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THE EFFECT OF STEAM OXIDATION ON THE STRENGTH AND ELASTIC MODULUS OF GRAPHITE H-451

by
**C. VELASQUEZ, W. JOHNSON, G. HIGHTOWER,
and R. BURNETTE**

**Prepared under
Contract EY-76-C-03-0167
Project Agreement No. 17
for the San Francisco Operations Office
Department of Energy**

DATE PUBLISHED: DECEMBER 1977

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy \$4.50; Microfiche \$3.00

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**GENERAL ATOMIC PROJECT 3224
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ABSTRACT

Graphite grade H-451, the reference material used as fuel and reflector elements in General Atomic large high-temperature gas-cooled reactors, was oxidized to 20% burnoff by weight in steam-helium mixtures, and the effects of oxidation on ultimate tensile strength (UTS) and elastic modulus (E) were studied. Large numbers of small cylindrical samples cored from selected locations in a log of preproduction H-451 graphite were oxidized at 1073 and 1273 K (1472° and 1832°F) in helium containing 3% water vapor and 5% H₂. The UTS and E of oxidized specimens were measured and the results compared with those for nonoxidized control specimens. The average rate of change of UTS and E with burnoff at 1273 K (1832°F) (up to 20% burnoff) averaged 3.6% and 5.2%, respectively. Statistical analysis (comparison of population means) of the low burnoff strength data showed no significant differences between the nonoxidized control and oxidized specimens at burnoffs of up to approximately 2%.

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1. INTRODUCTION

Graphite oxidation in a high-temperature gas-cooled reactor (HTGR) may occur because of two distinct types of steam ingress: (1) a major steam leak caused by, for example, rupture of a heat exchanger steam tube and (2) continuous low-level in-leakage. The degree of oxidation due to the first type of leak would be negligible because the reactor would be shut down within seconds of such an event (Ref. 1). A continuous low-level 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-yr life of the reactor graphite components. Low levels of steam for long periods of time could lead to small but measurable oxidation of the core graphite.

The fuel element blocks are subject to mechanical stresses including compressive stresses (i.e., those due to the weight of the core components) and tensile stresses (those due to irradiation and thermal gradient effects). The fuel element blocks may have to withstand additional stresses resulting from seismic events. Because of these in-service requirements, it is essential that the blocks retain their structural integrity. Consequently, the effect of oxidation on the ultimate tensile strength (UTS) and elastic modulus (E) was determined.

The purpose of this report is to characterize H-451 graphite,* the reference material for fuel and replaceable reflectors in the General Atomic (GA) large high-temperature gas-cooled reactor (LHTGR), by determining the effect of uniform oxidation on UTS and E. The oxidation experiments were

* Great Lakes Carbon Company Grade H-451 is commercially manufactured by extrusion with petroleum-based near-isotropic cokes. A description of Grade H-451, its properties, and impurity content is given in Ref. 2.

performed in steam-helium mixtures using small specimens taken from one axial location in a single preproduction log (GA log 6384-34). Control specimens taken from the same population as those used for the oxidation experiments were used to determine changes in UTS and E.

2. EXPERIMENTAL PROCEDURES

The experimental work consisted of uniform and isothermal oxidation of large numbers of small test specimens at 1073 and 1273 K (1472° and 1832°F) in steam-helium mixtures and subsequent measurement of the UTS and E of the oxidized specimens. In a few cases, strain at fracture was determined. The UTS and E values of the oxidized specimens were compared with those of the nonoxidized control specimens, which were taken from the same population as the specimens utilized for oxidation, to determine the changes caused by burnoff.

2.1. SAMPLING AND SPECIMEN PREPARATION

Commercial graphite logs of the size used for fuel and reflector elements in HTGRs [0.43-m (17-in.) diameter, 0.86-m (34-in.) length] have been shown to have a nonuniform distribution of properties within a single log (Ref. 2). It has been observed, for example, that the UTS and E of H-451 graphite are highest in the axial direction (parallel to extrusion), lowest at the midlength center (MLC) of a log, and increase from the center to the edges. (Ref. 2) Specimens were selected from quarter-length center (QLC) and quarter-length edge (QLE) positions of a GA log 6384-34 to obtain data on material of highest and lowest strength. Axial and radial specimens were selected as indicated in Figs. 1 through 4. Specimen cores with diameters of 7.93 mm (0.3125 in.) and lengths of 63.4 mm (2.5 in.) were removed from each section (Figs. 3,4), and the cores were machined by centerless grinding into specimens with diameters of 6.34 mm (0.25 in.). Groups of samples were randomized and allocated for oxidation according to Table 1. The specimens were oxidized in 63.4-mm (2.5-in.) lengths. After oxidation, approximately 0.6 mm (0.25 in.) was removed from each end of each oxidized specimen, and each specimen was cut in half to provide two specimens 6.34 mm (0.25 in.) in diameter and 23 mm (0.9 in.) in length.

Fig. 1. Sampling plan of graphite log showing material (slab) designated for oxidation tests

Fig. 2. Slab sectioning

Fig. 3. Sampling diagram of slab 5A/5B: center section

Fig. 4. Sampling diagram of slab 5A/5B: edge section

TABLE 1
ALLOCATION OF GRAPHITE SAMPLES^(a) FOR OXIDATION STUDIES

Log-Slab-Section Number	Specimen Number									
	Axial Direction							Radial Direction		
	Controls	1%(b) 1073 K	2% 1073 K	4% 1073 K	1% 1273 K	2% 1273 K	4% 1273 K	Controls	4% 1073 K	4% 1273 K
← QLC →										
6484-34-5AC	1	2	3	4	8	10	7	43	42	40
	5	13	6	15	14	12	9	49	48	50
	16	17	18	25	19	22	11	54	52	56
	20	26	21	28	32	24	27	60	55	59
	33	31	23	34	35	29	30	64	62	61
	37		36	38			39	66	65	63
6484-34-5BC	11	1	4	3	2	8	5	40	41	45
	14	7	15	6	12	13	10	47	43	48
	21	9	29	17	25	18	16	52	44	51
	24	28	30	19	27	22	20	57	54	61
	26	33	32	23	31		35	59	58	65
	38		34	36		39	37	62	63	67
← QLE →										
6484-34-5AE	101			103			102	128	126	129
	106			107			109	132	127	130
	111			112			110	134	133	131
	116			114			113	136	137	135
	121			118			117	138	141	143
	122			119			124	139	142	144
6484-34-5BE	103			102			101	129	126	125
	104			106			105	131	132	127
	112			108			111	122	134	128
	115			113			114	136	137	135
	117			116			120	141	138	139
	123			122			124	144	142	143

(a) Samples cored from H-451 graphite log 6484-34.

