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RADIATION DAMAGE RATES IN NUCLEAR REACTORS

I. The Electrical Resistance of Graphite Over the Temperature Range 8-90°C: Initial Damage and Its Temperature Coefficient

by

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I. The Electrical Resistance of Graphite Over the Temperature Range 8-90°C: Initial Damage and Its Temperature Coefficient

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ABSTRACT

The behavior of $\frac{1}{8}$ -in. spectroscopic graphite rods is shown to be variable beyond the variation of measurement. Statistical measures are given for the variability before and with irradiation. The linear regression of the reciprocal per cent change in resistance against the reciprocal exposure was determined over the range from about 25 to 90% change of electrical resistance. The linear regression of the above regression coefficients was determined for the range from 8 to 90°C. The number of specimens required to achieve a given accuracy in monitoring is calculated. Within the precision of the data, there is no evidence for departure from isothermal damaging, hence no positive evidence of radiation annealing at these temperatures and extents of damage.

INTRODUCTION

This work is part of a program to obtain more quantitative data for radiation effects occurring in nuclear reactors. It is hoped to achieve data reliable to several per cent in contrast to the 50-200% figure which must now be placed on the reliability of much of the data which is available. It is hoped that a better knowledge of the relation between the agent (the energetic neutrons which scatter atoms in the solid) and the effect will lead to a better understanding of the basic phenomena, as well as provide better methods for predicting behavior in cases of technical importance.

The present work is an extension of that started by Primak and Fuchs⁽¹⁻³⁾ and Primak⁽⁴⁾ some years ago. That work possessed the serious difficulty that it was performed (of necessity at that time) at the ambient temperature of the facilities. These temperatures were quite variable, and it seemed reasonable therefore to associate much of the variability of results with this temperature variation, and to assign the remainder to variations in neutron flux, which also were known to occur. It will be shown here that the graphite is itself quite variable. The extent of this variability has been measured for the particular graphite chosen.

The importance of graphite to the present program arises from its great technical importance and the large changes which occur in its properties on irradiation. For these reasons it has been greatly studied and has been irradiated under very varied conditions. That the damage rate varies with temperature has been known, but the variation in rate has not been determined carefully for this temperature range. The purpose of the present investigation was to establish the temperature dependence of the damage rate.

The experiments which are reported here were planned with the anticipation that with a better control of conditions of irradiation the variability would be greatly lessened. When this was not found, the treatment of the data had to be modified completely. The treatment given here follows the usual treatment of small-sample statistics as given, e.g., by Ostle.⁽⁵⁾ The procedure is to develop estimates of means $\bar{m}$ and variances s^2 ; to test them and establish confidence limits through Snedecor's F distribution test, Student's t test, Pearson's χ^2 distribution, etc. In order to develop the necessary statistics which form the basis of the argument, there are presented many data which were obtained for other reasons and which would have been omitted had resort to statistical argument been unnecessary. If the development of the argument appears clumsy in places, it should be remembered that the data were originally gathered with a different experimental plan in mind.

The general experimental procedure was that described in Ref. 1-4.

IRRADIATION

A heavy water circulating loop was arranged within one of the fuel assemblies of Argonne's Research Reactor CP-5, hole No. 7. Temperature was controlled to several degrees centigrade. The specimens were placed in perforated metal cans through which the loop water passed in contact with the specimens. The irradiation temperature of the specimens was thus known accurately. The final procedure was to store the irradiated specimens in a Dewar filled with dry ice and alcohol until the major portion of the radioactivity had decayed, and then to transfer them to a freezer (kept at about -8°C) for storage and measurement. Variant storage treatments are noted with the data for the individual specimens.

MATERIAL

The graphite used was from the same box of $\frac{1}{8}$ -in. spectroscopic graphite rods used by Primak and Fuchs for their work. Actual diameters were within a few ten-thousandths of an inch of 0.121 in. Diameters are given in Table XI (see p. 17).

MEASUREMENTS

The electrical resistance of graphite rods was determined by methods used in previous work at this laboratory. The old apparatus was the one used by Primak⁽⁴⁾ and was suitable only for measurements at room temperature. A new apparatus was made for measurements at low temperatures. All measurements at low temperatures were made with the apparatus immersed in alcohol to prevent formation of frost which would have interfered with electrical contacts. All measurements except those specifically referred to otherwise were made with the new apparatus. Most of the measurements were performed at a temperature of $-8 \pm 2^\circ\text{C}$. Other temperatures of measurement are noted in the tables.

Resistance was determined by measurement of current and potential drop. The current (about 0.04 amp) was determined from the potential drop across a fixed resistor. The potential drop along the specimen was determined by means of two probes at a fixed distance apart, which in the new apparatus was 0.88 cm. Resistances obtained with the new apparatus were thus for a cylinder of graphite close to 0.121 in. in diameter and always 0.88 cm long.

After irregularities in the irradiation behavior were noted, diameters of the specimens were determined. This measurement was made in the freezer at -8°C , after irradiation. The expansion on irradiation is negligible at these doses, hence the diameters may also be taken as the original diameter.

REPRODUCIBILITY OF RESISTANCE MEASUREMENTS

To compare the new (ν) apparatus with the old one (0), 48 specimens were measured at room temperature, first in the one and then in the other apparatus. The results are given in Table VII (see p.12). If the variance of measurement is the same for both apparatuses, then for each set of measurements,

$$\delta \equiv R_\nu - fR_0 \quad ,$$

where f is a factor relating the probe spacings:

$$f = \frac{1}{n} \sum \frac{R_\nu}{R_0} = 0.8838765 \quad .$$

Thus an estimate of the variance for a pair of measurements is

$$s^2 = \frac{1}{2} (R_\nu - fR_0)^2 \quad , \tag{1}$$

and for n specimens

$$\begin{aligned}\overline{s^2} &= \Sigma(R_{\nu} - fR_0)^2/2n \\ &= (\Sigma R_{\nu}^2 + f^2 \Sigma R_0^2 - 2f \Sigma R_0 R_{\nu})/2n\end{aligned}$$

The subsequent use of these specimens to study the effect of measurement in the freezer led to a subdivision into three groups: the first of 11 specimens, the second of 36, and the third of a single specimen. The statistics are given in Table I.

Table I

RESISTANCE MEASUREMENT STATISTICS

Pairs	Degrees of Freedom (DF)	$\overline{s^2}$ ($\times 10^{-10}$)	$\overline{s}$ ($\times 10^{-5}$)	$100\overline{s}/\overline{R}$ (%)
11	11	14	3.8	.52
36	36	53	7.2	.98
48	48	45	6.7	.91

The $\underline{F}$ test shows that there is a significant difference between the variances of the first 11 pairs of measurements and that for the remaining pairs. The reason for this is not known.

