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GA Technologies Inc.

ISSUE SUMMARY

TITLE: TEST REPORT: THERMAL PROPERTIES OF FORT ST. VRAIN FUEL ELEMENT 1-2415

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APPROVAL LEVEL 2

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1. INTRODUCTION

The test plan for the destructive examination of the cracked Fort St. Vrain fuel element 1-2415 calls for measurements of mechanical and thermal properties on coupon specimens cored from the element after removal of the fuel [1]. The results of the tensile tests are reported in Ref. [2]. This report gives the results of thermal expansivity and thermal diffusivity measurements. Thermal diffusivity values are converted to thermal conductivity by multiplying by the density and the heat capacity. Check-out tests on unirradiated H-327 graphite are also reported.

2. MATERIAL

2.1 Unirradiated H-327 Graphite

Unirradiated comparison specimens were machined from H-327 graphite billet 6484-136, Great Lakes Carbon Corp. lot number 56, piece number 5612. Specimens were taken about 1-in. from the edge of a 6-in. deep slab cut perpendicular to the billet axis at about the midlength location. The thermal expansivity specimens were rods measuring 1.0-in. long x 0.25-in. diameter. Those with even identification numbers were oriented parallel to the billet axis, and those with odd identification numbers were oriented transverse to the billet axis. The thermal diffusivity specimens were discs measuring 0.40-in. diameter x 0.08-in. thick, with the thickness dimension oriented radially with respect to the billet axis.

2.2 Irradiated Material

Specimens of irradiated graphite were taken from the cracked Fort St. Vrain fuel element 1-2415, made from H-327 graphite, which had received a neutron exposure of approximately 1.55×10^{21} n/cm^2 (E < 0.18 MeV, HTGR) at a time- and volume-averaged temperature of approximately 650°C [1]. After removal of

the fuel the element was cut into sections as shown in Figure 1, and the 6-in. deep section was used for machining coupon specimens for mechanical and thermal property tests. The six hexagonal faces were identified by letter, as shown in Figure 1. The cracked face was designated B.

A slab approximately 0.44-in. thick was cut adjacent to each of the six faces and cores were taken as shown in Figure 2. The small diameter cores measured approximately 0.27-in. diameter x 4-in. long, and the large diameter cores measured approximately 0.40-in. diameter x 0.44-in. long. The test specimens were machined from the cores with a lathe enclosed in a glove box. The final dimensions for the thermal expansivity specimens were 0.25 in. diameter x 1.00 in. long, and those for the thermal diffusivity specimens were 0.40 in. diameter x 0.08 in. thick. Thermal expansivity specimens with both axial and transverse orientations were tested. All the thermal diffusivity specimens were oriented with the heat flow direction radial with respect to the fuel element axis. The specimens were identified by the face number followed by the core number as shown in Figure 2.

3. TEST METHODS

3.1 Thermal Expansivity

Thermal expansivity measurements were made in a fused silica dilatometer with an argon atmosphere. The dilatometer enclosure was exhausted through an absolute filter. The temperature was raised from room temperature to 500-600°C at 3°C/minute. The thermal expansivity was calculated from the dilatation at 500°C. Further details are given in Ref. [3]. Three replicate specimens for each location and orientation were tested.

3.2 Thermal Diffusivity

The thermal diffusivity was measured by subjecting the front face of the specimen to a pulse of radiant energy from a xenon flash tube while the temperature of the back face was monitored with a chromel-alumel thermocouple. The enclosure was exhausted through an absolute filter. The thermal diffusivity, α (cm^2/s), is related to the specimen thickness, ℓ (cm) and the time for the back face to rise to half its maximum value, $t_{1/2}$(s) by the expression:

$$\alpha = \frac{\omega \ell^2}{t_{1/2}}$$

where ω is a constant which is equal to 0.139 when heat losses are small and $t_{1/2}$ is long compared with the pulse length [4]. The thermal conductivity, K(cal/cm-s-°C), was calculated from α using the expression:

$$K = \alpha \rho C_p$$

where ρ is the density in g/cm^3 and C_p is the specific heat. Values for C_p were obtained from the literature [5]. Tests were made at intervals between room temperature and 600°C, using an argon atmosphere. Two or three replicate specimens from each location were tested; one was measured at intervals of 100°C (±10°C), and the others were measured at intervals of 200°C (±10°C). Further details of the test method are given in Ref. [4].

3.3 Calibrations

The dilatometer calibration was checked using a specimen of NBS-certified tungsten. The measured thermal expansivity agreed with the certified value to within 1%. The rise-time measurement

for the thermal diffusivity determination is measured with a quartz crystal oscillator which is periodically checked against the line frequency and is accurate to better than 0.01%. Poco AXM-5Q graphite is used as a reference material for check-out purposes. Measurements on this material agreed with the accepted values obtained by other laboratories [6] to within 5%.

