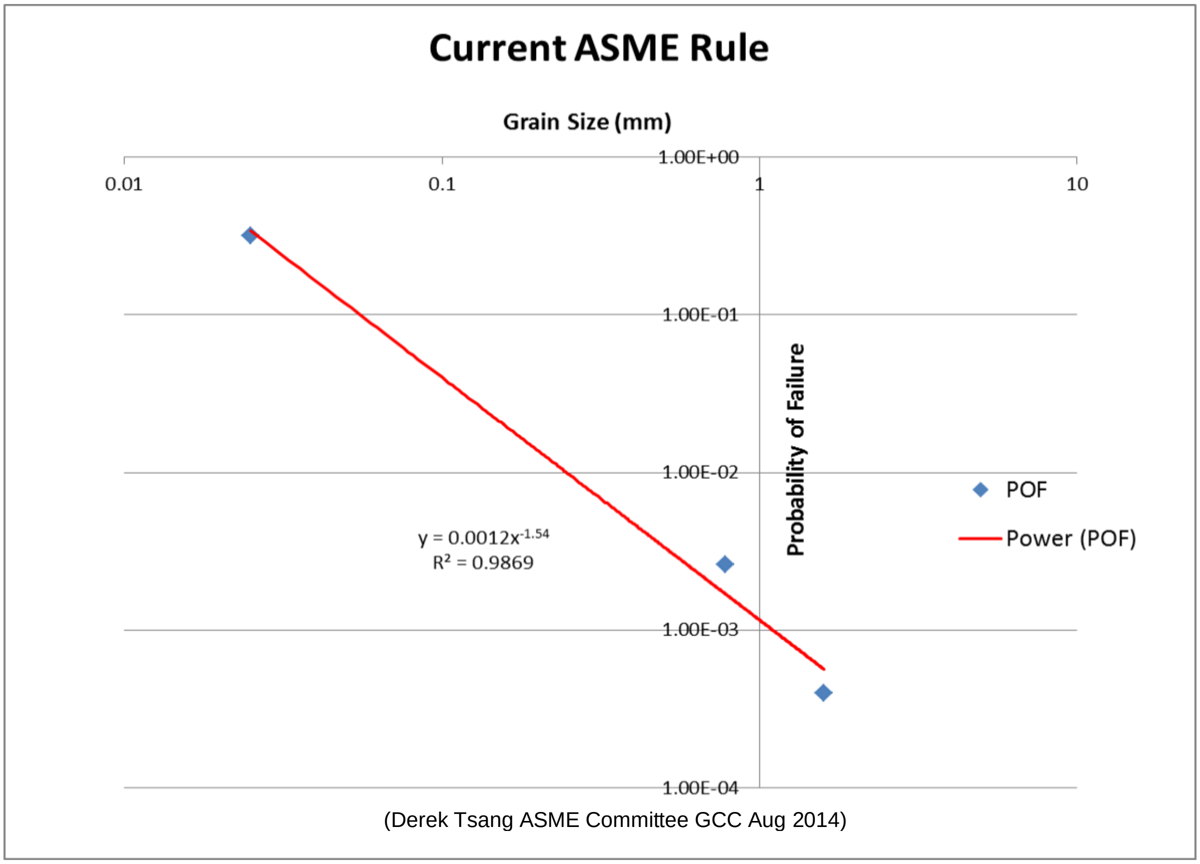

Figure 19 Calculated probability of failure for nuclear graphite core components as a function of Grain Size, mm.

The actual integration volume, V_m, used in the stress analysis should depend upon several factors, such as:

- Graphite texture (grain size is not a good indicator of texture).
- Component geometry (i.e., section size, web thickness, component size)
- Anticipated stress or stress gradient

The designer must have some discretion when determining the integration volume. What we describe here is suggested guidance on the initial selection of the integration volume. Essentially, the integration volume is a kind of process zone, and as such, should be equated with the fracture process zone given by equation 3, previously. As discussed above, the fracture process zone is a better descriptor of graphite texture than is the grain or filler particle size when describing fracture as a function of texture. Calculated values of the fracture Process Zone are given in Table 3 for the graphite grades in the current study. Note that the definition of the process zone size (r_c) is the width/diameter of the region in front of the crack tip. From the critical radius (one half of the PZ size) the appropriate integration volume, V_m, has been calculated and is given in Table 6. Note that the "Proposed New Rule" columns and data from Rev.0 of this report have been included to show the differences due to the corrections.

Table 6 Existing and Proposed new V_m for the ASME Sect III, Div. 5 Graphite code (HHA)

	Existing ASME Rule		Proposed New Rule (Rev.0)		**Proposed New Rule (Rev.1)**		
	Grain size	V_m	PZ size, r_c (mm)	Proposed V_m	PZ size, r_c (mm)	Proposed V_m	Proposed V_m, Rev. 1
GRADE	mm	mm^3	mm	$4/3(Pi)r_c^3$, mm^3	mm	$4/3(Pi)r_c^3$, mm^3	$4\pi/3*(r_c/2)^3$, mm
NBG-18 (WG)	1.6	4096	6.6	1198.8	0.67	1.25	0.156
NBG-18 (AG)	1.6	4096	7.8	1995.5	0.79	2.07	0.259
PCEA (WG)	0.8	512	~~10.85~~ 6.9 [a]	~~5335.5~~ 1404 [a]	0.70	1.46	0.183
PCEA (AG)	0.8	512	~~8.60~~ 13.4 [a]	~~2664.3~~ 10169 [a]	1.36	10.58	1.322
IG-110	0.02	0.008	3.0	113.1	0.30	0.117	0.0146
2114	0.013	0.0022	1.7	21.7	0.17	0.022	0.00280

[a] Values struck through were from a switch of PCEA strength values reported in Rev.0 Table 3. Note incorrect calculation of r_c used for consistency.

The proposed new integration volume, V_m, varies by only ~x 10 between IG-110 to NBG-18, rather than the ~x1000000 variation of the existing ASME definition of V_m. An ASME code action has been initiated in response to a formal enquiry from SINAP, Shanghai, China to try to eliminate the conservatism bought about by linking V_m to the graphite grain size. The ASME graphite committee expects to conduct a series of benchmarks using set verification problems to determine (i) the validity of this approach to estimating the FEM integration volume, and (ii) the appropriate value of Δ, the stress range parameter for this approach.

5. CONCLUSIONS

Here we have reported the K_{Ic} and K_{IIc} values for several nuclear graphite grades of interest to the USDOE Advanced Reactor Technologies program. The determination of K_{IIc} from the Double Edge Notched Compression (DENC) specimen was successful, our new data agreeing well with our previously reported data. However, the realization that K_{IIc} may not be a material constant means we will not pursue this line of research further. K_{Ic} data was generated for four grades (both orientations for three grades) ranging from the fine grain isostatic pressed grades (IG-110 and 2114) to the medium grained vibrationally molded NBG-18 and the extruded medium grained PCEA. The acquisition of these data has allowed a minimum value for nuclear graphite K_{Ic} to be identified ($K_{Ic(min)}$ = 0.95 MPa$\sqrt{m}$). This value and the K_{Ic} ASTM test standard (with an appropriate note about the recommended specimen size) will be added to the ASTM specifications for Nuclear Graphite.

Acoustic Emission was monitored during fracture and is thought to be related to activity stemming from fracture activities in the fracture process zone. Both the cumulative acoustic emission counts and the measured K_{Ic} increase with increasing fracture process zone critical radius and increasing grain size. However, the correlation is much better for the K_{Ic} vs process zone radius than for the K_{Ic} vs grain size, suggesting that fracture mechanics derived process zone size is a better indicator of graphite texture than is the widely used grain size.

The ASME design Code for graphite cores uses a probabilistic approach in which the stress from a FEM analysis is compared to a known strength distribution for the selected graphite. The code rules specify how the FEM integration volume should be calculated based upon the graphite grain size. This methodology has been shown to penalize the use of fine grain graphite. A code action has been initiated to link the FEM cell size (Integration volume) to the fracture process zone size (derived from the K_{Ic} and σ_t). Note that σ_t is currently obtained from ASTM C565[16] or ASTM C749[17] dog-bone type specimens whose size does not always lend itself to testing irradiated graphite. Consequently, the DO2.F Committee on Manufactured Carbons and Graphite is pursuing a standard for the Brazilian Disc specimen (Split-disk specimen) for σ_t whose geometry does lends itself to smaller and irradiated samples.

6. ACKNOWLEDGEMENTS

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7. DISTRIBUTION

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APPENDIX A EXPERIMENTAL DATA

Table 7 K_{Ic} and AE data for grade 2114, WG specimen (AG fracture orientation)

2114 (15x20x200 mm, a/W=0.40)

Specimen ID	Spec Orientation	Crack Orientation	g	P(max)		S	B*(W^(3/2))	3((a/W)^(1/2))	2(1-(a/W))^(3/2))	KIc	Onset Force		ΣAE at max load	ΣAE at total fracture (50 N or 11.24 lbf load)
				lbf	N	M				MPa√m	lbf	N	AE Counts	AE Counts
2114-Block-2-WG-2	WG	AG	1	34.09	148.30	0.16	4.24E-05	1.897	0.930	1.14	33.34	148.30	1053	10772
2114-Block-2-WG-3	WG	AG	1	33.19	147.63	0.16	4.24E-05	1.897	0.930	1.14	26.95	119.87	1153	13227
2114-Block-2-WG-4	WG	AG	1	32.30	143.67	0.16	4.24E-05	1.897	0.930	1.11	26.95	119.87	1289	7937
2114-Block-2-WG-5	WG	AG	1	34.20	152.12	0.16	4.24E-05	1.897	0.930	1.17	29.55	131.44	984	18284
2114-Block-2-WG-6	WG	AG	1	33.16	147.50	0.16	4.24E-05	1.897	0.930	1.14	27.30	121.43	715	19853
2114-Block-2-WG-7	WG	AG	1	33.73	150.03	0.16	4.24E-05	1.897	0.930	1.15	26.38	117.34	1726	26582
2114-Block-2-WG-8	WG	AG	1	33.30	148.12	0.16	4.24E-05	1.897	0.930	1.14	28.61	127.26	1870	20658
2114-Block-2-WG-9	WG	AG	1	34.58	153.81	0.16	4.24E-05	1.897	0.930	1.18	32.33	143.80	600	6308
2114-Block-2-WG-10	WG	AG	1	33.23	147.81	0.16	4.24E-05	1.897	0.930	1.14	29.48	131.13	1521	10233
2114-Block-2-WG-11	WG	AG	1	34.02	151.32	0.16	4.24E-05	1.897	0.930	1.16	28.55	126.99	1498	26485
2114-Block-2-WG-12	WG	AG	1	32.66	145.27	0.16	4.24E-05	1.897	0.930	1.12	27.52	122.41	1564	19721
2114-Block-2-WG-13	WG	AG	1	34.02	151.32	0.16	4.24E-05	1.897	0.930	1.16	26.33	117.12	1634	20640
2114-Block-2-WG-14	WG	AG	1	33.42	148.65	0.16	4.24E-05	1.897	0.930	1.14	30.66	136.38	693	11455
2114-Block-2-WG-15	WG	AG	1	31.64	140.73	0.16	4.24E-05	1.897	0.930	1.08	30.52	135.75	697	7453
2114-Block-2-WG-18	WG	AG	1	34.42	153.10	0.16	4.24E-05	1.897	0.930	1.18	27.91	124.14	1438	11028
2114-Block-2-WG-19	WG	AG	1	32.77	145.76	0.16	4.24E-05	1.897	0.930	1.12	29.42	130.86	2447	16047
2114-Block-2-WG-20	WG	AG	1	33.95	151.01	0.16	4.24E-05	1.897	0.930	1.16	28.31	125.92	920	7545
2114-Block-2-WG-21	WG	AG	1	31.34	139.40	0.16	4.24E-05	1.897	0.930	1.07	27.59	122.72	1872	8953
2114-Block-2-WG-22	WG	AG	1	32.11	142.83	0.16	4.24E-05	1.897	0.930	1.10	17.70	78.73	1722	16293
2114-Block-2-WG-23	WG	AG	1	32.97	146.65	0.16	4.24E-05	1.897	0.930	1.13	27.77	123.52	1325	13988
2114-Block-2-WG-24	WG	AG	1	31.31	139.27	0.16	4.24E-05	1.897	0.930	1.07	27.17	120.85	856	7291
2114-Block-2-WG-25	WG	AG	1	34.94	155.41	0.16	4.24E-05	1.897	0.930	1.20	29.13	129.57	1028	6920

