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March 31, 1951

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DR PILE LATTICE CONDUCTANCE STUDY

INTRODUCTION

The start-up of the DR Pile at a time when every effort was being made to increase the power levels of the older piles, suggested the possibility of studying, during the early damage period, some of the conditions which were limiting the operating levels of the old piles. Of the operational limitations restricting the power level of the old piles, the maximum graphite temperature is the most severe and actually determines the operating level of the B, D, and F Piles and, to some extent, the H Pile. Though it was known that irradiation damage of the central part of the old piles had been arrested by the increased temperatures which resulted from the replacement of holium by carbon dioxide as the pile atmosphere, the extent of damage to be expected at the new DR Pile, where graphite temperatures were to be maintained as high as possible from the start, was not known, except for the H Pile startup where conditions were somewhat different.

This report is intended to be a summary of the lattice conductance variations at the DR Pile during the first five months of operation. From the recorded conductances an attempt has been made to estimate the probable minimum conductance conditions which will be reached in the future, and from these, the power level limitations to be expected from graphite temperatures. Also a development of the equations used in calculating apparent thermal conductivity is included.

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SUMMARY

Though this study was not of a conclusive nature, it suggests several interesting conditions which may not otherwise be apparent:

1. The thermal conductivity of the central graphite of the near side of the DR Pile is noticeably poorer than that of the far side, as of March 1, 1951.
2. The rate of decrease of central lattice conductance is greater on the near side of the DR Pile than on the far side. This suggests considerable variation in ultimate conductivity levels, and may restrict heat generation rates on the near side long before critical graphite temperatures are reached elsewhere.
3. It does not appear that DR Pile operation at power levels below 600 MW would produce graphite temperatures in excess of 380°C during 1951, but by the summer of 1952, it is possible that poison distribution and/or control rod pattern concessions will have to be made to hold central graphite temperatures on the near side of the pile below the 380°C limit if power levels over 500 MW are maintained.
4. Graphite damage is suggested to be partially of a saturation nature; i.e., following a shutdown of several days, the conductivity appears to be improved for a time, but gradually recedes to the original trend after a week or more of normal operation. This might be explained by considering graphite damage to be made up of two components; one of a permanent nature, dependent upon exposure history, and the other of a temporary form, which gradually approaches a saturation state for a given flux condition, but which decays off when the neutron field is removed.

The indicated poorer conductivity of the near side graphite presents a problem both as to the cause and as to a means of correction before the damage becomes critical. If the maximum damage expected in this region were comparable to that expected on the far side of the unit, graphite temperatures above the present 380°C limit should not be a problem at the DR Pile for power levels below 600 MW.

DETAILS AND DISCUSSION

1. Source of Data

The graphite-tube lattice conductance for the various graphite thermocouple locations of the DR Pile have been calculated and compared on a daily basis between October 12, 1950 and March 1, 1951. These conductance values were determined from the data relating to thirteen thermocouples located in the 56th horizontal filler-block layer of the graphite backing and to two thermocouples, 6G and 7G, located in tube blocks 2580 and 2573, respectively, of packing layer 55. The relative locations of the filler-block thermocouples are shown in plan by Figure 2, and are described in further detail on page 12.

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The tube blocks of the DR Pile are undercut vertically and are concave on the sides as indicated by Figure 1. This block design allows considerable tube-block growth before the pile structure is affected, but would be undesirable from a heat conduction standpoint.

Figure 1; DR Tube Blocks and Relative Thermocouple Locations.

Past experience has indicated that a major part of the effective irradiation damage occurs in the graphite adjacent to the water cooled process tube. This condition would be most severe at the front of the pile where the water was the coldest, and might be alleviated by enlarging the gas gap between the process tube and the graphite channel. To determine the effectiveness of this method, the four tube channels (2580, 2581, 2680, 2681) surrounding graphite thermocouple 9G were bored out from the front of the packing to a point beyond this thermocouple. This allows an increased gas gap which would have the effect of raising the temperature level of the adjacent graphite packing, and thereby reduce the irradiation damage effect.