4. RESULTS

4.1 Thermal Expansivity

4.1.1 Unirradiated Specimens

The thermal expansivity measurements on unirradiated H-327 graphite (25-500°C) are listed in Table 1. The mean values were 1.23×10^{-6} °C^{-1} for the axial direction and 2.69×10^{-6} °C^{-1} for the transverse direction. These compare with nominal hand book values of 1.20×10^{-6} °C^{-1} (axial) and 3.07×10^{-6} °C^{-1} (transverse) [7]. The agreement is satisfactory.

4.1.2 Irradiated Specimens

The thermal expansivity measurements on the irradiated specimens are listed in Table 2. The same data are plotted for each face of the fuel element in Figure 3. The test data have very little experimental scatter and there is no systematic variation in thermal expansivity between the six faces of the fuel element. The mean values are 1.38×10^{-6} °C^{-1} (axial) and 3.28×10^{-6} °C^{-1} (transverse).

For the irradiation conditions experienced by the fuel element, the thermal expansivity would be expected to increased by 2% over the unirradiated value [7]. The expected values are 1.23×10^{-6} °C^{-1} (axial) and 3.14×10^{-6} °C^{-1} (transverse), which are in good agreement with the measured values.

4.2 Thermal Conductivity

4.2.1 Unirradiated Specimens

The test data on unirradiated material are listed in Table 3, and plotted as a function of measurement temperature in Figure 4. The data show considerable specimen-to-specimen scatter. This is probably due to the coarse filler grain size of H-327 graphite; the largest grains are approximately the same size as the specimen thickness. Since the thermocouple wires make point contacts on the back of the specimen, the measured thermal diffusivity is sensitive to the local grain orientation at the thermocouple contacts.

Handbook values [7] for the thermal conductivity of unirradiated H-327 graphite (radial orientation) are shown by the upper solid line in Figure 4. Within the scatter of the data, the agreement with the measured values is satisfactory.

4.2.2 Irradiated Specimens

Table 4 shows the thermal diffusivity measurements on the irradiated specimens. The data are plotted for each face of the fuel element in Figure 5, and the average values are shown as a function of measurement temperature in Figure 4. The data scatter is similar to that of the unirradiated specimens.

Neutron irradiation reduces the thermal conductivity of graphite and flattens its dependence on measurement temperature. For a fluence of 1.55 x 10^{21} n/cm^2 at 650°C, current design

methods [7] predict that at room temperature the thermal conductivity of H-327 graphite in the radial direction would be reduced from 127 w/m-K, to 31 w/m-K, and at 600°C the conductivity would be reduced from 80 w/m-K to 32 w/m-K. The predicted values are shown by the lower solid line in Figure 4. Agreement with the average of the measurements at each temperature is good.

The data in Figure 5 do not reveal any obvious systematic trend in thermal conductivity with the face of the fuel element, and an analysis of variance on the data showed no significant face-to-face variations. Any variations that might have been present (caused, for example, by differences in the irradiation temperature of the faces), would be masked by the scatter in the data.

5. SUMMARY AND CONCLUSIONS

As part of the destructive examination of Fort St. Vrain fuel element 1-2415, thermal expansivity and thermal diffusivity measurements were made on coupons machined from each of the six hexagonal faces of the graphite block. Thermal conductivity values were calculated from the thermal diffusivities. There were no significant variations in either thermal expansivity or thermal conductivity between specimens from the six faces, and the measurements agreed well with current design values for H-327 graphite. The thermal expansivity measurements were very reproducible, but the thermal conductivities showed considerable scatter. Any variations in thermal conductivity between the six faces due to differences in irradiation temperature would have been masked by scatter in the data. It is concluded that there was nothing abnormal about the thermal properties in the vicinity of the crack in face B, and the properties of the fuel element are consistent with the general population of H-327 graphite billets.

6. REFERENCES

[1] F. McCord, "Test Procedure for the Destructive Examination of Fort St. Vrain Fuel Element 1-2415," Document No. 906770, Issue A (Feb. 25, 1983).

[2] R.J. Price, "Tensile Properties of Fort St. Vrain Fuel Element 1-2415," Document No. 907057, Issue A (Sept. 23, 1983).

[3] "Standard Method of Test for Linear Thermal Expansion of Rigid Solids with a Vitreous Silica Dilatometer," ASTM Test Method E-228 (ASTM Annual Book of Standards, **17**, ASTM, Philadelphia, 1982).

[4] "Standard Method of Test for Thermal Diffusivity of Carbon and Graphite by a Thermal Pulse Method," ASTM Test Method C-714 (Annual Book of ASTM Standards, **15**, ASTM, Philadelphia, 1983).

