EXPERIMENTAL DETERMINATION

OF THE EFFECTS OF REACTOR RADIATION

ON THE THERMAL CONDUCTIVITY

OF URANIUM-IMPREGNATED GRAPHITE

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EXPERIMENTAL DETERMINATION
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CONDUCTIVITY OF URANIUM-
IMPREGNATED GRAPHITE

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Carbide and Carbon Chemicals Company (ORNL) 25-36
Carbide and Carbon Chemicals Company (Y-12 Plant) 37-42
Chicago Patent Group 43
Chief of Naval Research 44
Department of the Navy - Op 3 45
duPont Company 46-50
General Electric Company (ANPP) 51-53
General Electric Company, Richland 54-57
Hanford Operations Office 58
Idaho Operations Office 59-65
Iowa State College 66
Knolls Atomic Power Laboratory 67-70
Los Alamos Scientific Laboratory 71-72
Massachusetts Institute of Technology (Kaufman) 73
Mound Laboratory 74-76
National Advisory Committee for Aeronautics, Cleveland 77
National Advisory Committee for Aeronautics, Washington 78
New York Operations Office 79-80
Nuclear Development Associates, Inc. 81
Patent Branch, Washington 82
Rand Corporation 83
San Francisco Operations Office 84
Savannah River Operations Office, Augusta 85
Savannah River Operations Office, Wilmington 86
University of California Radiation Laboratory 87
Vitro Corporation of America 88
Walter Kidde Nuclear Laboratories, Inc. 89
Westinghouse Electric Corporation 90-93
Wright Air Development Center 94-102
Technical Information Service, Oak Ridge 103-117
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>7</td>
</tr>
<tr>
<td>I. Introduction</td>
<td>8</td>
</tr>
<tr>
<td>II. Description of the Experiment</td>
<td>8</td>
</tr>
<tr>
<td>A. Description of the Specimens</td>
<td>9</td>
</tr>
<tr>
<td>B. Measurements</td>
<td>10</td>
</tr>
<tr>
<td>III. Preparation and Testing of Apparatus</td>
<td>11</td>
</tr>
<tr>
<td>A. Capsule Assembly</td>
<td>11</td>
</tr>
<tr>
<td>B. Instrumentation</td>
<td>12</td>
</tr>
<tr>
<td>IV. Analysis</td>
<td>13</td>
</tr>
<tr>
<td>A. Calculation of Exposure</td>
<td>13</td>
</tr>
<tr>
<td>B. Sample 107-1</td>
<td>16</td>
</tr>
<tr>
<td>C. Sample 107-2</td>
<td>17</td>
</tr>
<tr>
<td>D. Absolute Conductivity at Zero Exposure</td>
<td>19</td>
</tr>
<tr>
<td>E. Comparison with Data from Outgassing Experiment</td>
<td>20</td>
</tr>
<tr>
<td>V. Application to the NAA Homogeneous Graphite Research Reactor (LPRR, Model S-5)</td>
<td>21</td>
</tr>
<tr>
<td>A. Initial Temperature Difference</td>
<td>21</td>
</tr>
<tr>
<td>B. Maximum Temperature in the Model S-5 Core</td>
<td>23</td>
</tr>
<tr>
<td>VI. Summary</td>
<td>24</td>
</tr>
<tr>
<td>Appendices</td>
<td></td>
</tr>
<tr>
<td>A. Instrumentation</td>
<td>68</td>
</tr>
<tr>
<td>B. Relative Effect of Fission Fragments and Neutrons</td>
<td>71</td>
</tr>
<tr>
<td>References</td>
<td>73</td>
</tr>
</tbody>
</table>
LIST OF TABLES

I. Isotopic Analysis of Uranium Used in Preparing Impregnated Samples ........................................ 26
II. Description of Specimens ............................................................................................................. 26
III. Calculated Exposures for Impregnated Graphite Samples ........................................................ 27
A-1. Resistance to Ground for Thermocouple Systems .................................................................. 70

LIST OF FIGURES

1. Radial Distribution of Uranium Impregnation Density ............................................................... 28
2. Location of Absolute and Differential Thermocouples in Samples ........................................... 29
3. Thermal Conductivity Test Capsule ............................................................................................. 30
4. Thermal Conductivity Test Apparatus ......................................................................................... 31
5. Sealing Barrier Assembly ........................................................................................................... 32
6. Capsule Assembly ...................................................................................................................... 33
7. Circuit Diagram for Temperature Measurements ....................................................................... 34
8. Central and Surface Temperature vs Exposure for Sample 107-1 ............................................. 35
9. Relative Thermal Resistivity K_o/K_1 vs Exposure for Sample 107-1 (Low Exposure) ........... 36
10. Relative Thermal Resistivity K_o/K_2 vs Exposure for Sample 107-1 (Low Exposure) ........... 37
11. Relative Thermal Resistivity K_o/K_3 vs Exposure for Sample 107-1 (Low Exposure) .......... 38
12. Relative Thermal Resistivity K_o/K_4 vs Exposure for Sample 107-1 (Low Exposure) ........... 39
13. Relative Thermal Resistivity K_o/K_5 vs Exposure for Sample 107-1 (Low Exposure) .......... 40
14. Relative Thermal Resistivity K_o/K_1 vs Exposure for Sample 107-1 ......................................... 41
15. Relative Thermal Resistivity K_o/K_2 vs Exposure for Sample 107-1 ......................................... 42
LIST OF FIGURES (Continued)

16. Relative Thermal Resistivity $K_0/K_3$ vs Exposure for Sample 107-1 ................. 43
17. Relative Thermal Resistivity $K_0/K_4$ vs Exposure for Sample 107-1 .................. 44
18. Relative Thermal Resistivity $K_0/K_5$ vs Exposure for Sample 107-1 .................. 45
19. Relative Thermal Resistivity and Temperature vs Radius at Various Exposures for Sample 107-1. .................. 46
20. Central and Surface Temperature vs Exposure for Sample 107-2 .................. 47
21. Ratio of Differential Temperature $\Delta T_1$ to Relative Flux vs Exposure for Sample 107-2 (Low Exposure) .................. 48
22. Ratio of Differential Temperature $\Delta T_2$ to Relative Flux vs Exposure for Sample 107-2 (Low Exposure) .................. 49
23. Ratio of Differential Temperature $\Delta T_3$ to Relative Flux vs Exposure for Sample 107-2 (Low Exposure) .................. 50
24. Ratio of Differential Temperature $\Delta T_4$ to Relative Flux vs Exposure for Sample 107-2 (Low Exposure) .................. 51
25. Ratio of Differential Temperature $\Delta T_5$ to Relative Flux vs Exposure for Sample 107-2 (Low Exposure) .................. 52
26. Relative Thermal Resistivity $K_0/K_1$ vs Exposure for Sample 107-2 (Low Exposure) .................. 53
27. Relative Thermal Resistivity $K_0/K_2$ vs Exposure for Sample 107-2 (Low Exposure) .................. 54
28. Relative Thermal Resistivity $K_0/K_3$ vs Exposure for Sample 107-2 (Low Exposure) .................. 55
29. Relative Thermal Resistivity $K_0/K_4$ vs Exposure for Sample 107-2 (Low Exposure) .................. 56
30. Relative Thermal Resistivity $K_0/K_5$ vs Exposure for Sample 107-2 (Low Exposure) .................. 57
31. Relative Thermal Resistivity $K_0/K_1$ vs Exposure for Sample 107-2 .................. 58
LIST OF FIGURES (Continued)

Page No.