(b) Planned percent burnoff and temperature of oxidation (1073 K = 1472°F; 1273K = 1832°F).

The apparatus used for the oxidation measurements is shown in Fig. 5. Several of the cylindrical graphite specimens were simultaneously oxidized in each experiment. The specimens were supported by racks made from H-451 graphite and contained in quartz vessels. The quartz vessels were heated to 1073 or 1273 K in clamshell resistance furnaces; temperatures were controlled to within ± 10 K. During the oxidation phase, the vessels were purged with a gas mixture composed of 3% water vapor, 5% hydrogen, and 92% helium. The purge gas entered the vessels via a quartz tube which penetrated the length of the vessels along the bottom, under the graphite sample racks. Gas entered the vessels through holes drilled along the length of the entry tube. In this way, the process gas contacted all samples in a relatively uniform manner. A flow of one liter (nominal temperature and pressure) per minute of process gas was maintained throughout the tests. During periods of heat-up and cooldown, inert helium was purged through the reaction tubes. To determine the extent of oxidation, the oxidation was periodically interrupted and the samples cooled and weighed to ± 0.1 mg. The percent burnoff was calculated from changes in specimen weight.

It was anticipated that use of small-diameter samples [6.34 mm (0.25 in.)] in a hydrogen-rich gas mixture would ensure relatively uniform oxidation throughout the bulk of the samples. Uniformity of burnoff was confirmed by determining the radial density profiles for a number of nonoxidized and oxidized specimens. The specimens were weighed and dimensioned to determine their average bulk density, and the radius was reduced by predetermined increments using a precision lathe. The machined graphite residue was collected with a small vacuum filter device attached directly to the cutting tool. After each incremental cut, the sample was reweighed and dimensioned, and the density of the material removed was calculated from the weight difference of the specimen and/or the weight of the collected residue.

Fig. 5. Steam-graphite oxidation apparatus

2.2. 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. 2). The UTS of each specimen was calculated by dividing the load at fracture by the original cross sectional area of the specimen. The E of each specimen was calculated from its stress-strain curve as the slope of the chord 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 stress excursion (see Ref. 2 for details). Strain at fracture is $\Delta L/L$, where L is the sample length.

3. EXPERIMENTAL RESULTS

Complete data sets of UTS, E, and strain at fracture are tabulated in the Appendix.

3.1. ULTIMATE TENSILE STRENGTH AND ELASTIC MODULUS

The UTS data are given in Figs. 6 through 11, and the E data, in Figs. 12 and 13; the data are summarized in Tables 2 through 4. The UTS and E values for nonoxidized control material were highest in the axial direction, increased from center to edge (see Table 2), and are in general agreement with other data obtained for this log and other logs of H-451 graphite (Ref. 2).

Statistical analyses were performed on the data to (1) determine whether the distribution of UTS was Gaussian [using chi square analysis (Refs. 3,4)]; (2) compare population mean values of UTS and E for control and oxidized specimens [using the comparison of population means (CPM) test (Ref. 5)]; and (3) determine the maximum, minimum, and most probable (mean) rates of property change with burnoff at 95% confidence (using the CONFID computer code, derived from a technique given in Ref. 5).

The chi square analysis verified that the UTS data followed a Gaussian distribution. This is in agreement with the observations of Price, who found that the UTS of H-451 (Ref. 6) and the properties of other reactor graphites (Ref. 7) follow a Gaussian distribution. Confirmation of a Gaussian distribution is important since both the CPM test and the CONFID computer code assume Gaussian distributions.

Fig. 6. Tensile strength versus burnoff for H-451 graphite (log 6484-34) oxidized at 1073 K (1472°F): quarter-length axial edge and center specimens

Fig. 7. Tensile strength versus burnoff for H-451 graphite (log 6484-34) oxidized at 1273 K (1832°F): quarter-length axial edge and center specimens

Fig. 8, Tensile strength versus burnoff for H-451 graphite (log 6484-34): quarter-length axial center specimens

Fig. 9. Tensile strength versus burnoff for H-451 graphite (log 6484-34) oxidized at 1073 K (1472°F): quarter-length radial specimens

Fig. 11. Elastic modulus versus burnoff for H-451 graphite (log 6484-34): quarter-length axial center specimens

Fig. 12. Elastic modulus versus burnoff for H-451 graphite (log 6484-34) oxidized at 1273 K (1832°F): quarter-length axial specimens

Fig. 13. Elastic modulus versus burnoff for H-451 graphite (log 6484-34) oxidized at 1273 K (1832°F): quarter-length radial edge specimens

TABLE 2
MEAN ULTIMATE TENSILE STRENGTH AND MEAN ELASTIC MODULUS FOR NONOXIDIZED
CONTROL SPECIMENS^(a)

Location	Axial Direction		Radial Direction	
	UTS [MPa (psi)]	E [GPa(10 ⁻⁶ psi)]	UTS [MPa (psi)]	E [GPa(10 ⁻⁶ psi)]
QLC	12.94 ± 1.8 (1877 ± 26)	7.47 ± 1.1 (1.08 ± 0.16)	12.22 ± 1.3 (1772 ± 19)	6.90 ± 0.59 (1.00 ± 0.08)
QLE	18.94 ± 1.7 (247 ± 25)	8.56 ± 1.42 (1.24 ± 0.21)	16.1 ± 1.8 (2335 ± 26)	7.96 ± 0.75 (1.15 ± 0.11)

^(a)Log 6384-34.