2114-Block-2-WG-26	WG	AG	1	33.25	147.90	0.16	4.24E-05	1.897	0.930	1.14	20.33	90.43	2695	8785
2114-Block-2-WG-27	WG	AG	1	ERROR		0.16	4.24E-05	1.897	0.930	ERROR				
2114-Block-2-WG-28	WG	AG	1	33.41	148.61	0.16	4.24E-05	1.897	0.930	1.14	29.56	131.48	657	13574
2114-Block-2-WG-29	WG	AG	1	31.56	140.38	0.16	4.24E-05	1.897	0.930	1.08	27.62	122.85	1771	8092
2114-Block-2-WG-30	WG	AG	1	33.16	147.50	0.16	4.24E-05	1.897	0.930	1.14	27.84	123.83	1877	11602
2114-Block-2-WG-31	WG	AG	1	33.48	148.92	0.16	4.24E-05	1.897	0.930	1.15	30.56	135.93	702	11784
2114-Block-4-WG-2	WG	AG	1	33.28	148.03	0.16	4.24E-05	1.897	0.930	1.14	27.52	122.41	2236	10301
2114-Block-4-WG-3	WG	AG	1	34.70	154.35	0.16	4.24E-05	1.897	0.930	1.19	28.50	126.77	669	8957
2114-Block-4-WG-4	WG	AG	1	34.53	153.59	0.16	4.24E-05	1.897	0.930	1.18	27.00	120.10	1604	9800
2114-Block-4-WG-5	WG	AG	1	ERROR		0.16	4.24E-05	1.897	0.930	ERROR				
2114-Block-4-WG-6	WG	AG	1	34.81	154.83	0.16	4.24E-05	1.897	0.930	1.19	20.55	91.41	2435	37007
2114-Block-4-WG-7	WG	AG	1	34.94	155.41	0.16	4.24E-05	1.897	0.930	1.20	30.19	134.29	1320	9405
2114-Block-4-WG-8	WG	AG	1	34.31	152.61	0.16	4.24E-05	1.897	0.930	1.17	28.91	128.59	2665	33905
2114-Block-4-WG-9	WG	AG	1	34.14	151.85	0.16	4.24E-05	1.897	0.930	1.17	27.64	122.94	1134	19987
2114-Block-4-WG-10	WG	AG	1	33.77	150.21	0.16	4.24E-05	1.897	0.930	1.16	30.09	133.84	2877	22462
2114-Block-4-WG-11	WG	AG	1	35.20	156.57	0.16	4.24E-05	1.897	0.930	1.21	31.36	139.49	1965	17828
2114-Block-4-WG-12	WG	AG	1	35.08	156.04	0.16	4.24E-05	1.897	0.930	1.20	25.09	111.60	1565	39453
2114-Block-4-WG-13	WG	AG	1	35.19	156.53	0.16	4.24E-05	1.897	0.930	1.20	29.66	131.93	745	46895
2114-Block-4-WG-14	WG	AG	1	34.09	151.63	0.16	4.24E-05	1.897	0.930	1.17	28.47	126.63	1739	29652
2114-Block-4-WG-15	WG	AG	1	35.08	156.04	0.16	4.24E-05	1.897	0.930	1.20	33.48	148.92	464	5359
2114-Block-4-WG-18	WG	AG	1	34.33	152.70	0.16	4.24E-05	1.897	0.930	1.18	27.66	123.03	1771	15318
2114-Block-4-WG-19	WG	AG	1	33.86	150.61	0.16	4.24E-05	1.897	0.930	1.16	27.78	123.57	2081	19128
2114-Block-4-WG-20	WG	AG	1	30.75	136.78	0.16	4.24E-05	1.897	0.930	1.05	28.47	126.63	1275	8560
2114-Block-4-WG-21	WG	AG	1	33.44	148.74	0.16	4.24E-05	1.897	0.930	1.15	2.88	12.81	634	14525
2114-Block-4-WG-22	WG	AG	1	33.80	150.34	0.16	4.24E-05	1.897	0.930	1.16	25.50	113.42	1417	10702
2114-Block-4-WG-23	WG	AG	1	33.64	149.63	0.16	4.24E-05	1.897	0.930	1.15	30.09	133.84	1776	21849
2114-Block-4-WG-24	WG	AG	1	34.06	151.50	0.16	4.24E-05	1.897	0.930	1.17	30.31	134.82	954	33842
2114-Block-4-WG-25	WG	AG	1	33.33	148.25	0.16	4.24E-05	1.897	0.930	1.14	23.86	106.13	3473	25938
2114-Block-4-WG-26	WG	AG	1	33.14	147.41	0.16	4.24E-05	1.897	0.930	1.13	25.17	111.96	1964	20205
2114-Block-4-WG-27	WG	AG	1	34.58	153.81	0.16	4.24E-05	1.897	0.930	1.18	31.67	140.87	564	9827

2114-Block-4-WG-28	WG	AG	1	34.03	151.37	0.16	4.24E-05	1.897	0.930	1.17	28.72	127.75	1906	16275
2114-Block-4-WG-29	WG	AG	1	33.89	150.74	0.16	4.24E-05	1.897	0.930	1.16	27.75	123.43	3445	9671
2114-Block-4-WG-30	WG	AG	1	34.72	154.43	0.16	4.24E-05	1.897	0.930	1.19	30.25	134.55	993	22103
2114-Block-4-WG-31	WG	AG	1	34.27	152.43	0.16	4.24E-05	1.897	0.930	1.17	28.67	127.52	2730	27464
				Mean	149.62					1.15	27.64	122.95	1532	16813
				SD	4.62					0.04	4.33	19.26	725	8992

Table 8 K_{Ic} and AE data for grade 2114, AG specimen (WG fracture orientation)

2114 (15x20x200 mm, a/W=0.40)														
Specimen ID	Spec Orientation	Crack Orientation	g	P(max)		S	B*(W^(3/2))	3((a/W)^(1/2))	2(1-(a/W))^(3/2))	KIc	Onset Force		ΣAE at max load	ΣAE at total fracture (50 N or 11.24 lbf load)
				lbf	N	M				MPa.√m	lbf	N	AE Counts	AE Counts
2114-Block-2-AG-2	AG	WG	1	34.77	154.66	0.16	4.24E-05	1.897	0.930	1.19	33.89	150.74	2128	18609
2114-Block-2-AG-3	AG	WG	1	33.52	149.10	0.16	4.24E-05	1.897	0.930	1.15	30.92	137.53	1447	19446
2114-Block-2-AG-4	AG	WG	1	34.61	153.95	0.16	4.24E-05	1.897	0.930	1.19	29.36	130.59	2798	18300
2114-Block-2-AG-5	AG	WG	1	33.06	147.05	0.16	4.24E-05	1.897	0.930	1.13	30.75	136.78	1148	7844
2114-Block-2-AG-6	AG	WG	1	33.25	147.90	0.16	4.24E-05	1.897	0.930	1.14	32.02	142.42	487	6796
2114-Block-2-AG-7	AG	WG	1	34.06	151.50	0.16	4.24E-05	1.897	0.930	1.17	29.88	132.91	1020	7284
2114-Block-2-AG-8	AG	WG	1	33.66	149.72	0.16	4.24E-05	1.897	0.930	1.15	28.48	126.68	1746	7090
2114-Block-2-AG-9	AG	WG	1	33.11	147.27	0.16	4.24E-05	1.897	0.930	1.13	28.47	126.63	1530	14231
2114-Block-2-AG-10	AG	WG	1	33.80	150.34	0.16	4.24E-05	1.897	0.930	1.16	30.23	134.46	723	14783
2114-Block-2-AG-11	AG	WG	1	33.72	149.99	0.16	4.24E-05	1.897	0.930	1.15	30.94	137.62	1682	17627
2114-Block-2-AG-12	AG	WG	1	33.55	149.23	0.16	4.24E-05	1.897	0.930	1.15	30.61	136.15	2286	13801
2114-Block-2-AG-13	AG	WG	1	34.28	152.48	0.16	4.24E-05	1.897	0.930	1.17	25.14	111.82	3200	61041
2114-Block-2-AG-14	AG	WG	1	32.44	144.29	0.16	4.24E-05	1.897	0.930	1.11	28.02	124.63	1844	10957
2114-Block-2-AG-15	AG	WG	1	32.81	145.94	0.16	4.24E-05	1.897	0.930	1.12	29.00	128.99	2438	9283
2114-Block-2-AG-18	AG	WG	1	33.30	148.12	0.16	4.24E-05	1.897	0.930	1.14	27.80	123.65	2267	22766
2114-Block-2-AG-19	AG	WG	1	32.98	146.70	0.16	4.24E-05	1.897	0.930	1.13	29.77	132.42	1763	5039
2114-Block-2-AG-20	AG	WG	1	33.44	148.74	0.16	4.24E-05	1.897	0.930	1.15	27.33	121.56	2869	39956
2114-Block-2-AG-21	AG	WG	1	33.98	151.14	0.16	4.24E-05	1.897	0.930	1.16	30.30	134.77	1250	11975
2114-Block-2-AG-22	AG	WG	1	33.33	148.25	0.16	4.24E-05	1.897	0.930	1.14	30.02	133.53	1588	12484
2114-Block-2-AG-23	AG	WG	1	32.97	146.65	0.16	4.24E-05	1.897	0.930	1.13	28.63	127.35	1453	10374
2114-Block-2-AG-24	AG	WG	1	32.81	145.94	0.16	4.24E-05	1.897	0.930	1.12	23.17	103.06	1066	22923
2114-Block-2-AG-25	AG	WG	1	34.08	151.59	0.16	4.24E-05	1.897	0.930	1.17	27.75	123.43	1615	15020