32. Relative Thermal Resistivity $K_o/K_2$ vs Exposure for Sample 107-2 .................................. 59
33. Relative Thermal Resistivity $K_o/K_3$ vs Exposure for Sample 107-2 .................................. 60
34. Relative Thermal Resistivity $K_o/K_4$ vs Exposure for Sample 107-2 .................................. 61
35. Relative Thermal Resistivity $K_o/K_5$ vs Exposure for Sample 107-2 .................................. 62
36. Relative Thermal Resistivity and Temperature vs Radius at Various Exposures for Sample 107-2. .................................. 63
37. Relative Thermal Resistivity $K_o/K_1$ and Central Temperature vs Exposure for Sample 107-2 .................................. 64
38. Undamaged Thermal Conductivity $K_o$ vs Radius for Sample 107-2 .................................. 65
39. NAA Model S-5 Homogeneous Graphite Research Reactor .................................. 66
40. Maximum Core Temperature in LPRR vs Operating Time. .................................. 67
ABSTRACT

Experiments designed to measure the change in thermal conductivity of uranium-impregnated graphite under neutron irradiation are described. Thermal resistivities relative to the thermal resistivity of undamaged impregnated graphite are reported as functions of exposure. The relative thermal resistivity after 6.17 kwh/cm$^3$ ranged from 15 to 23, depending upon location, in the sample having an initial surface temperature of 85° C; and from 19 to 30 in the sample having an initial surface temperature of 25° C. Because of an unforeseen change in external conditions, the surface temperature of the first sample dropped from 85° C to 25° C after one-third of the exposure and remained at 25° C for the duration of the exposure, resulting in a slight increase in the damage rate.

The central temperature at the end of each exposure was about 340° C. In general, each sample exhibited less radiation damage in the interior regions, which were farthest removed from the coolant.

The initial thermal conductivity is calculated to be 0.10 ± 0.03 cal/sec-cm-°C for the impregnated sample at 25° C. Independent measurements of thermal conductivity of unimpregnated graphite from the same stock range from 0.26 to 0.29 cal/sec-cm-°C. No explanation for the discrepancy is available, since there is no indication that the process of impregnation should have such a marked effect on the thermal conductivity.

Applications of the experimental results to the North American Aviation homogeneous graphite research reactor indicate that the peak temperature in the core will not exceed 349° C, with the reactor power at 200 kilowatts at the end of 5 x 10$^6$ kilowatt hours operation. The corresponding volume-average temperature for the entire core is 235° C. If the core graphite has an initial thermal conductivity greater than 0.10 cal/sec-cm-°C, these temperatures would be correspondingly lower.

This report is based upon studies conducted for the Atomic Energy Commission under Contract AT-11-1-GEN-8.
I. INTRODUCTION

The homogeneous graphite research reactor (LPRR) designed by North American Aviation, Inc. has a core consisting of graphite fuel elements impregnated with uranium oxide. The moderator is not protected from direct bombardment by fission fragments as in a heterogeneous pile having aluminum-clad fuel slugs, so that the rate at which radiation damage occurs will be greater than would be expected in a heterogeneous reactor operating at the same power.

Perhaps the most striking effect of radiation damage in graphite is the marked decrease of thermal conductivity. Since heat is generated in the moderator even in a heterogeneous pile, the peak moderator temperature increases with continued operation of the reactor. The increased temperature does alleviate the condition somewhat because of increased annealing rates, but the effect could conceivably increase the mean neutron temperature to the point where sufficient excess reactivity for start-up would not be available. Further a large increase in temperature could reduce the intrinsic safety provided by the negative temperature coefficient of reactivity.

The LPRR core is expected to operate initially at a temperature of about 85° C. Previous work done on measuring the effect of radiation damage to uranium-impregnated graphite has been in the temperature range of 600° C to 800° C. Such information may serve as a guide for calculating irradiation damage, but due to the highly uncertain temperature dependence of annealing rates, the calculations may be greatly in error. Consequently, it is important to obtain thermal conductivity data which may be correlated with burn-up for use in the LPRR design at the lower operating temperature.

II. DESCRIPTION OF THE EXPERIMENT

Two similar graphite specimens (described below) impregnated with U\textsuperscript{235} enriched uranium were sealed in aluminum capsules and irradiated in a Hanford pile process tube. By means of a series of thermocouples located within the specimen, the temperatures were measured at several points.
Thermal conductivities were determined from the ratio of initial temperature differences to subsequent differences and correlated to both the flux and the burn-up. The exposure period required to duplicate the LPRR burn-up is 6.17 kwh/cm³ (see Part IV). The two specimens, NAAM-1050-107-1 and NAAM-1050-107-2, received thermal neutron exposures of $2.95 \times 10^{19}$ neutrons/cm² and $2.86 \times 10^{19}$ neutrons/cm², respectively (at the final readings). These correspond to exposures of 6.28 kwh/cm² and 6.23 kwh/cm², respectively (see Part IV).

The samples were irradiated in channel 0174 of the Hanford D pile. Sample 107-1 was exposed from July 6 to August 9, 1952, and sample 107-2 from August 11 to September 17, 1952.

A. Description of the Specimens

The specimens were machined from type AUF graphite (a fine grain graphite produced by the National Carbon Company), each with its axis parallel to the direction of extrusion. To obtain specimens of uniform density, they were both machined out of stock cut from the center of one graphite billet.

The two graphite cylinders, machined to the proper diameter but longer than the final length, were impregnated with uranium by a process developed at North American Aviation, Inc. for the LPRR core. This process uniformly distributes uranium oxide ($\text{UO}_2$) particles approximately 1 micron in diameter throughout the pores of the graphite. The extra long specimens were machined in a lathe to the desired length by removing a section near the center with a parting tool. Graphite powder from the successive annular rings removed was analyzed for uranium to determine the concentration and uniformity of the impregnation. A plot of uranium concentration vs radius is given in Fig. 1.

The two pieces of the specimen which resulted from the sectioning for analysis were then drilled to receive 11 thermocouples in a pattern shown in Fig. 2. Ten of the thermocouples operated in pairs to measure temperature differentials. The eleventh was located at the surface of the specimen to monitor the surface temperature. The thermocouples were led through 0.050 inch diameter holes in one piece, and terminated in holes 0.040 inch in diameter by 0.25 inch deep in the second piece. Assembly consisted of
drawing the thermocouples through the first piece and cementing them into
the second piece with a mixture of magnesium oxide and water glass which
yielded a $\mathrm{MgSiO}_3$, porcelain-like mixture on subsequent heating. The two
pieces were then slipped together and pressed into the aluminum shell. A
sketch of the apparatus is shown in Fig. 3, and photographs are shown in
Figs. 4, 5 and 6.

The uranium used for the impregnation was isotopically analyzed at
Argonne National Laboratory, and the results are presented in Table I. A
detailed description of the two specimens is presented in Table II.

B. Measurements

The thermal flux in the center of an essentially empty process tube is about $1 \times 10^{13}$ neutrons/cm$^2$-sec. As shown in Part IV, the temperature
difference between the center and the surface of each sample is about 12° C
for undamaged graphite at this flux. It was expected that this temperature
difference might increase as much as 50 times during the course of 1 month's
exposure.