Another experiment to determine the variance consisted of twenty reinsertions and measurements on each of two specimens, No. 1081 (unirradiated) and No. 1200 (irradiated). These measurements were performed in alcohol in the freezer (at about -8°C). Further data available are several groups of measurements which were made on four specimens which served as standards. The statistics are given in Table II. These estimated variances are significantly different at the 95% level, as shown by an $\underline{F}$ test, and appear to be nearly in the ratio of the means. This is discussed below in arriving at weights for the measurements. There does not appear to be any special effect associated with making the measurements under alcohol. The estimated variance for the unirradiated specimen corrected for the ratio of the means lies nearly midway between the values for the eleven pairs and the 36 pairs above.

The experimental procedure which was to be employed required irradiation in contact with circulating water. Measurements were made after immersing the specimens in distilled water, and also after immersing in process water.

Table II

REPEATED MEASUREMENTS IN ALCOHOL IN THE FREEZER ($\sim -8^{\circ}\text{C}$)Resistance (10^{-5} ohm)

Specimen No.		Dec. 15	Dec. 20	Resoldered Lead	Dec. 21	
1081		835 833 830 827 841 829 835 837 832 845	829 837 830 828 833 827	828	825 837 831	DF = 19 m = 832.4 $s^2 = 26.3 \times 10^{-10}$ s = 5.03×10^{-5} 100s/m = 0.60%
	Dec. 15	Dec. 15 (contd.)	Dec. 20			
1200	2259 2281 2249 2277 2274 2257 2282	2275 2282 2278 2255 2270 2262	2264 2268 2256 2263 2249 2266 2263			
	Dec. 14	Dec. 12	Nov. 2	Apr. 12	Mean ($\times 10^{-5}$)	$\overline{s^2}$ (3DF)
1081	832	828	840	830	832.5	46×10^{-10}
1082	846	840	843	837	841.5	15
1083	735	739	735	736	736.3	4
1084	743	748	742	732	741.3	45
$\overline{s^2} = 28 \times 10^{-10}$ $\overline{s} = 5.2$ $100\overline{s}/\overline{m} = 0.7\%$						

The data are given in Table III. Estimated variances from the original measurements are seen to be in the range obtained in measuring individual specimens and are not significant.

After the irradiation, the specimens were to be cooled to low temperature for storage. To test whether this treatment might have any effect on the resistances, specimens were first loaded with water by boiling and then cooled in water. This was followed by cooling to low temperature.

Table III

EFFECT OF SOAKING IN WATER

Successive Treatments	Resistance (10^{-5} ohm)		DF	$\overline{s^2}$ ($\times 10^{-10}$)	100s/m (%)
	Spec A	Spec B			
Original	1131	1126			
Soak in water 5 min, wipe dry	1120	1107	(2)	120	0.9
Soak in water $\frac{1}{2}$ hr, wipe dry	1119	1130	(2)	40	0.5
Oven dry 15 min at 108°C	1132	1128	(2)	1.5	0.12
Oven dry 15 min at 108°C	1135	1128	(2)	5	0.18
Soak 36 hr in water, wipe dry	1131	1147	(2)	110	0.87
Let stand in ap- paratus 15 min	1134	1133	(2)	14	0.3
	Spec 970	Spec 971			
Original	992	990			
Reactor water soak overnight and 3 hr in dessicator	994	980	(2)	26	0.5

The results for two such sets of tests are given in Table IV. The mean changes do not reveal any effect. The estimated variances for each set are in the range for normal statistics. Since the room-temperature measurements were not made in alcohol, it may be concluded that the following treatments did not show any significant effect: measurement in alcohol, measurement in air, boiling, cooling with liquid nitrogen, or cooling with dry ice-alcohol. Because the mechanical operations which were to be performed would be affected by ice on the specimens, dry ice and alcohol storage was chosen.

INDIVIDUAL RESISTANCES OF THE SPECIMENS

Resistances of the specimens used here varied from 690-870 $\times 10^{-5}$ ohm. This is a variation of $\pm 12\%$. Neubert in his work used one 4 x 4-in. bar of graphite, cut off about an inch from the surfaces, and made his specimens from the remainder. His specimens varied $\pm 3\%$.

Table IV
EFFECT OF DRY ICE AND LIQUID NITROGEN UPON THE RESISTANCES^{a b}

(Resistances in ohms)

SET A

Treatment ^c	(1)	(2)		(3)			
Sample	I	II	III	IV	V	VI	VII
not numbered	670	(8) 712	680	(8) 706	(9) 708	684	(9) 686
not numbered	754	(8) 767	750	(9) 769	(9) 787	743	(9) 770
not numbered	690	(9) 702	693	(11) 709	(11) 706	693	(8) 714
not numbered	744	(11) 776	749	(10) 767	(10) 765	742	(8) 776
Columns							
Quantity ^d	I, III	II, IV	IV, V	I, VI	IV, VII		
$\sum \delta$	3.5	-1.5	3.8	1.0	-5		
s^2	19	+21	42	41	+63		
$\bar{s}$	4.4	4.6	6.5	6.4	7.9		
$100\bar{s}/\bar{R}(\%)$	0.59	0.62	0.88	0.87	1.08		

SET B

Treatment ^e	(1)		(2)		(3)	(4)	
Sample	I	II	III	IV	V	VI	VII
1085	(9) 753	720	(12) 745	718	(8) 745	(9) 752	716
1086	(8) 749	715	(10) 745	722	(8) 761	(9) 755	723
1087	(9) 709	681	(9) 710	687	(7) 714	(11) 705	686
1088	(8) 767	736	(9) 763	731	(8) 764	(11) 765	732
Columns							
Quantity ^d	I, III	II, IV	I, V	I, VI	II, VII		
$\sum \delta$	-15	+1.0	+6	-1	+1.3		
s^2	12	8	31	7	15		
$\bar{s}$	3.5	2.8	5.6	2.6	3.9		
$100\bar{s}/\bar{R}(\%)$	0.47	0.54	0.76	0.35	0.4		

^aAll quantities are to be multiplied by 10^{-5} , except $\bar{s}^2$, which is multiplied by 10^{-10} , and $\bar{s}/\bar{R}$, which has proper units

^bTemperatures are given (in parentheses) for measurements made in the freezer and are to be understood as $-^{\circ}\text{C}$. Other measurements were made at room temperature, $23-24^{\circ}\text{C}$

^cTreatment (1) was as cut, treatment (2) after boiling in water and immersion in liquid nitrogen, treatment (3) was a repetition of (2)

