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TECHNICAL DATA PERTINENT TO GRAPHITE CONTRACTION

October 30, 1958

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TECHNICAL DATA PERTINENT TO GRAPHITE CONTRACTION

I. INTRODUCTION

Initially, the graphite stacks in the oldest HAPO reactors expanded during low temperature operation, due to radiation induced graphite crystal growth. This damage was annealed out in the central zones by raising the operating temperature. Late in 1952, the graphite in the top central section of the H Reactor stack was observed to have subsided to an elevation below that of original lay-up. Net graphite contraction was observed in F Reactor late in 1954. This graphite contraction continued at a modest rate, giving little concern until it was observed that the contraction rate was increasing, and that the increase in rate was roughly proportional to increases in power level.

Graphite contraction, in itself, does not pose an operating problem as long as the resulting curvature of the process tube channel does not interfere with charging and discharging fuel elements, replacing process tubes, and operation of control and safety rods. The process channel curvature due to contraction is aggravated, however, by the graphite growth associated with low temperature operation near the front and rear ends of the active zone.

Extrapolating present graphite contraction rates, and factoring in projected power level increases, it appears that process channel curvature resulting from graphite distortion may cause operating difficulties about the year 1963 in some reactors (H, C, K's) and that significant maintenance attention may be required in all reactors thereafter.

Since the New Production Reactor is scoped to have higher power density than the existing reactors, graphite contraction is a critical factor in its design.

II. SUMMARY

A. Quality of Data

1. Laboratory Data

Ample data are available to describe graphite distortion at low temperatures (30°C). These data were obtained from water cooled test holes in the HAPO reactors. Very few data are available for temperatures between 50°C and 400°C. Between 400°C and 500°C considerable data are available up to 5000 MWD/AT exposure: these data were obtained in test holes at the HAPO reactors wherein the temperature was not controlled, but reflected the ambient in-reactor graphite temperatures. Between 600°C and 1050°C a few graphite irradiations have been made in the Materials Testing Reactor L-42 position. Since graphite damage depends upon the energy distribution of the incident neutrons, and since the neutron flux spectrum differs significantly between the MTR and HAPO reactors, determination of the equivalent HAPO exposure corresponding to a measured MTR exposure involves large uncertainties. Furthermore, the small size of the samples (1 inch) irradiated in the MTR and the very small change in dimension observed after irradiation introduce additional uncertainties into the data obtained from the MTR. Thus only sketchy and uncertain data are available for graphite temperatures higher than found in existing HAPO reactors.

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- 3 -

HW-58026 RD

Laboratory data on graphite distortion are summarized in Figures 1 through 8.

2. Gross Reactor Data

Contraction of the HAP0 reactor graphite is monitored primarily by obtaining elevations along a process tube near the top center of the reactor. Determinations of elevation relative to a base point on the front shield are accurate to within 0.01 inch. However, profiles obtained partly from the front face and partly from the rear face may not meet. This probably reflects only a lack of correspondence in elevation between front and rear base points. At the K Reactors graphite profiles have been obtained using front to rear test holes located just above the topmost row of process tubes.

3. Comparison of Data: Graphite Contraction Rates

(CSF, GBF) Laboratory Data (Fig. 4,5): $0.02 \pm .007\%/1000 \text{ MWD/AT}$ at
(400-500°C) 3000-5000 MWD/AT exposure.

Gross Reactor Data: $\sim 0.03 \text{ } \%/1000 \text{ MWD/AT}$

(Graphite temperature 500-600°, exposure > 5000 MWD/AT,
calculated for K and F Reactors by approximate methods).

B. Trends Indicated by Data

The development of central reactor contraction for representative reactors (F, H and K's) is shown in Figure 10. It is observed that H Reactor exhibits three distinct (and increasing) contraction rates corresponding approximately to three levels of equilibrium power.

It is seen that the central graphite at H Reactor has been subsiding at about the following rates:

1950-1954	0.15 in./yr.
1954-1956	0.3 in./yr.
1957-1958	0.5 in./yr.

This increase seems to be directly attributable to increases in power level.

Representative development of process tube profile distortion is shown in Figures 10 through 13. Graphite temperatures and maximum process tube powers since January, 1957 are shown in Figure 14.

