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EFFECT OF STEAM OXIDATION ON STRENGTH, ELASTIC MODULUS, AND STRAIN AT FRACTURE OF GRAPHITE 2020

by

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ABSTRACT

Stackpole Carbon's graphite grade 2020, a candidate material for support posts in GA HTGRs, was oxidized in steam-helium mixtures to 25 wt % burnoff. The effects of the oxidation on ultimate strength, elastic modulus, and strain at fracture are reported.

A large number of nonoxidized and oxidized tensile specimens were tested to failure. Average losses of 6.7 wt % in strength and 7.4 wt % in elastic modulus at 1% burnoff were obtained. No significant change in strain at fracture was observed for burnoffs up to 5%. The elastic modulus and ultimate tensile strength of the oxidized samples correlated with bulk density. No significant radial gradients in strength or elastic modulus were observed in the log; however, slight differences in elastic modulus and strain at fracture were observed along the length of the log. Radial specimens had significantly higher strength and elastic modulus than axial specimens.

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1. INTRODUCTION

Graphite oxidation in an HTGR could occur as a result of accidental steam ingress of two distinct types: (1) a major steam leak such as from the rupture of a heat exchanger steam tube, and (2) a continuous low level leakage. The degree of oxidation due to the first type of leak is negligible because the reactor would be shut down within seconds of such an event (Ref. 1). The second type of leak is of more concern because such a leak is permitted under the proposed technical specifications for normal full-power operation. This type of leak could result in moisture concentrations in the range 1 to 10 Pa (10 to 100 μ atm) over the 40-year life of the reactor graphite components. This could lead to small but measurable oxidation of the support structure.

The support posts in an HTGR are arranged in groups of three under each support block and support the weight of each multiple-column fuel assembly, which includes hexagonal reflectors, a core support block, and the gas pressure differential from top to bottom of the core. Similar posts are also utilized to support the permanent side reflector blocks and their floor support block (Fig. 1).^{*} Support post seats are abutted to the support posts at the bottom of the support floor blocks and to bottom support pads which insulate the support posts from the prestressed concrete floor.

In view of the load-bearing requirements of the support posts and their relative inaccessibility, it is necessary to establish the ability of the materials chosen to maintain their structural integrity and strength under oxidizing conditions in reactor service.

The purpose of the oxidation studies presented in this paper is to characterize Stackpole Carbon's grade 2020 graphite by determining the

^{*}Figures appear at the end of the text.

effect of uniform burnoff on strength, elastic modulus, and strain at fracture. Grade 2020 is a candidate material for support posts in GA HTGRs (Ref. 2). The oxidation experiments reported here were performed in steam-helium mixtures on small specimens taken uniformly throughout a single log. Control specimens, taken from the same population as the specimens used for the oxidation experiments, were utilized to determine changes in strength, elastic modulus, and strain at fracture.

2. MATERIAL

Stackpole Carbon's grade 2020 is manufactured commercially by iso-static molding as logs 245 mm in diameter by 1829 mm long. A description of grade 2020, along with properties and impurity content, is given in Refs. 1 and 3. All specimens were taken from grade 2020 GA log number 6799-00.

3. EXPERIMENTAL PROCEDURES

The experimental work consisted of oxidizing large numbers of small test specimens uniformly and isothermally at an elevated temperature in steam-helium mixtures and subsequently measuring the strength, elastic modulus, and strain at fracture of the oxidized specimens. The property values from the oxidized specimens were compared with values from non-oxidized control specimens, taken from the same population as the specimens utilized for oxidation, to determine the changes due to oxidation burnoff.

3.1. SAMPLING AND SPECIMEN PREPARATION

Commercial graphite logs of the size required for HTGR support posts have been shown to have, in some cases, a nonuniform distribution of properties within a log (Refs. 2 through 5). Thus, for the characterization experiment reported here it was necessary to include axial and radial specimens from three slabs along the length of the log: slabs 1, 3, and 5 (see Appendix A, Fig. A-1). A systematic sampling plan was adopted and specimens were machined from the slabs as shown in Appendix A, Fig. A-2.

Specimens were 12.8 mm (0.505 in.) in diameter by 76.2 mm (3 in.) long prior to oxidation. After oxidation approximately 6 mm (0.25 in.) was removed from each end to facilitate testing.

The specimens were divided into three specimen sets: slabs 1, 3, and 5. The specimens from each slab were further divided into axial and radial specimen sets. Specimens from the same slab and the same orientation (same population) were randomly selected to provide control specimens and specimens for oxidation. When property changes due to oxidation were determined, the values for the oxidized specimens were only compared with values for control specimens taken from the same population as the specimens

used for oxidation. This permitted an unambiguous determination of the property changes.

3.2. OXIDATION

A total of 236 specimens were isothermally oxidized in quartz reaction vessels. The specimens, 15 per batch, were supported in the reaction vessels by racks machined from the same graphite as used for the specimens. The reaction vessels were heated to a preselected temperature using clam-shell resistance furnaces. The apparatus is schematically depicted in Fig. 2. Temperatures were monitored with Chromel-Alumel thermocouples. Temperatures were maintained at 1150 K (875°C) by suitable temperature control devices. During oxidation the vessels were purged with a gas mixture composed of 3 kPa (0.03 atm) water vapor, 5 kPa (0.05 atm) hydrogen, and the balance helium. The total pressure was approximately 100 kPa (1 atm). The flow rate of 1 liter (STP)/min was maintained at all times. The oxidizing gas mixture was introduced into the vessel through a quartz tube extending the length of the hot zone and positioned below the sample racks. The entry tube contained several small holes to emit the gas mixture and, thus, uniformly expose each specimen simultaneously. During heatup and cooldown, the reaction vessel was purged with helium. The extent of oxidation was determined by intermittently removing and weighing each sample to ± 0.1 mg. The percent oxidation (burnoff) was calculated from the weight change. Average rates of oxidation were determined by dividing the weight change by the oxidation time.

Relatively uniform burnoff at the selected oxidation temperatures was achieved by adding hydrogen to the gas mixtures to inhibit the reaction rates, thus maintaining a relatively uniform oxidant level within the pores. The conditions chosen to achieve minimal burnoff gradients were based on experimentally determined oxidation profiles measured on H-451 and ATJ graphites (Refs. 6, 7).