^dStatistics $\sum \delta$ is the algebraic sum of the differences of the columns stated, $\bar{s}^2$ is an estimate of the variance (4 degrees of freedom) obtained by taking 1/8 of the sum of squares of the differences of the columns stated, $\bar{s} = \sqrt{\bar{s}^2}$, $\bar{R}$ was taken as 735×10^{-5} ohm for all the values given

^eTreatment (1) was as cut, (2) dry ice and alcohol, (3) freezer, (4) liquid nitrogen

In the present work, the specimens were cut from several $\frac{1}{8}$ -in. rods. The distribution of resistances for the present set of experiments is Set I in Table V. Those for another set of experiments, Set II, were obtained by cutting a few specimens from each of a larger number of rods. The grouping of Table V is too fine to yield good distribution curves, but reasonable ones can be obtained by combining adjacent groups. The distribution curves are peaked, for the second set quite symmetrical, for the first, somewhat skewed to lower resistances. The wide variation is not caused by differences in diameter, for they are constant to better than 1%. The estimated mean resistance was $m = 750 \times 10^{-5}$ ohm for the probe spacing employed for most of the measurements. The estimated variance $\underline{s}^2$ was 25×10^{-8} , $\underline{s}$ was 5×10^{-4} , and $100\underline{s}/\underline{m}$ was 6.6%. The results obtained in the present work may be more typical of graphite behavior than the results given by Neubert for a more selected group of specimens.

Table V

DISTRIBUTION OF
ORIGINAL RESISTANCES

Range of Resistance ($\times 10^{-5}$ ohm)	Set I No.	Set II No.
690 700		3
700 710	12	6
710 720	21	4
720 730	6	2
730 740	8	12
740 750	14	18
750 760	7	23
760 770	18	10
770 780	8	12
780 790	1	6
790 800	0	18
800 810	0	14
810 820	1	9
820 830	3	11
830 840	9	6
840 850	12	1
850 860	2	2
860 870	1	2
870 880	1	1

THERMAL COEFFICIENT OF RESISTANCE

To permit a comparison with results reported in other investigations, the thermal coefficient of resistance was measured for both unirradiated and irradiated specimens. A specimen was inserted in the apparatus, and the temperature of the alcohol bath was adjusted. Measurements were made at about 10-deg intervals from -40 to 30°C. Over this range, the resistances were quite precisely linear with temperature,

$$R = p + qT$$

where $\underline{p}$ is the resistance at 0°C, $\underline{q}$ is the slope, and $\underline{T}$ is the temperature given in °C. Thus,

$$R/p = 1 + (q/p)T.$$

The results are given in Table VI.

Table VI

TEMPERATURE DEPENDENCE OF
RESISTANCE OF GRAPHITE

Graphite	p	q ($\times 10^{-5}$)	q/p ($\times 10^{-5}$)
unirradiated 1	0.0078	-0.98	-126
unirradiated 2	0.0075	-1.03	-137
irradiated 1 hr at 60°C	0.0090	-1.49	-165
irradiated 4 hr at 60°C	0.0133	-2.50	-187
irradiated 16 hr at 60°C	0.0207	-2.50	-121

In addition to these results, measurements were made at several temperatures in establishing the technique of measurement in the freezer. These results give both a thermal coefficient for the unirradiated graphite and an estimate of the variance of this coefficient among specimens. The data are given in Table VII. The two sets of data

$$\delta = (R_F - R_V)$$

for (1) the first 11 specimens and (2) the following 36 specimens constitute resistance differences for two temperature differences. Although the variation of resistance among specimens is larger than this, the analysis of variance given in Table VIII shows the temperature differences to be very highly significant.

Table VII

RESISTANCES OF 48 SPECIMENS IN TWO APPARATUSES AND AT TWO TEMPERATURES

Resistance $\times 10^{-6}$ ohm

Specimen Number	Room Temperature		Freezer Temperature R_F (New Apparatus)
	R_O (Old Apparatus)	R_N (New Apparatus)	
			$-19.8 \pm 1.8^\circ \text{C}$
1045	8153	7185	7532
1046	9049	8031	8504
1047	9066	7991	8594
1048	8319	7322	7728
1049	7692	6852	7267
1050	7734	6807	7226
1051	7847	6846	7254
1052	8297	7446	7883
1053	9186	8191	8659
1054	7773	6876	7265
1055	9259	8194	8635
			$-8.4 \pm 1.4^\circ \text{C}$
1056	8991	8146	8494
1057	7868	7012	7089
1058	9208	8151	8501
1059	8026	7251	7398
1060	8121	7350	7485
1061	7990	7028	7313
1062	7923	7035	7234
1063	7824	6853	7079
1064	7685	6802	7025
1065	7934	7196	7406
1066	8007	7153	7309
1067	7735	6981	7175
1068	7682	6824	7065
1069	8347	7384	7608
1070	8128	7156	7450
1071	8172	7173	7491
1072	8326	7259	7616
1073	9125	8168	8468
1074	9238	8066	8368
1075	8058	7074	7396
1076	7930	7008	7216
1077	9049	7971	8329
1078	8998	8074	8508
1079	8117	7186	7534
1080	9013	7965	8402
1081	9104	7933	8301
1082	8945	7991	8368
1083	8061	7027	7359
1084	8145	7138	7324
1085	8174	7161	7412
1086	8191	7052	7445
1087	7640	6840	7116
1088	8347	7327	7647
1089	7865	6694	7165
1090	9232	8095	8443
1091	8204	7152	7506
			-10.5°C
1092	7633	6613	7013

Table VIII

ANALYSIS OF VARIANCE FOR TEMPERATURE DIFFERENCES

Item	DF	Sum of Squares	Mean Square
Among Temperature Differences	1	4290×10^{-10}	4290×10^{-10} } ratio 192 21.7×10^{-10} } ${}_{45}^1 F_{(99.95)} = 14$
Among Specimens	45	978×10^{-10}	
Total	46	5268×10^{-10}	114.5×10^{-10}

From

$$R = p + qT,$$

values for the quantities $\underline{q}$, $\underline{p}$ and $\underline{q}/\underline{p}$ were obtained as follows:

$$R_{\nu} = p + qT_{\nu}$$

$$R_F = p + qT_F;$$

hence,

$$q = (R_{\nu} - R_F)/(T_{\nu} - T_F)$$

$$p = R_{\nu} - [(R_{\nu} - R_F)T_{\nu}/(T_{\nu} - T_F)]$$

$$q/p = (R_{\nu} - R_F)/[R_{\nu}(T_{\nu} - T_F) - (R_{\nu} - R_F)T_{\nu}]$$

and are given in Table IX.