TABLE 3
SUMMARY OF MECHANICAL PROPERTIES AND COMPARISON OF POPULATION MEANS FOR
QUARTER-LENGTH SAMPLES FROM H-451(a)

Location and Orientation (b)	Oxidation		Ultimate Tensile Strength				Elastic Modulus			
	Temperature [K (°F)]	Burnoff (%)	Mean [MPa (psi)]	Standard Deviation [MPa (psi)]	Number of Data Points	CPM Test Results (c)	Mean [GPa(10 ⁻⁶ psi)]	Standard Deviation [GPa(10 ⁻⁶ psi)]	Number of Data Points	CPM Test Results (c)
CA	--	0	12.9 (1870)	1.8(261)	19	--	7.5 (1.09)	1.1(0.16)	8	--
CA	1073(1472)	0.7 to 0.36	13.4 (1944)	1.7(247)	12	NSD	7.2 (1.04)	0.6(0.09)	4	NSD
CA	1073(1472)	0.49 to 0.69	13.2 (1915)	1.5(217)	16	NSD	7.9 (1.15)	0.77(0.11)	13	NSD
CA	1073(1472)	0.86 to 1.60	12.5 (1813)	1.4(203)	37	NSD	6.9 (1.00)	1.1(0.16)	19	SD
CA	1273(1832)	0.99 to 1.30	13.4 (1944)	1.2(174)	14	NSD	7.1 (1.03)	0.6(0.09)	8	NSD
CA	1273(1832)	1.47 to 1.90	12.5 (1813)	1.5(217)	16	NSD	7.0 (1.02)	1.0(0.15)	8	NSD
CA	1273(1832)	5.38 to 7.83	10.7 (1552)	1.3(189)	20	SD	5.8 (0.84)	0.7(0.10)	8	SD
CR	--	0	12.2 (1769)	1.3(189)	20	--	6.9 (1.00)	0.6(0.09)	9	--
CR	1073(1472)	0.25 to 0.33	10.6 (1537)	1.1(160)	12	SD	--	--	--	--
CR	1073(1472)	8.4 to 10.0	6.1 (885)	0.9(131)	12	SD	--	--	--	--
CR	1273(1832)	10.2 to 14.5	6.9 (1001)	1.2(174)	12	SD	--	--	--	--
CR	1273(1832)	15.7 to 19.6	4.2 (609)	1.3(189)	9	SD	--	--	--	--
EA	--	0	18.9 (2741)	1.7(247)	15	--	8.6 (1.25)	1.4(0.20)	12	--
EA	1073(1472)	1.0 to 2.5	16.8 (2437)	1.4(203)	24	SD	--	--	--	--
EA	1273(1832)	3.3 to 5.2	14.8 (2147)	1.1(160)	20	SD	6.3 (0.91)	0.7(0.10)	8	SD
ER	--	0	16.1 (2335)	1.8(261)	18	--	8.0 (1.16)	0.8(0.12)	11	--
ER	1073(1472)	0.49 to 0.59	10.7 (1552)	1.3(189)	12	SD	--	--	--	--
ER	1073(1472)	10.5 to 13.8	7.4 (1073)	1.1(160)	12	SD	--	--	--	--
ER	1273(1832)	3.4 to 4.8	13.0 (1885)	1.2(174)	9	SD	5.1 (0.74)	0.6(0.09)	4	SD
ER	1273(1832)	5.8 to 7.6	10.9 (1581)	1.3(189)	10	SD	4.3 (0.62)	0.4(0.06)	4	SD
ER	1273(1832)	3.4 to 7.6	11.9 (1726)	1.6(232)	19	SD	4.7 (0.68)	0.7(0.10)	8	SD

(a) Log 6484-34.

(b) CA = center axial specimens; CR = center radial specimens; EA = edge axial specimens; ER = edge radial specimens.

(c) NSD = no significant difference (95% confidence) between property averages of controls and oxidized samples; SD = significant difference (95% confidence) between property averages of controls and oxidized samples.

TABLE 4
REDUCTION IN ULTIMATE TENSILE STRENGTH AND ELASTIC MODULUS
WITH OXIDATION

Location (a)	Burnoff Temperature [K (°F)]	Burnoff Range (%)	% Reduction/1% Burnoff		
			Maximum 2.3% Probability	Mean (Most Probable)	Minimum 2.3% Probability
UTS					
CA	1073(1472)	0 to 2	11.17	5.60	0.0
CA	1273(1832)	0 to 2	7.32	1.73	0.0
CA	1273(1832)	0 to 8	3.85	2.82	1.70
EA	1273(1832)	0 to 6	6.48	5.14	3.74
CR	1073(1472)	0 to 10	6.06	5.32	4.32
ER	1073(1472)	0 to 14	5.14	4.60	3.23
CR	1273(1832)	0 to 20	3.92	3.59	3.18
ER	1273(1832)	0 to 8	5.93	4.79	3.72
E					
CA	1073(1472)	0 to 2	19.04	10.46	0.01
CA	1273(1832)	0 to 2	11.56	3.71	0.0
CA	1273(1832)	0 to 8	4.88	3.26	1.45
EA	1273(1832)	0 to 5	9.53	6.10	1.96
ER	1273(1832)	0 to 6	9.31	7.83	6.11

(a) CA = center axial specimens; EA = edge axial specimens; CR = center radial specimens; ER = edge radial specimens.

The results of the CPM and CONFID analyses are given in Tables 3 and 4, respectively. The rates of changes in UTS and E from the CONFID calculations are illustrated in Figs. 6 through 13, where the most probable rate changes are shown as linear regression lines. A comparison of nonoxidized and oxidized UTS values showed strength to decrease with oxidation. The population means of the control and oxidized specimens were also compared (Table 3), and no significant reduction in UTS or E was observed at 95% confidence in axial specimens oxidized up to 2% and 1% burnoff, respectively.

The effect of oxidation on UTS for axial edge and center specimens oxidized at 1073 K (1472°F) is shown in Fig. 6. There was no decrease in strength in the center specimens up to 2% burnoff, whereas a slight decrease was observed in the edge specimens. The UTS reduction rates for 1273 K (1832°F) oxidation are shown in Fig. 7. Again, the edge specimens lost strength at a higher rate than the center specimens. The combined data for axial center samples at low burnoffs are shown in Fig. 8. No strength reduction was observed for burnoffs of up to 2% at either 1073 or 1273 K (1472° or 1832°F). The UTS data for radial edge and center specimens are presented in Figs. 9 and 10 for oxidation at 1073 and 1273 K (1472° and 1832°F), respectively. The radial specimens lost strength at a faster rate than the axial specimens, and in both cases the edge specimens lost strength at a faster rate than the center specimens.