3.3. STRENGTH, ELASTIC MODULUS, AND STRAIN-AT-FRACTURE MEASUREMENTS

Tensile stress-strain curves were obtained in ambient air at room temperature using a standard method described in Ref. 4.

The tensile strength of each specimen was calculated by dividing the load at fracture by the original cross-sectional area of the specimen. Strain at fracture is $\Delta L/L$, where L is the length of the sample and ΔL is the elongation.

The elastic modulus of each specimen was calculated from its stress-strain curve as the slope of the chord (chord modulus) drawn between points on a second loading portion of the stress-strain curve corresponding to stresses of 0.69 MPa (100 psi) and 6.9 MPa (1000 psi). This chord modulus represents the effective modulus of a graphite component after its first strain excursion (see Ref. 4 for details).

A small number of the specimens from slab 1 were measured as a separate batch early in the program (about 1975). These specimens have been separated from the remainder of the specimens which were measured in 1977. The early batch of specimens was tested to failure without measuring the modulus and omitting the load-unload technique as described in Ref. 4. The early specimens taken from slab 1 are identified in Appendix A in Tables A-1, A-2, A-5, and A-6 as lot BKR, whereas the later specimens taken from slabs 1, 2, and 3 are identified in Tables A-3, A-4, and A-7 through A-14 as lot GDB. Differences in strength due to oxidation were calculated using control and oxidized specimens from the same population and testing lot, i.e., lot BKR controls with BKR oxidized specimens and lot GDB controls with GDB oxidized specimens.

4. EXPERIMENTAL RESULTS

4.1. CHARACTERIZATION DATA (NONOXIDIZED SPECIMENS)

4.1.1. Bulk Density

The variation of bulk density within log 6799-00 is presented in Table 1. The variation in bulk density along the length of log 6799-00 was about 1%.

4.1.2. Impurity Content

Results of spectrochemical analyses on specimens taken along the length of log 6799-00 are shown in Table 2. The iron content varied along the length, ranging from 40 ppm at one end to <1 ppm at the other (Fig. 3). Similar gradients in iron and ash content were observed in log 6487-110 (Ref. 3).

4.1.3. Oxidation Rates

Details of the oxidation rates observed in this study are given in Ref. 8, where it was found that the measured oxidation rates of the tensile specimens varied by up to a factor of 60 within the same oxidation furnace load. The variation in oxidation rate correlated with the position of the specimen within the log, with the highest rates observed in edge samples taken from slab 1 (Fig. 4). It is also significant that iron, a known catalyst for graphite oxidation, exhibited a similar gradient (Fig. 3). It is concluded that the variation in iron content is responsible for the variation in oxidation rates. This conclusion is supported by the data in Ref. 8.

TABLE 1
VARIATION OF BULK DENSITY IN LOG 6799-00

	Density (Mg/m ³)	
	Mean	σ
Slab 1	1.780	0.004
Slab 3	1.785	0.003
Slab 5	1.802	0.005

TABLE 2
IMPURITIES FOUND IN STACKPOLE 2020 GRAPHITE (LOG 6799-00)

Specimen Number	Impurity Concentration (ppm)												Distance from Top of Log (mm)	Slab
	Al	Ba	B	Ca	Cu	Fe	Pb	Mg	Nb	Si	Ti	V		
6799-52-11	60	20	2	200	<1	40	6	<0.5	<6	20	20	20	10	1
6799-52-34	20	20	2	100	<1	10	60	<0.5	<6	80	2	<0.5	20	
6799-53-43	20	20	2	100	8	10	<6	1	20	40	40	20	85	3
6799-53-58	60	20	2	100	<1	4	<6	<1	<6	60	40	20	95	
6799-54-71	<1	10	2	100	<0.5	<1	<6	1	<6	60	20	10	155	5
6799-54-98	100	20	2	200	<1	<1	<6	1	<6	60	10	8	175	
Mean	43	18	2	133	2	14	15	0.8	8	63	22	13		

4.1.4. Tensile Strength, Elastic Modulus, and Strain at Fracture (Control Specimens)

Complete data sets for ultimate tensile strength, elastic modulus, and strain at fracture are tabulated in Appendix A, Tables A-1 through A-14.

The mean ultimate tensile strength (UTS), elastic modulus, and strain-at-fracture values for log 6799-00 are shown in Table 3. Based on analysis by statistical t-tests, the UTSs of the three slabs were judged to be from a single population since no significant differences from center to edge were found at the 95% confidence level. The mean UTS of axial specimens was 15.3 ± 1.5 MPa and the mean of the radial specimens was 18.1 ± 2.0 MPa.

The UTS data followed a Gaussian distribution, as shown in Fig. 5. Strength measurements on H-451, the reference fuel element graphite for HTGRs, were also found to follow a Gaussian distribution (Ref. 5). A chi-square, goodness-of-fit analysis showed that the radial and axial UTS data reasonably fit a Gaussian distribution. Statistical analyses, discussed in more detail in later sections, are based on Gaussian distributions.

There was no correlation between the UTS and bulk density for the non-oxidized control specimens over the density range 1.78 to 1.81 Mg/m³.

4.2. CHARACTERIZATION DATA (OXIDIZED SPECIMENS)

Complete data sets for UTS, elastic modulus, and strain at fracture for the oxidized samples and controls are tabulated in Appendix A, Tables A-1 through A-14. A summary of the changes in these properties due to oxidation is given in Table 4. Two lots are reported, as discussed in Section 3.3.