It was intended to heat the water in the process channel and to control
its temperature at 85° C by means of the outermost thermocouple (T6 in
Fig. 2). It was found, however, that after about 10 days exposure of the
sample 107-1 [approximately $1 \times 10^{19}$ neutrons/cm$^2$], the heating of the
water was interfering with the flow of water through the process channel.
It became necessary, therefore, to discontinue use of the water heater.

Since it was anticipated that at the beginning of the exposures the tem­
peratures would vary parabolically along the radius, the thermocouple pairs
were so located that initially each differential temperature measured would
be about 2° C. It was important that these temperatures be measured as
accurately as possible, since all subsequent measurements must be related
to the initial measurements extrapolated to zero exposure.

The relative thermal resistivity was determined for each thermo­
couple pair from the relation

$$\frac{K_o}{K} = \frac{\Delta T/\phi}{(\Delta T/\phi)_o}$$

\[1\]
where the ratio \((\Delta T/\phi)_0\) is the ratio of differential temperature to flux extrapolated to zero exposure. The fluxes were obtained from the rise of water temperature in the adjacent uranium-bearing process tubes. In addition to serving as part of a differential thermocouple, the innermost junction of each of the five pairs was referenced to 0° C in an ice bath and was used to determine its absolute temperature. These temperatures were automatically recorded by two Brown print-type potentiometers. Accurate measurements were made with a manually operated Rubicon potentiometer. The analysis of the temperature data was based on the values measured with the Rubicon potentiometer. The recorders provided trend information to support the accurate temperature measurements.

III. PREPARATION AND TESTING OF APPARATUS

Precautions were taken to prevent all foreseeable hazards which might arise during the in-pile experiment. To insure successful in-pile measurements, a procedure for preparing accurate thermocouples was developed; thermal conductivities of unimpregnated graphite samples were measured using small temperature differences, spurious thermal voltages were eliminated, the instruments were thoroughly calibrated, and the complete capsule assembly was tested in a mock-up of the Hanford process tube.

A. Capsule Assembly

Wherever possible, the capsule parts were Heliarc welded. In locations where it was impossible to obtain a good Heliarc weld, an aluminum-silicon braze was used and applied on inner surfaces so that a minimum of the braze material would be exposed to water. The braze flux was removed by boiling water.

Two types of leak detectors were used in assembling the capsule: a General Electric Helium Leak Detector capable of detecting \(2 \times 10^{-7}\) micron-liters/sec, and the Distillation Products, Inc. Freon Leak Detector capable of detecting \(10^{-6}\) micron-liters/sec. In every case, a weld or seal was considered satisfactory only if the helium leak detector indicated a "zero"
leak. All Heliarc welds were peened before testing to open any potential leaks.

B. Instrumentation

The thermocouple wiring diagram is shown in Fig. 7. A detailed description of the instruments and operation is given in Appendix A. The information given below concerns the reliability of measurements obtained using these instruments.

Since the reliability of the experimental results ultimately depends on the thermocouples, considerable effort was expended on thermocouple preparation. Of several methods tested, the following was found to be the best:

a. The iron and constantan wires of duplex stock, glass covered, asbestos wrapped, No. 30 B & S were bared and arced together (75 volts dc, 500 μf) in a helium atmosphere.

b. The wires were trimmed closed to the junction. The junction was fused into a sphere about 0.030 inch in diameter by arcing between the wires and a pool of mercury which was covered with mineral oil (90 volts dc, 500 μf condenser in parallel).

c. The junction was then carefully cleaned, and shipped to the Sprague Electric Company at North Adams, Massachusetts for coating with "Ceroc 200" insulation.

The thermocouples were prepared in pairs, and each junction was formed from material which was originally adjacent to the other junction in the stock wire. Calibration of such paired thermocouples showed variations from one another of about 5 microvolts (0.1°C) up to 250°C.

The Cannon plug was assembled and tested for spurious thermoelectric effects. It was found that, for temperature differences of the order of 100°C, fictitious temperatures of about 2°C were evident. This error was reduced to about 0.1°C for the same temperature difference by eliminating soldered and spot-welded connections. Mechanical contact was made between the wires and the drilled-out prongs of the Cannon plug by press-fitting a small brass pin which forced the wire firmly against the prong.
Bench tests were made in order to develop the technique for determining thermal conductivities of graphite with small temperature differences. A specimen of unimpregnated AUF graphite which was dimensionally similar to the in-pile specimen was prepared. It was heated electrically at the cylindrical surface and cooled at the center by a water-cooled copper tube 0.312 inch in diameter which was press-fitted into the graphite. Thermocouples were imbedded in the specimen at several positions in the mid-plane of the specimen. With temperature differences of the order of 2° C between the thermocouples, computed values for the thermal conductivity of the graphite ranged from $K = 0.26$ to $K = 0.29$, using two specimens at several different power levels.

The temperature difference between the cooling water and the graphite surface at the cooling tube was measured to determine the heat transfer coefficient of such a system. The coefficient was calculated to be 1.4 watt/°C/cm$^2$.

The Hanford process tube mock-up utilized in testing the assembled capsules is described in Ref. 8.

### IV. ANALYSIS

The method of analysis of the data may be summarized as follows:

1. The ratio of differential temperature to flux is calculated for each reading.
2. This ratio is extrapolated to zero exposure to obtain its value for undamaged graphite.
3. The result of the extrapolation is used to normalize the observed values of differential temperature per unit flux, yielding relative thermal resistivity $K_o/K$ vs exposure.

#### A. Calculation of Exposure

The flux of thermal neutrons is calculated from*

$$N = 0.09 \Delta T \quad \ldots \quad (2)$$

* Supplied by the Pile Technology Group ($N = 0.08928 \Delta T$).
where $N$ is $10^{-16}$ times the integrated exposure (nvt) per hour and $\Delta T$ is the average water temperature rise in the two adjacent process channels on the same level (0173 and 0175). This represents the flux at the center of an empty process channel and contains an uncertainty of 20 per cent. (Note that this uncertainty does not appear in the values for $K_o/K$.)

In sample 107-1, the volume average density of impregnation is 0.0242 gram $U^{235}$ per cm$^3$. The effective cross section for fission is 487 barns.* The variation of flux across the radius of the sample is negligible, but the flux depression around the sample is estimated as 7 per cent. The number of fissions per cm$^3$ is then equal to 0.0282nvt, and the number of fission fragments is 0.0564nvt.

To evaluate the fast neutron exposure the sample is treated as though it were essentially a portion of the moderator. There are 10,900 carbon atoms per $U^{235}$ atom in the Hanford lattice and $8 \times 10^{22}$ carbon atoms per cm$^3$. Assuming 2.5 neutrons per fission, it is found that an average of $8.93nvt \times 10^{-3}$ neutrons per cm$^3$ slowing down from fission energies to thermal in the vicinity of the sample.

In Appendix B the result is derived from data on radiation expansion that eight neutrons slowing down from fission energies to thermal produce damage in graphite equivalent to the effect of one fission fragment, in impregnated graphite where the uranium oxide particles have diameters in the neighborhood of 1 micron. The effect of the fast neutron exposure in the experimental samples is therefore equivalent to an additional 0.0011nvt fission fragments per cm$^3$, yielding a total exposure equivalent to the effect of 0.0575nvt fission fragments per cm$^3$. Most of the neutrons born within the sample itself escape into the surrounding moderator and constitute a negligible contribution to the fast flux in the vicinity.