The effect of oxidation on the E of axial center specimens at 1073 and 1273 K (1472° and 1832°F) is given in Fig. 11. There was no effect of burnoffs of up to 1%, but above 1% the reduction of E was significant. Changes in the E of axial center and edge specimens are compared in Fig. 12. The E of the edge specimens was reduced at a higher rate than that of the center specimens. A plot of elastic modulus versus burnoff for radial specimens oxidized at 1273 K (1832°F) is shown in Fig. 13.

All trends for UTS and E are summarized in Table 4 by comparing the relative reduction of each property at 1% burnoff. The results in Table 4 were obtained from CONFID, which can be used to calculate at 95% confidence the most probable (50% probability) or "mean" decrease in property and the maximum and minimum (2.3% probability) decrease in property. The reductions in UTS and E were greater when the specimens were oxidized at 1073 K (1472°F) compared with 1273 K (1832°F). Also, as noted previously, changes in UTS and E were greater for edge specimens than for center specimens. This phenomenon was particularly significant for the modulus data, where the average decrease in edge specimens at 1273 K (1832°F) was twice that of the center specimens.

3.2. STRAIN AT FRACTURE

Changes in strain at fracture were measured for controls and specimens oxidized to burnoffs of up to 12%; these data are presented in Table 5. The data were anomalous, showing no changes in axial center specimens at 4.3% burnoff, about 50% reduction in radial center specimens at 2.8% to 9.3% burnoff, and about 40% in radial edge specimens at 5.5% to 12% burnoff. No firm conclusions can be drawn from these data.

3.3. OXIDATION-INDUCED BULK DENSITY PROFILES

Bulk density profiles for a nonoxidized control specimen of H-451 and for three oxidized specimens are given in Figs. 14 through 17. The large scatter in the data is due to (1) experimental difficulties in measuring small changes in weight and dimensions, (2) the heterogeneous nature of the graphite, and (3) the relatively large H-451 particle sizes, which lead to some tearing out of graphite particles during machining. When a large number of increments were taken across the radius of a specimen [about 1.5 mm (0.06 in.) for an initial diameter of 6.3 mm (0.25 in.)], the scatter in the data tends to be average. The final central core of the machined specimens [diameter ~3 mm (0.12 in.)], which can be accurately determined, was used as the final data point on the curves in Figs. 14 through

TABLE 5
EFFECT OF OXIDATION ON STRAIN AT FRACTURE

Location In Slab	Specimen Orientation	Mean Value (%)	Standard Deviation (%)	Number of Specimens Tested	Burnoff (%)	
					Range	Average
Edge	Axial	0.36(a)	0.04	7	Control	
Edge	Axial	0.33(a)	0.03	8	3.3 to 5.2	4.3
Center	Radial	0.28	0.04	9	Control	
Center	Radial	0.13	0.02	10	2.6 to 3.3	2.80
		0.13	0.02	11	8.4 to 10.0	9.31
Edge	Radial	0.32	0.04	10	Control	
Edge	Radial	0.17	0.02	11	5.0 to 5.9	5.5
		0.19	0.02	12	10.5 to 12.8	12.1

(a) Judged not significantly different at 95% confidence level using student's t-test.

Fig. 14. Bulk density profile of H-451 graphite: 0% burnoff

Fig. 15. Bulk density profile of H-451 graphite (sample 6484-34-5B): quarter-length axial center specimen oxidized at 1073 K (1472°F) to 0.96% burnoff

Fig. 16. Bulk density profile of H-451 graphite (sample 6484-34-5B): quarter-length axial center specimen oxidized at 1273 K (1832°F) to 4.3% burnoff

Fig. 17. Bulk density profile of H-451 graphite (sample 6484-34-5A-29B): quarter-length axial center specimen oxidized at 1273 K (1832°F) to 1.5% burnoff

17 and in all cases confirmed the apparent density trends of the smaller increments taken near the outer edge of the specimens.

The oxidation profiles are uniform for all specimens oxidized at 1073 or 1273 K (1472° or 1832°F). It was anticipated that some preferential oxidation on the outer surface of the samples would occur at 1273 K (1832°F); i.e., the final density profile along the radius after oxidation should increase from the outer edge toward the center. This type of gradient was observed in specimen 34-5B (see Fig. 16). In the other cases, as shown in Fig. 17, oxidation at 1273 K (1832°F) produced a uniform profile. It is concluded from the bulk density profile data that all UTS specimens were uniformly oxidized across the radius.

4. CONCLUSIONS

The following conclusions have been reached:

1. The E and UTS of H-451 graphite were decreased by an average of 3.6% and 5.2% respectively, per percent burnoff for specimens oxidized at 1273 K (1832°F) and 5.2% UTS and 10.5% E for specimens oxidized at 1073 K (1472°F). This conclusion is based on averaging data from specimens of all log locations, orientations, and burnoffs.
2. There was no significant reduction in UTS in center axial specimens oxidized to burnoffs of up to 1.9% at either 1073 or 1273 K (1472° or 1832°F) and no significant reduction in E in the same specimens oxidized to burnoffs of up to 1.9% at 1273 K (1832°F). These results are of particular importance because the maximum volumetric burnoff in the HTGR fuel element blocks has been calculated to be 1%.
3. The rate of reduction of UTS and E for center axial specimens was greater at 1073 K (1472°F) than at 1273 K (1832°F). This difference is not important for design, because the volumetric burnoff of the fuel element blocks is calculated to be about 0.1% to 0.2% at 1073 K (1472°F).
4. In general, the reduction rate of E with burnoff was greater than that of UTS. The higher reduction rate of E is important in design because a lower modulus decreases the secondary stresses, i.e., the thermal stresses resulting from gradients and differential irradiation-induced strain.

5. The rate of reduction of UTS and E for axial specimens oxidized at 1273 K (1832°F) was greater at the edge than at the center of a log. This does not impose a limitation in design, because the UTS of a fuel element block is always measured at the center of the log, where the minimum strength occurs. The UTS of the edge material of a log oxidized up to 2% burnoff was never less than the UTS at the center samples for 0% to 2% burnoff.
6. In general, the reduction in UTS and E for radial specimens was higher than that for axial specimens. The higher seismically induced stresses in an HTGR fuel element are in the radial direction, and thus this phenomenon could affect the design. However, the reduction in E of the radial specimens was greater than the strength loss, and hence the overall effect on seismic performance will be negligible.