2114-Block-2-AG-26	AG	WG	1	33.67	149.76	0.16	4.24E-05	1.897	0.930	1.15	30.28	134.69	897	20713
2114-Block-2-AG-27	AG	WG	1	33.23	147.81	0.16	4.24E-05	1.897	0.930	1.14	29.89	132.95	1733	39895
2114-Block-2-AG-28	AG	WG	1	32.83	146.03	0.16	4.24E-05	1.897	0.930	1.12	28.83	128.24	1841	10635
2114-Block-2-AG-29	AG	WG	1	34.28	152.48	0.16	4.24E-05	1.897	0.930	1.17	27.97	124.41	1499	21790
2114-Block-2-AG-30	AG	WG	1	33.48	148.92	0.16	4.24E-05	1.897	0.930	1.15	10.61	47.19	1461	8409
2114-Block-2-AG-31	AG	WG	1	33.39	148.52	0.16	4.24E-05	1.897	0.930	1.14	28.70	127.66	1433	20701
2114-Block-4-AG-2	AG	WG	1	35.23	156.70	0.16	4.24E-05	1.897	0.930	1.21	30.02	133.53	1220	15296
2114-Block-4-AG-3	AG	WG	1	32.83	146.03	0.16	4.24E-05	1.897	0.930	1.12	24.58	109.33	3234	29936
2114-Block-4-AG-4	AG	WG	1	34.38	152.92	0.16	4.24E-05	1.897	0.930	1.18	31.02	137.98	1092	13689
2114-Block-4-AG-5	AG	WG	1	33.08	147.14	0.16	4.24E-05	1.897	0.930	1.13	30.08	133.80	790	10858
2114-Block-4-AG-6	AG	WG	1	33.59	149.41	0.16	4.24E-05	1.897	0.930	1.15	28.33	126.01	1989	8739
2114-Block-4-AG-7	AG	WG	1	33.23	147.81	0.16	4.24E-05	1.897	0.930	1.14	28.91	128.59	1704	11864
2114-Block-4-AG-8	AG	WG	1	32.38	144.03	0.16	4.24E-05	1.897	0.930	1.11	28.13	125.12	547	6328
2114-Block-4-AG-9	AG	WG	1	33.50	149.01	0.16	4.24E-05	1.897	0.930	1.15	30.84	137.18	867	7086
2114-Block-4-AG-10	AG	WG	1	31.73	141.14	0.16	4.24E-05	1.897	0.930	1.09	24.03	106.89	1355	18986
2114-Block-4-AG-11	AG	WG	1	34.19	152.08	0.16	4.24E-05	1.897	0.930	1.17	28.66	127.48	794	5311
2114-Block-4-AG-12	AG	WG	1	34.36	152.83	0.16	4.24E-05	1.897	0.930	1.18	31.30	139.22	1175	14359
2114-Block-4-AG-13	AG	WG	1	ERROR		0.16	4.24E-05	1.897	0.930	0.00	ERROR			
2114-Block-4-AG-14	AG	WG	1	33.25	147.90	0.16	4.24E-05	1.897	0.930	1.14	27.78	123.57	880	32525
2114-Block-4-AG-15	AG	WG	1	33.64	149.63	0.16	4.24E-05	1.897	0.930	1.15	27.34	121.61	3608	18412
2114-Block-4-AG-18	AG	WG	1	32.84	146.07	0.16	4.24E-05	1.897	0.930	1.12	31.33	139.36	1698	7980
2114-Block-4-AG-19	AG	WG	1	33.28	148.03	0.16	4.24E-05	1.897	0.930	1.14	28.06	124.81	672	8479
2114-Block-4-AG-20	AG	WG	1	33.28	148.03	0.16	4.24E-05	1.897	0.930	1.14	29.73	132.24	1382	9807
2114-Block-4-AG-21	AG	WG	1	33.20	147.67	0.16	4.24E-05	1.897	0.930	1.14	29.67	131.97	949	12141
2114-Block-4-AG-22	AG	WG	1	32.05	142.56	0.16	4.24E-05	1.897	0.930	1.10	29.30	130.33	881	8345
2114-Block-4-AG-23	AG	WG	1	33.75	150.12	0.16	4.24E-05	1.897	0.930	1.16	31.20	138.78	1363	11084
2114-Block-4-AG-24	AG	WG	1	33.63	149.59	0.16	4.24E-05	1.897	0.930	1.15	29.22	129.97	505	5728
2114-Block-4-AG-25	AG	WG	1	34.00	151.23	0.16	4.24E-05	1.897	0.930	1.16	28.31	125.92	1003	10919
2114-Block-4-AG-26	AG	WG	1	33.53	149.14	0.16	4.24E-05	1.897	0.930	1.15	28.31	125.92	1528	27756
2114-Block-4-AG-27	AG	WG	1	32.64	145.18	0.16	4.24E-05	1.897	0.930	1.12	28.92	128.64	2035	12369

2114-Block-4-AG-28	AG	WG	1	33.56	149.27	0.16	4.24E-05	1.897	0.930	1.15	28.11	125.03	547	16745
2114-Block-4-AG-29	AG	WG	1	32.81	145.94	0.16	4.24E-05	1.897	0.930	1.12	25.64	114.05	931	10379
2114-Block-4-AG-30	AG	WG	1	33.17	147.54	0.16	4.24E-05	1.897	0.930	1.14	30.59	136.06	2221	17049
2114-Block-4-AG-31	AG	WG	1	35.34	157.19	0.16	4.24E-05	1.897	0.930	1.21	33.44	148.74	1134	25155
				Mean	148.77					1.15		127.49	1503	15713
				SD	3.05					0.02		14.10	717	10229

Table 9 K_{Ic} and AE data for grade IG-110 (Graphite assumed to be isotropic)

IG-110 (15x20x200 mm, a/W=0.40)														
Specimen ID	Spec Orientation	Crack Orientation	g	P(max)		S	B*(W^(3/2))	3((a/W)^(1/2))	2(1-(a/W))^(3/2))	KIc	Onset Force		ΣAE at max load	ΣAE at total fracture (50 N or 11.24 lbf load)
				lbf	N	M				MPa.√m	lbf	N	AE Counts	AE Counts
IG-110/1	x	x	1	30.48	135.58	0.16	4.243E-05	1.897	0.930	1.04	29.06	129.26	642	8241
IG-110/2	x	x	1	31.84	141.62	0.16	4.243E-05	1.897	0.930	1.09	29.86	132.82	224	9671
IG-110/3	x	x	1	31.95	142.11	0.16	4.243E-05	1.897	0.930	1.09	28.83	128.24	233	13478
IG-110/4	x	x	1	31.17	138.64	0.16	4.243E-05	1.897	0.930	1.07	26.58	118.23	334	9914
IG-110/5	x	x	1	31.73	141.14	0.16	4.243E-05	1.897	0.930	1.09	26.61	118.36	357	8825
IG-110/6	x	x	1	30.77	136.86	0.16	4.243E-05	1.897	0.930	1.05	26.64	118.49	399	12438
IG-110/7	x	x	1	31.88	141.80	0.16	4.243E-05	1.897	0.930	1.09	29.13	129.57	143	14181
IG-110/8	x	x	1	31.63	140.69	0.16	4.243E-05	1.897	0.930	1.08	28.86	128.37	481	9717
IG-110/9	x	x	1	31.08	138.24	0.16	4.243E-05	1.897	0.930	1.06	28.16	125.26	85	11846
IG-110/10	x	x	1	31.61	140.60	0.16	4.243E-05	1.897	0.930	1.08	24.03	106.89	478	11904
IG-110/11	x	x	1	29.44	130.95	0.16	4.243E-05	1.897	0.930	1.01	27.06	120.36	593	11047
IG-110/12	x	x	1	31.73	141.14	0.16	4.243E-05	1.897	0.930	1.09	31.39	139.62	333	12184
IG-110/13	x	x	1	30.88	137.35	0.16	4.243E-05	1.897	0.930	1.06	38.67	172.00	219	10521
IG-110/14	x	x	1	32.05	142.56	0.16	4.243E-05	1.897	0.930	1.10	20.8	92.52	643	11009
IG-110/15	x	x	1	32.56	144.83	0.16	4.243E-05	1.897	0.930	1.11	24.42	108.62	63	11228
IG-110/16	x	x	1	28.34	126.06	0.16	4.243E-05	1.897	0.930	0.97	23.75	105.64	447	9265
IG-110/17	x	x	1	29.92	133.08	0.16	4.243E-05	1.897	0.930	1.02	26.67	118.63	1474	12300
IG-110/18	x	x	1	31.61	140.60	0.16	4.243E-05	1.897	0.930	1.08	24.52	109.06	1630	15043
IG-110/19	x	x	1	31.31	139.27	0.16	4.243E-05	1.897	0.930	1.07	25.91	115.25	307	10161
IG-110/20	x	x	1	31.63	140.69	0.16	4.243E-05	1.897	0.930	1.08	28.19	125.39	760	11794
IG-110/21	x	x	1	31.73	141.14	0.16	4.243E-05	1.897	0.930	1.09	27.41	121.92	222	12629
IG-110/22	x	x	1	32.20	143.23	0.16	4.243E-05	1.897	0.930	1.10	30.22	134.42	795	10831
IG-110/23	x	x	1	31.52	140.20	0.16	4.243E-05	1.897	0.930	1.08	29.48	131.13	1174	14337

IG-110/24	x	x	1	30.86	137.27	0.16	4.243E-05	1.897	0.930	1.06	28.38	126.23	319	10683
IG-110/25	x	x	1	30.56	135.93	0.16	4.243E-05	1.897	0.930	1.05	29.67	131.97	500	10711
IG-110/26	x	x	1	30.94	137.62	0.16	4.243E-05	1.897	0.930	1.06	27.22	121.07	358	13217
IG-110/27	x	x	1	31.34	139.40	0.16	4.243E-05	1.897	0.930	1.07	28.97	128.86	510	13519
IG-110/28	x	x	1	31.48	140.02	0.16	4.243E-05	1.897	0.930	1.08	27.17	120.85	1199	12578
IG-110/29	x	x	1	30.86	137.27	0.16	4.243E-05	1.897	0.930	1.06	24.84	110.49	1368	13215
IG-110/30	x	x	1	29.83	132.68	0.16	4.243E-05	1.897	0.930	1.02	27.92	124.19	450	13709
IG-110/31	x	x	1	31.08	138.24	0.16	4.243E-05	1.897	0.930	1.06	28.61	127.26	1630	11240
IG-110/32	x	x	1	32.09	142.74	0.16	4.243E-05	1.897	0.930	1.10	30.14	134.06	364	14189
				Mean	138.74					1.07		123.59	585	11738
				SD	3.91					0.03		13.42	446	1738

Table 10 K_{Ic} and AE data for grade PCEA, WG specimen (AG fracture orientation)