[5] A.T.D. Butland and R.J. Maddison, "The Specific Heat of Graphite: An Evaluation of Measurements," J. Nucl. Mater. **49**, 45 (1973-74).

[6] R.E. Taylor and H. Groot, "Thermophysical Properties of Poco Graphite," High Temperatures-High Pressures, **12**, 147 (1980).

[7] Graphite Design Data Manual, Document No. 906374, Issue 1 (May 19, 1983).

Notations in this column indicate where changes have been made

Table 1. Thermal Expansivity of Unirradiated H-327 Graphite, Billet 6484-136, 25-500°C

Orientation	Specimen Number	CTE (10^{-6} °C^{-1})
Axial	2C	1.37
	4C	1.04, 1.10
	6C	1.20, 1.42
	Mean (± std. dev.)	1.23 ± 0.17
Transverse	1C	2.69, 2.77
	3C	2.87, 2.86
	5C	2.31, 2.63
	Mean (± std. dev.)	2.69 ± 0.21

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Table 2. Thermal Expansivity (25-500°C) of Coupon Specimens from Fort St. Vrain Fuel Element 1-2415 (H-327 Graphite)

	Axial		Transverse	
Face	Specimen Number	CTE (10^{-6} $°C^{-1}$)	Specimen Number	CTE (10^{-6} $°C^{-1}$)
A	2	1.44	1	3.37
	4	1.29	7	3.29
	6	1.30	9	3.26
	Mean	1.34 ± 0.08	Mean	3.31 ± 0.06
B	2	1.39	1	3.28
	4	1.30	3	3.25
	6	1.30	7	3.24
	Mean	1.33 ± 0.05	Mean	3.26 ± 0.02
C	2	1.35	1	3.43
	4	1.40	3	3.25
	6	1.45, 1.31	5	3.27
	Mean	1.38 ± 0.06	Mean	3.32 ± 0.10
D	2	1.52	3	3.19
	4	1.40	5	3.19
	6	1.44	7	3.33
	Mean	1.45 ± 0.06	Mean	3.24 ± 0.08
E	2	1.42	1	3.29
	4	1.34	3	3.36
	6	1.42	5	3.21
	Mean	1.39 ± 0.05	Mean	3.29 ± 0.08
F	2	1.34	1	3.25
	4	1.45	5	3.22
	6	1.34	7	3.36
	Mean	1.38 ± 0.06	Mean	3.28 ± 0.07
All Faces		1.38 ± 0.07		3.28 ± 0.07
Handbook Value		1.23 ± 0.40		3.14 ± 0.70

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Table 3. Thermal Conductivity of Unirradiated H-327 Graphite, Billet 6484-136, Radial Direction, Edge of Billet

Specimen Number	Thermal Conductivity (w/m-K) at[a] 25°C	100°C	200°C	300°C	400°C	500°C
TD-11	77.3		99.3		71.6	
TD-13	125.3	115.2	107.3	103.3	90.3	90.3
TD-15	135.1		104.1		80.7	
Mean	112.5	115.2	103.5	103.3	80.8	90.3

(a) Actual measurement temperature was within 10°C of the nominal temperature.

Table 4. Thermal Conductivity of Coupon Specimens from Fort St. Vrain Fuel Element 1-2415 (H-327 Graphite; Radial Direction)

Face	Specimen Number	Thermal Conductivity (w/m-K) at						
		25°C	100°C	200°C	300°C	400°C	500°C	600°C
A	TD-13	40.9	42.8	40.7	39.8	42.3	40.6	35.8
	TD-15	41.4		45.8		40.0		33.1
B	TD-11	38.3	41.5	40.9	40.5	38.2	38.9	40.6
	TD-13	44.9		55.0		44.4		38.1
	TD-15	40.9		43.8		38.3		36.3
C	TD-11	33.9		38.5		35.3		35.9
	TD-13	28.1	28.8	28.8	30.0	28.2	27.7	32.4
	TD-15	40.8		44.8		40.9		34.5
D	TD-11	35.6		48.2	46.3	37.9		39.2
	TD-13	28.5		24.3		22.2		25.6
	TD-15	29.5	32.7	35.4	32.0	30.7	27.9	26.9
E	TD-11	29.7		30.4		29.7		26.7
	TD-15	30.5	34.1	34.0	33.6	34.0	33.0	36.1
F	TD-13	31.9		37.4		37.4		31.6
	TD-15	20.2	23.5	24.6	23.7	22.5	22.9	20.1
All	Mean	34.3±6.7	33.9±7.4	38.1±6.8	35.1±7.6	34.9±6.7	31.8±6.9	32.8±5.7
-	Handbook	30.7	31.9	32.9	33.1	32.7	32.4	31.8