ACKNOWLEDGMENTS

The authors wish to thank C. H. Richards, J. H. Whaley, and F. R. Hogan, Sr., for preparing the specimens and measuring the strength and modulus and G. B. Engle for his helpful comments and editing of the text.

REFERENCES

1. Barsell, A. W., and M. B. Perroomian, "Consequences of Water Ingress Into the HTGR Primary Coolant," General Atomic Report GA-A13171, April 15, 1975.
2. Johnson, W. R., and G. B. Engle, "Properties of Unirradiated Fuel Element Graphites H-451 and TS-1240," ERDA Report GA-A13752, General Atomic, January 31, 1976.
3. Bevington, P. R., Data Reduction and Error Analysis for the Physical Sciences, McGraw-Hill, New York, 1969, pp. 84, 314.
4. Johnson, N. L., and F. C. Leone, Statistics and Experimental Design, v. 1, John Wiley and Sons, New York, 1964, p. 104.
5. Bevington, P. R., op. cit., p. 104.
6. Price, R. J., and H. R. W. Cobb, "Application of Weibull Statistical Theory to the Strength of Reactor Graphite," Gulf General Atomic Report GA-10257, August 6, 1970.
7. Price, R. J. "Statistical Study of the Strength of Near-Isotropic Graphite," ERDA Report GA-A13955, General Atomic, May 24, 1976.

APPENDIX

TENSILE PROPERTIES OF H-451 GRAPHITE: LOG NO. 6484-34
(SPECIMEN DIAMETER = 6.4 MM,
LENGTH = 23 MM)

CONTROLS

Specimen Number	Orientation	Location	Density (mg/m ³)	Young's Modulus (GPa)	Permanent Set (%)	Fracture Strain (%)	Tensile Strength (MPa)
5651-23-5A-1A	Axial	QLC	1.726	0.865	0.039	0.235	11.38
1B			1.721	--	--	--	11.52
5A			1.730	1.046	0.031	0.279	11.10
5B			--	--	--	--	13.22
16A			1.726	0.882	0.049	0.307	12.95
16B			--	--	--	--	10.83
20A			1.724	1.250	0.022	0.228	13.20
20B			--	--	--	--	13.07
33A			1.726	--	--	--	4.50
33B			--	--	--	--	13.89
37A			--	--	--	--	--
37B			--	--	--	--	--
11A			1.725	1.084	0.032	0.185	9.05
11B			1.723	--	--	--	16.85
14A			1.714	--	--	--	13.96
14B			--	--	--	--	12.10
21A			1.732	1.168	0.038	0.326	15.11
21B			--	--	--	--	14.21
24A			1.724	1.323	0.032	0.247	15.13
24B			--	--	--	--	12.55
26A			1.726	1.046	0.040	0.300	13.66
26B			--	--	--	--	12.16

OXIDIZED AT 1073 K (1472°F)

Specimen Number	Orientation	Location	Density (mg/m ³)	Young's Modulus (GPa)	Permanent Set (%)	Fracture Strain (%)	Tensile Strength (MPa)	Burnoff (%)
5651-23-5A-2A	Axial	QLC	1.710	--	--	--	11.6	0.17
2B			1.715	--	--	--	14.0	0.17
13A			1.703	Bond failure			--	0.97
13B			1.698	--	--	--	12.6	0.97
17A			1.697	7.29	0.03	0.29	14.0	0.36
17B			1.700	6.46	0.04	0.25	11.1	0.36
26A			1.698	--	--	--	16.0	0.21
26B			1.690	--	--	--	15.6	0.21
31A			1.685	7.21	0.04	0.30	13.9	1.37
31B			1.685	6.21	0.03	0.28	13.0	1.37
5651-23-5B-1A			1.703	--	--	--	14.2	1.30
1B			1.677	--	--	--	11.8	1.30
7A			1.702	--	--	--	11.7	0.27
7B			1.703	--	--	--	11.4	0.27
9A			1.705	7.85	0.03	0.26	14.4	0.19
9B			1.710	7.05	0.04	0.31	14.6	0.19
28A			1.700	6.97	0.04	0.27	12.8	0.87
28B			1.698	6.97	0.05	0.32	13.4	0.87
33A			1.717	--	--	--	12.8	0.35
33B			1.705	--	--	--	13.5	0.35

OXIDIZED AT 1073 K (1472°F)

Specimen Number	Orientation	Location	Density (mg/m ³)	Young's Modulus (GPa)	Permanent Set (%)	Fracture Strain (%)	Tensile Strength (MPa)	Burnoff (%)
5651-23-5A-3A	Axial	QLC	1.695	7.21	0.06	0.271	12.1	1.15
3B			1.693	5.39	0.04	0.253	8.7	1.15
6A			1.700	6.67	0.06	0.351	13.7	0.88
6B			1.708	6.27	0.03	0.374	13.2	0.88
18A			1.677	--	--	--	11.7	1.60
18B			1.678	--	--	--	13.1	1.60
21A			1.695	5.39	0.05	0.339	11.9	1.44
21B			1.694	8.38	0.05	0.215	11.2	1.44
23A			1.694	5.69	0.01	0.280	11.2	1.43
23B			1.694	4.50	0.07	0.270	10.3	1.43
36A			1.683	--	--	--	10.8	1.40
36B			1.678	--	--	--	11.7	1.40
5651-23-5B-4A			1.699	--	--	--	13.2	0.92
4B			1.698	--	--	--	11.5	0.92
15A			1.697	--	--	--	12.1	0.96
15B			1.683	--	--	--	12.8	0.96
29A			1.690	--	--	--	13.6	1.34
29B			1.694	← Bond failure →			--	1.34
30A			1.683	--	--	--	10.8	1.28
30B			1.675	← Bond failure →			--	1.28
32A			1.695	--	--	--	12.7	0.86
32B			1.700	--	--	--	10.6	0.86
34A			1.698	--	--	--	13.5	1.01
34B			1.703	--	--	--	12.3	1.01

OXIDIZED AT 1073 K (1472°F)

