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CONTRACTION OF GRAPHITE: A COMPARISON OF
LABORATORY AND PRODUCTION REACTOR DATA
PART I - B, D, F, E, DR, AND C REACTORS

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CONTRACTION OF GRAPHITE: A COMPARISON OF LABORATORY
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PART I - B, D, F, H, DR, and C REACTORS

R. C. Giberson and W. C. Morgan

August 6, 1962

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CONTRACTION OF GRAPHITE: A COMPARISON OF LABORATORY AND PRODUCTION REACTOR DATA
PART I: B, D, F, H, DR, AND C REACTORS

INTRODUCTION

A program has been carried on at Hanford for a number of years to study the effect of neutron radiation on the dimensional changes in graphite. This program has been concerned with the changes measured on small graphite samples which have been exposed to various conditions of temperature and neutron flux. Theoretical studies have also been conducted to determine damage mechanisms. The prime purpose of this research program has been to develop, with the support of the carbon companies, a radiation resistant graphite for use as a reactor moderator at high temperatures.

As a result of the expansion experienced at B, D, and F Reactors during their early operation, efforts were directed towards development of a non-expanding graphite for all subsequent reactors up to and including the K Reactors. In recent years it has been found that graphite contracts under prolonged neutron exposure at temperatures above approximately 300° C. This contraction is of concern because of the possible effects on reactor operation and life. For example, distortion of process tubes, vertical safety rods, and horizontal control rod channels can cause increased operating and maintenance problems.

The present report presents information on the actual depression of the graphite moderator at B, D, F, H, DR, and C Reactors. A subsequent report will discuss contraction in the two K Reactors.¹ Relationships between observed reactor contraction rates and the rates for small samples are determined. All contraction

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data presented here are measured transverse to the extrusion axis of the graphite bars. As used in this report, the depression rates refer to the rate of reduction in height of the top center of the reactor moderators. The depression rate is converted to an apparent contraction rate of the filler graphite bars. This "apparent" rate includes the effects of expansion and contraction of the graphite in the top and bottom fringe regions, and thus is not a true contraction rate like that obtained on small graphite samples.

SUMMARY

The net moderator depression can be related to the total reactor power generation. The rate of depression is linear with reactor power generation over periods of several years for H, DR, and C Reactors. When the apparent contraction rates of the reactor moderators are expressed as a function of fast neutron exposure, the rates of the reactor moderator bars are found to be about 2.5 times the rate of standard-size (0.43 in. diameter x 4 in.) graphite samples. The data support previous results which indicate that the contraction rates are a function of fast neutron exposure, graphite type, and sample size. Because of the uncertain effects of several variables, it has not been possible to detect an effect of temperature on the contraction rate of the reactor moderators.

MEASUREMENTS OF MODERATOR DISTORTION

Reactor moderator distortion in the vertical plane is monitored by use of a mercury manometer. The traverse readings, which are obtained from the bottom inside surface of the aluminum process tubes, are reproducible to ± 0.01 in. A fixed reference point, 18 in. from the front Van-stone flange has been used over the years

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with an assumed constant elevation of 0.00 in. This report will be concerned with vertical traverse data taken on a top center process tube at each of the six oldest Hanford reactors. The data were obtained by personnel in Irradiation Testing Operation, IPD.

Typical vertical-traverse profiles are shown in Figs. 1 to 6 for E, D, F, H, DR and C, respectively. Three curves are drawn on each of the figures. The first shows the maximum height attained at the center of the reactor moderator. B, D, and F Reactors attained a height of from 2 to 4 in. during the early years of operation at low graphite temperatures. The second curve is of a typical traverse obtained when the top center had returned approximately to the lay-up level. The final curve is of a recent traverse; it illustrates the depression that has occurred in the top center of the graphite stack.

Standard-size samples and 4 x 4 x 24 in. bars have been irradiated in the Hanford reactors. These have been measured with a precision of about ± 0.005 per cent by use of a micrometer. Small samples, irradiated in the General Electric Test Reactor, were measured with a precision of about ± 0.001 per cent by use of a Bausch and Lomb DR-25 Optical Gage (Type 33-14-23).