There is no evidence that graphite contraction is temperature-dependent in the range of temperatures from about 300°C to the highest temperatures (about 600°C) experienced in the HAP0 reactors. However, refined measurements may indicate that some temperature dependence does exist. If so, it is not expected to be large. MTR data at 750°C tends to support the

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HW-58026 RD

idea that graphite contraction is not significantly temperature dependent up to that temperature. There are indications, however, that some place between 750°C and 975°C the graphite may greatly increase its contraction rate. Due to the paucity of data in this range and to inaccuracies inherent in the MTR experiments the degree to which graphite contraction is temperature dependent cannot now be accurately determined.

No evidence of saturation of graphite contraction in the HAP0 reactors has been obtained.

C. Potential Quantitative Problem at Existing Reactors

Based upon the following three assumptions:

- (1) Graphite stack contraction rate is a direct function of power level,
- (2) Contraction continues without reaching a practical saturation point,
- (3) Contraction rate is independent of temperature below 850°C,

and based upon the achievement of projected power level increases, the extrapolation of current trends would indicate that,

1) The B, D, and F Reactors would approach less than +1 inch maximum fringe elevation and a central elevation of -3.0 to -3.5 inches at the top row of process tubes by 1963. By 1968 the central elevation will have dropped an additional 3 inches without appreciable change in the fringe.

2) For DR, C, H and K Reactors, the central elevation of the top row of process tubes will be 5 to 6 inches below lay up elevations by 1964. By 1968 the central elevation may well have dropped an additional 3 inches.

D. Research and Development Programs

The following research and development programs are in progress or have been initiated to obtain graphite data necessary to further define graphite behavior and to point the way toward solving the problems associated with graphite distortion:

1. Pile Monitoring Program

- a. Obtain process tube profiles quarterly at all reactors to monitor contraction and permit accurate determination of rates of contraction.
- b. Traverse available test and through holes to determine graphite contraction gradients throughout the reactor.

2. Laboratory Programs (Goals)

- a. Determine conditions under which graphite contraction will saturate.
- b. Establish range and magnitude of temperature dependence of graphite contraction.

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- c. Develop methods for producing graphite with improved dimensional stability.
- d. Establish correlations between laboratory data and observed reactor graphite behavior.
- e. Determine if pile life is best described by operating years or by total production.

3. Engineering Program (Goals)

- a. Determine limits of tolerable stack deformation from the operating point of view.
- b. Develop methods for correcting or "living with" graphite stack deformations.

III. DISCUSSION

A. The Contraction Problem, and Its Significance

The expansion of the graphite stack which accompanied the initial operation of the BDF reactors was soon recognized and identified as being the result of neutron irradiation at low graphite temperatures. A corrective program of raising graphite operating temperature by substituting carbon dioxide for helium as a pile gas atmosphere and raising power levels was initiated in 1948. This program arrested the expansion trends and soon reversed the trend by annealing out some of the accumulated expansion. Having recognized the importance of graphite operating temperature, H Reactor was started up in 1949 with a pile gas atmosphere of 100% carbon dioxide and had a maximum graphite temperature in excess of 300°C. During the first 8-10 months of operation at H Reactor, the graphite stack expanded to a point where the vertical height traverse of tube 4674 indicated an increase in elevation of 0.3". From about mid-1950 until about mid-1954 the central elevation of tube 4674 decreased at about 0.15"/year becoming less than the original lay up elevation during 1952. From about mid-1954 until the first of 1957, the rate of decrease in elevation was about 0.3"/year. In the last 1-1/2 years, this rate has increased to approximately 0.5"/year. A similar rate of contraction of the stack has recently been observed at the K Reactors. The increased rate of contraction observed at H Reactor seems to be the direct result of the increase in power level that has occurred since 1954.

The original cosine expansion, which amounted to almost 4" at D Reactor in 1947, was subsequently annealed in the B, D, and F Reactors during period from 1948-1954 and has now contracted such that the central elevation of the top central tube at each of these reactors is over an inch below original lay up elevation. The rate of contraction for the last four years has been about 0.3"/year. To further complicate the situation, that expansion which existed in the fringe zones of BDF reactors in 1947 has not been annealed. Thus, the top of the reactor has developed a crater-like profile. The process tube curvature for those tubes in the top of the reactor has caused some difficulty in charging fuel elements in these tubes. This tube curvature has

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been improved at B and F Reactors in the last 6-8 months by relocating the fuel element charge and by utilization of downstream control rods such that the neutron flux and thus graphite temperature have been substantially increased in the front fringe region of the reactor.