Specimen Number	Orientation	Location	Density (mg/m ³)	Young's Modulus (GPa)	Permanent Set (%)	Fracture Strain (%)	Tensile Strength (MPa)	Burnoff (%)
5651-23-5A- 4A	Axial	EC	1.699	8.4	0.008	0.362	11.4	0.94
4B			1.700	8.2	0.017	0.209	12.1	↓
-15A			1.693	7.3	0.024	0.254	14.2	
-15B			1.700	7.4	0.005	0.261	14.7	
-25A			1.703	6.6	0.012	0.213	12.2	0.58
-25B			1.707	8.1	--	0.181	13.2	↓
-28A			1.702	7.4	0.010	0.225	12.8	
-28B			1.705	8.1	0.004	0.192	12.8	
-34A			1.699	7.7	0.020	0.210	11.7	0.56
-34B			1.701	7.0	0.030	0.214	10.8	↓
-38A			1.706	7.6	0.019	0.279	15.2	0.81
-38B			1.710	7.9	0.011	0.322	16.0	↓

OXIDIZED AT 1273 K (1832°F)

Specimen Number	Orientation	Location	Density (mg/m ³)	Young's Modulus (GPa)	Permanent Set (%)	Fracture Strain (%)	Tensile Strength (MPa)	Burnoff (%)
5651-23-5A- 8A	Axial	QLC	1.703	6.74	0.039	0.310	14.2	1.05
8B			1.697	7.56	0.039	0.208	13.2	1.05
14A			1.695	--	--	--	14.1	1.20
14B			1.677	← Bond failure →			--	1.20
19A			1.685	← Bond failure →			--	1.30
19B			1.690	--	--	--	15.0	1.30
32A			1.702	6.46	0.041	0.342	13.2	1.24
32B			1.701	7.21	0.044	0.236	11.5	1.24
35A			1.692	← Bond failure →			--	1.01
35B			1.693	← Bond failure →			--	1.01
5651-23-5B- 2A			1.689	--	--	--	13.4	1.26
2B			1.697	← Bond failure →			--	1.26
12A			1.709	8.16	0.032	0.277	14.5	1.28
12B			1.708	6.89	0.040	0.251	12.3	1.28
25A			1.701	7.29	0.014	0.290	14.6	0.99
25B			1.703	6.53	0.039	0.322	13.4	0.99
27A			1.696	--	--	--	11.1	1.23
27B			1.699	--	--	--	14.4	1.23
31A			1.692	--	--	--	12.8	1.03
31B			1.699	← Bond failure →			--	1.03

OXIDIZED AT 1273 K (1832°F)

Specimen Number	Orientation	Location	Density (mg/m ³)	Young's Modulus (GPa)	Permanent Set (%)	Fracture Strain (%)	Tensile Strength (MPa)	Burnoff (%)
5651-23-5A-10A	Axial	QLC	1.675	7.66	0.051	0.26	12.7	1.90
10B			1.676	5.96	0.048	0.31	12.1	1.90
12A			1.678	--	--	--	10.1	1.83
12B			1.679	--	--	--	13.4	1.83
22A			1.688	--	--	--	13.9	1.71
22B			1.685	--	--	--	11.9	1.71
24A			1.683	6.33	0.050	0.25	10.3	1.80
24B			1.686	8.05	0.049	0.20	10.5	1.80
29A			1.686	← Bond failure →			--	1.55
29B			1.687	← Bond failure →			12.7	1.55
5651-23-5B- 8A			1.684	7.29	0.036	0.27	13.0	1.85
8B			1.686	6.46	0.031	0.30	10.7	1.85
13A			1.694	5.58	0.050	0.35	12.2	1.57
13B			1.692	8.27	0.018	0.26	13.0	1.57
18A			1.692	--	--	--	15.0	1.90
18B			1.680	← Bond failure →			--	1.90
22A			1.667	← Bond failure →			--	1.79
22B			1.679	← Bond failure →			--	1.79
39A			1.685	--	--	--	13.6	1.47
39B			1.690	--	--	--	14.5	1.47

OXIDIZED AT 1273 K (1832°F)

Specimen Number	Orientation	Location	Density (mg/m ³)	Young's Modulus (GPa)	Permanent Set (%)	Fracture Strain (%)	Tensile Strength (MPa)	Burnoff (%)
5651-23-5A- 7A	Axial	QLC	1.543	--	--	--	11.8	6.68
7B			1.600	--	--	--	10.5	6.68
9A			1.593	--	--	--	11.4	7.08
9B			1.597	--	--	--	11.1	7.08
11A			--	--	--	--	--	7.43
11B			--	--	--	--	--	7.43
27A			1.611	--	--	--	10.5	5.48
27B			1.584	--	--	--	11.9	5.48
30A			1.609	--	--	--	11.1	7.12
30B			1.598	--	--	--	10.7	7.12
39A			--	--	--	--	--	6.00
39B			--	--	--	--	--	6.00
5651-23-5B- 5A			1.594	--	--	--	10.3	7.31
5B			1.589	--	--	--	8.6	7.31
10A			1.589	--	--	--	8.6	6.82
10B			1.610	--	--	--	12.5	6.82
16A			1.613	--	--	--	12.2	6.48
16B			1.592	--	--	--	10.8	6.48
20A			1.593	--	--	--	11.1	7.57
20B			1.586	--	--	--	11.1	7.57
35A			1.575	--	--	--	10.2	7.83
35B			1.604	--	--	--	9.0	7.83
37A			1.638	--	--	--	11.7	5.38
37B			1.630	--	--	--	8.0	5.38

CONTROLS

Specimen Number	Orientation	Location	Density (mg/m ³)	Young's Modulus (GPa)	Permanent Set (%)	Fracture Strain (%)	Tensile Strength (MPa)
5651-23-5A-43A	Radial	QLC	1.724	6.82	0.041	0.253	11.58
43B			--	--	--	--	13.64
49A			1.722	6.74	0.049	0.358	14.49
49B			1.720	6.33	0.049	0.290	11.97
54A			1.722	6.39	0.043	0.280	11.37
54B			--	--	--	--	12.80
60A			1.717	6.08	0.037	0.322	14.06
60B			1.712	--	--	--	13.38
64A			1.725	--	--	--	10.97
64B			--	--	--	--	11.27
5651-23-5B-40A			1.720	1.034	0.026	0.220	10.85
40B			1.725	--	--	--	11.47
47A			1.717	1.0	0.031	0.246	12.41
47B			--	--	--	--	13.09
52A			1.735	--	0.044	0.270	13.29
52B			--	--	--	--	11.71
57A			1.715	--	--	--	11.40
57B			--	--	--	--	12.39
59A			1.713	--	0.025	0.250	13.11
59B			--	--	--	--	9.18