4.2.1. Effect of Oxidation on Ultimate Tensile Strength

The UTS of the control specimens and the effect of oxidation on the reduction of tensile strength were found to be different for axial and

TABLE 3
SUMMARY OF TENSILE STRENGTH, ELASTIC MODULUS, AND STRAIN AT FRACTURE
OF NONOXIDIZED CONTROL SPECIMENS, LOG 6799-00

	Ultimate Tensile Strength (MPa)		Elastic Modulus (GPa)		Fracture Strain (%)	
	Mean	σ	Mean	σ	Mean	σ
Axial						
1	15.7	1.8	8.3	0.3	0.240	0.030
3	15.4	1.1	8.7	0.8	0.224	0.028
5	14.9	1.5	9.0	0.3	0.203	0.022
Radial						
1	17.8	3.4	8.7	0.4	0.248	0.053
3	18.0	1.4	9.8	0.3	0.235	0.020
5	18.5	1.1	10.4	0.4	0.236	0.020

TABLE 4
SUMMARY OF CHANGES IN ULTIMATE TENSILE STRENGTH, ELASTIC MODULUS, AND STRAIN AT FRACTURE
DUE TO OXIDATION, (a,b) LOG 6799-00

Sample Location, Slab No. and Orientation	(Percent Reduction in Property)/(Percent Burnoff)								
	Ultimate Tensile Strength			Elastic Modulus			Strain at Fracture		
	Maximum (2.3% Probability)	Mean (Most Probable)	Minimum (2.3% Probability)	Maximum (2.3% Probability)	Mean (Most Probable)	Minimum (2.3% Probability)	Maximum (2.3% Probability)	Mean (Most Probable)	Minimum (2.3% Probability)
1 axial (c)	4.0	3.5	3.0						
1 axial	10.0	5.9	1.3	8.3	6.7	4.8	3.8	0	0
3 axial	11.3	9.6	6.9	11.2	8.6	8.3	4.3	0.5	0
5 axial	5.1	2.6	0	6.8	4.0	0	1.8	0	0
Mean axial	7.6	5.4	2.8	8.8	6.4	4.4	3.3	0.2	0
1 radial (d)	7.4	6.0	4.4						
3 radial	11.5	9.1	5.3	10.2	8.9	7.0	3.2	0.4	0
5 radial	11.0	8.9	6.1	11.0	8.8	5.0	8.9	2.8	0
Mean radial	10.0	8.0	5.3	10.6	8.9	6.0	6.0	1.6	0
Mean axial and radial	8.8	6.7	4.0	9.5	7.4	5.0	4.7	0.9	0

(a) Oxidation conditions: 1148 K, 3 kPa H₂O, 5 kPa H₂, balance He.

(b) Analysis based on CONFID computer code which assumes linear fit to data.

(c) Burnoffs to 25%, lot BKR.

(d) Burnoffs to 15%, lot BKR.

radial specimens; thus, the axial and radial data are treated separately in the following sections.

4.2.1.1. Axial Samples

The effect of oxidation on the UTS of axial samples for each slab is shown in Figs. 6 through 8. The data from lot BKR slab 1 are shown in Fig. 9. The average rate of strength loss and the maximum and minimum values based on 95% confidence were calculated using CONFID, a GA computer code which calculates confidence limits for a linear slope. Based on the results of statistical calculations at the 95% confidence level, the ultimate tensile strengths of all axial control specimens were combined to form a single control population. The reduction in axial UTS using all specimens (excluding lot BKR) was calculated. The results are shown in Fig. 10. The upper and lower lines in Fig. 10 are 95% confidence limits based on calculations using CONFID. Edge and center samples are identified and show no significant difference.

Figure 11 is a plot of axial UTS versus density. The two characteristics of interest are: (1) the continued data dispersion around the calculated mean at all densities and (2) the developed relationship between UTS and bulk density. The data were analyzed by POLFIT, a GA computer code which fits a linear slope by the method of least-squares, and the standard deviation of the dependent variable. In Fig. 11 the dashed lines represent one standard deviation.

A variability of UTS is particularly apparent in the oxidized specimens from slab 5 (Fig. 8).

At ~1% burnoff strength values were not significantly different from the strengths of the controls (Fig. 12). A similar result was obtained for axial and radial specimens of oxidized H-451 graphite (Ref. 6). The data from lot BKR (Fig. 9) show a linear dependence of strength for burnoffs to 25%.

4.2.1.2. Radial Samples

Figures 13 (log BKR), 14, and 15 show UTS versus burnoff for oxidized radial specimens.

The results of t-test analysis showed that all nonoxidized radial specimens could be treated as a single control population. The ultimate tensile strengths of all oxidized and nonoxidized specimens are plotted in Fig. 16. The data were analyzed using CONFID to establish limits on the effect of burnoff (dashed lines in Fig. 16 show limits at 95% confidence). In contrast to the results for axial specimens, relatively large UTS losses were found at low burnoff levels (Fig. 17).

Figure 18 is a plot of UTS versus bulk density for radial oxidized and nonoxidized specimens. The dashed lines represent boundaries of one standard deviation established by POLFIT. The solid line represents the slope of UTS versus density as a result of a least-squares regression fit. A relationship between UTS and bulk density is apparent.

4.2.2. Effect of Oxidation on Elastic Modulus - Axial and Radial Specimens

The effect of oxidation on elastic modulus is shown in Figs. 19 through 24. The figures include 95% confidence limits on the linear slope calculated using CONFID. A summary of the modulus data of oxidized specimens is given in Table 3. The mean control modulus in slab 1 was judged significantly different on a statistical basis from the mean control modulus in slab 5 (see Table 3 and Figs. 19 through 23). In Fig. 24 modulus is plotted versus burnoff for all slabs. The large scatter in the data is attributed to slab 5.

In Figs. 25 and 26 modulus is plotted versus specimen bulk density for axial and radial specimens, respectively. The data show a monotonic relationship between density and modulus.

4.2.3. Effect of Oxidation on Strain at Fracture

The effect of oxidation on strain at fracture for each slab and axial and radial specimens is given in Figs. 27 through 31. The data from all slabs are shown in Fig. 32. Only a slight effect of oxidation is noted. Statistical t-testing of the control group indicated that the axial specimens from slab 5 were statistically significantly different from slabs 1 and 3. The strain-at-fracture data for the control groups fit a Gaussian distribution (see Fig. 33).

5. CONCLUSIONS

Conclusions are summarized as follows:

1. No differences were detected in UTS, elastic modulus, and strain at fracture between edge and center specimens.
2. The reduction in UTS and elastic modulus of axial specimens having a mean strength of 15.3 MPa prior to oxidation are 5.4% and 6.4%, respectively, at 1% burnoff.
3. The reduction in UTS and elastic modulus of radial specimens having a mean strength of 18.1 MPa prior to oxidation are 8% and 8.9%, respectively, at 1% burnoff.
4. Changes in strain at fracture at burnoffs up to 5% were negligible.
5. The UTS of nonoxidized control specimens followed a Gaussian distribution. The strain at fracture of nonoxidized and oxidized specimens also followed a Gaussian distribution. No statistical difference in the mean UTS could be detected in control specimens taken from slabs 1, 3, or 5; however, elastic modulus and strain at fracture in slab 5 were judged statistically different from slabs 1 and 3.
6. The relationship found between UTS and elastic modulus and bulk density for nonoxidized and oxidized specimens may represent a parameter for evaluating in situ strength of reactor support posts and warrants further consideration.