DISTORTION TRENDS IN REACTOR MODERATORS

The graphite distortion showing the displacement at certain locations has been plotted versus calendar date in earlier reports.^{2,3} Though this procedure can show trends, it must be normalized in determining quantitative behavior when comparing different reactors or periods of operation at different power levels. In Fig. 7 and 8, the displacement in inches near the midpoint of the top center

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tube at the point, where the maximum changes have been observed, is plotted versus the cumulative power generation, x , in units of megawatt days for B, D, and F and H, DR and C Reactors, respectively.

B, D, and F Reactors. Before start-up of the first Hanford reactor, speculation on the dimensional behavior of the graphite included predictions of growth, contraction and even disintegration. It was not long, however, until a relatively rapid expansion was observed. It was because of this expansion damage that B Reactor was shut down in March of 1945 (after reaching a height of ~ 2.5 in.) so that it could be held in reserve in case D and F Reactors expanded beyond usefulness.

Expansion damage, which is highly temperature dependent, is caused by neutrons displacing carbon atoms from normal layers into interplanar spaces of the graphite crystal lattice. It was suggested in 1947 that the addition of carbon dioxide to the reactor atmosphere might preferentially oxidize the interstitial carbon atoms, and thereby reduce the expansion.⁴ Addition of carbon dioxide actually decreased the thermal conductivity and increased the operating temperature of the graphite, which did, in fact, anneal some of the expansion. This is illustrated in Fig. 7.

In the period 1954-55, B, D, and F Reactors, which were constructed with KC graphite in the core, were observed to have contracted below lay-up level in the top center of the stack. This depression apparently proceeded almost linearly with exposure from 1957 to late 1959. Since 1960 there has been a decrease in the rate of depression of the top center of the graphite moderator with exposure.

The process tube blocks of B, D, and F Reactors, which were initially the same size as the filler blocks, have received a larger fast neutron dose and have

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operated at lower temperatures than the filler blocks. As a result of both these differences, the process tube blocks should be larger than the adjacent filler blocks. Thus, any changes in moderator height should be dependent upon the changes in the process tube block dimensions as well as the changes in filler block dimensions. This dependency is in contrast to all other Hanford reactors where the process tube blocks are undercut on top and do not affect the moderator height changes. Because of these peculiarities in the distortion behavior at B, D, and F Reactors, it is not possible to calculate a meaningful contraction rate for the filler graphite such as will be done for the other reactors.

H, DR and C Reactors. Graphites that would expand at lower rates at temperatures below 300° C were developed and utilized in the H, DR and C Reactors. In addition, these reactors were not operated at low temperatures for significant periods of time as were B, D, and F. Certain other changes were incorporated into the moderator design⁶ in order to increase graphite temperatures. As a result of these changes only a small amount of expansion occurred at H, DR and C Reactors during early operation as illustrated on Fig. 8.

H Reactor was the first reactor to exhibit net contraction of the graphite stack at the top center. This occurred in 1952. As shown on Fig. 8 straight lines can be drawn on the Δh vs X plots that fit the data of all three reactors quite well. An exception, which is unexplained, is the behavior of H Reactor from 1953 to 1957.

The most probable slopes have been determined for DR and C data points of 0.83 and 0.79 in. per 10^6 Mwd, respectively. An analysis of the variability of the data points shows that there is less than 1 chance in 100 that the most

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probable slopes are in error by more than ± 0.03 and ± 0.04 in. per 10^6 Mwd at DR and C, respectively. Comparing these two slopes and their variances, there is greater than 95 per cent probability that the two slopes are different. Though the calculated slopes are different, this difference is of no operational significance at the present time. Since 1957 H Reactor has shown a rate of depression of 0.95 in. per 10^6 Mwd. There is less than 1 chance in 100 that the slope determined for H Reactor is in error by more than ± 0.06 in. per 10^6 Mwd. The probability is less than 1 in 1000 that the slope determined at H Reactor is the same as either DR or C Reactors.

EFFECT OF TEMPERATURE

There is an indication from data obtained on small samples⁷ that the rate of contraction may go through a minimum near 800°C . At temperatures below 250°C only expansion is observed.⁸⁻¹⁰ Between 250 and 800°C the rate of contraction appears first to increase, and then to decrease with increasing temperature,⁹⁻¹¹ but the exact behavior is not yet known.