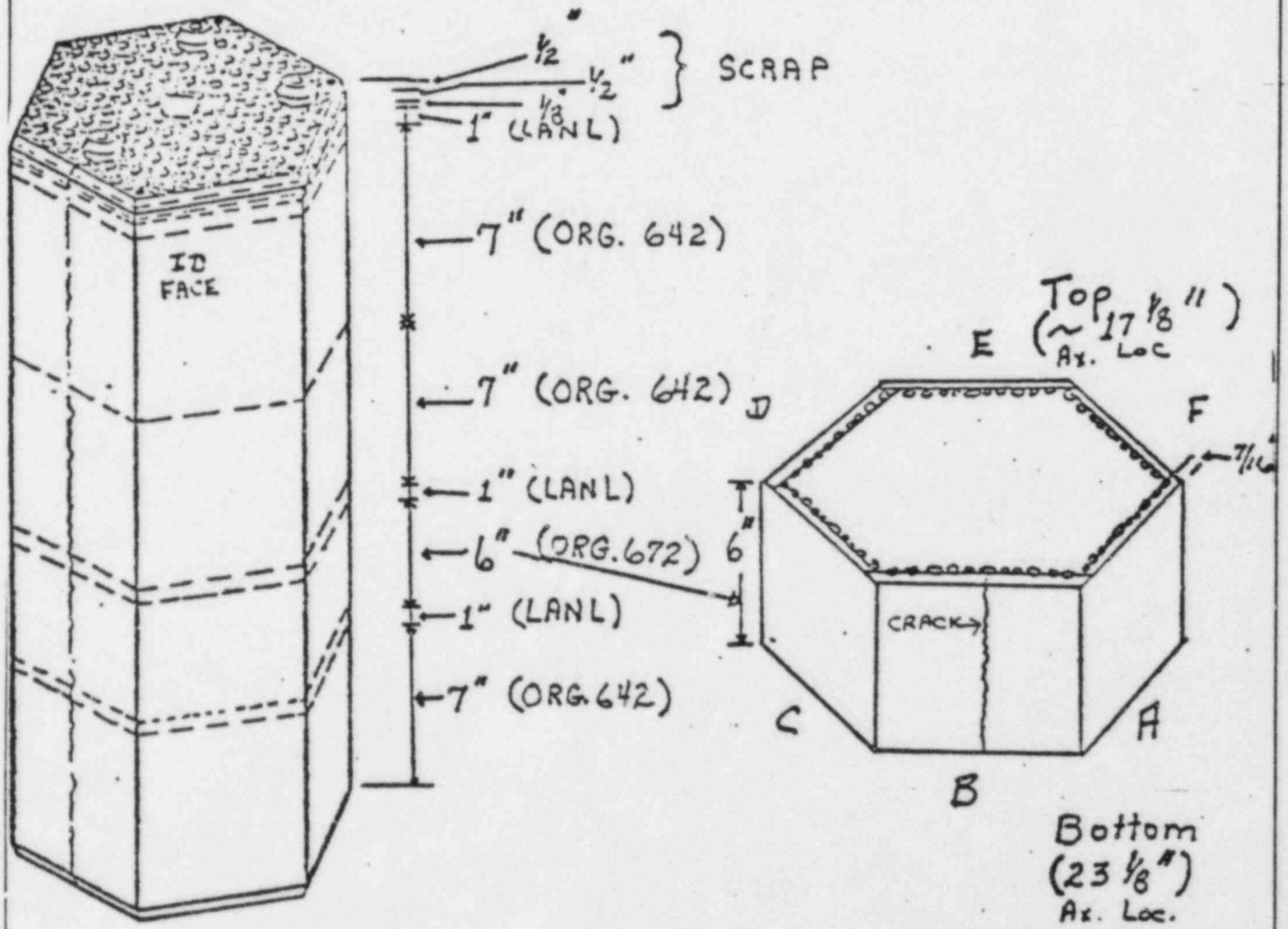

Figure 1. Sectioning of FSV Fuel Element 1-2415

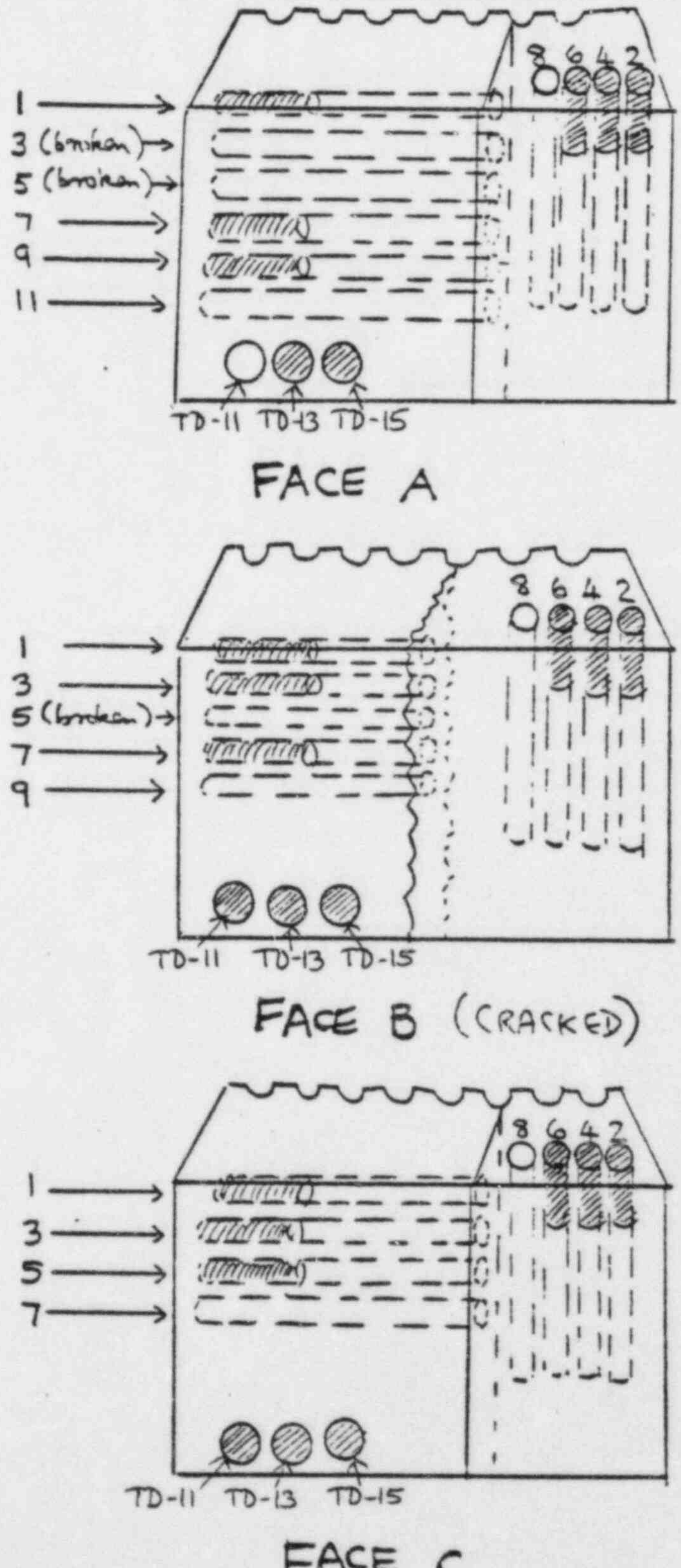

Figure 2(a). Coring Plan - Faces A, B, and C
(Tested specimens shaded)