6. ACKNOWLEDGMENTS

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Fig. 1. HTGR core and support arrangement

Fig. 2. Steam-graphite oxidation apparatus

Fig. 3. Fe contamination versus location in log

Fig. 4. Average and range of reaction rates of each section versus distance from end of log

Fig. 5. Gaussian distribution fits to UTS data, 2020 graphite, log 6799-00

Fig. 6. UTS versus burnoff, axial, slab 1

Fig. 8. UTS versus burnoff, axial, slab 5

Fig. 9. UTS versus burnoff, axial, slab 1 (lot BKR)

Fig. 10. UTS versus burnoff, axial, all slabs

Fig. 11. UTS versus density for oxidized and nonoxidized axial specimens

Fig. 12. UTS versus burnoff (to 1%), axial samples

Fig. 13. UTS versus burnoff, radial, slab 1, lot BKR

Fig. 14. UTS versus burnoff, radial, slab 3

Fig. 15. UTS versus burnoff, radial, slab 5

Fig. 16. UTS versus burnoff, radial, slabs 3 and 5

Fig. 17. UTS versus burnoff (to 1%), radial specimens

Fig. 18. UTS versus density of oxidized and nonoxidized radial specimens

Fig. 19. Elastic modulus versus burnoff, axial, slab 1

Fig. 20. Elastic modulus versus burnoff, axial, slab 3

Fig. 21. Elastic modulus versus burnoff, axial, slab 5

Fig. 22. Elastic modulus versus burnoff, radial, slab 3

Fig. 23. Elastic modulus versus burnoff, radial, slab 5

Fig. 24. Elastic modulus versus burnoff, all slabs

Fig. 25. Elastic modulus versus bulk density, axial specimens

Fig. 26. Elastic modulus versus bulk density, radial specimens

Fig. 27. Strain at fracture versus burnoff, axial, slab 1

Fig. 28. Strain at fracture versus burnoff, axial, slab 3

Fig. 29. Strain at fracture versus burnoff, axial, slab 5

Fig. 30. Strain at fracture versus burnoff, radial, slab 3

Fig. 31. Strain at fracture versus burnoff, radial, slab 5

Fig. 32. Strain at fracture versus burnoff, all specimens

Fig. 33. Gaussian distribution of strain at fracture for oxidized and nonoxidized specimens

APPENDIX A

TABLE A-1

TENSILE PROPERTIES OF 2020 GRAPHITE

LOT NO.		BKR		SPEC. DIA.		12.8 MM	
LOG NO.		6799 (CONT.)		SPEC. LENGTH		76. MM	
LOG DENSITY				MG/M**3			
SPECIMEN NUMBER	ORIENT- ATION	LOCA- TION	DENSITY (MG/M**3)	YOUNGS MODULUS (GPA)	PERM- ANENT SET (PCT)	FRAC- TURE STRAIN (PCT)	TENSILE STRENGTH (MPA)
SLAB 1	202	AX	END	1.787			19.1
SLAB 1	212	AX	END	1.784			19.0
SLAB 1	214	AX	END	1.789			19.4
SLAB 1	220	AX	END	1.780			18.9
SLAB 1	226	AX	END	1.788			16.5
SLAB 1	230	AX	END	1.785			19.4
SLAB 1	238	AX	END	1.780			18.1
SLAB 1	240	AX	END	1.781			17.4
MEAN				1.784			18.5 (2680.PSI)
STD. DEV.				.004			1.0 (151.PSI)

TABLE A-2

TENSILE PROPERTIES OF 2020 GRAPHITE

LOT NO.	BKR	SPEC. DIA.	12.8 MM
LOG NO.	6799 (OXID.)	SPEC. LENGTH	76. MM
LOG DENSITY	MG/M**3		

SPECIMEN NUMBER	ORIENT- ATION	LOCA- TION	DENSITY (MG/M**3)	YOUNGS MODULUS (GPA)	PERM- ANENT SET (PCT)	FRAC- TURE STRAIN (PCT)	TENSILE STRENGTH (MPA)
SLAB 1	201	AX	END	1.784			2.4
	203	AX	END	1.787			13.3
	205	AX	END	1.789			13.1
	207	AX	END	1.793			2.1
	209	AX	END	1.784			4.5
	211	AX	END	1.784			15.9
	213	AX	END	1.788			16.1
	215	AX	END	1.786			10.1
	217	AX	END	1.786			16.1
	219	AX	END	1.783			14.1
	221	AX	END	1.784			16.8
	223	AX	END	1.785			14.4
	225	AX	END	1.789			15.0
	227	AX	END	1.783			3.8
	229	AX	END	1.785			10.4
MEAN				1.786			11.2
							(1625.PSI)
STD. DEV.				.003			5.4
							(778.PSI)

TABLE A-3

TENSILE PROPERTIES OF 2020 GRAPHITE								
LOT NO. GDB				SPEC. DIA.		12.8 MM		
LOG NO. 6799 (OXID.)				SPEC. LENGTH		76. MM		
LOG DENSITY				MG/M**3				
SPECIMEN NUMBER	ORIENT- ATION	LOCA- TION	DENSITY (MG/M**3)	YOUNGS MODULUS (GPA)	PERM- ANENT SET (PCT)	FRAC- TURE STRAIN (PCT)	TENSILE STRENGTH (MPA)	
SLAB 1	-231	AX	END	1.772	7.6	.015	.316	18.5
	-233	AX	END	1.704	5.3	.015	.250	11.3
	-235	AX	END	1.731	6.9	.015	.260	14.5
	-237	AX	END	1.767	7.8	.011	.259	16.2
	-239	AX	END	1.688	5.0	.024	.252	10.5
MEAN			1.733	6.5	.016	.267	14.2	
				(.94 MPsi)			(2060.Psi)	
STD. DEV.			.037	1.3	.005	.028	3.3	
				(.19 MPsi)			(482.Psi)	