Graphite temperatures and power levels in the Hanford reactors have often been increased during their operating history. This, coupled with changes in temperature distribution due to changes in reactor gas composition and thermal conductivity, has made it virtually impossible to assign reliable values to moderator graphite temperatures. The lack of a sufficient number of operating thermocouples over the life of the reactors, especially in the fringe, has further hindered estimates of temperature.

Even though the graphite temperatures have generally increased with time, the depression of the reactor moderator at H, DR and C, has continued linearly (Fig. 8). Therefore, it is not possible to detect a temperature effect from the reactor data.

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REACTOR CONTRACTION RATES

Neutron Dosage Units. Good agreement has been obtained in comparing the contraction rate of small samples on the basis of exposure to neutrons with energy above 0.18 Mev in significantly different neutron spectra. For example, from the data of Woodruff¹² the contraction rate of transverse CSF graphite samples exposed in the Y Hot Test Hole at C Reactor is 0.012 per cent per 10^{20} nvt* at an exposure temperature of approximately 550° C. The data of Davidson and Helm¹¹ on transverse CSF graphite irradiated in the GSTR at 475, 575, 625° C, when interpolated, to 550° C yield a contraction rate of approximately 0.011 per cent per 10^{20} nvt. Such good agreement between these two rates is probably fortuitous when one considers the small number of samples used to derive the rates and the differences routinely observed between different samples of the same type of graphite.

Reactor Contraction Rates, H, DR, and C Reactors. As the first step in obtaining reactor contraction rates as a function of neutron exposure, the specific power generated at the center of each reactor is computed. These calculations assume that the ratio of specific power to total reactor power has been approximately constant over the last few years during which linear depression rates were observed.

The coolant flow rate ($\dot{Q}$) and coolant temperature rise (Δt) were obtained¹³ for a representative central tube of each of the three reactors during periods of near-equilibrium operation. From these data and the conversion data of HW-63991,¹⁴ ratios were calculated for converting the total reactor power data to specific power generation at the center of each reactor. These ratios are given in Table I.

*This, and all subsequent exposures, are in terms of $E > 0.18$ Mev.

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TABLE I - CONVERSION OF REACTOR POWER TO SPECIFIC POWER

<u>Reactor</u>	<u>Date</u>	<u>G</u> <u>(gal/min)</u>	<u>At</u> <u>(°C)</u>	<u>Reactor power (Mw)</u>	<u>Mwd/At</u> <u>Mwd</u>
C	2-10-62	50.9	99.5	2285	7.11×10^{-3}
DR	2-17-62	46.4	100.0	1840	7.57×10^{-3}
H	2-17-62	43.3	84.2	1770	6.52×10^{-3}

The average neutron exposure per Mwd/At for Y Test Hole at C Reactor has been determined¹⁵ as $= 1.36 \times 10^{17}$ nvt per Mwd/At. There is an additional cyclic variation between process channels of ± 8 per cent relative to this average. The observed rate in the reactor, which represents an average of the minimum contraction rates of the individual bars, should therefore be calculated on the basis of the lower average ratio: 1.26×10^{17} nvt per Mwd/At. Since DR and H Reactors have the same configuration and lattice spacing as C Reactor, the above conversion ratio is assumed to apply equally well to them.

One additional assumption must be made prior to comparison of the reactor stack depression and graphite sample contraction data. A preferable situation would be to determine the amount of contraction occurring over a few reactor lattice distances near the center of the reactor; however, these data are not available. Observation of a few traverses, where more than one process tube in a column was examined on the same date^{16,17} or where other traverses can be compared with the top central depression,^{18,19} indicates that the total amount of moderator contraction has been primarily dependent on the contraction of the central zone blocks. This does not imply that there is no temperature dependence of the contraction rate as a function of exposure in these regions, but only that under these particular conditions the expansion and contraction of the individual bars outside the enrichment ring has resulted in an average change in height not much different from that found for graphite inside the enrichment ring.

Having made the above assumptions, one can now calculate the apparent graphite contraction rates for the individual reactors from the moderator height depression rates shown in Fig. 8. The apparent contraction rates, listed in Table II, were calculated with the assumption only the graphite between the top and bottom process tubes is effecting the height changes.