The operating life of the LPRR core is arbitrarily taken as the number of fissions corresponding to $5 \times 10^6$ kilowatt hours (25,000 hours at 200 kilowatts maximum power). Since the core contains $7.8 \times 10^5$ cm$^3$ of graphite, this is $6.40$ kwh/cm$^3$ which corresponds to $7.19 \times 10^{17}$ fissions per cm$^3$.

* Supplied by the Pile Technology Group for use in calculating the flux.
The total exposure is therefore $1.438 \times 10^{18}$ fission fragments per cm$^3$ and $1.800 \times 10^{18}$ fast neutrons per cm$^3$. Using the same equivalence between fission fragments and neutrons, the total effective exposure is $1.663 \times 10^{18}$ fission fragments per cm$^3$.

Now, in sample 107-1, the effective exposure is $0.0575nvt$ fission fragments per cm$^3$. Assuming the same number of carbon atoms per cm$^3$, the exposure required to duplicate the LPRR exposure is $nvt = 2.89 \times 10^{19}$ cm$^{-2}$, requiring about 33 days at a flux of $1 \times 10^{13}$ neutrons/cm$^2$-sec.

The heat developed in the sample may be calculated from the number of fissions. If the number of fissions per cm$^3$ is $0.0282nvt$, the kinetic energy of the fission fragments* is $7.50nvt \times 10^{-13}$ joules/cm$^3$. The heat produced by neutrons and gamma rays originating within the sample is negligible since most of these escape and dissipate their energy elsewhere.

If the heat developed by neutrons and gamma rays originating in neighboring fuel rods is also neglected, the only additional contribution arises from beta-decay of fission fragments. This is an additional 11 Mev per fission, of which 7 Mev escapes in the form of neutrinos. The total sensible heat is therefore 170 Mev per fission. Correcting the previous result by the ratio $170/166$, and noting that 1 kilowatt hour is $3.6 \times 10^{-6}$ joules, it is found that the heat developed in sample 107-1 is $2.13nvt \times 10^{-19}$ kwh/cm$^3$.

For sample 107-2, the results differ only in that the volume average impregnation density is $0.0247$ gram U$^{235}$ per cm$^3$. The number of fissions per cm$^3$ is $0.0288nvt$, the sensible heat, $2.18nvt \times 10^{-19}$ kwh/cm$^3$, and the exposure required to duplicate the LPRR burn-up is $nvt = 2.83 \times 10^{19}$ cm$^{-2}$. These results are summarized in Table III.

It is necessary to justify the step of neglecting the heat produced by neutrons and gamma rays originating in neighboring fuel rods. It was observed during the course of the experiment that a flux of $1 \times 10^{13}$ neutrons/cm$^2$-sec in the region near the samples corresponds to a power level of about 450 megawatts in the reactor. In sample 107-1 the corresponding fission power density is 7.66 watts/cm$^3$.

* Assuming an average of 83 Mev per fragment.
But the Hanford reactor core contains \(5.5 \times 10^8\) cm\(^3\) of graphite. Six per cent of the total reactor power is generated by neutrons and gamma rays in the moderator,\(^6\) and the power density in the graphite is therefore \(0.05\) watts/cm\(^3\). Since this is less than 1 per cent of the fission power in the sample, no attempt has been made to evaluate it more carefully and include it in the analysis.

B. Sample 107-1

The temperature history of sample 107-1 is shown in Fig. 8. The temperatures \(T_1\) and \(T_6\) (innermost and outermost thermocouples) are plotted against exposure expressed both as nvt and as kwh/cm\(^3\). Note that the failure of the water heating system provided for maintaining the graphite surface at \(85^\circ\) C is reflected in a downward displacement of the two curves at nvt \(\approx 1 \times 10^{19}\).

Differential temperatures were measured every hour during the early stages of the exposure. Unfortunately, the Rubicon potentiometer was inoperative for 3 hours, and a reliable extrapolation to zero exposure could not be made. Data from sample 107-2 were corrected for temperature as described below and used in normalizing the ratio of differential temperature to flux, yielding the relative thermal resistivities for sample 107-1.

Relative thermal resistivities vs exposure for the early stages of the experiment \((0 \leq \text{nvt} \leq 0.14 \times 10^{19})\) are plotted for each of the five differential measurements in Figs. 9 through 13. The subscript on each \(K_o/K\) refers to the number of the corresponding measurement of \(\Delta T\) as indicated in Fig. 2. Note that the thermal resistivities represent measurements "at temperature;" no attempt has been made to correct them to a reference temperature.

It is not known why there is a variation of initial slope among these curves. One might expect that the initial rate of radiation damage should be independent of temperature, whereas the observation here is that the initial slope is greater in the interior of the sample.

Relative thermal resistivities vs exposure for the full duration of the experiment are shown in Figs. 14 through 18. (Figs. 9 through 13 show, on a magnified scale, the details of the early stages as indicated.) Full burn-up for the LPRR is duplicated at nvt = \(2.89 \times 10^{19}\) cm\(^{-2}\) (6.17 kwh/cm\(^3\)).
as indicated in the figures.

With the exception of $K_o/K_5$ (Fig. 18) the expected trend is borne out; namely, that the interior of the sample where the temperature is highest should receive less damage. Final values for $K_o/K$ are approximately 15, 20, 21, 23 and 22 as one progresses outward from the center of the sample.

This is shown in Fig. 19 where the relative thermal resistivities are plotted together with temperature vs radius for four different exposures. Values of $K_o/K$ are plotted as histograms since each is actually an average resistivity determined throughout a region between the two points which correspond to the two junctions of a differential thermocouple.

Note that Figs. 19c and 19d are derived from data taken after the failure of the water heating system, so that the correlation between temperature and radiation damage is difficult to analyze. The effect of the heater failure is reflected in Figs. 14 through 18 by the presence of an increase in damage rates after $nt = 1 \times 10^{19}$. The final values for $K_o/K$ are probably slightly higher than they would have been had the heater not failed.

C. Sample 107-2

The temperature history of sample 107-2 is shown in Fig. 20. Note that four major shutdowns occurred during this exposure. The exposure of $6.17 \text{kwh/cm}^3$ was reached at $nt = 2.83 \times 10^{19} \text{cm}^{-2}$. Since no provision was made for heating the water, the inlet water temperature remained at approximately $20^\circ \text{C}$ throughout the exposure.

Since the normalization for the radiation damage curves for both samples was based on data from sample 107-2, the details of the extrapolation to zero exposure are presented in Figs. 21 through 25. The ordinate in these figures is $\Delta T/N$ where $\Delta T$ is the measured temperature differential in each case and $N$ is the flux expressed as $nt$ per hour times $10^{-16}$. The abscissa is the exposure for approximately the first 3 hours. Readings were taken every 10 minutes in view of the rapid changes in thermal conductivity observed in sample 107-1 during the first few hours.

Except for the first two points in each case, which were taken during the initial rapid power rise, the values of $\Delta T/N$ fall very closely on straight lines. These straight lines were extrapolated to zero exposure, yielding
the initial value for $\Delta T/N$ for each of the five sets of points. Dividing all
values of $\Delta T/N$ in each of the five sets by the appropriate initial value yields
the relative thermal resistivities $K_0/K$.

These initial values were applied directly to the data for sample 107-2,
yielding the values of $K_0/K$ plotted in Figs. 26 through 30 for the early stages
of the exposure ($0 < nvt < 0.14 \times 10^{19}$) and in Figs. 31 through 35 for the
full duration of the experiment. Four cross plots showing relative thermal
resistivity and temperature vs radius are presented in Fig. 36.