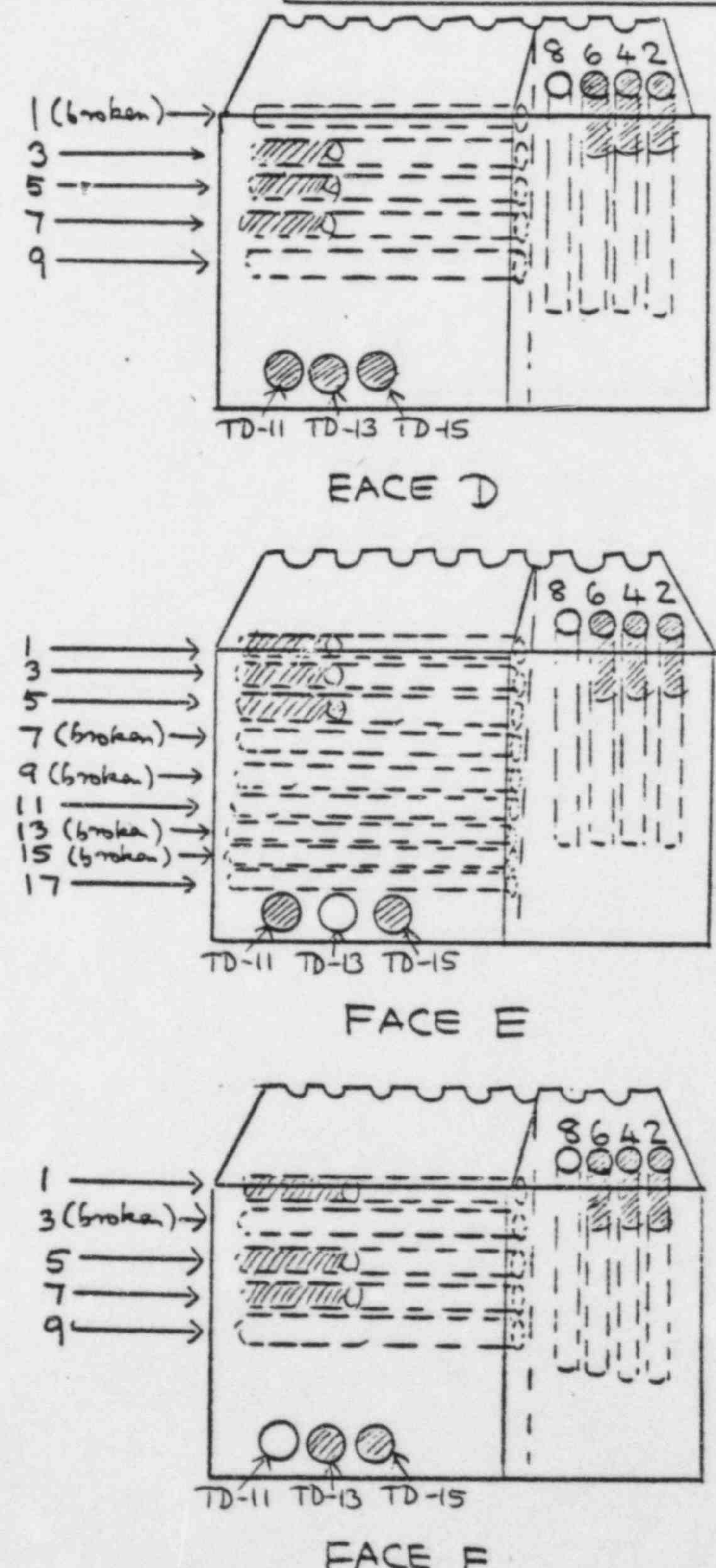

Figure 2(b). Coring Plan - Faces D, E, and F
(Tested specimens shaded)