2. Selection of Data

The existence of equilibrium conditions at the time data were taken was naturally of prime importance and values were discarded or considered questionable if transient conditions were indicated. This was particularly the case during the first days of operation, after shut-downs, following material power level changes, and immediately after control rod shifts. Varied control rod patterns appear to introduce considerable change in individual apparent conductivity factors, but do not generally cause material variation in average values. Pile power levels, control rod positions, and CO_2 percentage data were also taken regularly, but are herein used only to explain irregularities a particular change might introduce.

3. Method of Calculation

The lattice conductance values considered in this study are expressed as K' values in units of Kilowatts per Tube-Foot- $^{\circ}\text{C}$. The assumptions and the equations used for calculating these values, and their relation to other unit systems sometimes used, are shown beginning on page 10 of the Appendix of this report.

4. Reliability of Values

A review of the lattice conductance vs time curves for individual thermocouples, indicates considerable variation of individual values in some instances. Some of these may be the result of non-equilibrium data, either for the entire pile or for a

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particular location, and others may be attributed to errors of reading, recording, or calculating the data. With some control rod patterns, normal rod changes occasionally appear to cause peculiar trends in regions near the rods and leave discontinuities in the curve when the rod pattern is changed.

Rod changes much greater than those normally necessary at the old piles were required at the DR Pile during this period to compensate for reactivity gains of the order of two inhours per day. This is a more pronounced rate of gain than is normally encountered at the other piles and results from burnout of impurities in the new graphite and rapid product gain in a much higher concentration of green metal than exists in a pile under continued operation. Possibly the most obvious variation of K' values results from operation with a control rod pattern which seriously distorts the assumed cosine flux distribution. This condition would be reflected by the graphite temperatures but not by the calculated local heat generation; hence, the K' value would be low when a graphite temperature was abnormally high, and conversely. This type of effect naturally appears to be more pronounced on the control rod side of the pile, but could exist across most of the critical part of the pile if the rods involved were completely in. A similar, but more pronounced, effect would result when a control rod is located especially close to a graphite thermocouple, thereby producing a shadow effect which would lower the local graphite temperature relatively more than the indicated heat generation for the surrounding tube group, with a high conductivity value being the result. This condition should be the most apparent near the upstream thermocouples which are only some seventeen inches from the number six control rod; and erroneous data could be introduced in these conductance values when this rod is used. The number five control rod might possibly affect the central thermocouples similarly, but to a lesser extent, as it is some thirty inches from them. This possibility is not of concern in this study as the number five rod was not normally used.

Another factor which would be especially effective in producing erroneously high K' values is cone screen plugging. A partially plugged cone screen would reduce the flow through a tube, and also cause a lowered panellit pressure. The calculated flow and heat generation will then be above actual values and the high result will be reflected as a high K' value. The existence of this condition, though of appreciable magnitude, would be hard to verify under normal operation as it would build up slowly. Some screen plugging has been indicated, particularly for the central tube locations which is possibly due to eddy effects at the center of the header where the water from both risers mix. These as well as other conditions which may have been overlooked, appear to cause extreme variations in K' values of up

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to ten per cent from the mean at the upstream and downstream locations, and of up to five per cent from the mean for the central thermocouple locations. From this it follows that a single K' value, selected at random, for a central thermocouple position would probably be in error by about three per cent, and that for the other two locations by something like five per cent; but by being careful to select data taken under equilibrium conditions with balanced control rod patterns, a central K' value, for a given temperature level, should be reproducible to within $1\frac{1}{2}$ per cent.

5. Evaluation

The attached curves show K' values plotted as a function of the date only, with no adjustments made for varying power levels or shutdowns. This method admittedly may not be as accurate as using accumulated local exposure values, but it is more convenient, and since the most probable use of this type of analysis would be to forecast expected future conductivity conditions, it should be satisfactory. All average K' curves; Figures 4, 5, and 6 indicate higher conductance immediately following a down period, which suggests the possibility of an irradiated structural condition which decays when the unit is down and requires several days to again reach saturation after start-up. These curves also suggest that this condition may become less prominent as the total exposure is increased, but similar indications at the D Pile suggest that this may also occur at the old piles. The fact that film was removed from the tubes by purging during the shut-downs preceding the above indications suggests an explanation for improved overall conductance, but of only slight significance; also, no increased conductance trends were indicated after the short shutdown purge of January 5 or the purge during operation of February 7.