Table IX

TEMPERATURE DEPENDENCE OF THE RESISTANCE OF
DIFFERENT SPECIMENS OF GRAPHITE

Mean ($\times 10^{-5}$)	s^2 ($\times 10^{-10}$)	s ($\times 10^{-5}$)	100s/m (%)
$T_{\nu} = 23 \pm 1^{\circ}\text{C}$ $T_F = -19 \pm 1.8^{\circ}\text{C}$ $DF = 11$			
$p + 766.6$	3545	59.5	7.8
$q - 1.02$	0.0234	0.153	15.0
$q/p - 133.0$	212.0	14.6	10.9
$T_{\nu} = 23 \pm 1^{\circ}\text{C}$ $T_F = -8.4 \pm 1.4^{\circ}\text{C}$ $DF = 36$			
$p + 756.3$	2511	50.1	6.6
$q - 0.917$	0.0861	0.293	32.0
$q/p - 120.5$	1307	36.2	30.0

The range of values for $\underline{p}$ is, of course, very similar to that for R_{ν} and R_F , and represents typical statistics for these quantities. The means for $\underline{q}$ and $\underline{q}/\underline{p}$ are consistent with the values in Table VI. The variances for these quantities are not significantly different from the variances obtained by propagating those found in Table II for the measurement of a specimen

reinserted into the apparatus. Thus the data do not reveal the variance of the temperature coefficient among different specimens. However, from the analysis of variance, given in Table VIII, it would seem that the variance of q among specimens is relatively small, corresponding to a few per cent in 100s/m.

EXPOSURE

The original design of the experiment was that used by Primak and Fuchs,⁽¹⁾ except that the measurements were conducted at a lower temperature, as described above, to prevent appreciable post-irradiation annealing of the specimens irradiated at lower temperatures. The intention was to obtain relative doses by internal monitoring using graphite dosage specimens. Dosage specimens were included in the first as well as subsequent irradiations. It soon became evident from the variation in change of the specimens in a single irradiation can, that the use of duplicate specimens for monitoring would not give the precision required for the relative dosage. It was also evident that at least some of the variations previously attributed to external factors were caused by variations in graphite behavior.

Since the monitor or dosage rod data could not be used in the manner originally intended, exposure data of high consistency were sought. The KWH integrator at CP-5 involves rotating discs which are readjusted when the readings do not seem to be consistent with data from other reactor instruments; also, on occasion, it has been out of operation for several days. The currents from several peripheral ion chambers are recorded on 5-in. strip-charts. They are called "power level meters." They indicated that the power level of the reactor was subject to variations from its nominal level which were greater than the precision desired for the present irradiations. They also showed that the nominal time of irradiation obtained from reactor operation records are similarly of inadequate precision. These ion chamber current records seem to be the most reliable records which were available of the general pile operation, but their readings are apt to alter relative to general reactor operation when loadings are changed or when the instrument calibrations are altered. The procedure adopted here was to integrate the ion chamber current charts numerically to obtain the current-time integral. It was assumed that the ion chamber current was proportional to the reactor power over periods between loading changes or calibration changes. The proportionality factor (power level factor) was obtained from the product of steady-state (after $\frac{3}{4}$ -hr operation to take care of thermal lag and only for the 4-hr irradiations; the 1-hr irradiations were too short) D₂O temperature difference in the heat exchanger, the D₂O coolant flow rate, and a factor supplied by the reactor operations personnel. The last factor is a calibration factor which includes, among other things, corrections for the

D₂O temperature. This factor did not alter over the period of these irradiations by more than $\frac{1}{3}\%$ and hence was taken to have the same value, 2.91. The power level factor so obtained for a single experiment was not considered precise enough. Hence a statistical value was used. It was the average of one determination for each 4-hr irradiation in the set. The results obtained are given in Table X.

RESULTS

The results obtained for the effect of irradiation at the temperatures 8, 30, 60, and 90°C on the electrical resistance of the graphite are given in Table XI.

BEHAVIOR OF THE ELECTRICAL RESISTANCE

The analysis of the data in terms of the per cent change in the electrical resistance has the advantage of eliminating the effect of specimen diameter when the cross section is constant. Neubert used it for this reason, but it has not been shown that this is indeed the best variable to employ. Some calculations were carried on here with the change in resistance, but no consistent decrease in variation of the results was noted. The results presented here are for the per cent change in resistance. Novick⁽⁶⁾ found that the reciprocal per cent change of the electrical resistance was accurately proportional to the reciprocal dosage in the early stages of irradiation, and Primak and Fuchs found this in their work too. The data given here for successive irradiations of individual specimens confirm this result at all the temperatures used and are shown in Figures 1-4. (The reciprocal-resistance changes also obeyed this relation as did the per cent changes.) Thus, the temperature dependence of the radiation-induced electrical resistance changes in graphite can be described by giving the temperature dependence of the constants a and b in the equation

$$\frac{1}{y} = \frac{a}{x} + b,$$

where y is the per cent change in resistance and x is the dosage. However, especially at the short irradiations, there is considerable variation among different specimens. This results in part from the propagation of the measurement variance, in part from the specimen variance, and in part from the transformation into reciprocal coordinates. The temperature dependence of a and b proved to be so small that the graphical method used by Primak and Fuchs, while adequate for their work, proved unsatisfactory here. An objective statistical method was required.

Table X
EXPOSURE DATA FOR IRRADIATION

Part A					Part B			
Irradiation Number	1960 Mo/Day	Integrator Reading (Mwh)	Integrated Power level (meter x 10 ⁻⁴)	Exposure kwh	Irradiation Number	Av. Stable kw from flow and ΔT	Av. Stable Meter Reading x 10 ⁻³	Factor
Group I 55000 +					Group I (Meter No. 2)			
174A	4/24	683	6927	2330	175A	2236	685	3264
174B	4/27	802	7148	2400	175B	2294	674	3404
174C	4/30	944	7048	2370	175C	2307	674	3423
175A	4/24	685	27355	9200				Av. 3360
175B	4/27	804	27118	9120	Group II (Meter No. 3)			
175C	4/30	946	27027	9090	175A	2236	876	2553
Group II 55000 +					175B	2294	855	2683
174D	5/3	1060	8506	2250	175C	2307	857	2692
175D	5/3	1063	25169	6650				Av. 2640
Group III 56000 +					Group III (Meter No. 2)			
178A	5/18	785	25046	8860	179A	2193	624	3514
178B	5/21	917	6585	2330	179B	2187	627	3488
178C	5/24	1042	5794	2050	179C	2183	615	3550
179A	5/18	783	6360	2250	179D	2190	612	3578
179B	5/21	919	25031	8860				Av. 3530
179C	5/24	1044	24545	8690	Group IV (Meter No. 2)			
179D	5/27	1195	24649	8720	182A	2157	508	4246
Group IV 58000 +					182B	2184	507	4308
181A	6/27	487	5136	2210	182C	2201	519	4241
181B	6/30	624	5148	2220	182D	2245	508	4419
181C	7/3	769	5380	2320	184B	2149	509	4222
181D	7/6	899	5133	2210	184C	2201	515	4274
182A	6/27	489	20350	8760	184D	2236	512	4367
182B	6/30	626	20375	8770				Av. 4300
182C	7/3	771	20815	8960				
182D	7/6	902	20418	8780				
183B	6/14	058	5148	2220				
183C	6/17	196	5205	2240				
183D	6/20	356	5305	2280				
183E	6/23	494	5373	2310				
184B	6/14	060	20539	8840				
184C	6/17	199	20692	8900				
184D	6/20	358	20532	8830				
184E	6/23	497	(a)					