PCEA WG (PAR) orientation (15x20x200 mm, a/W=0.40)														
Specimen ID	Spec Orientation	Crack Orientation	g	P(max)		S	B*(W^(3/2))	3((a/W)^(1/2))	2(1-(a/W))^(3/2))	KIc	Onset Force		ΣAE at max load	ΣAE at total fracture (50 N or 11.24 lbf load)
	WG	AG		lbf	N	M				MPa.√m	lbf	N	AE Counts	AE Counts
1	WG	AG	1	43.36	192.87	0.16	4.243E-05	1.897	0.930	1.48	32.03	142.47	4437	35749
2	WG	AG	1	40.81	181.52	0.16	4.243E-05	1.897	0.930	1.40	21.60	96.08	1533	25520
3	WG	AG	1	40.16	178.63	0.16	4.243E-05	1.897	0.930	1.38	10.17	45.24	2390	19050
4	WG	AG	1	41.33	183.84	0.16	4.243E-05	1.897	0.930	1.42	37.91	168.62	772	30700
5	WG	AG	1	42.25	187.93	0.16	4.243E-05	1.897	0.930	1.45	15.69	69.79	2805	28561
6	WG	AG	1	41.13	182.95	0.16	4.243E-05	1.897	0.930	1.41	38.08	169.38	3105	24562
7	WG	AG	1	41.41	184.19	0.16	4.243E-05	1.897	0.930	1.42	24.34	108.26	4761	40729
8	WG	AG	1	43.05	191.49	0.16	4.243E-05	1.897	0.930	1.47	37.16	165.29	1523	22813
9	WG	AG	1	42.19	187.66	0.16	4.243E-05	1.897	0.930	1.44	25.75	114.54	3491	30377
10	WG	AG	1	42.94	191.00	0.16	4.243E-05	1.897	0.930	1.47	21.09	93.81	2986	28485
11	WG	AG	1	44.47	197.80	0.16	4.243E-05	1.897	0.930	1.52	21.34	94.92	1877	30416
12	WG	AG	1	41.09	182.77	0.16	4.243E-05	1.897	0.930	1.41	29.28	130.24	5789	44433
13	WG	AG	1	39.81	177.07	0.16	4.243E-05	1.897	0.930	1.36	24.89	110.71	4294	32401
14	WG	AG	1	42.52	189.13	0.16	4.243E-05	1.897	0.930	1.46	27.86	123.92	3016	32940
15	WG	AG	1	40.75	181.26	0.16	4.243E-05	1.897	0.930	1.40	24.52	109.06	1066	25032
16	WG	AG	1	41.28	183.61	0.16	4.243E-05	1.897	0.930	1.41	26.44	117.61	4257	29954
17	WG	AG	1	40.91	181.97	0.16	4.243E-05	1.897	0.930	1.40	30.56	135.93	2136	30591
18	WG	AG	1	41.92	186.46	0.16	4.243E-05	1.897	0.930	1.44	35.52	157.99	1491	20411
19	WG	AG	1	42.70	189.93	0.16	4.243E-05	1.897	0.930	1.46	35.77	159.10	205	8631
20	WG	AG	1	42.83	190.51	0.16	4.243E-05	1.897	0.930	1.47	29.45	130.99	3509	31582
21	WG	AG	1	42.20	187.71	0.16	4.243E-05	1.897	0.930	1.44	28.55	126.99	3835	35986
22	WG	AG	1	41.77	185.79	0.16	4.243E-05	1.897	0.930	1.43	26.42	117.52	6319	38339

23	WG	AG	1	40.30	179.25	0.16	4.243E-05	1.897	0.930	1.38	21.52	95.72	5543	29834
24	WG	AG	1	43.45	193.27	0.16	4.243E-05	1.897	0.930	1.49	29.13	129.57	2200	27514
25	WG	AG	1	40.52	180.23	0.16	4.243E-05	1.897	0.930	1.39	24.91	110.80	4616	38495
26	WG	AG	1	39.45	175.47	0.16	4.243E-05	1.897	0.930	1.35	28.02	124.63	1496	25556
27	WG	AG	1	41.42	184.24	0.16	4.243E-05	1.897	0.930	1.42	31.89	141.85	2769	24581
28	WG	AG	1	41.19	183.21	0.16	4.243E-05	1.897	0.930	1.41	32.02	142.42	4044	28204
29	WG	AG	1	41.95	186.59	0.16	4.243E-05	1.897	0.930	1.44	30.28	134.69	4697	32077
30	WG	AG	1	39.44	175.43	0.16	4.243E-05	1.897	0.930	1.35	26.61	118.36	3400	24835
31	WG	AG	1	41.52	184.68	0.16	4.243E-05	1.897	0.930	1.42	23.48	104.44	710	19807
32	WG	AG	1	40.97	182.23	0.16	4.243E-05	1.897	0.930	1.40	29.67	131.97	2392	22120
33	WG	AG	1	40.11	178.41	0.16	4.243E-05	1.897	0.930	1.37	33.69	149.85	2244	25451
34	WG	AG	1	42.75	190.15	0.16	4.243E-05	1.897	0.930	1.46	33.75	150.12	3208	27906
35	WG	AG	1	43.16	191.98	0.16	4.243E-05	1.897	0.930	1.48	27.53	122.45	1005	27353
36	WG	AG	1	43.08	191.62	0.16	4.243E-05	1.897	0.930	1.48	29.00	128.99	2915	24021
37	WG	AG	1	40.88	181.83	0.16	4.243E-05	1.897	0.930	1.40	30.48	135.58	3639	25483
38	WG	AG	1	42.42	188.68	0.16	4.243E-05	1.897	0.930	1.45	35.45	157.68	1150	17289
39	WG	AG	1	43.64	194.11	0.16	4.243E-05	1.897	0.930	1.49	34.48	153.37	3474	28578
40	WG	AG	1	42.03	186.95	0.16	4.243E-05	1.897	0.930	1.44	34.63	154.03	3503	35985
41	WG	AG	1	43.95	195.49	0.16	4.243E-05	1.897	0.930	1.50	37.84	168.31	1176	30191
42	WG	AG	1	41.50	184.59	0.16	4.243E-05	1.897	0.930	1.42	30.75	136.78	2451	29300
43	WG	AG	1	42.64	189.66	0.16	4.243E-05	1.897	0.930	1.46	33.27	147.98	3911	22513
44	WG	AG	1	42.42	188.68	0.16	4.243E-05	1.897	0.930	1.45	23.39	104.04	2158	24498
45	WG	AG	1	42.23	187.84	0.16	4.243E-05	1.897	0.930	1.45	36.70	163.24	1059	22596
46	WG	AG	1	42.50	189.04	0.16	4.243E-05	1.897	0.930	1.46	33.84	150.52	2471	30253
47	WG	AG	1	42.91	190.86	0.16	4.243E-05	1.897	0.930	1.47	31.03	138.02	729	26748
48	WG	AG	1	41.24	183.44	0.16	4.243E-05	1.897	0.930	1.41	53.33	237.21	1758	21367
49	WG	AG	1	42.02	186.90	0.16	4.243E-05	1.897	0.930	1.44	33.22	147.76	2678	29301
50	WG	AG	1	42.19	187.66	0.16	4.243E-05	1.897	0.930	1.44	24.22	107.73	2880	24097
51	WG	AG	1	46.30	205.94	0.16	4.243E-05	1.897	0.930	1.59	35.58	158.26	2752	21350
52	WG	AG	1	43.52	193.58	0.16	4.243E-05	1.897	0.930	1.49	29.59	131.62	3591	24394

53	WG	AG	1	44.14	196.33	0.16	4.243E-05	1.897	0.930	1.51	28.00	124.54	2581	23293
54	WG	AG	1	42.13	187.39	0.16	4.243E-05	1.897	0.930	1.44	24.45	108.75	2847	27831
55	WG	AG	1	41.22	183.35	0.16	4.243E-05	1.897	0.930	1.41	23.81	105.91	1460	16809
56	WG	AG	1	43.73	194.51	0.16	4.243E-05	1.897	0.930	1.50	34.97	155.55	1849	22870
57	WG	AG	1	46.94	208.79	0.16	4.243E-05	1.897	0.930	1.61	33.05	147.01	1397	17864
58	WG	AG	1	44.20	196.60	0.16	4.243E-05	1.897	0.930	1.51	33.31	148.16	3505	23493
59	WG	AG	1	45.44	202.12	0.16	4.243E-05	1.897	0.930	1.56	31.94	142.07	3114	23056
60	WG	AG	1	45.94	204.34	0.16	4.243E-05	1.897	0.930	1.57	36.05	160.35	2262	28776
61	WG	AG	1	44.38	197.40	0.16	4.243E-05	1.897	0.930	1.52	41.52	184.68	702	14357
62	WG	AG	1	45.25	201.27	0.16	4.243E-05	1.897	0.930	1.55	33.75	150.12	778	18215
63	WG	AG	1	44.63	198.51	0.16	4.243E-05	1.897	0.930	1.53	39.20	174.36	1000	16201
64	WG	AG	1	43.28	192.51	0.16	4.243E-05	1.897	0.930	1.48	31.09	138.29	5671	38815
65	WG	AG	1	45.05	200.38	0.16	4.243E-05	1.897	0.930	1.54	33.33	148.25	1000	16194
66	WG	AG	1	42.81	190.42	0.16	4.243E-05	1.897	0.930	1.47	25.25	112.31	4599	26816
67	WG	AG	1	45.13	200.74	0.16	4.243E-05	1.897	0.930	1.55	16.14	71.79	2290	23568
68	WG	AG	1	46.16	205.32	0.16	4.243E-05	1.897	0.930	1.58	35.55	158.13	3082	21736
69	WG	AG	1	42.91	190.86	0.16	4.243E-05	1.897	0.930	1.47	37.89	168.53	1093	14163
70	WG	AG	1	46.08	204.96	0.16	4.243E-05	1.897	0.930	1.58	34.77	154.66	1456	14056
71	WG	AG	1	43.30	192.60	0.16	4.243E-05	1.897	0.930	1.48	31.72	141.09	2887	34545
72	WG	AG	1	44.08	196.07	0.16	4.243E-05	1.897	0.930	1.51	36.22	161.11	1005	15303
73	WG	AG	1	43.92	195.36	0.16	4.243E-05	1.897	0.930	1.50	30.48	135.58	3245	13706
74	WG	AG	1	44.38	197.40	0.16	4.243E-05	1.897	0.930	1.52	30.92	137.53	3212	32921
75	WG	AG	1	45.20	201.05	0.16	4.243E-05	1.897	0.930	1.55	26.80	119.21	801	14184
76	WG	AG	1	43.19	192.11	0.16	4.243E-05	1.897	0.930	1.48	21.41	95.23	493	18771
77	WG	AG	1	43.73	194.51	0.16	4.243E-05	1.897	0.930	1.50	32.83	146.03	910	16602
78	WG	AG	1	45.95	204.39	0.16	4.243E-05	1.897	0.930	1.57	33.06	147.05	1764	19228
79	WG	AG	1	44.17	196.47	0.16	4.243E-05	1.897	0.930	1.51	31.69	140.96	1191	17845
80	WG	AG	1	44.59	198.34	0.16	4.243E-05	1.897	0.930	1.53	35.16	156.39	1684	14945
81	WG	AG	1	45.17	200.92	0.16	4.243E-05	1.897	0.930	1.55	31.19	138.73	2711	26095
82	WG	AG	1	43.67	194.24	0.16	4.243E-05	1.897	0.930	1.50	30.64	136.29	1548	13227