OXIDIZED AT 1073 K (1472°F)

Specimen Number	Orientation	Location	Density (mg/m ³)	Young's Modulus (GPa)	Permanent Set (%)	Fracture Strain (%)	Tensile Strength (MPa)	Burnoff (%)
5651-23-41AA	Radial	QLC	1.556	--	--	0.127	5.9	9.514
-41AB			1.565	--	--	0.137	5.7	9.514
-42AA			1.566	--	--		6.3	9.328
-42AB			1.563	6.2	0.020	0.146	7.6	9.328
-43AA			1.556	--	--	0.154	6.0	9.408
-43AB			1.558	--	--	0.155	6.7	9.408
-44AA			1.575	--	--	0.100	5.5	8.442
-44AB			1.573	--	--	0.087	5.1	8.442
-48AA			1.554	--	--	0.148	6.9	10.026
-48AB			1.542	--	--	0.124	6.2	10.026
-52AA			1.555	--	--	0.115	4.2	9.124
-52AB			1.562	--	--	0.149	7.1	9.124
-54AA			1.671	--	--	--	9.4	2.588
-54AB			1.679	11.3	0.014	0.149	12.1	2.588
-55AA			1.659	9.2	0.020	0.168	11.2	3.337
-55AB			1.661	13.2	0.009	0.102	9.8	3.337
-58AA			1.670	10.2	0.013	0.126	9.7	2.488
-58BB			1.673	12.7	0.010	0.132	11.5	2.488
-62AA			1.676	--	--	--	10.4	2.709
-62AB			1.656	10.9	0.005	0.111	10.4	2.709
-63AA			1.665	9.7	0.016	0.105	8.2	2.905
-63AB			1.665	10.9	0.010	0.139	11.0	2.905
-65AA			1.662	10.5	0.010	0.138	11.1	2.955
-65AB			1.667	11.7	0.010	0.140	11.8	2.955

OXIDIZED AT 1273 K (1832°F)

Specimen Number	Orientation	Location	Density (mg/m ³)	Young's Modulus (GPa)	Permanent Set (%)	Fracture Strain (%)	Tensile Strength (MPa)	Burnoff (%)
5651-23-5A-40A	Radial	QLC	1.416				2.82	19.5
40B			1.377				3.52	19.5
50A			1.456				1.83	15.7
50B			1.445				5.63	15.7
56A			1.490				6.03	13.4
56B			1.464				6.61	13.4
59A			1.522				7.87	10.6
59B			1.536				6.46	10.6
61A			1.405				5.63	18.9
61B			1.368				5.05	18.9
63A			1.464				6.76	13.5
63B			1.483				7.73	13.5
5651-23-5B-45A			1.457				4.51	14.5
45B			1.490				5.92	14.5
48A			--				--	11.8
48B			--				--	11.8
51A			1.397				3.54	18.0
51B			1.448				4.66	18.0
61A			1.444				5.07	16.2
61B			1.431				--	16.2
65A			1.505				8.98	13.5
65B			1.486				6.75	13.5
67A			1.534				6.32	10.1
67B			1.529				8.29	10.1

CONTROLS

Specimen Number	Orientation	Location	Density (mg/m ³)	Young's Modulus (GPa)	Permanent Set (%)	Fracture Strain (%)	Tensile Strength (MPa)
5651-24-5A-101A	Axial	QLE	--	--	--	--	18.84
-101B			--	--	--	--	18.55
-106A			1.759	9.12	0.025	--	--
-106B			1.758	7.56	0.036	0.370	19.26
-111A			--	--	--	--	--
-111B			--	--	--	--	19.82
-116A			1.724	6.74	0.025	0.291	13.82
-116B			1.724	8.38	0.036	0.357	17.94
-121A			1.761	7.56	0.047	0.416	21.35
-121B			1.760	9.26	0.025	--	--
-122A			--	--	--	--	17.97
-122B			--	--	--	--	18.11
5651-24-5B-103A			--	--	--	--	--
-103B			--	--	--	--	--
-104A			1.739	7.05	0.022	--	--
-104B			1.740	8.49	0.029	0.371	19.92
-112A			1.758	12.16	0.030	--	--
-112B			1.759	8.49	0.039	0.388	20.82
-115A			--	--	--	--	20.11
-115B			--	--	--	--	--
-117A			--	--	--	--	18.84
-117B			--	--	--	--	18.86
-123A			1.740	8.38	0.023	--	--
-123B			1.746	9.54	0.029	0.343	19.84

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OXIDIZED AT 1073 K (1472°F)

Specimen Number	Orientation	Location	Density (mg/m ³)	Young's Modulus (GPa)	Permanent Set (%)	Fracture Strain (%)	Tensile Strength (MPa)	Burnoff (%)
5651-24-5A-103A	Axial	QLE					18.7	1.22
103B							18.2	1.22
107A							17.0	2.24
107B							17.1	2.24
112A							16.9	2.40
112B							17.1	2.40
114A							16.3	1.45
114B							17.7	1.45
118A							19.1	1.10
118B							16.7	1.10
119A							16.1	1.98
119B							16.0	1.98
5651-24-5B-102A							16.6	2.23
102B							17.1	2.23
106A							19.1	1.43
106B							18.8	1.43
108A							16.0	1.15
108B							17.9	1.15
113A							14.0	2.39
113B							13.8	2.39
116A							15.5	2.61
116B							15.3	2.61
122A							16.6	1.58
122B							16.6	1.58

OXIDIZED AT 1273 K (1832°F)