TABLE A-4

TENSILE PROPERTIES OF 2020 GRAPHITE

LOT NO.	GDB	SPEC. DIA.	12.8 MM
LOG NO.	6799 (CONT.)	SPEC. LENGTH	76. MM
LOG DENSITY	MG/M**3		

SPECIMEN NUMBER	ORIENT- ATION	LOCA- TION	DENSITY (MG/M**3)	YOUNGS MODULUS (GPA)	PERM- ANENT SET (PCT)	FRAC- TURE STRAIN (PCT)	TENSILE STRENGTH (MPA)	
SLAB 1	-204	AX	END	1.804	8.4	.008	.229	16.1
	-206	AX	END	1.784	8.6	.010	.219	14.8
	-208	AX	END	1.783	8.2	.010	.232	15.1
	-210	AX	END	1.785	8.3	.015	.232	15.1
	-216	AX	END	1.781	7.8	.011	.234	14.9
	-218	AX	END	1.784	8.6	.015	.209	13.9
	-222	AX	FND	1.783	7.8	.010	.262	16.0
	-224	AX	END	1.784	8.3	.003	.266	15.7
	-228	AX	END	1.780	8.4	.010	.235	15.7
	-232	AX	END	1.782	8.7	.008	.309	20.3
	-234	AX	END	1.783	8.5	.009	.189	13.6
	-236	AX	END	1.779	8.4	.009	.262	17.5
MEAN			1.784	8.3	.010	.240	15.7	
				(1.21 MPsi)			(2281.PSI)	
STD. DEV.			.006	.3	.003	.031	1.8	
				(.04 MPsi)			(258.PSI)	

TABLE A-5

TENSILE PROPERTIES OF 2020 GRAPHITE

LOT NO.	BKR	SPEC. DIA.	12.8 MM
LOG NO.	6799 (CONT.)	SPEC. LENGTH	76. MM
LOG DENSITY	MG/M**3		

SPECIMEN NUMBER	ORIENT- ATION	LOCA- TION	DENSITY (MG/M**3)	YOUNGS MODULUS (GPA)	PERM- ANENT SET (PCT)	FRAC- TURE STRAIN (PCT)	TENSILE STRENGTH (MPA)
--------------------	------------------	---------------	----------------------	----------------------------	--------------------------------	----------------------------------	------------------------------

SLAB 1	003	RAD	END	1.779			19.3
	006	RAD	END	1.785			18.4
	011	RAD	END	1.780			20.3
	014	RAD	END	1.777			21.5
	019	RAD	END	1.778			19.3
	022	RAD	END	1.779			17.0
	031	RAD	END	1.783			16.6
	034	RAD	END	1.781			17.7

MEAN	1.780	18.8	(2720.PSI)
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STD. DEV.	.003	1.7	(241.PSI)
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TABLE A-6

TENSILE PROPERTIES OF 2020 GRAPHITE

LOT NO. BKR	SPEC. DIA.	12.8 MM
LOG NO. 6799(OXID.)	SPEC. LENGTH	76. MM
LOG DENSITY	MG/M**3	

SPECIMEN NUMBER	ORIENT- ATION	LOCA- TION	DENSITY (MG/M**3)	YOUNGS MODULUS (GPA)	PERM- ANENT SET (PCT)	FRAC- TURE STRAIN (PCT)	TENSILE STRENGTH (MPA)
--------------------	------------------	---------------	----------------------	----------------------------	--------------------------------	----------------------------------	------------------------------

SLAB 1	1 RAD	END	1.778				8.7
	4 RAD	END	1.786				5.2
	8 RAD	END	1.780				6.3
	9 RAD	END	1.779				4.1
	12 RAD	END	1.779				16.4
	16 RAD	END	1.776				13.7
	17 RAD	FND	1.775				9.6
	20 RAD	END	1.777				14.4
	21 RAD	END	1.778				12.7
	24 RAD	END	1.781				15.5
	25 RAD	END	1.783				13.6
	28 RAD	END	1.782				13.8
	29 RAD	END	1.784				15.7
	32 RAD	END	1.782				16.3

MEAN	1.780	11.9
		(1720.PSI)

STD. DEV.	.003	4.3
		(618.PSI)

TABLE A-7

TENSILE PROPERTIES OF 2020 GRAPHITE

LOT NO.	GDB	SPEC. DIA.	12.8 MM
LOG NO.	6799 (CONT.)	SPEC. LENGTH	76. MM
LOG DENSITY	MG/M**3		

SPECIMEN NUMBER	ORIENT- ATION	LOCA- TION	DENSITY (MG/M**3)	YOUNGS MODULUS (GPA)	PERM- ANENT SET (PCT)	FRAC- TURE STRAIN (PCT)	TENSILE STRENGTH (MPA)
SLAB 3	-242	AX ML	1.790	8.2	.008	.281	17.4
	-244	AX ML	1.784	8.0	.006	.216	14.4
	-250	AX ML	1.787	7.9	.006	.238	15.7
	-254	AX ML	1.786	7.7	.005	.244	15.5
	-258	AX ML	1.786	10.5	.004	.180	14.5
	-260	AX ML	1.787	8.9	.011	.222	15.5
	-262	AX ML	1.790	8.7	.009	.208	14.7
	-266	AX ML	1.786	9.0	.011	.257	17.8
	-268	AX ML	1.791	8.9	.016	.216	15.0
	-272	AX ML	1.786	8.9	.010	.200	14.5
	-274	AX ML	1.788			.193	14.3
	-276	AX ML	1.789	9.0	.017	.229	15.8
MEAN			1.787	8.7 (1.26 MPsi)	.009	.224	15.4 (2239.PSI)
STD. DEV.			.002	.8 (.11 MPsi)	.004	.028	1.1 (166.PSI)