83	WG	AG	1	45.69	203.23	0.16	4.243E-05	1.897	0.930	1.56	28.69	127.61	2446	19372
84	WG	AG	1	44.73	198.96	0.16	4.243E-05	1.897	0.930	1.53	37.73	167.82	898	14848
85	WG	AG	1	45.52	202.47	0.16	4.243E-05	1.897	0.930	1.56	35.48	157.82	1721	21557
86	WG	AG	1	43.63	194.07	0.16	4.243E-05	1.897	0.930	1.49	31.97	142.20	1775	21024
87	WG	AG	1	43.67	194.24	0.16	4.243E-05	1.897	0.930	1.50	25.20	112.09	3086	24318
88	WG	AG	1	43.09	191.66	0.16	4.243E-05	1.897	0.930	1.48	31.56	140.38	2779	23439
89	WG	AG	1	44.44	197.67	0.16	4.243E-05	1.897	0.930	1.52	35.09	156.08	1409	21010
90	WG	AG	1	46.03	204.74	0.16	4.243E-05	1.897	0.930	1.58	39.11	173.96	371	21345
91	WG	AG	1	44.09	196.11	0.16	4.243E-05	1.897	0.930	1.51	27.48	122.23	1964	19446
92	WG	AG	1	46.88	208.52	0.16	4.243E-05	1.897	0.930	1.61	38.80	172.58	1611	18068
93	WG	AG	1	42.81	190.42	0.16	4.243E-05	1.897	0.930	1.47	27.59	122.72	1016	15203
94	WG	AG	1	45.56	202.65	0.16	4.243E-05	1.897	0.930	1.56	36.58	162.71	341	13760
95	WG	AG	1	46.50	206.83	0.16	4.243E-05	1.897	0.930	1.59	24.19	107.60	1486	17939
96	WG	AG	1	44.36	197.31	0.16	4.243E-05	1.897	0.930	1.52	32.44	144.29	2361	20620
97	WG	AG	1	44.77	199.14	0.16	4.243E-05	1.897	0.930	1.53	34.69	154.30	1568	18041
98	WG	AG	1	44.30	197.05	0.16	4.243E-05	1.897	0.930	1.52	37.36	166.18	867	18274
99	WG	AG	1	42.81	190.42	0.16	4.243E-05	1.897	0.930	1.47	28.72	127.75	2300	22060
100	WG	AG	1	41.06	182.63	0.16	4.243E-05	1.897	0.930	1.41	38.83	172.72	1143	14030
101	WG	AG	1	41.30	183.70	0.16	4.243E-05	1.897	0.930	1.41	31.00	137.89	667	11278
102	WG	AG	1	43.75	194.60	0.16	4.243E-05	1.897	0.930	1.50	31.16	138.60	2084	16320
103	WG	AG	1	43.70	194.38	0.16	4.243E-05	1.897	0.930	1.50	27.84	123.83	1809	15632
104	WG	AG	1	43.78	194.73	0.16	4.243E-05	1.897	0.930	1.50	28.27	125.74	938	19574
105	WG	AG	1	42.88	190.73	0.16	4.243E-05	1.897	0.930	1.47	33.39	148.52	1566	20127
106	WG	AG	1	44.50	197.94	0.16	4.243E-05	1.897	0.930	1.52	26.86	119.47	1087	18967
107	WG	AG	1	45.56	202.65	0.16	4.243E-05	1.897	0.930	1.56	36.72	163.33	1740	27702
108	WG	AG	1	43.89	195.22	0.16	4.243E-05	1.897	0.930	1.50	29.33	130.46	2915	24105
109	WG	AG	1	43.75	194.60	0.16	4.243E-05	1.897	0.930	1.50	21.03	93.54	590	17429
110	WG	AG	1	46.81	208.21	0.16	4.243E-05	1.897	0.930	1.60	25.81	114.80	1797	20208
111	WG	AG	1	44.66	198.65	0.16	4.243E-05	1.897	0.930	1.53	32.80	145.89	2303	25544
112	WG	AG	1	44.95	199.94	0.16	4.243E-05	1.897	0.930	1.54	22.95	102.08	940	19030

113	WG	AG	1	45.36	201.76	0.16	4.243E-05	1.897	0.930	1.55	33.80	150.34	2372	25110
114	WG	AG	1	45.39	201.89	0.16	4.243E-05	1.897	0.930	1.55	34.44	153.19	1156	16514
115	WG	AG	1	45.19	201.01	0.16	4.243E-05	1.897	0.930	1.55	33.75	150.12	3766	28066
116	WG	AG	1	41.53	184.73	0.16	4.243E-05	1.897	0.930	1.42	33.00	146.78	1325	27697
117	WG	AG	1	42.83	190.51	0.16	4.243E-05	1.897	0.930	1.47	29.11	129.48	3264	19394
118	WG	AG	1	46.75	207.94	0.16	4.243E-05	1.897	0.930	1.60	36.00	160.13	2211	20707
				Mean	192.62					1.48		136.78	2288	23578
				SD	7.97					0.06		26.02	1291	6821

Table 11 K_{Ic} and AE data for grade PCEA, AG specimen (WG fracture orientation)

PCEA AG (PER) orientation (15x20x200 mm, a/W=0.40)														
Specimen ID	Spec Orientation	Crack Orientation	g	P(max)		S	B*(W^(3/2))	3((a/W)^(1/2))	2(1-(a/W))^(3/2))	KIc	Onset Force		ΣAE at max load	ΣAE at total fracture (50 N or 11.24 lbf load)
	AG	WG		lbf	N	M				MPa.√m	lbf	N	AE Counts	AE Counts
1	AG	WG	1	37.94	168.76	0.16	4.243E-05	1.897	0.930	1.30	28.5	126.77	3294	27403
2	AG	WG	1	37.91	168.62	0.16	4.243E-05	1.897	0.930	1.30	4.05	18.01	4128	22595
3	AG	WG	1	38.09	169.42	0.16	4.243E-05	1.897	0.930	1.30	23.13	102.88	1926	7149
4	AG	WG	1	36.83	163.82	0.16	4.243E-05	1.897	0.930	1.26	24.75	110.09	2265	24061
5	AG	WG	1	38.23	170.05	0.16	4.243E-05	1.897	0.930	1.31	32.55	144.78	1295	18248
6	AG	WG	1	38.88	172.94	0.16	4.243E-05	1.897	0.930	1.33	27.02	120.18	1836	22146
7	AG	WG	1	37.27	165.78	0.16	4.243E-05	1.897	0.930	1.28	31.59	140.51	1177	18708
8	AG	WG	1	36.72	163.33	0.16	4.243E-05	1.897	0.930	1.26	30.72	136.64	2878	20993
9	AG	WG	1	36.63	162.93	0.16	4.243E-05	1.897	0.930	1.25	31.34	139.40	2561	17332
10	AG	WG	1	38.25	170.14	0.16	4.243E-05	1.897	0.930	1.31	27.20	120.99	2669	17948
11	AG	WG	1	38.00	169.02	0.16	4.243E-05	1.897	0.930	1.30	31.05	138.11	1939	25492
12	AG	WG	1	38.02	169.11	0.16	4.243E-05	1.897	0.930	1.30	27.78	123.57	1491	25606
13	AG	WG	1	38.20	169.91	0.16	4.243E-05	1.897	0.930	1.31	29.69	132.06	2794	21366
14	AG	WG	1	37.19	165.42	0.16	4.243E-05	1.897	0.930	1.27	30.58	136.02	506	19765
15	AG	WG	1	36.28	161.37	0.16	4.243E-05	1.897	0.930	1.24	25.36	112.80	1389	20452
16	AG	WG	1	38.83	172.72	0.16	4.243E-05	1.897	0.930	1.33	25.16	111.91	3971	20284
17	AG	WG	1	37.84	168.31	0.16	4.243E-05	1.897	0.930	1.30	31.41	139.71	2534	24765
18	AG	WG	1	37.02	164.66	0.16	4.243E-05	1.897	0.930	1.27	19.33	85.98	1899	26736
19	AG	WG	1	38.16	169.74	0.16	4.243E-05	1.897	0.930	1.31	32.89	146.29	1260	21288
20	AG	WG	1	36.66	163.06	0.16	4.243E-05	1.897	0.930	1.26	32.44	144.29	1419	23220
21	AG	WG	1	38.50	171.25	0.16	4.243E-05	1.897	0.930	1.32	28.42	126.41	492	21194

22	AG	WG	1	37.84	168.31	0.16	4.243E-05	1.897	0.930	1.30	20.52	91.27	1259	29206
23	AG	WG	1	38.34	170.54	0.16	4.243E-05	1.897	0.930	1.31	31.70	141.00	3095	24336
24	AG	WG	1	37.64	167.42	0.16	4.243E-05	1.897	0.930	1.29	21.05	93.63	1689	1724
25	AG	WG	1	37.11	165.07	0.16	4.243E-05	1.897	0.930	1.27	25.16	111.91	2372	20006
26	AG	WG	1	38.42	170.89	0.16	4.243E-05	1.897	0.930	1.32	30.99	137.84	817	21799
27	AG	WG	1	37.02	164.66	0.16	4.243E-05	1.897	0.930	1.27	30.53	135.80	2327	20764
28	AG	WG	1	38.89	172.98	0.16	4.243E-05	1.897	0.930	1.33	32.64	145.18	2998	25038
29	AG	WG	1	38.81	172.63	0.16	4.243E-05	1.897	0.930	1.33	25.95	115.43	1156	22052
30	AG	WG	1	37.02	164.66	0.16	4.243E-05	1.897	0.930	1.27	23.89	106.26	1184	15749
31	AG	WG	1	36.88	164.04	0.16	4.243E-05	1.897	0.930	1.26	26.17	116.40	1859	22394
32	AG	WG	1	37.20	165.47	0.16	4.243E-05	1.897	0.930	1.27	27.20	120.99	5388	31909
33	AG	WG	1	37.86	168.40	0.16	4.243E-05	1.897	0.930	1.30	23.61	105.02	1520	13496
34	AG	WG	1	38.84	172.76	0.16	4.243E-05	1.897	0.930	1.33	23.39	104.04	1241	26466
35	AG	WG	1	37.59	167.20	0.16	4.243E-05	1.897	0.930	1.29	20.59	91.58	2541	20106
36	AG	WG	1	37.42	166.44	0.16	4.243E-05	1.897	0.930	1.28	27.34	121.61	2423	21789
37	AG	WG	1	36.50	162.35	0.16	4.243E-05	1.897	0.930	1.25	24.2	107.64	5643	39300
38	AG	WG	1	Test Error		0.16	4.243E-05	1.897	0.930	0.00	Test Error			
39	AG	WG	1			0.16	4.243E-05	1.897	0.930	0.00				
40	AG	WG	1	38.45	171.03	0.16	4.243E-05	1.897	0.930	1.32	28.7	127.66	2116	24798
41	AG	WG	1	37.27	165.78	0.16	4.243E-05	1.897	0.930	1.28	16.84	74.90	1766	17615
42	AG	WG	1	39.92	177.56	0.16	4.243E-05	1.897	0.930	1.37	25.8	114.76	1246	20415
43	AG	WG	1	39.48	175.61	0.16	4.243E-05	1.897	0.930	1.35	31.83	141.58	1138	19168
44	AG	WG	1	38.77	172.45	0.16	4.243E-05	1.897	0.930	1.33	26.59	118.27	2523	23824
45	AG	WG	1	37.78	168.05	0.16	4.243E-05	1.897	0.930	1.29	31.45	139.89	1849	24080
46	AG	WG	1	38.53	171.38	0.16	4.243E-05	1.897	0.930	1.32	34.27	152.43	511	22520
47	AG	WG	1	38.56	171.51	0.16	4.243E-05	1.897	0.930	1.32	33.19	147.63	585	20991
48	AG	WG	1	37.27	165.78	0.16	4.243E-05	1.897	0.930	1.28	24.88	110.67	2149	29039
49	AG	WG	1	38.66	171.96	0.16	4.243E-05	1.897	0.930	1.32	28.89	128.50	2245	26924
50	AG	WG	1	38.7	172.14	0.16	4.243E-05	1.897	0.930	1.33	27.3	121.43	3699	25070
51	AG	WG	1	39.81	177.07	0.16	4.243E-05	1.897	0.930	1.36	24.83	110.44	1468	16145