In general, the thermocouple locations on the far side of the unit, away from the partial control rod effects, show more consistent conductivity values than the others. The near side, in particular, reflects the effect of front to rear flux distortion with the accompanying K' values high on one side of center and low on the other. By averaging the conductances for the three locations surrounded by a given set of tubes, it was possible to cancel out much of this effect; Figures 5 and 6; and by averaging K' values for all thirteen thermocouples, Figure 4, a very stable value was obtained.

K' values from the tube block containing the 6G thermocouple, Figure 11, shows an increased overall conductance during the latter two months of the study. An increased power level accompanied by higher temperatures at about the beginning of this trend suggests the possibility of recovery under higher temperature-flux concentrations. This as well as some indication of improving conductivity in regions of increased temperature and

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flux at the old piles, is added evidence for the existence of a saturated damage level which is proportional to a function of the product of temperature and flux. The 7G thermocouple similarly located in another tube block did not show a trend parallel to that of 6G, however; Figure 6.

RESULTS OF STUDY

A review of the plot showing all of the K' curves on the same axis, Figure 3, makes the relative values and trends involved. On this curve is also indicated the maximum water temperature rise, for a water flow of 22 gpm per tube, and an inlet water temperature of 20°C, that would be allowable for a given conductivity level when the 380°C maximum graphite temperature limit was not exceeded.

As expected, the central part of the pile showed the least damage while the cooler upstream regions showed the greatest. The rate of damage, at the present time, appears to be most pronounced on the near side near the 15G and 16G thermocouples, and limiting graphite temperature may become a problem much sooner in this region than elsewhere. The 9G location, the surrounding channels of which are bored out, appears to now have a lower overall apparent conductivity than would be expected for that location having regular tube blocks, Figure 8, but the rate of damage does not appear to be as pronounced and the minimum value ultimately reached may be as high as that expected for this location with blocks of normal bore.

Figure 2, showing relative K' contours for March 1, 1951, appears to be fairly reliable as practically all individual K' values were stable and close to their mean curves at this time. The expected minimum values, shown by this figure, and also by Figure 3, are subject to some question, but are believed to be conservative, except possibly for the 15G region which appears rather unstable. It also seems that for central thermocouple locations except 16G and possibly 15G, the expected minimum K' value should be considerably above the limiting 0.075 value defined by the 380°C graphite temperature limit, a 68°C water temperature rise limit, and an assumed 20°C inlet water temperature. From these figures, it appears that the DR Pile with the present water flow rate and temperature rise limits should not be restricted by graphite temperatures for some time. The 15G and 16G regions may become critical by the summer of 1952, but for a time, the heat generation in this region could be maintained within limits by control rod positioning or poison adjustment. A concession of this type would not be desirable from most standpoints, but may become expedient. This is the type of condition which now exists at the D Pile, except that there, the highest central conductivity region is the lower near side of the pile, and to take advantage of this, the poison concentration has been increased in the poorer conductivity regions elsewhere, with a non-symmetrical heat generation the result.

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Figure 2 ; DR File Apparent Thermal Conductivity Map.

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CONCLUSIONS

The most outstanding indication of this study is the apparent difference between conductivity conditions of the near and far sides of the central graphite. The cause of this is not immediately determined, but since the only material variable is the position of the control rods, this must be the cause, either directly or indirectly. During the early weeks of operation, the region of greatest heat generation and highest graphite temperature was centered on the far side of the pile with 13G indicating the highest graphite temperature. This indirectly could be attributed to the control rod pattern as early operating practice did not utilize rod flattening, and the use of several control rods partially through the pile was more common than a smaller number of rods completely through. From these indications, it would seem desirable to recommend that the use of partial control rods be avoided, if possible, and that under conditions where graphite temperature is not the operational limit, the central graphite be maintained at as high a temperature level as possible by using front or rear control rods instead of the central ones; however, the effect of this on graphite expansion should be considered. From a conductivity standpoint, the use of rear control rods would be the most desirable as the higher water temperature there appears to effectively hold a conductivity level farther above the limiting value than in other regions.