TABLE A-8

TENSILE PROPERTIES OF 2020 GRAPHITE

LOT NO.	GDB	SPEC. DIA.	12.8 MM
LOG NO.	6799 (OXID.)	SPEC. LENGTH	76. MM
LOG DENSITY	MG/M**3		

SPECIMEN NUMBER	ORIENT- ATION	LOCA- TION	DENSITY (MG/M**3)	YOUNGS MODULUS (GPA)	PERM- ANENT SET (PCT)	FRAC- TURE STRAIN (PCT)	TENSILE STRENGTH (MPA)
SLAB 3	-243	AX ML	1.755	7.0	.013	.175	10.6
	-245	AX ML	1.772	8.3	.011	.220	14.7
	-247	AX ML	1.756	6.8	.014	.170	10.2
	-249	AX ML	1.761	7.0	.011	.203	12.1
	-251	AX ML	1.773	8.3	.010	.175	12.2
	-253	AX ML	1.747	6.7	.011	.185	10.8
	-255	AX ML	1.712	5.2	.015	.208	9.6
	-257	AX ML	1.764	8.1	.010	.184	13.2
	-259	AX ML	1.732	5.9	.014	.211	7.4
	-261	AX ML	1.722	5.7	.010	.209	10.7
	-263	AX ML	1.778	8.8	.011	.234	15.9
	-265	AX ML	1.761	7.0	.011	.243	14.3
	-267	AX ML	1.768	7.6	.015	.254	15.5
	-269	AX ML	1.747	6.6	.012	.200	11.4
	-271	AX ML	1.771	8.3	.008	.255	16.9
	-273	AX ML	1.710	5.1	.015	.244	10.4
	-275	AX ML	1.719	5.5	.015	.200	9.8
	-277	AX ML	1.765	7.6	.010	.191	12.7
	-279	AX ML	1.743	6.5	.011	.234	13.0
	-281	AX ML	1.701	5.2	.014	.231	10.5
MEAN			1.748	6.9 (1.00 MPsi)	.012	.211	12.1 (1752.PSI)
STD. DEV.			.024	1.2 (.17 MPsi)	.002	.027	2.4 (351.PSI)

TABLE A-9

TENSILE PROPERTIES OF 2020 GRAPHITE

LOT NO. GDB	SPEC. DIA. 12.8 MM
LOG NO. 6799 (CONT.)	SPEC. LENGTH 76. MM
LOG DENSITY	MG/M**3

SPECIMEN NUMBER	ORIENT- ATION	LOCA- TION	DENSITY (MG/M**3)	YOUNGS MODULUS (GPA)	PERM- ANENT SET (PCT)	FRAC- TURE STRAIN (PCT)	TENSILE STRENGTH (MPA)
SLAB 3	-035 RAD	ML	1.784				17.3
	-042 RAD	ML	1.788	10.3	.001	.225	19.9
	-043 RAD	ML	1.784	9.7	.014	.244	18.3
	-050 RAD	ML	1.785	9.6	.007	.234	17.0
	-051 RAD	ML	1.773	10.2	.012	.210	16.4
	-054 RAD	ML	1.782	9.3	.009	.240	17.7
	-055 RAD	ML	1.779	9.7	.009	.203	16.2
	-062 RAD	ML	1.783	9.7	.009	.261	19.4
	-063 RAD	ML	1.784	9.8	.011	.261	19.9
MEAN			1.782	9.8	.009	.235	18.0
				(1.42 MPsi)			(2612.PSI)
STD. DEV.			.004	.3	.004	.021	1.4
				(.05 MPsi)			(209.PSI)

TABLE A-10

TENSILE PROPERTIES OF 2020 GRAPHITE								
LOT NO. GDB				SPEC. DIA. 12.8 MM				
LOG NO. 6799 (OXID.)				SPEC. LENGTH 76. MM				
LOG DENSITY				MG/M**3				
SPECIMEN NUMBER	ORIENT- ATION	LOCA- TION	DENSITY (MG/M**3)	YOUNGS MODULUS (GPA)	PERM- ANENT SET (PCT)	FRAC- TURE STRAIN (PCT)	TENSILE STRENGTH (MPA)	
SLAB 3	-036	RAD	ML	1.742	7.1	.010	.244	14.4
	-037	RAD	ML	1.710	6.2	.016	.215	11.2
	-040	RAD	ML	1.772	7.5	.010	.235	14.9
	-041	RAD	ML	1.715	6.3	.015	.250	12.8
	-044	RAD	ML	1.737	7.2	.015	.202	12.1
	-045	RAD	ML	1.770	8.9	.011	.231	16.2
	-048	RAD	ML	1.734	6.9	.011	.225	13.1
	-049	RAD	ML	1.738	7.6	.010	.218	13.5
	-052	RAD	ML	1.765	8.3	.011	.241	15.8
	-053	RAD	ML	1.762	9.4	.011	.246	17.2
	-056	RAD	ML	1.736	6.6	.014	.247	13.7
	-057	RAD	ML	1.785	8.6	.006	.212	15.4
	-060	RAD	ML	1.709	6.0	.014	.239	12.0
	-061	RAD	ML	1.705	6.2	.014	.180	9.7
	-064	RAD	ML	1.771	8.9	.012	.225	16.1
	-065	RAD	ML	1.725	6.7	.012	.260	14.0
	-068	RAD	ML	1.773	9.0	.008	.191	14.2
MEAN			1.744	7.5	.012	.227	13.9	
				(1.09 MPsi)			(2017.PSI)	
STD. DEV.			.026	1.1	.003	.022	2.0	
				(.16 MPsi)			(286.PSI)	

TABLE A-11

TENSILE PROPERTIES OF 2020 GRAPHITE

LOT NO.	GDB	SPEC. DIA.	12.8 MM
LOG NO.	6799 (CONT.)	SPEC. LENGTH	76. MM
LOG DENSITY	MG/M**3		

SPECIMEN NUMBER	ORIENT- ATION	LOCA- TION	DENSITY (MG/M**3)	YOUNGS MODULUS (GPA)	PERM- ANENT SET (PCT)	FRAC- TURE STRAIN (PCT)	TENSILE STRENGTH (MPA)	
SLAB 5	-282	AX	END	1.802	9.5	.005	.184	14.8
	-286	AX	END	1.800	8.7	.007	.185	13.7
	-288	AX	END	1.800	8.7	.005	.179	13.4
	-292	AX	END	1.801	9.0	.010	.220	15.6
	-294	AX	END	1.799	9.0	.007	.218	15.8
	-298	AX	END	1.800	9.0	.014	.208	14.8
	-302	AX	END	1.807	8.8	.010	.217	15.4
	-304	AX	END	1.805	9.0	.012	.172	12.7
	-308	AX	END	1.805	9.4	.006	.240	18.1
	-314	AX	END	1.802	9.0	.009	.203	14.8
MEAN			1.802	9.0	.008	.203	14.9	
				(1.30 MPsi)			(2165.Psi)	
STD. DEV.			.003	.3	.003	.022	1.5	
				(.04 MPsi)			(219.Psi)	