52	AG	WG	1	37.48	166.71	0.16	4.243E-05	1.897	0.930	1.28	32.77	145.76	2501	18760
53	AG	WG	1	39.09	173.87	0.16	4.243E-05	1.897	0.930	1.34	33.05	147.01	2352	18133
54	AG	WG	1	40.53	180.28	0.16	4.243E-05	1.897	0.930	1.39	28.98	128.90	1930	18919
55	AG	WG	1	41.23	183.39	0.16	4.243E-05	1.897	0.930	1.41	34.55	153.68	428	8894
56	AG	WG	1	42.30	188.15	0.16	4.243E-05	1.897	0.930	1.45	31.73	141.14	1187	17078
57	AG	WG	1	41.22	183.35	0.16	4.243E-05	1.897	0.930	1.41	24.34	108.26	1868	18972
58	AG	WG	1	42.30	188.15	0.16	4.243E-05	1.897	0.930	1.45	30.61	136.15	1405	11603
59	AG	WG	1	41.11	182.86	0.16	4.243E-05	1.897	0.930	1.41	32.34	143.85	846	9783
60	AG	WG	1	40.66	180.86	0.16	4.243E-05	1.897	0.930	1.39	33.89	150.74	1390	18192
61	AG	WG	1	42.33	188.28	0.16	4.243E-05	1.897	0.930	1.45	30.88	137.35	3522	20576
61	AG	WG	1	41.34	183.88	0.16	4.243E-05	1.897	0.930	1.42	21.69	96.48	2975	23179
63	AG	WG	1	41.45	184.37	0.16	4.243E-05	1.897	0.930	1.42	37.34	166.09	1620	16675
64	AG	WG	1	39.34	174.98	0.16	4.243E-05	1.897	0.930	1.35	31.98	142.25	1328	19707
65	AG	WG	1	41.20	183.26	0.16	4.243E-05	1.897	0.930	1.41	36.48	162.26	956	12977
66	AG	WG	1	39.98	177.83	0.16	4.243E-05	1.897	0.930	1.37	22.97	102.17	2236	23597
67	AG	WG	1	41.03	182.50	0.16	4.243E-05	1.897	0.930	1.40	35.59	158.30	981	20981
68	AG	WG	1	40.53	180.28	0.16	4.243E-05	1.897	0.930	1.39	33.67	149.76	165	10608
69	AG	WG	1	42.53	189.17	0.16	4.243E-05	1.897	0.930	1.46	36.05	160.35	797	11246
70	AG	WG	1	43.50	193.49	0.16	4.243E-05	1.897	0.930	1.49	29.95	133.22	2868	28433
71	AG	WG	1	42.61	189.53	0.16	4.243E-05	1.897	0.930	1.46	25.61	113.91	1594	21574
72	AG	WG	1	39.70	176.59	0.16	4.243E-05	1.897	0.930	1.36	30.88	137.35	4542	23286
73	AG	WG	1	41.05	182.59	0.16	4.243E-05	1.897	0.930	1.41	25.38	112.89	2132	17076
74	AG	WG	1	41.78	185.84	0.16	4.243E-05	1.897	0.930	1.43	12.31	54.75	1784	18668
75	AG	WG	1	40.53	180.28	0.16	4.243E-05	1.897	0.930	1.39	34.53	153.59	1495	21593
				Mean	7.98					1.33		125.03	1992	20603
				SD	7.98					0.06		24.95	1087	5753

Table 12 K_{Ic} and AE data for grade NBG-18, AG specimen-perpendicular to long axis of billet (WG fracture orientation)

NBG-18 (15x20x200 mm, a/W=0.40)														
Specimen ID	Spec Orientation	Crack Orientation	g	P(max)		S	B*(W^(3/2))	3((a/W)^(1/2))	2(1-(a/W))^(3/2))	KIc	Onset Force		ΣAE at max load	ΣAE at total fracture (50 N or 11.24 lbf load)
				lbf	N	M				MPa.√m	lbf	N	AE Counts	AE Counts
NBG-18-4B	perp 1	para	1	36.06	160.39	0.16	4.243E-05	1.897	0.930	1.23	33.64	149.63	599	26681
NBG-18-4B	perp 2	para	1	40.42	179.79	0.16	4.243E-05	1.897	0.930	1.38	28.91	128.59	10,095	60,693
NBG-18-4B	perp 3	para	1	43.97	195.58	0.16	4.243E-05	1.897	0.930	1.51	25.61	113.91	1692	51,091
NBG-18-4B	perp 4	para	1	40.98	182.28	0.16	4.243E-05	1.897	0.930	1.40	29.48	131.13	3295	39,855
NBG-18-4B	perp 5	para	1	36.84	163.86	0.16	4.243E-05	1.897	0.930	1.26	19.23	85.54	12177	82986
NBG-18-4B	perp 6	para	1	39.33	174.94	0.16	4.243E-05	1.897	0.930	1.35	31.08	138.24	1181	25424
NBG-18-4B	perp 7	para	1	40.94	182.10	0.16	4.243E-05	1.897	0.930	1.40	12.47	55.47	7345	53357
NBG-18-4B	perp 8	para	1	35.13	156.26	0.16	4.243E-05	1.897	0.930	1.20	17.00	75.62	1777	19834
NBG-18-4B	perp 9	para	1	40.98	182.28	0.16	4.243E-05	1.897	0.930	1.40	34.36	152.83	3400	46207
NBG-18-4B	perp 10	para	1	41.28	183.61	0.16	4.243E-05	1.897	0.930	1.41	31.61	140.60	3319	47280
NBG-18-4B	perp 11	para	1	42.23	187.84	0.16	4.243E-05	1.897	0.930	1.45	27.77	123.52	4311	57434
NBG-18-4B	perp 12	para	1	35.25	156.79	0.16	4.243E-05	1.897	0.930	1.21	22.73	101.10	2690	28195
NBG-18-4B	perp 13	para	1	43.88	195.18	0.16	4.243E-05	1.897	0.930	1.50	29.78	132.46	3412	52624
NBG-18-4B	perp 14	para	1	42.31	188.19	0.16	4.243E-05	1.897	0.930	1.45	31.06	138.15	2247	40316
NBG-18-4B	perp 15	para	1	41.63	185.17	0.16	4.243E-05	1.897	0.930	1.43	32.14	142.96	6122	64970
NBG-18 3B	perp 1	para	1	39.67	176.45	0.16	4.243E-05	1.897	0.930	1.36	29.69	132.06	1170	22898
NBG-18 3B	perp 2	para	1	41.84	186.10	0.16	4.243E-05	1.897	0.930	1.43	17.44	77.57	5012	55472
NBG-18 3B	perp 3	para	1	36.94	164.31	0.16	4.243E-05	1.897	0.930	1.26	28.09	124.94	2168	30326
NBG-18 3B	perp 4	para	1	42.56	189.31	0.16	4.243E-05	1.897	0.930	1.46	36.72	163.33	3388	43929
NBG-18 3B	perp 5	para	1	33.45	148.79	0.16	4.243E-05	1.897	0.930	1.15	21.39	95.14	1768	21859
NBG-18 3B	perp 6	para	1	37.89	168.53	0.16	4.243E-05	1.897	0.930	1.30	29.97	133.31	949	20175
NBG-18 3B	perp 7	para	1	38.69	172.09	0.16	4.243E-05	1.897	0.930	1.32	32.78	145.81	3423	46857
NBG-18 3B	perp 8	para	1	40.14	178.54	0.16	4.243E-05	1.897	0.930	1.37	25.39	112.93	3662	32795

NBG-18 3B	perp 9	para	1	36.41	161.95	0.16	4.243E-05	1.897	0.930	1.25	29.24	130.06	945	28084
NBG-18 3B	perp 10	para	1	41.09	182.77	0.16	4.243E-05	1.897	0.930	1.41	34.20	152.12	3298	42977
				Mean	176.12					1.36		123.08	3578	41693
				SD	12.81					0.10		27.31	2806	16115

Table 13 K_{Ic} and AE data for grade NBG-18, WG specimen-parallel to long axis of billet (AG fracture orientation)

NBG-18 (15x20x200 mm, a/W=0.40)															
Spec	Spec Orientation	Crack Orientation	g	P(max)		S	B*(W^(3/2))	3((a/W)^(1/2))	2(1-(a/W))^(3/2))	KIc	Onset Force		ΣAE at max load	ΣAE at total fracture (50 N or 11.24 lbf load)
				lbf	N					MPa .√m	lbf	N	AE Counts	AE Counts
NBG-18-3B	par 1	perp	1	36.98	164.49	0.16	4.243E-05	1.897	0.930	1.27	22.22	98.83	5748	55674
NBG-18-3B	par 2	perp	1	43.39	193.00	0.16	4.243E-05	1.897	0.930	1.49	25.94	115.38	3,812	48,474
NBG-18-3B	par 3	perp	1	41.78	185.84	0.16	4.243E-05	1.897	0.930	1.43	23.61	105.02	5325	78,777
NBG-18-3B	par 4	perp	1	41.28	183.61	0.16	4.243E-05	1.897	0.930	1.41	29.48	131.13	4210	51,883
NBG-18-3B	par 5	perp	1	40.86	181.75	0.16	4.243E-05	1.897	0.930	1.40	28.03	124.68	3826	57460
NBG-18-3B	par 6	perp	1	38.83	172.72	0.16	4.243E-05	1.897	0.930	1.33	29.61	131.71	4641	60117
NBG-18-3B	par 7	perp	1	40.63	180.72	0.16	4.243E-05	1.897	0.930	1.39	18.88	83.98	5045	64099
NBG-18-3B	par 8	perp	1	42.66	189.75	0.16	4.243E-05	1.897	0.930	1.46	31.91	141.94	2393	46733
NBG-18-3B	par 9	perp	1	40.52	180.23	0.16	4.243E-05	1.897	0.930	1.39	20.47	91.05	11825	48650
NBG-18-3B	par 10	perp	1	42.42	188.68	0.16	4.243E-05	1.897	0.930	1.45	28.19	125.39	4091	55132
NBG-18-3B	par 11	perp	1	42.27	188.02	0.16	4.243E-05	1.897	0.930	1.45	22.23	98.88	6423	52933
NBG-18-3B	par 12	perp	1	43.19	192.11	0.16	4.243E-05	1.897	0.930	1.48	29.78	132.46	2253	71502
NBG-18-3B	par 13	perp	1	42.20	187.71	0.16	4.243E-05	1.897	0.930	1.44	18.66	83.00	6490	62971
NBG-18-3B	par 14	perp	1	40.70	181.03	0.16	4.243E-05	1.897	0.930	1.39	31.86	141.71	3693	36406
NBG-18-3B	par 15	perp	1	40.03	178.05	0.16	4.243E-05	1.897	0.930	1.37	30.98	137.80	6566	48518
NBG-18-3B	par 16	perp	1	41.66	185.30	0.16	4.243E-05	1.897	0.930	1.43	31.02	137.98	3774	53527
NBG-18-3B	par 17	perp	1	41.86	186.19	0.16	4.243E-05	1.897	0.930	1.43	34.95	155.46	1300	37149
NBG-18-3B	par 18	perp	1	40.13	178.50	0.16	4.243E-05	1.897	0.930	1.37	26.28	116.89	1193	62687
NBG-18-3B	par 19	perp	1	40.78	181.39	0.16	4.243E-05	1.897	0.930	1.40	26.2	116.54	5590	60061
NBG-18-3B	par 20	perp	1	43.31	192.64	0.16	4.243E-05	1.897	0.930	1.48	25.86	115.03	2316	53549
NBG-18-3B	par 21	perp	1	41.00	182.37	0.16	4.243E-05	1.897	0.930	1.40	11.52	51.24	3818	43040
NBG-18-3B	par 22	perp	1	40.19	178.77	0.16	4.243E-05	1.897	0.930	1.38	18.55	82.51	2775	44076
NBG-18-3B	par 23	perp	1	39.36	175.07	0.16	4.243E-05	1.897	0.930	1.35	17.67	78.60	3676	44261