Based on the present knowledge of graphite contraction, it is indicated that the fringe zone expansion at BDF reactors will continue to anneal and that the central region will continue to contract at their present rates, and these rates will increase as the pile power level is increased. Extrapolating current trends, it would appear that the top tube elevation profile at BDF Reactors would approach the profile of H Reactor with the maximum fringe elevation of less than 1" and central elevation of -3.0-3.5" by 1963. By 1968, the central elevation may have dropped an additional 3" without any appreciable changes in the fringe.

For H, C and K Reactors, where the current apparent contraction is about 0.5"/year, it is indicated that these rates will increase as forecast power levels are attained and may approach a contraction rate of 0.7-0.8"/year. By 1964 then, the central elevation of the top tubes at these reactors could be about 5" below lay up. By 1968, this might well be 8-9 inches below lay up.

Currently, it is felt that contraction of more than 4 inches would result in some operation difficulty and that contraction of more than 6" would require major corrective action.

It would thus appear that "trouble free operation" at all reactors can be assured until 1963-64 but some major renovation would be required to assure operation at programmed power levels until 1968.

The pertinent assumptions used in making such extrapolations are (1) Contraction of the stack is a direct function of power level; (2) Contraction continues without reaching a practical saturation point; (3) Contraction rate is independent of maximum graphite temperature below 850°C. There is some evidence to support each of these points; however, the data are available only in limited quantity and over a limited range of exposure. Precise extrapolations, therefore, are not possible.

B. Laboratory Data

1. Hanford Test Hole Data

Figure 1 presents a complete account of graphite distortion at 30°C for reactor graphite to exposures in excess of 6000 MWD/AT. These data are shown in this discussion of high temperature contraction to help in understanding the effect of temperature. Several effects are shown in these curves. KC graphite which has the most highly developed structure also has the highest degree of preferred orientation. Thus differences resulting from orientation effects are magnified. CSF, like KC is graphitized at a high temperature (2800°C) but the structure is not as fully developed. Crystallites are smaller and less perfect. It's likely

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that the crystallites are less well oriented by extrusion. TSGBF is graphitized at about 2450°C. The structure of TSGBF is the least developed of the graphites shown and damage effects which are dependent upon crystal orientation are less well separated.

There are only few data on radiation effects at intermediate temperatures (50-400°C). Some work has been done at 100-200°C⁽¹⁾ and the dimensional changes observed are shown in Figures 2 and 3. It can be seen that dimensional changes are highly temperature dependent in this range. Between 200 and 400°C only one piece of data exists⁽²⁾ which shows that CSF graphite is dimensionally stable to 1500 MD/CT at 335°C.

High temperature contraction was first observed in samples irradiated above 300°C. Figure 4 shows dimensional changes in CSF graphite in the temperature range 400-500°C to the highest available exposures and represents a composite of HAP0 experience with CSF graphite in this temperature range. For convenience in assessing the precision, limits of error which represent plus and minus one standard deviation of the mean have been added to the originally published⁽³⁾ curves. Each point has been rechecked and new points added as they became available. A further check into the history of the samples revealed that the lower curve was obtained from parallel samples of Bar 73. This bar does not seem to be very typical of CSF graphite and for this reason not too much significance should be placed upon the fact that this graphite seems to contract at a higher rate. The parallel contraction rate of other more typical CSF samples does not appear to differ significantly from transverse samples.

It should be understood that the temperature was not controlled during these irradiations. Data at low exposure were obtained at about 400°C while the high exposure samples were irradiated at 500 to 525°C. This is true of all data reported to have been irradiated at 400-500°C.

The effect of different cokes and manufacturing treatments on high temperature contraction is shown in Figure 5. KC graphite (no longer available) shows the least transverse distortion and also the greatest anisotropy. This is consistent with the hypothesis of graphite contraction which will be developed later. CSGBF, a graphite typical of the K Reactor process shows less contraction than CSF.

From the data shown in Figures 4 and 5 it is apparent that with the possible exception of CSF material, contraction is less in the transverse orientation. Differences in rates appear to be a function of graphite coke and manufacturing process, the latter concerned principally with the graphitizing temperature. Figure 6, which is self-explanatory, shows the effect on contraction caused by large variations in graphitization temperature.

2. MTR High Temperature Irradiations

Irradiation of graphite has been performed in the temperature range 600 to 1050°C in the MTR L-42 position. These irradiation temperatures were carefully controlled and accurate flux measurements were made.