Specimen Number	Orientation	Location	Density (mg/m ³)	Young's Modulus (GPa)	Permanent Set (%)	Fracture Strain (%)	Tensile Strength (MPa)	Burnoff (%)
5651-24-5A-102A	Axial	QLE	1.658	6.39	0.035	0.350	15.50	4.76
102B			1.663	5.44	0.043	0.348	14.24	4.76
109A			1.686	6.27	0.041	0.349	15.91	3.31
109B			1.686	6.33	0.049	0.324	14.36	3.31
110A			--	--	--	--	14.51	5.21
110B			--	--	--	--	14.93	5.21
113A			--	--	--	--	--	4.86
113B			--	--	--	--	--	4.86
117A			--	--	--	--	15.48	3.37
117B			--	--	--	--	15.48	3.37
124A			--	--	--	--	15.46	4.70
124B			--	--	--	--	13.62	4.70
5651-24-5B-101A			--	--	--	--	15.92	3.30
101B			--	--	--	--	15.92	3.30
105A			--	--	--	--	--	4.6
105B			--	--	--	--	--	4.6
111A			--	--	--	--	15.21	4.15
111B			--	--	--	--	15.38	4.15
114A			1.656	6.67	0.022	0.365	16.33	4.16
114B			1.659	5.30	0.041	0.280	11.57	4.16
120A			1.661	7.13	0.032	0.290	14.09	4.59
120B			1.645	6.97	0.032	0.350	15.80	4.59
124A			--	--	--	--	13.69	4.34
124B			--	--	--	--	14.70	4.34

CONTROLS

Specimen Number	Orientation	Location	Density (mg/m ³)	Young's Modulus (GPa)	Permanent Set (%)	Fracture Strain (%)	Tensile Strength (MPa)
5651-24-5A-128A	Radial	QLE	1.744	6.82	0.030	0.390	18.25
-128B			1.728	8.49	0.029	--	--
-132A			--	--	--	--	17.10
-132B			--	--	--	--	--
-134A			1.722	6.60	0.031	0.275	12.98
-134B			1.744	8.62	0.031	0.307	15.96
-136A			--	--	--	--	6.80
-136B			--	--	--	--	19.10
-138A			--	--	--	--	12.31
-138B			--	--	--	--	17.56
-139A			1.747	8.16	0.038	0.359	17.88
-139B			1.721	7.66	0.044	0.290	14.47
-129A			1.744	8.16	0.012	0.276	15.44
-129B			1.741	--	--	--	--
-131A			1.736	8.27	0.026	0.299	15.39
-131B			1.753	8.05	0.014	0.360	17.91
-122A			--	--	--	--	--
-122B			--	--	--	--	--
-136A			--	--	--	--	14.73
-136B			--	--	--	--	17.60
-141A			1.725	7.56	0.030	0.310	15.15
-141B			1.751	9.12	0.015	0.284	16.00
-144A			--	--	--	--	15.60
-144B			--	--	--	--	17.14

OXIDIZED AT 1073 K (1472°F)

Specimen Number	Orientation	Location	Density (mg/m ³)	Young's Modulus (GPa)	Permanent Set (%)	Fracture Strain (%)	Tensile Strength (MPa)	Burnoff (%)
5651-24-126AA	Radial	QLE	1.519	--	--	0.170	6.6	12.803
-126AB			1.512	--	--	0.179	6.6	12.803
-126BA			1.524	5.3	0.024	0.206	8.3	11.387
-126BB			1.533	6.1	0.020	0.139	7.2	11.387
-127AA			1.494	--	--	0.192	6.9	13.790
-127AB			1.499	--	--	0.164	6.0	13.790
-132AA			1.542	5.4	0.035	0.214	8.7	10.512
-132AB			1.565	5.9	0.025	0.186	8.7	10.512
-133AA			1.491	--	--	0.212	6.6	13.724
-133AB			1.500	--	--	0.194	6.3	13.724
-134AA			1.554	6.4	0.022	0.175	9.0	10.567
-134AB			1.558	4.9	0.034	0.213	8.3	10.567
-137AA			1.620	9.1	0.020	0.118	8.0	5.300
-137AB			4.887	10.3	0.013	0.167	12.2	5.300
-137BA			1.608	7.5	0.021	0.176	10.3	5.865
-137BB			1.624	8.3	0.013	0.189	11.9	5.865
-138AA			1.624	7.0	0.021	0.170	10.0	5.708
-138AB			1.607	7.0	0.025	0.176	9.6	5.708
-141AA			1.643	9.1	0.015	0.180	12.3	5.269
-141AB			1.614	9.9	0.015	0.142	10.1	5.269
-142AA			1.531	--	--		9.7	5.751
-142AB			1.531	8.1	0.016	0.194	12.0	5.751
-142BA			1.537	8.1	0.010	0.190	11.6	4.954
-142BB			1.547	7.4	0.020	0.190	11.2	4.954

OXIDIZED AT 1273 K (1872°F)

Specimen Number	Orientation	Location	Density (mg/m ³)	Young's Modulus (GPa)	Permanent Set (%)	Fracture Strain (%)	Tensile Strength (MPa)	Burnoff (%)
5651-24-5A-129A	Radial	QLE	--	--	--	--	13.98	3.44
129B			--	--	--	--	14.96	3.44
130A			--	--	--	--	--	4.00
130B			--	--	--	--	--	4.00
131A			1.616	5.08	0.057	0.37	12.52	4.28
131B			1.665	5.64	0.045	0.40	14.22	4.28
135A			--	--	--	--	7.61	7.57
135B			--	--	--	--	10.99	7.57
143A			1.603	3.78	0.045	0.41	11.78	5.97
143B			1.651	4.74	0.043	0.33	11.33	5.97
144A			--	--	--	--	11.60	5.77
144B			--	--	--	--	11.30	5.77
5651-24-5B-125A			1.642	4.40	0.047	0.36	11.45	6.28
125B			1.618	4.14	0.081	0.42	11.45	6.28
127A			--	--	--	--	10.16	7.54
127B			--	--	--	--	11.69	7.54
128A			--	--	--	--	--	5.69
128B			--	--	--	--	--	5.69
135A			--	--	--	--	--	4.41
135B			--	--	--	--	13.26	4.41
139A			1.598	4.27	0.048	0.37	11.02	4.33
139B			1.678	5.44	0.023	0.32	12.82	4.33
143A			--	--	--	--	12.28	4.75
143B			--	--	--	--	12.00	4.75