NBG-18-3B	par 24	perp	1	40.39	179.65	0.16	4.243E-05	1.897	0.930	1.38	30.31	134.82	3445	42021
NBG-18-3B	par 25	perp	1	40.70	181.03	0.16	4.243E-05	1.897	0.930	1.39	30.56	135.93	1991	72604
				MEAN	182.75					1.41		116.20	4249	54092
				S.D.	6.56					0.05		20.98	2209	10826

Table 14 K_{IIc} data for grade PCEA, specimen cut parallel to billet long axis or extrusion direction

PCEA Par specs (AG Notch should be tougher)										
		Compressive pert. (shear force), lbs	Compressive pert. (shear force), N	H=2h	W=2w	T=2t	σc=F/(w*T)	TADA'S EQUATION Kiic=(σc/4)*SQT(Pi*a*E-3)	2a	a
Spec no	fracture comments			mm	mm	mm	N/mm^2	MPa.√m	mm	mm
PCEA-Block 2-Para-1	Load pert. and AE	39075	170043.3	100.13	130.18	50.09	52.15	2.54	24.20	12.10
PCEA-Block 2-Para-2	AE	33221.9	144572.3	100.13	130.15	50.10	44.34	2.16	24.15	12.08
PCEA-Block 2-Para-3	AE	36159.4	157355.4	100.12	130.12	50.02	48.35	2.35	24.14	12.07
PCEA-Block 2-Para-4	Load pert. and AE	40375	175700.5	100.19	130.20	50.04	53.94	2.63	24.15	12.07
PCEA-Block 2-Para-5	AE	34687.5	150950.1	100.13	130.14	50.05	46.36	2.26	24.14	12.07
PCEA-Block 2-Para-6	Load pert. and AE	40968.8	178284.6	100.24	130.23	50.05	54.71	2.65	23.88	11.94
PCEA-Block 2-Para-7	Load pert. and AE	43125	187667.8	100.15	130.12	50.00	57.69	2.81	24.11	12.05
PCEA-Block 2-Para-8	Load pert. and AE	33581	146135.0	100.15	130.13	50.05	44.88	2.18	24.11	12.05
PCEA-Block 2-Para-9	Load perturbation	38840.6	169023.3	100.17	130.16	50.06	51.88	2.53	24.13	12.06
PCEA-Block 2-Para-10	Load pert. and AE	36437.5	158565.7	100.18	130.21	50.01	48.70	2.37	24.07	12.03
PCEA-Block 2-Para-11	NOT ANALYZED			100.15	130.17	50.02			24.04	12.02
PCEA-Block 2-Para-12	Load pert. and AE	40262.5	189882.8	100.13	130.19	50.01	58.33	2.83	23.98	11.99
PCEA-Block 2-Para-13	Load pert. and AE	43634	189882.8	100.18	130.22	50.07	58.25	2.82	23.82	11.91
PCEA-Block 2-Para-14	Load pert. and AE	34206.3	148856.1	100.15	130.12	50.02	45.74	2.22	24.05	12.03
PCEA-Block 2-Para-15	Load pert. and AE	42934.8	186840.1	100.20	130.21	50.03	57.37	2.77	23.81	11.90
PCEA-Block 2-Para-16	Load pert. and AE	26900	117061.2	100.12	130.18	50.06	35.93	1.75	24.18	12.09
PCEA-Block 2-Para-17	AE	36965.6	160863.8	100.14	130.17	50.05	49.38	2.40	24.14	12.07
PCEA-Block 2-Para-18	Load pert. and AE	39806.3	173225.7	100.22	130.25	50.06	53.14	2.57	23.83	11.92
PCEA-Block 3-Para-1	Load pert. and AE	35003.9	152327.0	100.051	130.26	50.22	46.57	2.27	24.22	12.11
PCEA-Block 3-Para-2	AE	31185.4	135710.0	100.00	130.21	50.17	41.55	2.03	24.36	12.18
PCEA-Block 3-Para-3	AE	44858.1	195209.7	100.00	130.21	50.08	59.88	2.92	24.26	12.13
PCEA-Block 3-Para-4	Load pert. and AE	34463.1	149973.6	100.05	130.21	50.18	45.91	2.24	24.19	12.09

PCEA-Block 3-Para-5	AE&?????	38914.4	169344.4	100.08	130.24	50.25	51.75	2.52	24.22	12.11
PCEA-Block 3-Para-6	Load pert. and AE	43644	189926.3	100.04	130.25	50.18	58.12	2.84	24.26	12.13
PCEA-Block 3-Para-7	NOT ANALYZED			100.04	130.25	50.28			24.03	12.02
PCEA-Block 3-Para-8	Load pert. and AE	39121.8	170247.0	100.10	130.19	50.20	52.11	2.53	24.00	12.00
PCEA-Block 3-Para-9	Load pert. and AE	40371.8	175686.6	100.01	130.21	50.22	53.74	2.62	24.25	12.13
PCEA-Block 3-Para-10	Load pert. and AE	39840.6	173375.0	100.01	130.21	50.12	53.13	2.58	24.06	12.03
PCEA-Block 3-Para-11	NOT ANALYZED			100.05	130.24	50.19			24.14	12.07
PCEA-Block 3-Para-12	Load pert. and AE	41396.9	180147.6	99.99	130.22	50.09	55.24	2.68	24.05	12.02
PCEA-Block 3-Para-13	AE	37137.5	161611.9	100.05	130.27	50.22	49.41	2.41	24.15	12.08
PCEA-Block 3-Para-14	Load pert. and AE	36840.6	160319.8	100.14	130.23	50.19	49.06	2.38	23.95	11.98
PCEA-Block 3-Para-15	Load pert. and AE	31306.3	136236.1	100.11	130.97	50.20	41.45	2.01	23.92	11.96
PCEA-Block 3-Para-16	Load pert. and AE	37446.9	162958.3	100.14	130.09	50.21	49.90	2.42	23.92	11.96
PCEA-Block 3-Para-17	Load pert. and AE	36778.1	160047.8	100.18	130.26	50.13	49.02	2.38	24.02	12.01
PCEA-Block 3-Para-18	Load perturbation	35396.9	154037.3	100.19	130.13	50.18	47.18	2.29	23.96	11.98
PCEA-Block 4-Para-1	Load perturbation	38415.6	167173.8	99.99	130.22	50.15	51.20	2.49	24.01	12.00
PCEA-Block 4-Para-2	Load pert. and AE	32356.3	140805.4	100.01	130.23	50.17	43.10	2.10	24.13	12.07
PCEA-Block 4-Para-3	Load pert. and AE	34678.1	150909.2	99.85	130.21	50.15	46.22	2.26	24.42	12.21
PCEA-Block 4-Para-4	NOT ANALYZED			99.86	130.23	50.19			24.41	12.21
PCEA-Block 4-Para-5	Load perturbation	33156.3	144286.8	100.02	130.23	50.18	44.16	2.15	24.13	12.06
PCEA-Block 4-Para-6	Load pert. and AE	38415.6	167173.8	100.02	130.25	50.16	51.17	2.49	24.06	12.03
PCEA-Block 4-Para-7	Load pert. and AE	33403.1	145360.8	99.84	130.26	50.15	44.50	2.18	24.47	12.24
PCEA-Block 4-Para-8	Load pert. and AE	38496.9	167527.6	99.99	130.21	50.15	51.31	2.49	24.04	12.02
PCEA-Block 4-Para-9	Load pert. and AE	34487.5	150079.8	100.04	130.27	50.17	45.93	2.24	24.13	12.06
PCEA-Block 4-Para-10	Load perturbation	36678.1	159612.7	99.99	130.20	50.18	48.87	2.38	24.13	12.07
PCEA-Block 4-Para-11	NOT ANALYZED			99.85	130.21	50.14			24.44	12.22
PCEA-Block 4-Para-12	AE	33706.3	146680.2	100.00	130.18	50.19	44.90	2.19	24.12	12.06
PCEA-Block 4-Para-13	Load perturbation	39671.9	172640.8	99.80	130.24	50.18	52.84	2.59	24.54	12.27
PCEA-Block 4-Para-14	AE	38409.4	167146.8	100.01	130.24	50.20	51.13	2.48	23.98	11.99
PCEA-Block 4-Para-15	Load perturbation	33721.9	146748.1	100.00	130.19	50.19	44.92	2.19	24.23	12.12
PCEA-Block 4-Para-16	AE	46500	202354.8	100.00	130.20	50.16	61.97	3.02	24.16	12.08

PCEA-Block 4-Para-17	Load pert. and AE	41156.3	179100.5	99.97	130.19	50.20	54.81	2.67	24.08	12.04
PCEA-Block 4-Para-18	Load pert. and AE	39078.1	170056.8	99.85	130.21	50.19	52.04	2.54	24.28	12.14

Mean	163463.8		2.44
St. Dev.	17455.7		0.26

Table 15 K_{IIC} data for PCEA, specimens cut perpendicular to the billet long axis or extrusion direction