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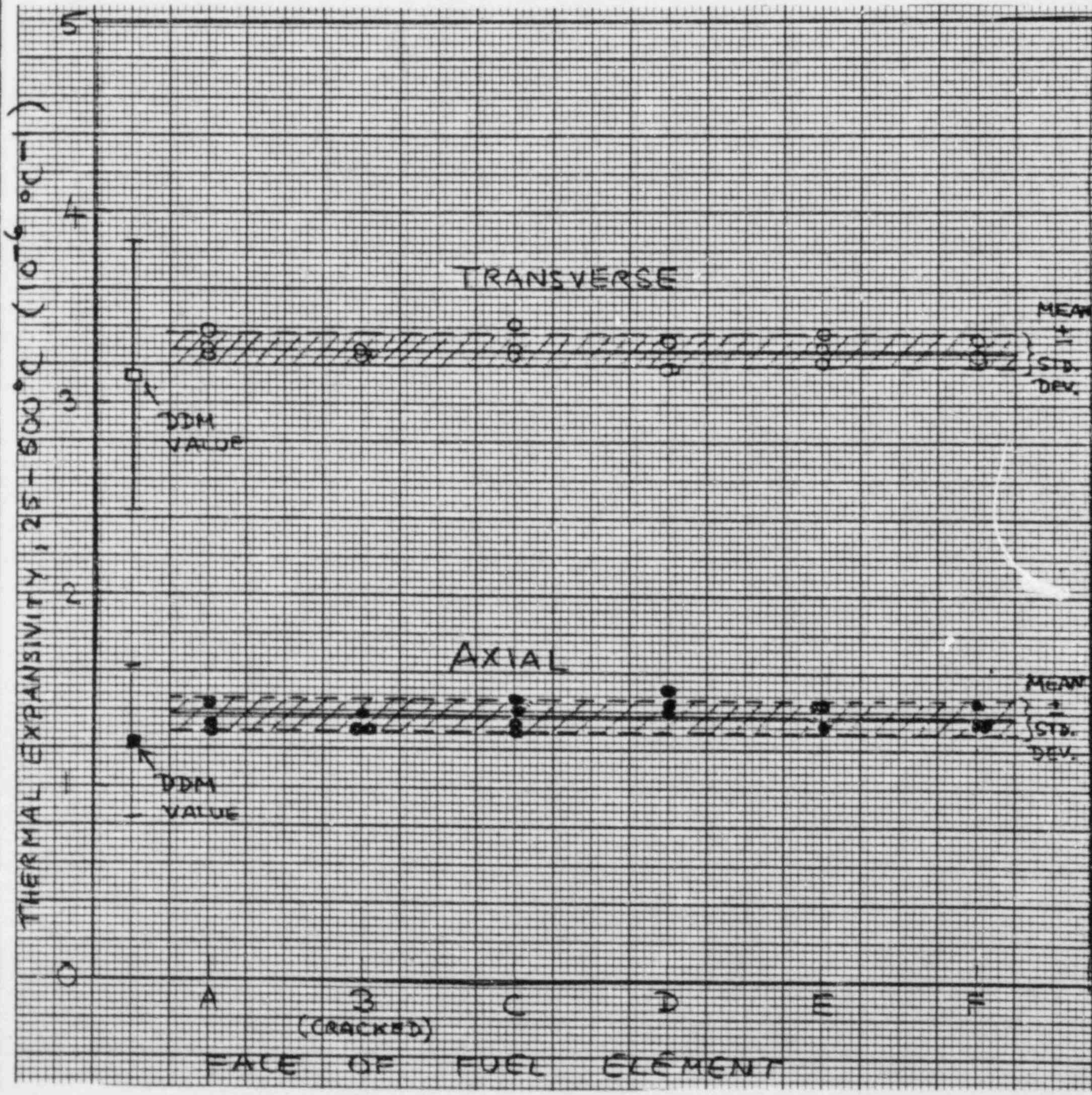