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Table I shows the results obtained in the limited number of GEH-9 irradiations conducted to date. The GEH-9-5 flux was calculated from flux traverses of L-42 while GEH-9-6 contained individual monitors at each sample position for cobalt-cadmium ratio, fast and thermal flux. It is recognized that flux spectrum differences, particularly in the resonance and fast region cause differences in radiation damage to graphite and as a result the data are difficult to correlate to HAPO conditions.

Two equivalent HAPO exposure estimates, a minimum and a maximum are given for the samples where possible. The first column represents a neutron count and may be considered the lowest applicable exposure. The correspondence to MWD/AT is based on 6.46×10^{17} nvt (total) being equivalent to one MWD/AT⁽³⁾ at Hanford. The second column is the best estimate of the damage equivalence due to spectral differences between Hanford test hole and MTR L-42. This equivalence is based on a number of graphite samples exposed in the MTR and compared, through the use of property changes to Hanford experience. An empirical relationship

$$\text{MTR MWD} = \frac{K \text{ Hanford MWD/AT}}{\phi \text{ fast}}$$

was developed and the value, K, (variable, depending on the location in the reactor) was determined. For the VH-2, the constant was determined to be 8×10^{12} and because of this positions-spectral similarity with L-42, it is the value used here.

Some justification for doing this is based upon the following reasoning. It is known that graphite contraction is radiation induced. The effect requires that high energy particles transmit to the graphite lattice sufficient energy for times long enough for diffusion and rearrangement of atoms or groups of atoms to occur. At low temperatures, motion is more restricted and the end result of these same damaging neutrons is the accumulation of atoms between layer planes which expand as much as 15%. Although expansion into voids or non-crystalline areas reduces the expansion of gross dimensions of a sample that would otherwise result, some gross expansion is observed (see Figure 1). In the second method of correlating Hanford and MTR high temperature data, it is assumed that the contraction results from high energy transfer processes and is proportional to the damage produced by high energy transfer processes at low temperature. This second method probably results in a high estimate of the equivalent Hanford exposure. Both methods should be used with the understanding that there is lack of knowledge regarding damage effects of spectral differences and/or intensities.

The standard deviation of measurement repetition is also shown in Table I. Although the precision of these measurements is good, it is important to consider the possibility that in the remote handling of samples, the edges could have been damaged resulting in a misleading large contraction. GEH-9 samples measure an inch across the face and it may readily be calculated, for example, that the loss of only one thousandth of an inch on

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HW-58026 RD

the edge appears as one-tenth percent contraction. Every effort has been made to prevent scuffing of the samples and it seems unlikely that this could be the source of the dimensional changes. Future GEH-9 tests have measurement interchecks based on edge to edge and at points interior to points interior. The latter technique will prove very useful in eliminating concern about sample handling because the reference is scribed platinum pins.

The effect of possible sample oxidation is not believed important because of the helium atmosphere and lack of indication of oxidation of the samples on previous experiments. The new measurement technique will circumvent this uncertainty, however.

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C. Discussion of Theory

1. A possible Interpretation of Graphite Contraction

Since the X-ray data indicate that the lattice spacing is increased slightly⁽³⁾, graphite, under high temperature neutron irradiation, apparently contracts because of a more efficient packing of the grains. This expectation is partially substantiated by pore size measurements which showed that the pore size distribution in irradiated graphites shifted to smaller pore diameters with increasing exposure.

A model, which yields consistent explanations for a number of phenomena at 30°C temperature, can be constructed on the basis of the production of interstitials and vacancies by the high energy knock-on carbon atoms. From the nature of the interatomic forces in the graphite structure, the interstitials will predominantly cause an expansion in the direction of the c axis. Vacancies have less effect on the spacing in the c direction, but may cause a puckering and apparent contraction of the planes due to the relaxation of the lattice around a vacancy.

As the particles are more highly oriented in the extrusion process one notes a more rapid expansion in the direction transverse to the extrusion direction. This more rapid expansion in one direction is accompanied by a more rapid contraction in the perpendicular direction. Such behavior is expected in this model since increasing orientation would increase the number of grains expanding in the transverse direction while simultaneously decreasing the number contracting in that direction; similarly the parallel direction would include a larger number of contracting grains accompanied by a smaller number of expanding grains.

It can be understood from this model why radiation-damage is reduced at higher temperatures. An increase in temperature increases the mobility of the interstitials, with two major consequences. First, there is a reduction in the concentration of vacancies and interstitials since recombination is facilitated. Because of this enhanced recombination probability, the rates of parallel contraction and transverse expansion are reduced. The second effect of increased mobility is increased probability of interstitials migrating to free surfaces of the grains.