(a) Chart ended during irradiation

Table XI

EFFECT OF IRRADIATION ON THE ELECTRICAL RESISTIVITY OF GRAPHITE

Sample Number	Irradiation Number	Treatment*	Exposure, (Mwh)	Diameter (mils)	Original Resistance, (10^{-5} ohm)	Irradiated Resistance, (10^{-5} ohm)
Irradiation Temperature 80°C						
1107 1108	181A	dA1	2.21	120.8 121.0	863 761	1069 950
1103 1104	181B	dA2	2.22	121.3 121.3	752 766	938 947
1115 1116	181C	dA3	2.32	120.9 121.1	747 775	942 956
1123 1124	181D	dA4	2.21	121.0 120.9	817 829	1013 1024
1117 1118	182A	dB1	8.76	120.7 120.4	708 726	1320 1345
1109 1110	182B	dB2	8.77	121.2 120.8	824 788	1453 1396
1119 1120	182C	dB3	8.96	120.8 121.4	713 740	1342 1362
1153 1154	182D	dB4	8.78	121.4 121.3	748 761	1350 1371
1139 1140	181A	cA1	2.21	120.9 121.2	712 768	898 949
1139 1140	181B	cA2	4.43	120.9 121.2	712 768	1066 1115
1139 1140	181C	cA3	6.74	120.9 121.2	721 768	1214 1256
1139 1140	181D	cA4	8.95	120.9 121.2	721 768	1355 1395
1141 1142	182A	cB1	8.76	120.9 121.1	712 766	1336 1368
1141 1142	182B	cB2	17.52	120.9 121.1	712 766	1749 1768
1141 1142	182C	cB3	26.48	120.9 121.1	712 766	2052 2028
1141 1142	182D	cB4	35.26	120.9 121.1	712 766	2252 2255

Sample Number	Irradiation Number	Treatment*	Exposure (Mwh)	Diameter (mils)	Original Resistance, (10^{-5} ohm)	Irradiated Resistance, (10^{-5} ohm)
Irradiation Temperature 300°C ^e						
1045 1046	174A	dA1	2.33	121.1 121.1	744 ^b 840 ^b	935 1036
1049 1050	174B	dA2	2.40	120.3 120.4	718 ^b 714 ^b	899 900
1057 1058	174C	dA3	2.37	120.4 121.0	709 850	898 1052
1061 1062	174D	dA4	2.25	120.5 120.5	731 723	912 916
1047 1048	175A	dB1	9.20	121.0 121.1	849 ^b 764 ^b	1489 1384
1051 1052	175B	dB2	9.12	120.3 120.9	716 ^b 778 ^b	1298 1406
1059 1060	175C	dB3	9.09	121.1 121.3	740 749	1364 1377
1063 1064	175D	dB4	6.64	120.4 120.5	708 703	1187 1185
1089 1090	174A	cA1	2.33	120.5 120.9	717 844	898 1045
1089 1090	174B	cA2	4.73	120.5 120.9	717 844	1054 1241
1089 1090	174C	cA3	7.10	120.5 120.9	717 844	1189 1376
1089 1090	174D	cA4	9.35	120.5 120.9	717 844	1305 1521
1091 1092	175A	cB1	9.20	121.4 121.0	751 701	1383 1291
1091 1092	175B	cB2	18.32	121.4 121.0	751 701	1793 1665
1091 1092	175C	cB3	27.41	121.4 121.0	751 701	2073 1927
1091 1092	175D	cB4	34.06	121.4 121.0	751 701	2255 2101

* d - dosage specimen, c - cumulative specimen. A - first series, mainly 1-hr irradiations, B - second series, mainly 4-hr irradiations; 1, 2, 3, 4 - set of specimens in the series

^b Measured at -20°C. Corrected to -90°C by means of the factor 0.9875.

^e Cumulative samples (cA2, cA3, cA4, cB2, cB3, cB4) for 300°C, 600°C, 900°C were transported from freezer to reactor facility at room temperature.

Table XI (cont'd.)

Sample Number	Irradiation Number	Treatment*	Exposure (Mwh)	Diameter, (mils)	Original Resistance, (10 ⁻⁵ ohm)	Irradiated Resistance, (10 ⁻⁵ ohm)
Irradiation Temperature 60°C ^e						
1111 1112	183B	dA1	2.22	121.3 120.7	755 738	922 909
1105 1106	183C	dA2	2.24	121.2 121.2	767 772	923 940
1101 1102	183D	dA3	2.28	121.3 121.0	725 833	873 982
1121 1122	183E	dA4	2.31	121.0 121.0	748 718	912 886
1137 1138	184B	dB1	8.84	120.8 121.1	717 774	1252 1302
1113 1114	184C	dB2	8.90	121.9 121.2	712 830	1226 1363
1127 1128	184D	dB3	8.83	121.2 120.5	763 876	1281 1438
1125 1126	184E	dB4	(8.80) ^a	120.9 120.8	828 833	1358 1365
1129 1130	183B	cA1	2.22	121.1 121.0	841 731	1008 892
1129 1130	183C	cA2	4.45	121.1 121.0	841 731	1129 1028
1129 1130	183D	cA3	6.74	121.1 121.0	841 731	1240 1145
1129 1130	183E	cA4	9.05	121.1 121.0	841 731	1368 1263
1131 1132	184B	cB1	8.84	121.3 121.1	772 830	1261 1386
1131 1132	184C	cB2	17.74	121.3 121.1	772 830	1622 1725
1131 1132	184D	cB3	26.57	121.3 121.1	772 830	1863 2001
1131 1132	184E	cB4	(35.4) ^a	121.3 121.1	772 830	2035 2192