Figure 3. Thermal Expansivity of Graphite From Fuel Element 1-2415 for Each Face of the Block

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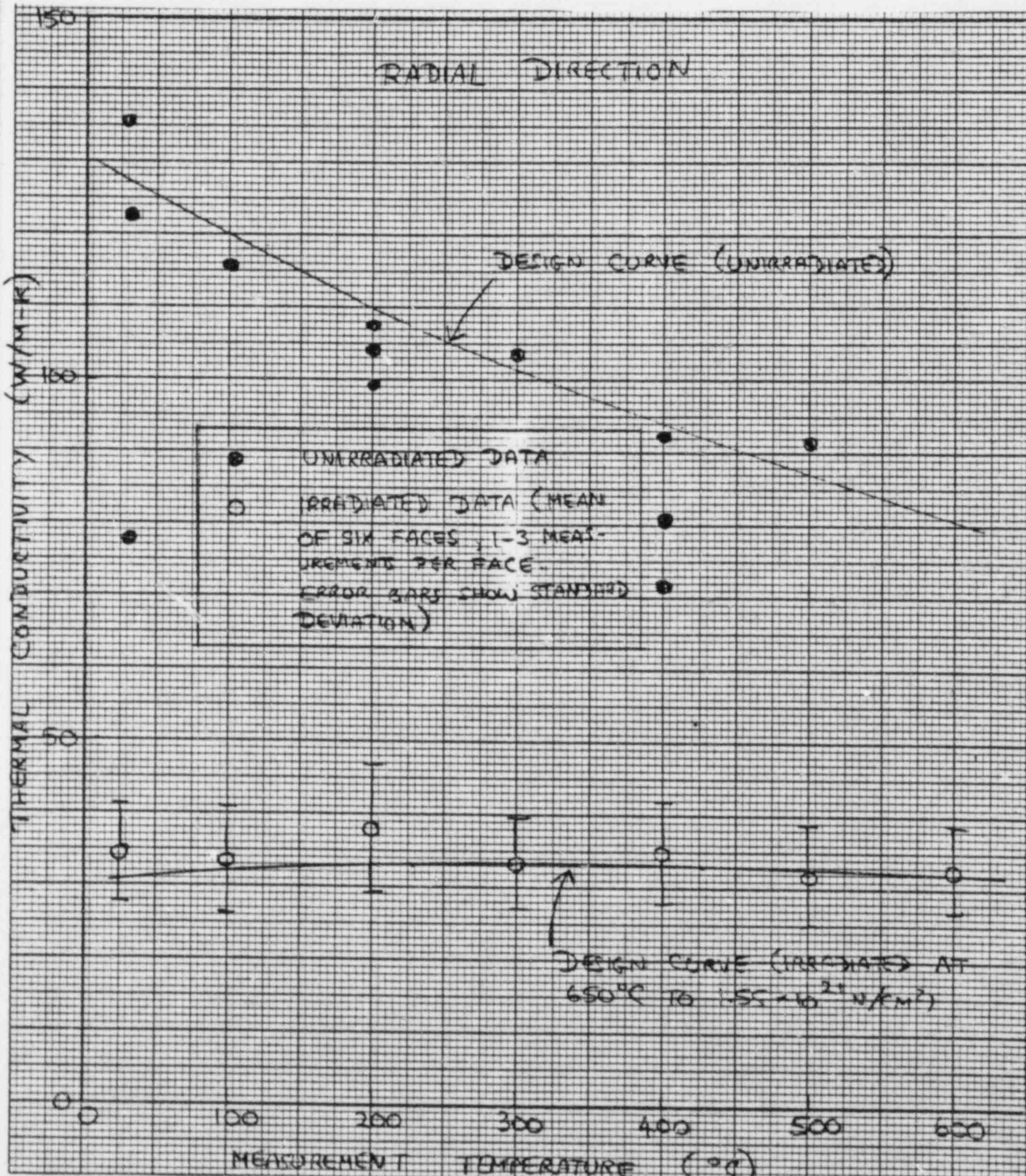