These initial values for $\Delta T/N$ from sample 107-2 were corrected for
initial temperature and applied to the data for sample 107-1. The initial
temperatures were $25^\circ$ C in sample 107-2 and $85^\circ$ C in sample 107-1. Since
these initial values of $\Delta T/N$ are proportional to the undamaged thermal re-

7 sistivity in sample 107-2, each must be increased by 6 per cent. Figs. 9
through 19 were obtained in this way.

The cross plots of Fig. 36 show the anomalous behavior of the values
of $K_0/K$ taken from the outermost differential thermocouple $\Delta T_5$. Although
this is the region of lowest temperature, $K_0/K_5$ is less than $K_0/K_4$ in three
of the four plots. The fact that this behavior appeared in Fig. 19 for sam-
ple 107-1 is naturally an artificial correlation, since the initial values of
$\Delta T/N$ for sample 107-2 were used in computing $K_0/K$ for both samples.
Note that the differential $\Delta T_5$ is probably the least reliable of the measure-
ments since the distance between junctions is least for this differential
thermocouple.

The sensitivity of radiation damage to temperature is markedly notice-
able. Fig. 37 is a composite showing the central temperature vs exposure
from Fig. 20 and the relative thermal resistivity $K_0/K_1$ vs exposure from
Fig. 31, but with straight lines drawn between the points. The temperature
does not drop all the way down during the four shutdowns because readings
were taken only three times a day after the first 36 hours' exposure.

After each shutdown, the power rose rapidly at first, then gradually,
requiring a day or so to reach full power. During this time radiation damage
was taking place at temperatures lower than those experienced by the sample
prior to the shutdown. The corresponding peaks in the damage curves may be
attributed to lower annealing rates during the time the power remained low.

This correlation appears to a less marked degree in Fig. 26, where the flux in the sample is plotted on the same scale as the relative thermal resistivity. A peak in flux corresponds to an inhibition of radiation damage because of the higher sample temperature and consequent increased annealing rates.

The temperature coefficient of thermal resistivity in graphite is normally positive, but it does undergo a reversal under continued radiation damage. A portion of the effect shown in Figs. 26 and 37 might be attributed to this phenomenon, but it is not sufficient to account for all of the increase in $K_0/K$.

The fact that radiation damage is not a point function of temperature and time is borne out by noting the effect of the heater failure. Sample 107-1 started at $85^\circ C$ surface temperature, but the final two-thirds of the exposure was carried out under the same conditions as those found in sample 107-2 for its entire exposure. Values of $K_0/K$ in sample 107-1 at the end of its exposure ranged from 15 to 23, while those in sample 107-2 ranged from 19 to 30, demonstrating that radiation damage is indeed a function of past history as well as of the conditions at the time of the measurement.

D. Absolute Conductivity at Zero Exposure

In an infinite cylinder containing a uniform distribution of steady heat sources and having a fixed surface temperature, the temperature difference between two points, $r = a$ and $r = b$, is

$$T = \frac{P}{K} \left( \frac{b^2 - a^2}{4K} \right)$$

where $P$ is the source density in cal/sec-cm$^3$ and $K$ is the thermal conductivity in cal/cm-sec-$^\circ C$. For a finite cylinder having the dimensions of the present samples and the same fixed temperature over all surfaces, the factor 4 in the denominator of Eq. (3) must be replaced by 4.6. The equation then expresses temperature difference between two points in a plane perpendicular to the axis midway between the ends of the cylinder.

In the experimental samples, the factor lies somewhere between 4 and 4.6, since the end planes are not near the coolant as are the cylindrical...
surfaces. This factor has been arbitrarily taken as 4.3.

The power density in sample 107-2 may be expressed as follows: the heat developed in an exposure \( nvt \) is \( 2.18nvt \times 10^{-19} \text{ kwh/cm}^3 \). Since the quantity \( N \) in Eq. (2) is \( 10^{-16} \) times the exposure \( nvt \) per hour, the power density is \( 2.18N \text{ watts/cm}^3 \) or \( 0.520N \text{ cal/sec-cm}^3 \).

Recalling that there is an uncertainty of ±20 per cent in calculating the value of \( N \) from the adjacent tube temperatures, values for thermal conductivity may be obtained from the formula*

\[
K = 0.121 \frac{(b^2 - a^2)}{(\Delta T/N)} \tag{4}
\]

In particular, if values of \( \Delta T/N \) extrapolated to zero exposure in Figs. 21 through 25 are chosen, initial conductivities \( K_0 \) are obtained for sample 107-2. These are plotted in Fig. 38, and the volume average thermal conductivity with its estimated uncertainty is \( 0.10 \pm 0.03 \text{ cal/sec-cm}^3 \).

This value of the conductivity is surprisingly low in view of the fact that the thermal conductivity of unimpregnated graphite from the same stock had been found to be in the range 0.26 to 0.29, as mentioned above. It is difficult to explain this variation, since there is no reason to suspect that the process of distributing small uranium oxide particles among the interstices in polycrystalline graphite should give rise to such a marked change in thermal conductivity.

E. Comparison with Data from Outgassing Experiment

Test NAAM-1050-106-1 for determining the outgassing of impregnated graphite is described elsewhere. The sample used was a graphite cylinder of the same radius, but with an impregnation density of 0.00326 gram \(^{235}\text{U} \) per cm\(^3\). This capsule was irradiated in the central zone of a Hanford reactor, with a flux of \( 3.3 \times 10^{13} \text{ neutrons/cm}^2 \text{-sec} \) corresponding to a reactor power of 550 megawatts. At \( nvt = 6 \times 10^{19} \text{ cm}^{-2} \) the temperature difference from the center to the surface was 110° C.

* This was compared with the results obtained by considering in detail the radial variation of power density due to the flux depression in the sample and the non-uniform density of impregnation. The maximum deviation from the conductivities calculated by means of Eq. (4) was less than 2 per cent. In view of the other sources of error, this deviation is insignificant.
Now the impregnation density in sample 107-2 was 0.0247 gram U\(^{235}\) per cm\(^3\). (This sample is chosen for the comparison because the surface temperature histories are approximately the same.) The flux depression in the outgassing experiment is about 1 per cent, and that in sample 107-2 is about 7 per cent. This means that the same radiation damage would be expected in 107-2 at an exposure (nvt) 7.15 times smaller, or nvt = 0.84 \(x\) 10\(^{19}\) cm\(^{-2}\). At this exposure, data for 107-2 show the temperature difference to be about 220° C and the incident flux 1.1 \(x\) 10\(^{13}\) neutrons/cm\(^2\)-sec.

Using the fact that the samples have the same radius, the ratio of their thermal conductivities may be found with the aid of Eq. (3). We have

\[
\frac{K(107-2)}{K(106-1)} = \frac{0.0247 \times 1.1 \times 10^{13} \times 93\% \times 110}{0.00326 \times 3.3 \times 10^{13} \times 99\% \times 220} = 1.2
\]

It is to be expected that the conductivity in sample 107-2 should be somewhat larger. Although this ratio is calculated for the same exposure (same number of fissions per carbon atom), the temperature and therefore the annealing rates were higher in sample 107-2, giving rise to less radiation damage.