Sample Number	Irradiation Number	Treatment*	Exposure, (Mwh)	Diameter, (mils)	Original Resistance, (10 ⁻⁵ ohm)	Irradiated Resistance, (10 ⁻⁵ ohm)
Irradiation Temperature 90°C ^e						
1069 1070	179A	dA1	2.25	120.8 121.1	761 745	892 882
1075 1076	178B	dA2	2.33	121.1 120.2	740 722	898 872
1079 1080	179C	dA3	2.05	121.1 121.0	753 840	1183 1300
1065 1066	178A	dB1	8.86	121.3 121.4	741 731	1180 1167
1073 1074	179B	dB2	8.86	121.0 120.9	847 837	1323 1314
1077 1078	178C	dB3	8.69	120.9 121.1	833 851	970 977
1095 1096	179D	dB4	8.72	121.3 121.5	749 739	1165 1153
1071 1072	179A	cA1	2.25	121.3 120.8	749 762	905 886
1071 1072	178B	cA2	4.58	121.3 120.8	749 762	1009 1013
1071 1072	179C	cA3	13.27	121.3 120.8	749 762	1375 1358
1067 1068	178A	cB1	8.86	120.5 120.6	718 707	1130 1125
1067 1068	179B	cB2	17.72	120.5 120.6	718 707	1434 1424
1067 1068	178C	cB3	19.77	120.5 120.6	718 707	1468 1461
1067 1068	179D	cB4	28.50	120.5 120.6	718 707	1669 1645

* d - dosage specimen, c - cumulative specimen, A - first series, mainly 1-hr irradiations, B - second series, mainly 4-hr irradiations, 1, 2, 3, 4 - set of specimens in the series

^a Integrated values not available. This is a numerical value

cA1 || 90°C specimens stored at room temperature after irradiation for the period of radioactive decay. Further storage and measurement in freezer.

^e Cumulative samples (cA2, cA3, cA4, cB2, cB3, cB4) for 30°C, 60°C, 90°C were transported from freezer to reactor facility at room temperature.

Fig. 1. Reciprocal per cent change in electrical resistance against reciprocal dosage for the specimens irradiated at 8°C. Some of the plotted points represent results for more than one specimen. At least two specimens were irradiated for each dosage used.

Fig. 2. Reciprocal per cent change in electrical resistance against reciprocal dosage for the specimens irradiated at 30°C. Some of the plotted points represent results for more than one specimen. At least two specimens were irradiated for each dosage used.

Fig. 3. Reciprocal per cent change in electrical resistance against reciprocal dosage for the specimens irradiated at 60°C. Some of the plotted points represent results for more than one specimen. At least two specimens were irradiated for each dosage used.

Fig. 4. Reciprocal per cent change in electrical resistance against reciprocal dosage for the specimens irradiated at 90°C. Some of the plotted points represent results for more than one specimen. At least two specimens were irradiated for each dosage used.

WEIGHTING

The transformation into reciprocal coordinates has a very high weighting associated with it. In the present case, if the error in measuring the per cent change $\underline{y}$ were proportional to $\underline{y}$, then the data must be weighted by the fourth power of $\underline{y}$. If the error is proportional to $\underline{R}$ (this would be the case if, for a homogeneous substance, the potential probe distance, the most likely source of measurement error, varied), the weighting is quite complex, varying from greater than the fourth power of $\underline{y}$ to the second power of $\underline{y}$ depending on the value of $\underline{y}$. If the error results from spurious emf's, the weighting is unity. The weighting associated with the inhomogeneity of the body (and also with a variation in current density) is difficult to predict. If only one source of error existed, its nature would be sufficient to determine the weighting even were its magnitude unknown. For a combination of different errors, their relative magnitude is also required when they have a different functional dependence on $\underline{y}$.

The problem of weighting is mentioned by Primak and Fuchs. Its importance in the present investigation became apparent when the different weightings were found to give values of $\underline{a}$ and $\underline{b}$ which led to different temperature dependences for these quantities. This was especially the case when all the data were used, because of the large effect exerted by the cumulative specimens. Since the data for the cumulative specimens were for only two specimens, the behavior of these two specimens dominated the results. How to handle the weighting to allow for both specimen variance and the transformation of coordinates when all the data were employed seemed too difficult a problem to solve. Accordingly, it was decided to use only the data for first irradiations to establish values of $\underline{a}$ and $\underline{b}$ for the determination of the thermal dependence of these quantities. The data thus remaining were for 1-hr and 4-hr irradiations. For each point there is an 8-fold or 10-fold specimen replication. The weighting was obtained by examining the graph of $\log s(1/\underline{y})$ against $\log m(1/\underline{y})$ where $\underline{s}^2$ was computed from the difference between the data point and the regression against $1/\underline{x}$. A preliminary examination of the data indicated a weighting proportional to $\underline{y}^2$. The results obtained with the $\underline{y}^2$ weighting are given in Table XII. The data are too few at any one temperature to obtain reliable weights. It is assumed the weighting is the same over this temperature range, and the results are combined to obtain the weighting. The number of degrees of freedom are nearly the same at all the temperatures. Out of ten observations for each time and each temperature, there are two 4-hr observations missing at 60°C and two 1-hr ones missing at 90°C. The mean is nearly 1.0; hence $\underline{s}$ is proportional to $1/\underline{y}$ and the weighting is as $\underline{y}^2$. Thus the weighting obtained here appears to be the same as that found earlier in this report when examining repeated measurements.

Table XII

DATA FOR OBTAINING THE OBSERVED WEIGHTING

Temperature, °C	log s(1/y)		log m(1/y)		Ratio of Differences for 1 hr and 4 hr
	1 hr	4 hr	1 hr	4 hr	
8	-2.789	-3.233	-3.348	-3.945	0.74
30	-2.458	-2.848	-3.368	-3.930	0.69
60	-2.227	-2.857	-3.353	-3.947	1.06
90	-2.293	-3.169	-3.345	-3.944	1.47
	Mean Ratio				0.99

REGRESSIONS AGAINST RECIPROCAL EXPOSURE
TREATED AS PROPORTIONAL TO
RECIPROCAL DOSAGE

The constants a and b were determined by the usual least-squares methods with the assumption of variation in the independent variable only. This procedure is reasonable in the present case in which specimen variation is large in comparison with that in exposure. To take care of the weighting, the quantities accumulated were the sums $\sum w_i/x_i$, $\sum w_i/x_i^2$, $\sum w_i/y_i$, $\sum w_i/y_i^2$, $\sum w_i/x_i y_i$, and $\sum i = n$, where w_i are the weights. These were all multiplied by the factor $n/\sum w_i$. Then, when these quantities were placed in the usual formulas for the unweighted least squares for the sums (X), (X²), (Y), (Y²), (XY), and n, respectively, the results for the weighted least squares were obtained in proper units. The quantities were calculated from the formulas in Table XIII and the analysis of variance in Table XIV. The results of the calculations are given in Table XV.