Contraction of perpendicular samples might, at first, be thought due to a further development of the graphite structure. However, changes in the C_0 spacing and apparent crystallite size, parameters often used to measure the degree of development of graphitic carbon, are in disagreement with this idea. Figure 7 shows that the C_0 distance increases and the apparent crystallite size decreases in both the C_0 and A_0 directions. The contraction apparently results from a more efficient packing of the crystallites. Thermal cycling experiments in the laboratory have not accomplished any dimensional changes in CSF material, and it appears that contraction occurs only in the presence of reactor irradiation.

The collision of fast displaced carbon atoms with lattice atoms dissipates a large amount of energy over a small volume and may supply the activation energy for the diffusion of many atoms in localized volumes of the crystallite. Crystallites which are snagged at edges and corners during the development of their structure may be freed by this radiation induced diffusion. In this way the stresses frozen-in during fabrication can be relieved by irradiation at high temperature and result in an increase in density.

2. Criteria for Dimensional Stability in Graphite

A series of experiments most relevant to this problem were reported in Reference (3). Pertinent data are shown in Figure 6. For 400-500°C irradiation up to 1000 MWD/AT, it appeared that greater graphitization would yield a more dimensionally stable product if all other factors were kept constant. However, it was also clearly shown that greater graphitization in itself was not a sufficient condition for dimensional stability.

On volumetric grounds, it would be expected that more densely packed material would ultimately display less contraction than less dense material. Commercial graphites are now available with densities of 1.90 to 2.0 gm/cm³. This is to be compared with the graphites currently in use which have a density of 1.65 gm/cm³. Since the theoretical density of graphite is 2.26 gm/cm³, this implies a 50 percent reduction in the void volume.

The pore size distribution in the graphite probably is of importance since the measurements of pore size in irradiated graphites indicated a shift in the pore size distribution to smaller pore diameters with increasing exposure. Upon fracture, a grain could more easily collapse into a large pore and hence material with a smaller pore size distribution might prove stable.

Finally, if the migration of interstitials to the grain surface is an important factor in controlling contraction, the material with a larger grain size, which presents a smaller surface to volume ratio, may prove to be more stable.

In summary, there appear to be several factors, interrelated and interdependent, which should tend to reduce the amount of contraction in graphite. These are increased graphitization, increased density, smaller pore size, and larger particle size. Most of these criteria are fulfilled by the low permeability, high density graphites which have recently been developed by the National Carbon Company and by the Graphite Specialties Corporation. Thus these graphites offer the best immediate hope for improvement in the dimensional stability of pile grade graphite. Development work leading to improved graphites is being conducted by all major graphite manufacturers. The high temperature radiation behavior is now being determined on some of these materials in the Hanford reactors and others will be tested as they are developed. As irradiation facilities planned for the MTR and ETR come into use, they will be tested at 600 to 1100°C.

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D. Research and Development Programs

1. Pile Monitoring

Because of the immediate nature of the process tube curvature problem at B, D and F Reactors a number of production tests have been carried out to resolve this problem. As a result, considerable vertical height traverse data exists for these reactors. For the newer reactors, with the exception of H, data are not as plentiful. It is now planned to obtain vertical height traverses in the top three positions at all reactors on a routine quarterly basis. Accumulation of this type of data will allow a more rigorous correlation of data and a better extrapolation to future operating conditions.

As our additional means of isolating and examining stack contraction, it is planned to make frequent measurements of the vertical distance between process tube layers by traversing various through holes and test holes. This type of information can be useful in determining the gradation of contraction throughout the stack in contrast to vertical height measurements where the data represent an accumulative effect.

2. Laboratory Program

Where the pile monitoring program is aimed at determining the status quo of each reactor, the laboratory program is aimed at understanding and forecasting future conditions. Of prime interest in this regard are the following objectives:

- 1) Determine if and/or when the contraction effect saturates.
- 2) Refine and resolve data to firmly establish the temperature dependence of contraction.
- 3) By analyzing irradiation effects, develop a criterion which can be used to develop a new graphite which is stable. This might be accomplished by dictating the choice of raw materials or a fabrication process or both.
- 4) Establish a correlation between laboratory data and observed pile information.
 - a. Irradiation of full sized bars.
 - b. Determine effect of load on contraction (not creep, since in creep there is no volume change).
- 5) Determine if pile life (in classical sense) is measured in terms of years or total production.