PCEA PERP specs										
		Compressive pert. (shear force), lbs	Compressive pert. (shear force), N	H=2h	W=2w	T=2t	σc=F/(w*T)	TADA'S EQUATION Kiic=(σc/4)*SQT(Pi*a*E-3)	2a	a
Spec no	Fracture comments			mm	mm	mm	N/mm2	MPa.√m	mm	mm
PCEA-Block 1-Perp-1	Load perturbation	33437.5	145510.5	100.13	130.18	50.09	44.63	2.18	24.20	12.10
PCEA-Block 1-Perp-2	AE	31625	137623.0	100.13	130.15	50.10	42.21	2.06	24.15	12.08
PCEA-Block 1-Perp-3	Load pert. & AE (??)	30450	132509.8	100.12	130.12	50.02	40.72	1.98	24.14	12.07
PCEA-Block 1-Perp-4	Load pert. & AE (??)	27940.6	121589.6	100.19	130.20	50.04	37.33	1.82	24.15	12.07
PCEA-Block 1-Perp-5	AE	29884.4	130048.4	100.13	130.14	50.05	39.94	1.94	24.14	12.07
PCEA-Block 1-Perp-6	Load pert. & AE (??)	33493.8	145755.5	100.24	130.23	50.05	44.73	2.17	23.88	11.94
PCEA-Block 2-Perp-1	Load pert. & AE	39075	170043.3	100.15	130.12	50.00	52.27	2.54	24.11	12.05
PCEA-Block 2-Perp-2	AE (??)	32765.6	142586.6	100.15	130.13	50.05	43.79	2.13	24.11	12.05
PCEA-Block 2-Perp-3	Load pert. & AE (??)	36175	157423.3	100.17	130.16	50.06	48.32	2.35	24.13	12.06
PCEA-Block 2-Perp-4	Load pert. & AE	32509.4	141471.7	100.18	130.21	50.01	43.45	2.11	24.07	12.03
PCEA-Block 2-Perp-5	Load pert. & AE (??)	31521.9	137174.4	100.15	130.17	50.02	42.13	2.05	24.04	12.02
PCEA-Block 2-Perp-6	Load pert. & AE	32746.9	142505.2	100.13	130.19	50.01	43.77	2.12	23.98	11.99
PCEA-Block 3-Perp-1	Load pert. & AE (??)	33143.8	144232.4	100.051	130.26	50.22	44.10	2.15	24.22	12.11
PCEA-Block 3-Perp-2	AE	32350	140778.0	100.00	130.21	50.17	43.10	2.11	24.36	12.18
PCEA-Block 3-Perp-3	Load pert. & AE (??)	36643.8	159463.4	100.00	130.21	50.08	48.91	2.39	24.26	12.13
PCEA-Block 3-Perp-4	Load pert. & AE	33456.3	145592.3	100.05	130.21	50.18	44.57	2.17	24.19	12.09

PCEA-Block 3-Perp-5	Load pert. & AE (??)	35806.3	155818.8	100.08	130.24	50.25	47.62	2.32	24.22	12.11
PCEA-Block 3-Perp-6	Load pert. & AE (??)	33946.9	147727.3	100.04	130.25	50.18	45.20	2.21	24.26	12.13
PCEA-Block 4-Perp-1	AE	36509.4	158878.5	99.99	130.22	50.15	48.66	2.36	24.01	12.00
PCEA-Block 4-Prep-2	Load pert. & AE (??)	32909.4	143212.4	100.01	130.23	50.17	43.84	2.13	24.13	12.07
PCEA-Block 4-Perp-3	Load perturbation??	39334.4	171172.1	99.85	130.21	50.15	52.43	2.57	24.42	12.21
PCEA-Block 4-Perp-4	Load pert. & AE (??)	38751.1	168633.8	99.86	130.23	50.19	51.60	2.53	24.41	12.21
PCEA-Block 4-Perp-5	Load pert. & AE (??)	34612.5	150623.8	100.02	130.23	50.18	46.09	2.24	24.13	12.06
PCEA-Block 4-Perp-6	Load pert. & AE (??)	35968.8	156526.0	100.02	130.25	50.16	47.91	2.33	24.06	12.03

Mean	147787.5	2.21
St. Dev.	12545.4	0.19

Table 16 K_{IIc} data for IG-110, isostatically pressed fine-grained graphite

E IG-110										
Spec no	Fracture comments	Compressive perturbation (shear force), lbs	Compressive perturbation (shear force), N	H=2h	W=2w	T=2t	σc=F/(w*T)	TADA'S EQUATION Kiic=(σc/4)*SQT(Pi*a*E-3)	2a	a
				mm	mm	mm	N/mm2	MPa.√m	mm	mm
E1	Load pert. and AE	43356.3	188674.3	100.79	130.01	50.01	58.04	2.86	24.82	12.41
E2	Load pert. and AE	43456.3	189109.5	100.69	130.02	50.02	58.16	2.86	24.66	12.33
E3	Load pert. and AE	44415.6	193284.1	100.76	130.00	50.02	59.45	2.93	24.76	12.38
E4	Load pert. and AE	40746.9	177318.9	100.88	130.03	50.02	54.52	2.70	24.90	12.45
E5	Load pert. and AE	46015.6	200246.8	100.76	130.03	50.00	61.61	3.03	24.68	12.34
E6	Load pert. and AE	43496.9	189286.2	100.74	130.02	49.97	58.27	2.87	24.75	12.37
E7	Load pert. and AE	42881.3	186607.2	100.06	130.08	49.90	57.49	2.80	24.15	12.07
E8	NOT ANALYSED			100.76	130.08	50.15			24.81	12.40
E9	Load pert. and AE	47768.8	207876.3	100.68	130.03	49.96	64.00	3.15	24.69	12.34
E10	Load pert. and AE	42325	184186.4	99.96	130.05	50.02	56.64	2.75	23.94	11.97
E11	Load pert. and AE	42640.6	185559.8	100.02	130.20	50.05	56.95	2.78	24.32	12.16
E12	Load pert. and AE	38846.9	169050.7	100.03	130.02	50.03	51.98	2.52	24.01	12.00
E13	Load pert. and AE	40387.5	175754.9	100.01	130.03	50.09	53.97	2.63	24.10	12.05
E14	Load pert. and AE	35406.3	154078.2	99.99	130.05	50.04	47.35	2.30	24.11	12.05
E15	Load pert. and AE	30256.3	131666.8	99.97	130.14	50.04	40.44	1.97	24.11	12.06
E16	Load pert. and AE	42406.3	184540.2	100.75	130.08	50.07	56.67	2.79	24.73	12.36
E17	Load pert. and AE	40403.1	175822.8	100.81	130.12	49.98	54.07	2.67	24.89	12.45
E18	Load pert. and AE	40240.6	175115.7	100.73	130.04	50.03	53.84	2.65	24.66	12.33
E19	Load pert. and AE	39075	170043.3	99.99	130.03	50.33	51.97	2.51	23.81	11.91
E20	Load pert. and AE	40403.1	175822.8	99.88	130.08	50.10	53.97	2.62	23.94	11.97
E21	Load pert. and AE	44340.6	192957.7	100.84	130.04	50.07	59.28	2.93	24.81	12.41
E22	Load pert. and AE	41171.9	179168.4	100.02	130.02	50.05	55.07	2.67	23.93	11.96

E23	load perturbation	36103.1	157110.4	99.99	130.01	50.14	48.21	2.34	23.98	11.99
E24	Load pert. and AE	44062.5	191747.5	100.03	130.05	50.06	58.91	2.88	24.26	12.13
E25	Load pert. and AE	42631.3	185519.3	100.01	130.02	50.13	56.93	2.77	24.06	12.03
E26	Load pert. and AE	35943.8	156417.2	99.98	130.09	50.10	48.00	2.34	24.13	12.07
E27	Load pert. and AE	42175	183533.6	99.97	130.05	50.21	56.21	2.73	23.98	11.99

Mean	190214.9	2.87
St. Dev.	8587.9	0.14

8. REFERENCES

[1] T. D. Burchell, Proc. CARBONE 90, International Carbon Conference, pp.278-279, Paris, France, July 16-20, 1990

[2] G. R. Romanoski and T. D. Burchell, In Proc. 20th Biennial Conference on Carbon, pp 584-585, University of California, Santa Barbara, CA., July 23-28 1991

[3] D7779 – 11 "Standard Test Method for Determination of Fracture Toughness at Ambient Temperature". Annual Book of ASTM Standards, Vol. 5.05, *Petroleum Product, Lubricants, and Fossil Fuels*, p. 832. Pub. ASTM International, West Conshohocken, PA (2016)

[4] D7219 – 08 "Standard Specification for Isotropic and Near-Isotropic Nuclear Graphite". Annual Book of ASTM Standards, Vol. 5.05, *Petroleum Product, Lubricants, and Fossil Fuels*, p. 802. Pub. ASTM International, West Conshohocken, PA (2016)

[5] D7301 – 11 "Standard Specification for Components Subjected to Low Neutron Irradiation Dose". Annual Book of ASTM Standards, Vol. 5.05, *Petroleum Product, Lubricants, and Fossil Fuels*, p. 807. Pub. ASTM International, West Conshohocken, PA (2016)

[6] Tim Burchell and Joe Strizak, ORNL/TM-2011/497, Post Irradiation Examination data for PCEA graphite Irradiated at 900°C in HFIR, May 2012

[7]T. Burchell and J. Strizak, "The effect of neutron irradiation on the fracture toughness of graphite", Nuclear Engineering and Design 271 (20140 262-269

[8] Hui Yang, He Li, Lihong Zhu, Dai Huang, Houzeng Wu, Mary Snead, Anne A. Campbell, Yutai Katoh and Timothy D. Burchell. International Nuclear Graphite Specialists Meeting, INGSM-17, Vienna, Austria, September 5-8, 2016

[9] Vallen Systeme, *Acoustic Emission Sensors Specification* Released Germany Dec. 2012, http://www.vallen.de

[10] T. D. Burchell, R. G. Cooke, B. McEnaney and I. M. Pickup. "Acoustic Emission from Graphite - the Effect of Texture. In Ext. Abs. & Prog. Carbone 84, Bordeaux, France. July 2-6,(1984) p.110.

[11] T. D. Burchell, R. G. Cooke, B. McEnaney and I. M. Pickup. "Acoustic Emission from Polygranular Graphite grades" Carbon 23 (1985) 739-747.

[12] G. R. Romanoski and T. D. Burchell, Chpt. 14:" Fracture in Graphite" In T. D. Burchell (Editor) Carbon Materials for Advanced Technologies, pp. 485-534 (1999)

[13] ORNL/TM-2014/614, Timothy D. Burchell and Don Erdmann III, The Shear Fracture Toughness (KIIc) of Graphite Dec. 2014

[14] Timothy D. Burchell, Don Erdmann III. "The shear fracture toughness, K_{IIc}, of graphite", Carbon 98 (2016) 267-279

[15] D. K. Shetty, Mixed-Mode Fracture Criteria for Reliability Analysis and Design with Structural Ceramics, Trans ASME J. Eng. Gas Turbines Power 109 (3) (1987) 282-289

[16] C565 – 93 (reapproved 2010) "Standard Test Method for Tension Testing of Carbon and Graphite Mechanical Materials". Annual Book of ASTM Standards, Vol. 5.05, *Petroleum Product, Lubricants, and Fossil Fuels,* p. 710. Pub. ASTM International, West Conshohocken, PA (2016)

[17] C7490 – 15"Standard Test Method for Tensile Stress-Strain of Carbon or Graphite". Annual Book of ASTM Standards, Vol. 5.05, *Petroleum Product, Lubricants, and Fossil Fuels,* p. 710. Pub. ASTM International, West Conshohocken, PA (2016)