Table XIII

FORMULAS FOR SIMPLE REGRESSION

Name	Quantity	Formula	Name	Quantity	Formula
	$\zeta =$	$(XY) - \frac{1}{n}(X)(Y)$	Slope	$a =$	ζ/ξ
	$\xi =$	$(X^2) - \frac{1}{n}(X)^2$	Intercept	$b =$	$[(Y) - a(X)]/n$
	$\eta =$	$(Y^2) - \frac{1}{n}(Y)^2$	Square standard error of regression coefficient	$s_a^2 =$	s_E^2/ξ
Square correlation coefficient	$r^2 =$	$\zeta^2/\xi\eta$	Square standard error of the intercept	$s_b^2 =$	$s_E^2 \{ [n\xi^2 + (X)^2]/n^2\xi^2 \}$
Square standard error of estimate	$s_E^2 =$	$(1-r^2)\eta/(n-2)$	Average 1/y	$\bar{Y} =$	$(Y)/n$
			Average 1/x	$\bar{X} =$	$(X)/n$

Table XIV

ANALYSIS OF VARIANCE FOR REGRESSION

	DF	Sum Squares	Mean Square	Expected Mean Square
Due to Regression (Reg.)	1	$r^2 \eta^2$	$r^2 \eta^2$	$\sigma_E^2 + \alpha^2 \xi^2$
Deviations about Regression (Dev.)	n-2	$(1-r^2) \eta^2$	s_E^2	σ_E^2
Total	n-1	η^2		

where σ_E and α are the actual values of the estimated quantities s_E and a .

Table XV

REGRESSION OF RECIPROCAL PER CENT CHANGE IN ELECTRICAL RESISTIVITY OF GRAPHITE RODS AGAINST RECIPROCAL EXPOSURE;
ONE- AND FOUR-HOUR SINGLE IRRADIATIONS: $(1/y) = (a/x) + b$.

Quantity	Temperature			
	8	30	60	90
r^2	0.991	0.989	0.980	0.977
r	0.996	0.995	0.990	0.988
s_E	0.000777	0.000854	0.00150	0.00159
a	86.3	86.1	96.5	109.9
s_a^2	3.65	4.38	11.62	17.8
s_a	1.91	2.09	3.41	4.23
b	0.00230	0.00266	0.00382	0.00497
s_b^2	0.00102	0.00127	0.00384	0.00486
s_b	0.00032	0.000357	0.000620	0.000697
Due to Regression				
DF	1	1	1	1
Sum Squares	0.001231	0.001233	0.001805	0.001714
Mean Square				
Deviation about Regression				
DF	18	18	16	16
Sum Squares	0.04109	0.04131	0.04360	0.04406
Mean Square				
(s_E^2)	0.00604	0.00730	0.005225	0.005254
Total				
DF	19	19	17	17
Sum Squares	0.001242	0.001246	0.001841	0.001755
$\bar{Y}$	0.0144	0.0150	0.0183	0.0203
$\bar{X}$	0.03140	0.03144	0.03149	0.03139

THE TEMPERATURE DEPENDENCE OF a AND b

The quantities a and b were treated in a similar fashion, weighting them according to the inverse of their respective estimates of variance s_a^2 and s_b^2 . The results are given in Table XVI. From the analysis of variance, it is clear that the regressions of a and b are both highly significant. The results are plotted in Figure 5.

Table XVI

TEMPERATURE DEPENDENCE OF a AND b

Quantity	<u>a</u>	<u>b</u>
r^2	0.829	0.959
r	0.910	0.980
s_E	4.19	0.000233
a'	0.258	0.0000314
s_a^2	0.00688	0.0 ₁₀ 209
s_a	0.0830	0.0 ₅ 457
b'	81.91	0.001929
s_b^2	10.54	0.0 ₇ 315
s_b	3.25	0.000178
Due to Regression		
DF	1	1
Sum Squares;		
Mean Square	170.1	0.0 ₅ 256
Deviations about Regression		
DF	2	2
Sum of Squares	35.19	0.0 ₆ 108
Mean Square (s_E^2)	17.60	0.0 ₇ 541
Total		
DF	3	3
Sum of Squares	205.3	0.0 ₅ 267

The temperature dependence found for the range from 8 to 90°C may thus be put into the form

$$\frac{1}{y} = \frac{a_0}{x} + b_0 + \left(\frac{a_1}{x} + b_1 \right) T,$$

Fig. 5. Temperature dependence of $\underline{a}$ and $\underline{b}$, the regression coefficients

where a_0 and b_0 refer to apparent values at 0°C outside the range of the region in which the dependence is established and $\underline{T}$ is the temperature in $^\circ\text{C}$; thus,

$$\frac{1}{y} = \frac{81.91}{x} + 0.001929 + \left(\frac{0.258}{x} + 0.0000314 \right) T.$$

A linear dependence on temperature is not expected, but the data are not adequate to find terms of higher order.

The temperature dependence of the resistance of unirradiated graphite can be used to calculate the constants which would be obtained had the measurements been made at another temperature.

It is easily shown that $\underline{a}$ would hardly be affected and $\underline{b}$ would be decreased by a few per cent, about 4% for the 90°C specimens, and correspondingly less for lower temperatures of irradiation, about 2% for room temperature irradiation. This would be small compared to the standard deviations obtained here for $\underline{b}$. The value 0.0033 obtained for $\underline{b}$ with room-temperature measurement by Primak and Fuchs⁽³⁾ thus corresponds to an irradiation temperature between 30°C and 60°C , as it should.

CORRELATION WITH INITIAL RESISTANCE

Specimens with high initial resistances seemed to give smaller changes on irradiation. When the changes observed were plotted against initial resistance, a regression was found, but the variation about the regression was much greater than the regression, and some specimens behaved in a manner contrary to the regression. To check whether it would be profitable to introduce a correction for initial resistance, multi-linear regressions were run for

$$1/y = b_0 + a_0/x + b_1 T + a_1(T/x) \dots \quad (\text{I})$$

and

$$1/y = b_0 + a_0/x + b_1 T + a_1(T/x) + cR_0 \dots \quad (\text{II})$$

The results are given in Table XVII.

Fig. 5. Temperature dependence of $\underline{a}$ and $\underline{b}$, the regression coefficients

where a_0 and b_0 refer to apparent values at 0°C outside the range of the region in which the dependence is established and T is the temperature in $^\circ\text{C}$; thus,

$$\frac{1}{y} = \frac{81.91}{x} + 0.001929 + \left(\frac{0.258}{x} + 0.0000314 \right) T.$$

A linear dependence on temperature is not expected, but the data are not adequate to find terms of higher order.