To accomplish these objectives will require extensive use of the MTR and ETR for temperature experiments. To accomplish objective #3, will require very close cooperation with various graphite manufacturers. The overall program at Hanford will require more reactor

DECLASSIFIED

-15-

HW-58026 RD

downtime and greater use of the experimental facilities. Most of the above programs have been underway for some time. However, in view of the potential effect of stack distortion on Hanford production these programs will have to be intensified.

3. Engineering Program

If it is assumed that the above extrapolations of stack distortion are correct, the problem then becomes one of, "What can be done about it?" The first step in this approach is to find the point of stack deformation at which operational difficulties will arise and what will be the nature of these difficulties. Utilization of the nine tube mock-up in 189-D Building should provide an excellent tool for such studies. Concurrent with these studies, methods of correcting or living with the stack contraction should be developed.

IV. ACKNOWLEDGMENT

The laboratory data and discussion of theory was obtained from a report⁽⁴⁾ prepared by J. M. Davidson, E. M. Woodruff and H. H. Yoshikawa under the supervision of R. E. Nightingale of HLO to provide this information. The authors are indebted to members of Process Technology and Operational Physics Operation for providing reactor operational information on very short notice.

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MTR HIGH TEMPERATURE GRAPHITE IRRADIATIONS

EXPERIMENT NUMBER REACTOR MWD	EXPOSURE CL'CD Thermal+ 1 MEV Res (nu+x10 ⁻²⁰)	EXPOSURE FLUX MONITOR			PERCENT LENGTH CHANGE	STANDARD DEVIATION %	EXPOSURE MEAS ϕ 6.5x10 ⁻¹⁷ /MWD/AT	EXPOSURE DAMAGE EQUIVALENT k = 8x10 ⁻¹²
		THERMAL 0-.4	RESONANCE .4 to 1 MEV	FAST 1 MEV				
SAMPLE POSITION SERIAL	.15 est. .08	(NVT x 10 ⁻²⁰)			-.04 0 3500 -.01 M	.02 .01		400 MWD/AT
	1-1-6 or c Fast 0.13 -5 2360 MWD							
					-.06 0 -.03 M	.02 .01	(3125)	7300 MWD/AT
					-.06 0	.02	(2320)	8420 MWD/AT
	.6 9.6 $\phi_{1T} = 15.73$		.53		-.32 0	.02	2410 MWD/AT	5600 MWD/AT
					-1.11 0 -.87 M	.02 .01	(5600)	15,300 MWD/AT
	.0 16 $\phi_T = 26$		1.0		-.13 0	.02	4000 MWD/AT	11,300 MWD/AT
	.0 16 $\phi_T = 26$		1.0		-.49 0	.02	4000 MWD/AT	11,700 MWD/AT
					-.07 0 -.05 M	.02 .01		2200 MWD/AT
	.3 1.7 $\phi_T = 4.2$		.17		+.020 0	.02	650 MWD/AT	1630 MWD/AT

DISTORTION OF REACTOR GRADE GRAPHITE AT 50°C

FIGURE 1 EXPOSURE MWD/AT

EM-11/58

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HW-58000 RD
PAGE 17

TEMPERATURE DEPENDENCE OF PHYSICAL DISTORTION

-0.2 LINE FOR 46.1 MD CT eq. TAKEN FROM ISOTHERMAL PLOT, FIG. 3

-0.5 0 100 200 300 400

FIGURE 2

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FIGURE 3.

DISTORTION OF CSF GRAPHITE AT 400-500 °C

FIGURE 4

LENGTH CHANGES IN REACTOR GRAPHITES AT 400-500 °C

FIGURE 3

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EFFECT OF GRAPHITIZATION TEMPERATURE ON CONTRACTION OF
TEXAS COKE GRAPHITES IRRADIATED AT 400° - 500°C

EXPOSURE 1D/AT
FIGURE 6

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HM-58026 RD
Page 22

CRYSTALLITE CHANGES IN CSF
GRAPHITE IRRADIATED AT 400 - 500°C

CONTRACTION RATE OF TRANSVERSE CUT
IRRADIATED TUBE GRAPHITE VS TEMPERATURE

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FIGURE 8

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FIGURE 9

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VERTICAL TRAVERSE

Y-2 HOLE

K REACTORS

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ΔH IN INCHES

FEET FROM FRONT VAN STONE

FIGURE 10

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HM-53093 RD
Page 20

FIGURE 11

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FIGURE 12

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TUBE 4674-H PROFILE
105-H

41'7" REAR VS.

FIGURE 13

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FIGURE 14

DATE

FILMED

8/9/94

END