TABLE II - CONTRACTION RATE AS A FUNCTION OF EXPOSURE

Reactor	Moderator height depression rate (in./ 10^6 Mwd)	Conversion factor (nvt/Mwd)	Contraction rate % per 10^{20} nvt ($E > 0.18$ Mev)
C	0.79	8.98×10^{14}	0.023
DR	0.83	9.55×10^{14}	0.023
H	0.95	8.23×10^{14}	0.031

Comparison of Reactor and Large Bar Contraction

1. C Reactor. Woodruff²² obtained data from several 4 x 4 x 24 in. bars of reactor-grade graphite irradiated from start-up of the reactor until April of 1960 in the G Hot Test Hole at C Reactor. One of these bars was of CS-BF graphite, like the graphite in the active zone of C Reactor.²⁰ A net transverse contraction of 0.566 per cent was observed after an exposure of 2.53×10^{21} nvt. This exposure was reached by the central reactor filler graphite at 2.82×10^6 Mwd total reactor power generation. From Fig. 8 the net stack-height contraction was about 1.74 in. at 2.82×10^6 Mwd or 0.462 per cent. The contraction of this particular bar is therefore 123 per cent of the apparent average reactor filler-bar contraction at this exposure. G Hot Test Hole operated at slightly lower temperatures than the center of C Reactor. The contraction of the sample bar should therefore be more than the contraction at the center of the reactor according to the temperature dependency found by Davidson and Helm.¹¹

2. H Reactor. The central zone of H Reactor was built from several different types of graphite;²² however, about 75 per cent of the graphite bars are of CSF graphite. Woodruff's data¹² from 3 Test Hole at C Reactor included a large bar of CSF graphite. The following comparison will be made with the assumption that the net reactor contraction is the same as if all the moderator bars were CSF graphite. The observed net transverse contraction after 2.53×10^{21} nvt was 0.529 per cent. This exposure was reached by the center filler of H Reactor at about 3.15×10^6 Mwd. From Fig. 8 the net contraction of the stack was about 2.60 in. at that time or 0.690 per cent. The large bar net contraction was therefore about 77 per cent of the apparent average reactor filler bar contraction at that exposure. This is about the same difference as found for CSGBF graphite, but in the opposite direction. H Reactor has operated at lower temperatures⁶ than has C Reactor, during a large part of its operating history. This difference in temperature may account for at least part of the difference between the sample bar and apparent reactor moderator contraction.

Effect of Sample Size on Contraction

Extrapolation of contraction of standard-size CSGBF samples from 1.63×10^{21} nvt to the same exposure as obtained by the $4 \times 4 \times 24$ in. bars (2.53×10^{21} nvt) yields a total contraction of 0.21 per cent.¹² This is only 37 per cent of the contraction of Woodruff's large CSGBF or 45 per cent of the apparent average filler-bar contraction. This difference in total contraction at equivalent exposures of small samples and large bars is interpreted as being indicative of a sample-size effect.

Extrapolation of Woodruff's standard-size CSF samples to 2.53×10^{21} nvt yields a net contraction of 0.25 per cent. This is only 47 per cent of the large

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bar contraction or 36 per cent of the apparent average filler-bar contraction at this exposure. These small sample to large bar contraction ratios are consistent with the ratios reported for CSGBF graphite. More recent data obtained from a comparison of standard-size and smaller samples²¹ of AGOT-18 graphite support the contention that sample size has a direct influence on graphite contraction rate.

Comparison of Contraction Rates

1. C Reactor. The apparent contraction rate of C Reactor filler graphite from Table II of about 0.023 per cent per 10^{20} nvt can be compared with the contraction rate of 0.01 per cent per 10^{20} nvt obtained from Woodruff's standard-size CSGBF samples. The contraction rate of the small samples is only 44 per cent of the apparent filler-bar contraction rate, and is consistent with the total contraction ratio obtained in the previous section for a single large bar of CSGBF graphite.

2. H Reactor. The apparent contraction rate of filler graphite from Table II of about 0.031 per cent per 10^{20} nvt, can be compared to the contraction rate obtained from Woodruff's standard-size CSF samples, which is about 0.012 per cent per 10^{20} nvt. The ratio of the small-to-large contraction rate of 0.39 is consistent with the previous ratios.

Comparison can also be made between the filler bar contraction rates and the CSF small-sample data of Davidson and Helm.¹¹ These samples were irradiated in the General Electric Test Reactor where the flux spectrum is much different than that obtained in H Reactor. Data at this time indicate that the contraction of CSF and other graphites may be dependent upon exposure temperature. The contraction rates derived from their data at three different temperatures are listed in Table III below.