Note that because of the different impregnation densities and incident fluxes, the rate of radiation damage (fissions per carbon atom per second) is 2.4 times greater in sample 107-1. The comparison of the two samples tends to bear out the assumption that radiation damage depends on integrated exposure, but not on the rate at which that exposure is made.

Note also that the conductivities in this comparison were calculated as though each were independent of radius. That this is not in general a good assumption is borne out by Fig. 36, but its use in making this comparison is justifiable since we are interested in the relative radiation damage in the two experiments and not in the absolute thermal conductivities.

V. APPLICATION TO THE NAA HOMOGENEOUS GRAPHITE RESEARCH REACTOR (LPRR, MODEL S-5)

A. Initial Temperature Difference

The coolant tubes in the NAA homogeneous graphite reactor (see Fig. 39) are spaced 4.25 inches apart in a square lattice. Using an equivalent cir-
circular cylindrical cell to represent each impregnated graphite fuel element, the temperature at any point in the fuel element is given by

\[ T = T_o + \frac{P}{2K} \left[ R^2 \ln \frac{r}{r_o} - \frac{1}{2} (r^2 - r_o^2) \right] \]  \hspace{1cm} (5)

where the symbols have the following meaning:

- \( T_o \): temperature at graphite surface near coolant (°C)
- \( P \): power density in impregnated graphite (cal/sec-cm\(^3\))
- \( K \): thermal conductivity (cal/sec-cm-°C)
- \( R \): equivalent radius of circular cell (centimeters)
- \( r_o \): bore radius (centimeters)

In the reactor, the average power density at 200 kilowatts is 0.0611 cal/sec-cm\(^3\). Using a peak-to-average correction of 80 per cent, the maximum power density is 0.0763 cal/sec-cm\(^3\).

The equivalent cell radius is 6.08 centimeters. The thermal conductivity for undamaged graphite at 25° C as determined from experiment 107-2 was 0.10 cal/sec-cm-°C. Since the Model S-5 bore surface temperature \( T_o \) is to be 85° C, the corrected value of 0.094 must be used. The temperature difference between the outer surface of the fuel block \((r = R)\) and the bore surface \((r = r_o)\) is 13.2° C.

This is to be compared with the temperature difference between center and surface for each of the experimental samples. This temperature difference is

\[ T = \frac{PR^2}{4.3K} \]

Here the outer radius \( R \) is 1.67 centimeters in each case, and the power densities are 0.508N cal/sec-cm\(^3\) in sample 107-1 and 0.520N cal/sec-cm\(^3\) in sample 107-2. The symbol \( N \) is that used in Eq. (2), and at full Hanford power it varied in the neighborhood of \( N = 4 \).

For sample 107-1 the undamaged conductivity must be taken as 0.094 cal/sec-cm-°C (85° C), and 0.10 cal/sec-cm-°C (25° C) may be used for 107-2. The temperature differences are then 14.0° C and 13.4° C, respectively. Since the samples very closely reproduce the 13.2° C tempera-
ture difference in the fuel element, the temperature history of the Model S-5 will closely parallel those of the samples.

B. Maximum Temperatures in the Model S-5 Core

In calculating the maximum core temperature as a function of exposure, the volume average conductivity calculated from Figs. 14 through 18 and 31 through 35 together with the approximate values of $T_o$ were used in Eq. (5) with $r = R$. The conductivity data were smoothed out into continuous monotonic curves.

The two curves showing maximum core temperature vs exposure are plotted in Fig. 40. The curve calculated from 107-1 data represents a reactor having $T_o = 85^\circ$ C, but the data are applicable only for the first third of the $5 \times 10^6$ kilowatt hours exposure because of the failure of the water-heating system. The remainder of the curve is shown dotted; had the heater not failed, the maximum temperature would not have risen to the high values indicated by the dotted curve.

Using the final temperature of $349^\circ$ C, however, leads to an estimate of $273^\circ$ C for the volume-average temperature in the central fuel element at 200 kilowatts after $5 \times 10^6$ kilowatt hours operation, and the volume-average temperature for the entire core at the same time would be $235^\circ$ C.

If the core is constructed from graphite having an initial conductivity of $0.24 \text{ cal/sec-cm-}^\circ$C, as originally intended, the final temperatures would be much lower than those shown in Fig. 40. The maximum temperature calculated from experiment 107-1 would be $195^\circ$ C instead of $349^\circ$ C, and that for 107-2 would be $155^\circ$ C instead of $336^\circ$ C.

One further uncertainty must be discussed. In the experimental samples, the coolant is located at the surface of the cylinder, so that the relatively cooler region is spread out over a large volume. In the reactor fuel element, the coolant is in a tube along the axis of the cylinder, so that the cooler region is restricted to a relatively small volume. Therefore, even though the overall temperature difference may be approximately the same, the detailed distributions of radiation damage are different.
By taking volume averages of the radiation damage data, we have overestimated the contribution from the cooler and hence more heavily damaged regions. The curves presented in Fig. 40 therefore probably overestimate the temperatures, but it would be impossible to evaluate precisely how much of an overestimate this constitutes, even if there were no doubt as to the reliability of the outermost differential thermocouple $\Delta T^*_5$.

**VI. SUMMARY**

The relative thermal resistivities after 6.17 kwh/cm$^3$ exposure of the impregnated graphite samples 107-1 and 107-2 fall into the following ranges depending upon the location in the specimen: $K_0/K = 15$ to 23 for sample 107-1 and $K_0/K = 19$ to 30 for sample 107-2. In sample 107-1 the graphite surface near the coolant was maintained nominally at 85° C for the first third of the exposure; this temperature then fell to 25° C and remained there for the duration of the experiment. In sample 107-2 this temperature was 25° C throughout the entire exposure. The central temperature at the end of each exposure was about 340° C (see Figs. 8 and 20).

Because the surface temperature in sample 107-1 was not maintained at the desired 85° C, it is not possible to predict the complete curve of maximum temperature in the Model S-5 core vs exposure for the 85° C initial temperature. It is expected that radiation damage in sample 107-1 would not have been as great if the temperature had been maintained at 85° C, so that the 349° C predicted by the dotted curve in Fig. 40 is probably slightly high.

Using the value 349° C, however, leads to an estimate of 273° C for the volume-average temperature in the central fuel element when the reactor is operating at 200 kilowatts after $5 \times 10^6$ kilowatt hours operation. The volume-average temperature for the entire core at the same time would be 235° C. This does not present any difficulties in terms of either structural strength or excess reactivity required for start-up, and the change in the temperature coefficient of reactivity caused by this increased neutron temperature is not serious.

The uranium oxide particles in each sample were of the order of 1 micron in diameter. It is difficult to estimate what fraction of the fission
fragment kinetic energy was dissipated in the graphite itself, but most of the fission fragments probably escaped from the uranium oxide and terminated their trajectories in graphite.

From a fundamental point of view, it would be more desirable to obtain clean-cut isothermal irradiations so that the effect of temperature could be more easily analyzed. This would require very small samples, because the generation of heat that accompanies radiation damage also gives rise to greater annealing rates in the interior of the specimen. The purpose of the present investigation was primarily to reproduce as nearly as possible the conditions in the impregnated graphite core of the LPRR, Model S-5.

It is difficult to compare this experiment with Hunter's results\(^3\) because the irradiations reported by Hunter were carried out at 600\(^\circ\) C and 800\(^\circ\) C. The exposures obtained by Hunter were greater (up to 60 kwh/cm\(^3\) for graphite of slightly lower density). It is significant to note that in Hunter's data the damage rate drops off after 1 kwh/cm\(^3\), much as in the data reported here, but that the damage curves rise sharply after 10 kwh/cm\(^3\). This is beyond the range of exposures reached by the present experiments.