TABLE A-12

TENSILE PROPERTIES OF 2020 GRAPHITE

LOT NO.		GDB		SPEC. DIA.		12.8 MM		
LOG NO.		6799 (OXID.)		SPEC. LENGTH		76. MM		
LOG DENSITY				MG/M**3				

SPECIMEN NUMBER	ORIENT- ATION		LOCA- TION	DENSITY (MG/M**3)	YOUNGS MODULUS (GPA)	PERM- ANENT SET (PCT)	FRAC- TURE STRAIN (PCT)	TENSILE STRENGTH (MPA)

SLAB 5	-283	AX	END	1.775	7.6	.014	.240	14.6
	-285	AX	END	1.718	6.0	.020	.183	8.7
	-287	AX	END	1.713	5.7	.015	.207	9.9
	-289	AX	END	1.789	10.0	.010	.165	13.1
	-291	AX	END	1.741	9.4	.010	.192	14.7
	-293	AX	END	1.710	8.7	.010	.238	16.8
	-295	AX	END	1.773	9.0	.011	.177	12.7
	-297	AX	END	1.758	9.5	.008	.233	17.1
	-299	AX	END	1.705	9.4	.008	.231	17.5
	-301	AX	END	1.757	8.5	.010	.215	14.8
	-303	AX	END	1.794	9.5	.010	.261	19.5
	-305	AX	END	1.723	7.1	.010	.195	11.8
	-307	AX	END	1.720	5.5	.015	.210	9.7
	-309	AX	END	1.782	5.4	.020	.220	9.9
	-311	AX	END	1.747	7.7	.010	.214	14.1
	-313	AX	END	1.708	6.6	.011	.224	12.5
	-315	AX	END	1.775	4.9	.020	.218	9.0
	-317	AX	END	1.720	7.4	.010	.219	13.4
	-319	AX	END	1.738	5.4	.021	.274	11.7
	-321	AX	END	1.769	6.0	.016	.193	10.0

MEAN				1.746	7.5	.013	.215	13.1
				(1.08 MPsi)		(1897.PSi)		

STD. DEV.				.030	1.7	.004	.027	3.1
				(.25 MPsi)		(449.PSi)		

TABLE A-13

TENSILE PROPERTIES OF 2020 GRAPHITE

LOT NO. GDB	SPEC. DIA.	12.8 MM
LOG NO. 6799 (CONT.)	SPEC. LENGTH	76. MM
LOG DENSITY	MG/M**3	

SPECIMEN NUMBER	ORIENT- ATION	LOCA- TION	DENSITY (MG/M**3)	YOUNGS MODULUS (GPA)	PERM- ANENT SET (PCT)	FRAC- TURE STRAIN (PCT)	TENSILE STRENGTH (MPA)
SLAB 5	-074 RAD	END	1.798	10.3	.007	.227	18.1
	-075 RAD	END	1.798	10.5	.012	.235	18.2
	-082 RAD	END	1.803	10.7	.012	.246	19.0
	-083 RAD	END	1.801	10.5	.006	.254	20.0
	-086 RAD	END	1.802	11.1	.010	.239	18.6
	-087 RAD	END	1.803	9.8	.010	.257	19.5
	-094 RAD	END	1.808	10.3	.008	.191	16.1
	-095 RAD	END	1.805	10.0	.008	.239	18.3
	-102 RAD	END	1.813	10.2	.010	.235	18.6
MEAN			1.804	10.4	.009	.236	18.5
			(1.51 MPsi)		(2683.PSI)		
STD. DEV.			.005	.4	.002	.019	1.1
			(.05 MPsi)		(160.PSI)		

TABLE A-14

TENSILE PROPERTIES OF 2020 GRAPHITE

LOT NO.	GDB	SPEC. DIA.	12.8 MM
LOG NO.	6799 (OXID.)	SPEC. LENGTH	76. MM
LOG DENSITY	MG/M**3		

SPECIMEN NUMBER	ORIENT- ATION	LOCA- TION	DENSITY (MG/M**3)	YOUNGS MODULUS (GPA)	PERM- ANENT SET (PCT)	FRAC- TURE STRAIN (PCT)	TENSILE STRENGTH (MPA)
SLAB 5	-069 RAD	END	1.752	7.4	.010	.224	13.8
	-072 RAD	END	1.721	6.8	.019	.251	13.7
	-073 RAD	END	1.745	7.6	.010	.251	15.2
	-076 RAD	END	1.777	5.0	.019	.249	10.4
	-077 RAD	END	1.722	6.0	.011	.157	8.6
	-080 RAD	END	1.718	6.2	.014	.177	9.6
	-081 RAD	END	1.783	7.0	.012	.245	14.1
	-084 RAD	END	1.760	8.0	.014	.256	16.2
	-085 RAD	END	1.760	7.7	.015	.241	14.7
	-088 RAD	END	1.759	5.3	.017	.220	9.9
	-089 RAD	END	1.734	6.4	.011	.211	11.6
	-092 RAD	END	1.713	5.5	.015	.176	8.6
	-093 RAD	END	1.765	6.5	.014	.220	12.0
	-096 RAD	END	1.740	6.5	.013	.222	12.2
	-097 RAD	END	1.756	7.1	.011	.248	14.6
	-100 RAD	END	1.782	8.9	.010	.236	16.4
	-101 RAD	END	1.720	6.0	.016	.199	10.0
MEAN			1.748	6.7	.014	.223	12.4
			(.97 MPsi)		(1806.PSI)		
STD. DEV.			.023	1.0	.003	.030	2.6
			(.15 MPsi)		(377.PSI)