TABLE III - VARIATION OF CSF CONTRACTION RATE WITH TEMPERATURE

<u>Exposure temperature, °C</u>	<u>Contraction rate, % per 10^{20} nvt</u>
475 $\pm$ 25	0.013
575 $\pm$ 25	0.010
625 $\pm$ 25	0.008

Interpolation of these data yields a contraction rate of about 0.011 per cent per 10^{20} nvt at 550° C, or about 36 per cent of the apparent reactor filler-bar contraction rate.

3. DR Reactor. The central zone of DR Reactor, like H Reactor, was built of several types of graphite;²³ however, approximately 75 per cent of the filler is KCF graphite. No irradiation data are available for transverse KCF graphite, but data are available for standard transverse samples of KC graphite. If one assumes that the contraction rates of the two graphites are not significantly different, the following comparison can be made. The contraction rate of about 4.6×10^{-5} in./in. per 10^{20} nvt, obtained from standard-size samples of KC graphite¹² is 20 per cent of the apparent contraction rate of the filler graphite in DR Reactor (Table II). This ratio is about one-half that obtained from the comparisons made between the small sample data and the C and H Reactor moderators. At present time, however, there is not sufficient data to assign a cause to this difference. There is a possibility the differences in temperature or radiation history may affect the contraction rates, or that the effect of sample size may be different for different types of reactor-grade graphites. There have been several changes in the manufacturing process of KC graphite; it is therefore possible that the KC graphite bar from which the small samples were obtained is not representative of the KCF graphite bars in DR Reactor moderator.

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SUMMARY AND CONCLUSIONS

A summary of the correlations of the contraction data of the graphite samples relative to each reactor is presented in Table IV. Table II listed the apparent contraction rates of the filler graphite for each of the reactors.

TABLE IV - RELATIVE CONTRACTION DATA

	<u>H Reactor</u> <u>(CSF graphite)</u>	<u>C Reactor</u> <u>(CSGBF graphite)</u>	<u>DR Reactor*</u> <u>(KC graphite)</u>
Average reactor stack (Contraction or contraction rate)	1.00	1.00	1.00
Large bar contraction (After 2.53×10^{21} nvt)	0.77	1.23	--
Standard-size sample contraction (After 2.53×10^{21} nvt)	0.36	0.45	--
Standard-size sample contraction rate (Data from Y Test Hole at C Reactor)	0.39	0.44	0.20
Small-sample contraction rate (Data from the GETR).	0.36	--	--

* DR core is largely KCF graphite, but the comparison was made with the contraction rate of standard-size samples of KC graphite.

The changes since 1959 in the depression rates of B, D, and F Reactors are probably related to expansion of process-tube blocks. More data are needed before a contraction rate can be determined for the filler graphite of these reactors.

The data for C and H Reactors indicate that the apparent contraction rate of the stack is about 2-1/2 times the contraction rate of small samples. There does not appear to be a large difference between the contraction of 4 x 4 x 24 in. bars and the depression of the reactor moderator. The difference in relative

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contraction rates between small samples and reactor moderator is larger at DR than at either C or H. This difference should be investigated more fully.

In order to determine more accurately the contraction rate of the graphite bars in the central moderator more reactor traverse data are needed from all reactors. Specifically, height traverses of several process tube channels, of the central column inside the enrichment ring, should be made routinely in addition to the traverses presently being obtained.

Additional irradiations will be performed to determine the effect of sample size more precisely.

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FIGURE 1

Vertical Traverse History - 4574-B

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FIGURE 2

Vertical Traverse History - 4674-D

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FIGURE 3

Vertical Traverse History - 4676-F

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FIGURE 4

Vertical Traverse History - 4674-H

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FIGURE 5

Vertical Traverse History - 4674-DR

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FIGURE 6

Vertical Traverse History - 4674-C

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FIGURE 7

Elevation of Top Center of Process Tube vs. Cumulative Power Generation
B, D and F Reactors

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D R O C H Δ												
	51	52	53	54	55	56	57	58	1959	1960	1961	
	53		54		55	56		57	58	1959	1960	1961
	50	51	52	53	54	55	56	57	58	1959	1960	1961

FIGURE 8

Elevation of Top Center of Process Tube vs. Cumulative Power Generation
H, DR and C Reactors

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