**Much further experimental information of a fundamental nature is needed.** In particular, careful investigations such as the following may be suggested:

1. Isothermal exposures for fixed \(^{235}\text{U}\) concentration and burn-up at various controlled temperatures to determine the temperature dependence of radiation damage over a wide range.

2. Investigation of the effect of varying particle size.

3. Exposures of various durations and uranium concentration to determine the effect (if any) of varying the time rate of dosage.
### TABLE I
**ISOTOPIC ANALYSIS OF URANIUM USED IN PREPARING IMPREGNATED SAMPLES**

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Per Cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{234}U$</td>
<td>$1.04 \pm 0.02%$</td>
</tr>
<tr>
<td>$^{235}U$</td>
<td>$93.58 \pm 0.06%$</td>
</tr>
<tr>
<td>$^{238}U$</td>
<td>$5.38 \pm 0.06%$</td>
</tr>
</tbody>
</table>

### TABLE II
**DESCRIPTION OF SPECIMENS**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>107-1</th>
<th>107-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (inches)</td>
<td>1.315</td>
<td>1.314</td>
</tr>
<tr>
<td>Length (inches)</td>
<td>4.262</td>
<td>4.250</td>
</tr>
<tr>
<td>Mass (gm)</td>
<td>153.00</td>
<td>152.20</td>
</tr>
<tr>
<td>Volume (cc)</td>
<td>94.87</td>
<td>94.46</td>
</tr>
<tr>
<td>Density (gm/cc)</td>
<td>1.612</td>
<td>1.611</td>
</tr>
<tr>
<td>Uranium content (gm)</td>
<td>2.278</td>
<td>2.285</td>
</tr>
<tr>
<td>$U^{235}$ (gm/cc)</td>
<td>0.0242</td>
<td>0.0247</td>
</tr>
</tbody>
</table>
## TABLE III

CALCULATED EXPOSURES FOR IMPREGNATED GRAPHITE SAMPLES

<table>
<thead>
<tr>
<th>Sample</th>
<th>107-1</th>
<th>107-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U^{235}$ content (gm/cm$^3$)</td>
<td>0.0242</td>
<td>0.0247</td>
</tr>
<tr>
<td>Actual fission fragments/cm$^3$</td>
<td>0.0564nvt</td>
<td>0.0576nvt</td>
</tr>
<tr>
<td>Fission fragment equivalent of neutrons/cm$^3$</td>
<td>0.0011nvt</td>
<td>0.0011nvt</td>
</tr>
<tr>
<td>Effective fission fragments/cm$^3$</td>
<td>0.0575nvt</td>
<td>0.0587nvt</td>
</tr>
<tr>
<td>nvt required to duplicate LPRR burn-up</td>
<td>$2.89 \times 10^{19}$ cm$^{-2}$</td>
<td>$2.83 \times 10^{19}$ cm$^{-2}$</td>
</tr>
<tr>
<td>Heat developed in nvt cm$^{-2}$ exposure</td>
<td>$2.13nvt \times 10^{-19}$ kwh/cm$^3$</td>
<td>$2.18nvt \times 10^{-19}$ kwh/cm$^3$</td>
</tr>
<tr>
<td>Heat developed in required exposure</td>
<td>6.17 kwh/cm$^3$</td>
<td>6.17 kwh/cm$^3$</td>
</tr>
</tbody>
</table>
Figure 1.
Radial Distribution of Uranium Impregnation Density
Figure 2.
Location of Absolute and Differential Thermocouples in Samples
Figure 3. Thermal Conductivity Test Capsule

Seal End of Capsule

Specimen End of Capsule
Figure 5.
Sealing Barrier Assembly
Figure 6.
Capsule Assembly
CIRCUIT DIAGRAM FOR TEMPERATURE MEASUREMENTS.

C = CONSTANTAN
Ct = COPPER
I = IRON

FIGURE 7

LOCATION IN SPECIMEN

UNCLASSIFIED
Figure 8.
Central and Surface Temperature Behavior for Sample 107-1
Figure 9.
Relative Thermal Resistivity $K_0/K_1$ vs Exposure for Sample 107-1 (Low Exposure)
Figure 10.
Relative Thermal Resistivity $K_0/K_2$ vs Exposure for Sample 107-1 (low Exposure)
Figure 11.
Relative Thermal Resistivity $K_0/K_3$ vs Exposure for Sample 107-1 (Low Exposure)
Figure 12.
Relative Thermal Resistivity $K_0/K_4$ vs Exposure for Sample 107-1 (Low Exposure)
Figure 13.
Relative Thermal Resistivity $K_0/K_5$ vs Exposure for Sample 107-1 (Low Exposure)
Figure 14.
Relative Thermal Resistivity $K_0/K_1$ vs. Exposure for Sample 107-1.
Figure 15
Relative Thermal Resistivity $K_0/K_2$ vs. $10^{19}$ fvt for Sample 107-1.
Figure 16.
Relative Thermal Resistivity $K_0/K_3$ vs Exposure for Sample 107-1.
Relative Thermal Resistivity $K_0/K_4$ vs Exposure for Sample 107-1.
Figure 18.
Relative Thermal Resistivity $K_0 / K_5$ vs Exposure for Sample 107-1

- LPRR BURNUP
$5 \times 10^6$ KWH

SEE FIG. 13
Figure 19.
Relative Thermal Resistivity and Temperature in the Sample at Various Exposures for Sample 107-1
Figure 20: Central and Surface Temperature vs Exposure for Sample 107-2
Figure 21.
Ratio of Differential Temperature $\Delta T_1$ to Relative Flux vs Exposure for Sample 107-2 (Low Exposure)
Figure 22.
Ratio of Differential Temperature $\Delta T_2$ to Relative Flux vs Exposure for Sample 107-2 (Low Exposure)
Figure 23.
Ratio of Differential Temperature $\Delta T_3$ to Relative Flux vs Exposure for Sample 107-2 (Low Exposure)
Figure 24.
Ratio of Differential Temperature $\Delta T_4$ to Relative Flux vs Exposure for Sample 107-2 (Low Exposure)
Figure 25.
Ratio of Differential Temperature $\Delta T_5$ to Relative Flux vs Exposure for Sample 107-2 (Low Exposure)
Figure 26.
Relative Thermal Resistivity $K_0/K_1$ vs Exposure for Sample 107-2 (Low Exposure)
Figure 27.
Relative Thermal Resistivity $K_0/K_2$ vs Exposure for Sample 107-2 (Low Exposure)
Figure 28.
Relative Thermal Resistivity $K_0/K_3$ vs Exposure for Sample 107-2 (Low Exposure)
Figure 29.
Relative Thermal Resistivity $K_0/K_4$ vs Exposure for Sample 107-2 (Low Exposure)
Figure 30.
Relative Thermal Resistivity $K_0/K_5$ vs Exposure for Sample 107-2 (Low Exposure)
Relative Thermal Resistivity $K_0/K_1$ versus Exposure for Sample 107-2.