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It is easily shown that $\underline{a}$ would hardly be affected and $\underline{b}$ would be decreased by a few per cent, about 4% for the 90°C specimens, and correspondingly less for lower temperatures of irradiation, about 2% for room temperature irradiation. This would be small compared to the standard deviations obtained here for $\underline{b}$. The value 0.0033 obtained for $\underline{b}$ with room-temperature measurement by Primak and Fuchs⁽³⁾ thus corresponds to an irradiation temperature between 30°C and 60°C , as it should.

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$$1/y = b_0 + a_0/x + b_1 T + a_1(T/x) \dots \quad (\text{I})$$

and

$$1/y = b_0 + a_0/x + b_1 T + a_1(T/x) + cR_0 \dots \quad (\text{II})$$

The results are given in Table XVII.

Table XVII

$$(I) \quad 1/y = b_0 + a_0 (1/x) + b_1 T + a_1 (T/x)$$

$$(II) \quad 1/y = b_0 + a_0 (1/x) + b_1 T + a_1 (T/x) + R_0$$

Term	Regression Coefficient		r_i		r_x	
	I	II	I	II	I	II
constant	0.001898	- 0.008387				
$1/x$	81.08	+80.05	0.958	0.958	0.96	0.97
$1/T$	0.000033	+ 0.000026	0.24	0.24	0.39	0.36
T/x	0.2792	0.2992	0.77	0.76	0.51	0.24
R_0		1.4016		0.14		0.50

The results for the multilinear regression I are seen to be nearly the same as that obtained in the preceding section, where the constants were derived by means of two linear regressions, the first against $1/x$ and the second against T . For the multilinear regression II, the constant term b_0 is negative. This is physically unacceptable since $1/b_0$ is the saturation value for the resistance. A negative value for b_0 was also obtained (the results are not quoted here because they were obtained for a different weighting) when R_0 was considered as a factor, i.e., for

$$1/y = b_0 + a_0/x + b_1 T + a_1 T/x + c R_0 + c_1 R_0/x + c_2 R_0 T + c_3 R_0 T/x.$$

In Table XVII, the total correlation coefficients are r_i , and the r_x are the partial correlation coefficients for that variable only.

It is clear that this kind of correlation with initial resistance is not useful in the present application.

PRECISION OF MONITORING WITH THE ELECTRICAL RESISTIVITY OF GRAPHITE

The confidence band for an unknown mean is

$$\pm t_{\alpha} s / \sqrt{n},$$

where α denotes the appropriate fractile of the t -distribution. Thus, for example, if monitoring is performed for periods giving the mean $\bar{Y}$ of

Table XV, and it is desired to obtain results within $\beta\%$ for 19 out of 20 times, then

$$t_{0.975} s \sqrt{n} < \beta \bar{Y} \quad .$$

For the 30°C data, 5% accuracy 95% of the time would require about seven specimens, whereas a 10% accuracy 95% of the time would require about four specimens. If one were content with a 5% accuracy 90% of the time, this could be achieved with six specimens; a 10% accuracy 90% of the time could be achieved with three specimens. Over the range of the 1-hr and 4-hr specimens, $\underline{s}$ seemed proportional to $1/y$; hence the same number of specimens is required over this range. When account is taken of the dependence of $\underline{s}$ on $\bar{Y}$, the values of $\underline{s}$ for the different temperatures are not significantly different. The statements made above for the number of specimens required to determine a dosage to a certain accuracy would therefore be correct to one or two specimens for all the temperatures used here and for a similar selection of graphite.

ISOTHERMAL DAMAGING

The theory of isothermal damaging is given by Primak.⁽⁷⁾ In the Vand approximation, the peak of the activation energy distribution may be taken as extending from

$$\epsilon_0 = \tau \ell n A t,$$

where τ is the temperature times Boltzmann's constant (in ev), $\underline{A}$ is a frequency factor, and $\underline{t}$ is the time (seconds). If $\ell n A$ is taken to be 30, then Neubert's curves may be examined to obtain the extent of the peak, 1.6 ev. The peak width is then $(1.6 - \epsilon_0)$. This was calculated for both 1-hr and 4-hr irradiations, and the results are given in Table XVIII. When these results are plotted against temperature, the peak widths are straight lines for which the fractional change (decrease) per degree is about 0.0050 per degree at 0°C as shown in Fig. 6. This would apply to the initial rate of change. The similar observed quantity can be calculated from the equation given in the section on the temperature dependence of $\underline{a}$ and $\underline{b}$. At very short times, the $\underline{b}$ constants can be neglected. Then,

$$1/y = (81.91 + 0.258 T)/x$$

$$y = x/(81.91 + 0.258 T)$$

$$(dy/y)/dT = 0.258/81.91 \text{ at } 0^\circ\text{C}$$

which is 0.0034 for the fractional change per degree at 0°C.

Table XVIII

PEAK WIDTH FOR THE VAND APPROXIMATION
TO ISOTHERMAL DAMAGING

$\ln A = 30$; end of distribution 1.6 eV

Temperature (°C)	ϵ_0 (eV)		Peak Width (eV)	
	1 hr	4 hr	1 hr	4 hr
8	0.924	0.958	0.676	0.642
30	0.997	1.033	0.603	0.567
60	1.096	1.136	0.504	0.464
90	1.191	1.235	0.409	0.365

Fig. 6. Peak widths as a function of temperature: one hour irradiation time, full, four hour irradiation time, dotted.

It should be noted that the functional dependence for the two relations, the one calculated from the activation energy distributions and this one from the temperature regression, are different. For the former there is a dependence on the time of irradiation, but this is not severe; for the latter there is no dependence on the time of irradiation for the initial rate is an extrapolation on the time axis.

There is no significant difference between the calculated and the observed values when the standard deviations of the quantities, 0.258 and 81.91, in the temperature regressions are considered; the standard deviation for the temperature dependence calculated from these quantities, 0.0034, is about 0.001.

The characteristic of radiation annealing is that the observed annealing is greater than can be accounted for by thermal annealing alone. The quantity 0.0034 carries the variance associated with a coefficient of a multilinear regression. The 95% confidence belt is therefore constructed as

$$\pm t_{0.975(n-k-1)} s.$$

The number of data n used in this regression was 76, and the number of variables k were 3: $1/x$, T , and T/x ; thus the number of degrees of freedom is 72 and the 95% confidence belt becomes

$$0.0034 \pm 0.002.$$

Thus it is clear that there is no evidence for radiation annealing, but the data are not sufficiently precise to prove none at all in fact occurred.

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