By following the preceding principles, particularly during the first months of operation, and by attaining maximum power levels as rapidly as advisable, it appears likely that the graphite conductivity of a DR type pile would remain sufficiently high to allow a power level of the order of 650 MW indefinitely without exceeding the 380°C graphite temperature limit. In line with the above, it is very probable that the rate of decrease of the near side central conductivity could be minimized, and the ultimate minimum conductivity of this region materially increased by the higher central flux-temperature conditions which should result from the use of rear control rods (plus front rods, if necessary) in preference to the central ones now used.

From present indications, Figure 3, it does not seem likely that a limiting K' of 0.075 for the 13G, 14G, and 15G regions will be reached for some time, and if the 15G and 16G trends can be improved, this limit may never be reached for the critical regions. This and indications of central graphite annealing of the old piles, at continued temperature levels approaching 380°C, suggests further that the DR Pile may never be limited by high graphite temperatures under the present maximum heat generation limits, and possibly not under the slightly higher limits which might arise from increased pump pressures and other minor changes.

After several more months of operation, more more definite predictions should be possible, and by late summer, when the inlet water temperature is high, a review of the problem should be beneficial.

Other factors suggested by this study are as follows:

1. The monitoring of graphite temperatures and apparent conductivities above and below the 56th graphite layer is not now possible at the DR pile, but would be very desirable.
2. The continuation of this study, and the institution of a similar program for the early months of operation of a new unit appear desirable.
3. New pile startup with enriched metal should result in less graphite damage as well as increased production during the first months of operation.

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APPENDIX

LOCATION OF GRAPHITE THERMOCOUPLES
IN 100 DR PILES

Filler Block Thermocouples

8G, 12G, and 17G are surrounded by process tubes 2587, 2588, 2687, and 2688.

9G, 13G, and 18G are surrounded by process tubes 2580, 2581, 2680, and 2681.

10G, 14G, and 19G are surrounded by process tubes 2573, 2574, 2673, and 2674.

11G, 15G, and 20G are surrounded by process tubes 25⁶⁶₇₃, 25⁶⁷₇₄, 26⁶⁶₇₃, and 26⁶⁷₇₄.

16G is surrounded by process tubes 2559, 2560, 2659, and 2660.

8G, 9G, 10G, and 11G are 7' - 1.344" upstream from the centerline of the graphite packing.

12G, 13G, 14G, 15G, and 16G are 10.46" downstream from the centerline of the graphite packing.

17G, 18G, 19G, and 20G are 7' - 1.844" downstream of the centerline of the graphite packing.

Process Tube Block Thermocouples

6G and 7G are thermocouples located in process tubes of layer 55.

6G is in tube channel 2580, 10.46" downstream from centerline of packing.

7G is in tube channel 2573, 10.46" downstream from centerline of packing.

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The following development of the method used in calculating lattice conductance makes use of several assumptions:

1. The heavy metal column is centered and is 23' 4" long; $x_1 = 11.67'$.
2. The flux distribution is represented by a centered cosine curve which passes through 1/4 cycle in 13.05 feet.
3. Six per cent of the total heat generation occurs in the graphite moderator.

$$Q_t = 2 \int_0^{x_1} y \, dx + 2(.06) \int_{x_1}^{x_2} y \, dx$$

$$(\text{Let } y = A \cos bx) Q_t = 2 \int_0^{x_1} A \cos bx \, dx + 2(.06) \int_{x_1}^{x_2} A \cos bx \, dx$$

$$= \frac{2A}{b} \sin bx \Big|_0^{x_1} + \frac{.12A}{b} \sin bx \Big|_{x_1}^{x_2}$$

$$= \frac{1.88A}{b} \sin bx_1 + \frac{.12A}{b} \sin bx_2$$

$$bx_2 = \pi/2 = 13.05 b; \quad b = \frac{\pi}{26.1}$$

$$= \frac{(1.88A)(26.1)}{26.1} \sin\left(\frac{11.67 \pi}{26.1}\right) + \frac{(.12A)(26.1)}{\pi}$$

$$= 15.619 A \sin 80.48^\circ + .997 A$$

$$A = Q_t/16.401$$

$$Q_x = Q_t/2 + A \int_0^x \cos bx \, dx$$

$$= Q_t/2 + (A/b) \sin bx$$

$$= Q_t/2 + 0.5065 Q_t \sin\left(\frac{\pi x}{26.1}\right)$$

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$$(1) \quad Q_x/Q_t = 1/2 + 0.5065 \sin \left(\frac{\pi x}{26.1} \right)$$

This is an expression for the fraction of the total heat that has been accumulated by the cooling water when it has reached a point x feet from the center of a tube.