Fig. A-1. Stackpole 2020 graphite

NO. 11-6799

S = SPECTROGRAPHIC ANALYSIS

C = CONTROL

SECTION	EDGE CENTER		
	CORE	SAMPLES	
	25.4 mm	COMPRESSION	
A	1	1	2C
	3	3C	4
	5	5	6C
	7	7	8
	9	9	10C
B	11	11S	12
	13	13	14C
	15	15C	16
	17	17	18C
C	19	19C	20
	21	21	22C
	23	23C	24
	25	25	26C
D	27	27C	28
	29	29	30
	31	31C	32
	33	33	34S
76.2 mm TENSILE			
A	1	1	2C
	3	3C	4
	5	5	6C
	7	7C	8
	9	9	10C
B	11	11C	12
	13	13	14C
	15	15C	16
	17	17	18C
C	19	19C	20
	21	21	22C
	23	23C	24
	25	25	26C
D	27	27C	28
	29	29	30C
	31	31C	32
	33	33	34C

Fig. A-2. Coring diagram, Stackpole 2020, slab 1, tensile and compression radial samples

NO. 12-6799
C = CONTROL

SECTION

	CORE	SAMPLES		
	COMPRESSION SAMPLES			
EDGE	201	201	215	229
	202	202C	216C	230
	203	203	217	231
	204	204	218C	232C
	205	205	219	233
	206	206C	220C	234C
	207	207	221	235
	208	208C	222C	236C
	209	209	223	237
	210	210C	224C	238C
	211	211	225	239
	212	212C	226C	240C
CENTER	213	213	227	241
	214	214C	228C	242C
	TENSILE SAMPLES			
EDGE	201	201	221	
	202	202C	222C	
	203	203	223	
	204	204C	224C	
	205	205	225	
	206	206C	226C	
	207	207	227	
	208	208C	228C	
	209	209	229	
	210	210C	230C	
	211	211	231	
	212	212C	232C	
	213	213	233	
	214	214C	234C	
	215	215	235	
	216	216C	236C	
	217	217	237	
CENTER	218	218C	238C	
	219	219	239	
	220	220C	240C	

Fig. A-3. Coring diagram, Stackpole 2020, slab 1, tensile and compression axial samples

NO. 11-6799

S = SPECTROGRAPHIC ANALYSIS

C = CONTROL

SECTION	EDGE CENTER		
	CORE	SAMPLES	
	25.4 mm	COMPRESSION	
E	35	35C	36
	37	37	38C
	39	39C	40
	41	41	42C
	43	43S	44
F	45	45	46C
	47	47	48
	49	49	50C
	51	51C	52
G	53	53	54C
	55	55C	56
	57	57	58S
	59	59C	60
H	61	61	62
	63	63C	64
	65	65	66C
	67	67C	68
76.2 mm TENSILE			
E	35	35C	36
	37	37	38C
	39	39C	40
	41	41	42C
	43	43C	44
F	45	45	46C
	47	47C	48
	49	49	50C
	51	51C	52
G	53	53	54C
	55	55C	56
	57	57	58C
	59	59C	60
H	61	61	62C
	63	63C	64
	65	65	66C
	67	67C	68

Fig. A-4. Coring diagram, Stackpole 2020, slab 3, tensile and compression radial samples

NO. 12-6799

C = CONTROL

SECTION

	CORE	SECTION		
		E	F	G
EDGE	COMPRESSION SAMPLES			
	243	243	257	271
	244	244C	258C	272C
	245	245	259	273
	246	246C	260C	274C
	247	247	261	275
	248	248C	262C	276
	249	249	263	277
	250	250	264C	278C
	251	251	265	279
	252	252C	266C	280C
	253	253	267	281
	254	254C	268C	282C
	255	255	269	283
	256	256C	270C	284C
EDGE	TENSILE SAMPLES			
	242	242C	262C	
	243	243	263	
	244	244C	264C	
	245	245	265	
	246	246C	266C	
	247	247	267	
	248	248C	268C	
	249	249	269	
	250	250C	270C	
	251	251	271	
	252	252C	272C	
	253	253	273	
	254	254C	274C	
	255	255	275	
	256	256C	276C	
CENTER	257	257	277	
	258	258C	278C	
	259	259	279	
	260	260C	280C	
	261	261	281	

Fig. A-5. Coring diagram, Stackpole 2020, slab 3, tensile and compression axial samples

NO. 11-6799

S = SPECTROGRAPHIC ANALYSIS

C = CONTROL

SECTION	EDGE CENTER		
	CORE	SAMPLES	
	25.4 mm	COMPRESSION	
I	69	69	70C
	71	71S	72
	73	73	74C
	75	75C	76
	77	77	78
J	79	79C	80
	81	81	82C
	83	83C	84
	85	85	86C
K	87	87C	88
	89	89	90C
	91	91C	92
	93	93	94C
L	95	95C	96
	97	97	98S
	99	99C	100
	101	101	102
	76.2 mm	TENSILE	
I	69	69	70C
	71	71C	72
	73	73	74C
	75	75C	76
	77	77	78C
J	79	79C	80
	81	81	82C
	83	83C	84
	85	85	86C
K	87	87C	88
	89	89	90C
	91	91C	92
	93	93	94C
L	95	95C	96
	97	97	98C
	99	99C	100
	101	101	102C

Fig. A-6. Coring diagram, Stackpole 2020, slab 5, tensile and compression radial samples

NO. 12-6799

C = CONTROL

SECTION

	CORE	SECTION		
		I	J	K
	SAMPLES			
	COMPRESSION SAMPLES			
EDGE	285	285	299	313
	286	286	300C	314C
	287	287	301	315
	288	288C	302C	316C
	289	289	303	317
	290	290C	304C	318C
	291	291	305	319
	292	292C	306C	320C
	293	293	307	321
	294	294C	308	322C
	295	295	309	323
	296	296C	310C	324C
CENTER	297	297	311	325
	298	298C	312C	326
	TENSILE SAMPLES			
EDGE	282	282C	302C	
	283	283	303	
	284	284C	304C	
	285	285	305	
	286	286C	306C	
	287	287	307	
	288	288C	308C	
	289	289	309	
	290	290C	310C	
	291	291	311	
	292	292C	312C	
	293	293	313	
	294	294C	314C	
	295	295	315	
	296	296C	316C	
	297	297	317	
CENTER	298	298C	318C	
	299	299	319	
	300	300C	320C	
	301	301	321	

Fig. A-7. Coring diagram, Stackpole 2020, slab 5, tensile and compression axial samples