Figure 31.
Figure 32.
Relative Thermal Resistivity $K_0/K_2$ vs
Exposure for Sample 107-2

SEE FIG. 27
Figure 33.
Relative Thermal Resistivity $K_p/K_3$ vs
Exposure for Sample 107-2
Figure 34.
Relative Thermal Resistivity $K_r/K_4$ vs. Exposure for Sample 107-2

Sample 107-2

$K_r/K_4$

See Fig. 29

LPRR
Burnup
$5 \times 10^6$ KWH

$KWH/\text{CM}^3$

$10^{-19}$ svt
Figure 35.
Relative Thermal Resistivity $K_o/K_s$ vs Exposure for Sample 107-2

SEE FIG. 30

LP RR
BURNUP
5 X 10^6 KWH
Figure 36.
Relative Thermal Resistivity and Temperature vs. Radius at Various Exposures for Sample 107-2
Figure 37. Relative Thermal Resistivity $K_\infty/K_1$ and Central Temperature vs Exposure for Sample 107-2
Figure 38.
Undamaged Thermal Conductivity $K_0$ vs Radius for Sample 107-2
Figure 39.
NAA Model S-5 Homogeneous Graphite Research Reactor
Figure 40.
Maximum Core Temperature In LPRR vs Operating Time
APPENDIX A

INSTRUMENTATION

The instrumentation required for this test was limited to that necessary for accurately determining and not-so-accurately recording temperatures throughout the graphite specimens. For these purposes, a Rubicon Type "B" manually operated potentiometer with a Rubicon galvanometer (1.6 μA/mm, CDRX 40 ohms) having a sensitivity of 0.1 microvolt was connected to the thermocouple network through a low-contact potential selector switch which permitted accurate determination of either absolute or differential temperatures. Two Minneapolis Honeywell, Brown 12-point recording potentiometers were used to obtain a continuous record of the absolute and differential temperatures. The potentiometer recording absolute temperatures had a range of 0 to 20 millivolts. The potentiometer recording differential temperatures had a range of 0 to 5 millivolts. Both were set for 3-minute, fixed cycle printing and, to prevent mutual interference, had to be operated at staggered cycles so that both did not function from a single thermocouple at one time. In addition, a laboratory type Rubicon potentiometer was included to provide means of recalibrating the recorders and for general utility.

These instruments were connected to the thermocouple network, as shown in Fig. 7. This network includes six independent thermocouple systems. Five of these systems are identical, each consisting of a pair of iron-constantan thermocouples (No. 30 gauge, asbestos wound and glass wrapped) connected in an opposing manner so as to indicate temperature differences within the specimen. The iron legs extended to the instruments; the constantan legs were connected, one to the other, at a pin in the Cannon plug. The resistance of this differential couple and connected cable was about 330 ohms. The absolute temperature was determined by a constantan conductor extending from the common pin on the plug to a junction with iron (thermostated in an ice bath) and continuing the iron to the absolute recorder, measuring between the iron direct from the junction and the iron via the constantan. The resistance of an absolute couple with its cable was 370 ohms.

The remaining thermocouple system consisted of a single thermocouple (located on the surface of the specimen) extending to a terminal strip.
at the instruments. The resistance of this couple with its cable is 370 ohms.

The resistances to ground for the systems are tabulated for the two test specimens in Table A-1. The shorts to ground do not seriously interfere with the function of the measurement system. Subsequently developed shorts would not interfere unless the short resistance were of the order of 300 ohms or less.

A three junction iron-constantan thermopile was located in the valve pit to monitor the incoming pile cooling water. Three copper-constantan thermocouples, attached to the exit nozzles of the three adjacent uranium-bearing tubes, were also connected to the recorder. These thermocouples indicated the temperature rise and hence the flux in the adjacent tubes.
### TABLE A-1

**RESISTANCE TO GROUND FOR THERMOCOUPLE SYSTEMS**

<table>
<thead>
<tr>
<th>System</th>
<th>Sample 107-1</th>
<th>Sample 107-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>$&gt;40 \times 10^6$ ohms</td>
<td>40,000 ohms</td>
</tr>
<tr>
<td>3-4</td>
<td>$&gt;40 \times 10^6$</td>
<td>$&gt;50,000$</td>
</tr>
<tr>
<td>5-6</td>
<td>$&gt;40 \times 10^6$</td>
<td>$&gt;50,000$</td>
</tr>
<tr>
<td>7-8</td>
<td>$&gt;40 \times 10^6$</td>
<td>2,000</td>
</tr>
<tr>
<td>9-10</td>
<td>$&gt;40 \times 10^6$</td>
<td>280</td>
</tr>
<tr>
<td>11</td>
<td>16</td>
<td>70</td>
</tr>
</tbody>
</table>
APPENDIX B

RELATIVE EFFECT OF FISSION FRAGMENTS AND NEUTRONS

The physical expansion resulting from the irradiation of impregnated graphite may be compared with that for unimpregnated graphite to determine relative damage rates for fission fragments and neutrons. This property represents the most reliable reference since it is known to be a linear function of exposure to extremely high values of total exposure.

Data on the rate of expansion of transverse-cut AGOT-KC graphite are given by Curtiss. In the D test-hole at Hanford at about 80°C there is a definite expansion rate of 0.5 per cent per 800 mwd/ct. From accompanying data, it may be seen that if the exposure had been made in a capsule instead of the D test-hole, the damage rate would have been 1.85 times as great. Hence, in a capsule at about 80°C, the expansion rate would be 0.00115 per cent per mwd/ct.

Manning and Simpson report expansion rates for uranium-impregnated AGOT-KC graphite (transverse-cut). For exposures in a Hanford capsule when the samples did not exceed 100°C, the initial rate of expansion was an average of 2.35 per cent for 27.3 mwd/ct, or 0.086 per cent per mwd/ct. Comparing these, the damage rate is seen to be 75 times greater in the impregnated sample. Since 1/75 of this damage was evidently caused by neutrons, the fission fragment damage was 74 times greater than the neutron damage.

The impregnation density in this sample was 0.012 gram U\(^{235}\) per gram of graphite with 0.90 per cent burn-up. Since one fission corresponds to 1.183 atoms or 4.61 \times 10^{-22} grams burn-up, the total exposure is 9.32 \times 10^{-6} fission fragments per carbon atom.

To obtain the concurrent neutron damage, note that 27.3 mwd/ct is 28.7 grams of U\(^{235}\) burn-up per ton of natural uranium in the Hanford reactor or 0.443 per cent burn-up. There are 10,900 carbon atoms per U\(^{235}\) atom in the Hanford lattice, so that this much burn-up corresponds to 4.07 \times 10^{-7} fissions per carbon atom or 1.02 \times 10^{-6} fission neutrons per carbon atom.
The corresponding damage was 74 times smaller than that due to $9.32 \times 10^{-6}$ fission fragments per carbon atom. Comparing these, it is found that each fission fragment is equivalent to eight neutrons slowing down from fission energy to thermal.\(^*\)

Since the size of uranium oxide particles used in the expansion experiments is comparable to that in the thermal conductivity experiments described in this report, the result may be applied in calculating exposures as in Part IV of the text.

Hunter\(^3\) obtained the result that one neutron is as effective as three fission fragments, but his comparison is with neutron damage sustained at a much lower temperature. The sample was later annealed at the temperature of irradiation for the impregnated samples. Since the complete temperature-time history of the sample is extremely significant, there is reason to doubt the validity of such a comparison.

\(^*\) Note that this is not the relative effectiveness per collision. Each particle will make many collisions before its energy is reduced below the threshold for displacement production.
REFERENCES