Figure 4. Thermal Conductivities of Graphite from Fuel Element 1-2415 as a Function of Measurement Temperature

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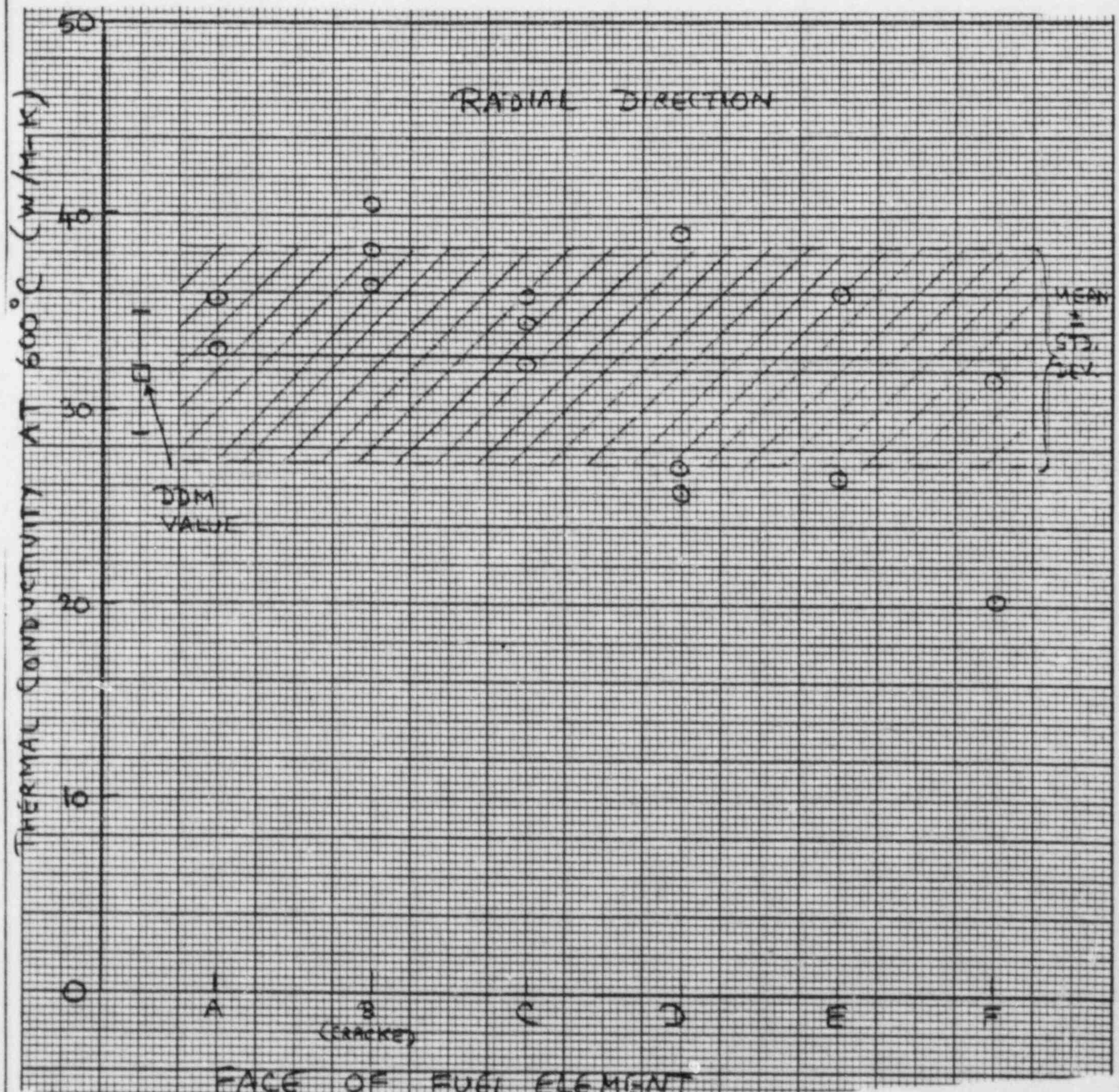

Figure 5. Thermal Conductivity of Graphite from Fuel Element 1-2415 for Each Face of the Block