The heat generation for a given foot of tube, x feet from the tube center, may now be determined as follows:

$$Q_x = \frac{Q_t}{2} + 0.5065 Q_t \sin \left(\frac{\pi x}{26.1} \right)$$

$$\frac{dQ_x}{dx} = \frac{0.5065 \pi}{26.1} Q_t \cos \left(\frac{\pi x}{26.1} \right)$$

$$= 0.06097 Q_t \cos(6.897 x)^\circ$$

$$Q_t = 501 \text{ (GPM)} (\Delta T_w) \text{ CHU/TB-FT-HR}$$

$$= 0.2643 \text{ (GPM)} (\Delta T_w) \text{ KILOWATTS/TB-FT}$$

$$(2) \quad \frac{dQ_x}{dx} = 30.54 \text{ (GPM)} (\Delta T_w) \cos(6.897 x)^\circ \text{ CHU/TB-FT-HR}$$

$$(3) \quad = 0.01611 \text{ (GPM)} (\Delta T_w) \cos(6.897 x)^\circ \text{ KW/TB-FT}$$

By assuming that of the total heat transferred for a given foot of process tube, 6.55 per cent is generated in the graphite moderator, the coefficient of expression (2), may be reduced to the units often used in lattice conductance calculations at the old piles.

$$(4) \quad \frac{dQ_{gx}}{dx} = 2 \text{ (GPM)} (\Delta T_w) \cos(6.897 x)^\circ \text{ CHU/TB-FT-HR}$$

By substitution of the "x" values for the three thermocouple locations, the following useful equations are defined:

For upstream thermocouples; $x = -7.154$

$$(3.1) \quad \frac{dQ_L}{dx} = 0.0105 \text{ (GPM)} (\Delta T_w) \text{ KW/TB-FT}$$

$$(4.1) \quad \frac{dQ_{gL}}{dx} = 1.30 \text{ (GPM)} (\Delta T_w) \text{ CHU/TB-FT-HR}$$

For central thermocouples; $x = 0.872$

$$(3.2) \quad \frac{dQ_L}{dx} = 0.0160 \text{ (GPM)} (\Delta T_w) \text{ KW/TB-FT}$$

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$$(4.2) \quad \frac{dQ_{GL}}{dx} = 1.99 \text{ (GPM)} (\Delta T_w) \quad \text{CHU/1B-FT-HR}$$

For downstream thermocouples; $x = 7.154'$

$$(3.3) \quad \frac{dQ_L}{dx} = 0.0105 \text{ (GPM)} (\Delta T_w) \quad \text{KW/TB-FT}$$

$$(4.3) \quad \frac{dQ_{GL}}{dx} = 1.30 \text{ GPM} (\Delta T_w) \quad \text{CHU/TB-FT-HR}$$

From equation (1), an expression for the determination of the local water temperature may be developed as follows:

$$(1) \quad \frac{Q_x}{Q_t} = 1/2 + 0.5065 \sin(6.897 x)$$

Since the water flow along a tube is constant,

$$\frac{Q_x}{Q_t} = \frac{\Delta T_x}{\Delta T_w}$$

$$\frac{\Delta T_x}{\Delta T_w} = 1/2 + 0.5065 \sin(6.897 x)$$

$$\Delta T_x = \Delta T_w \left[1/2 + 0.5065 \sin(6.897 x) \right]$$

$$T_L = T_1 + \Delta T_x$$

$$(5) \quad = T_1 + \Delta T_w \left[1/2 + 0.5065 \sin(6.897 x) \right]$$

For upstream thermocouples; $x = -7.154'$

$$(5.1) \quad T_L = T_1 + 0.116 \Delta T_w$$

For central thermocouples; $x = 0.872'$

$$(5.2) \quad T_L = T_1 + 0.554 \Delta T_w$$

For downstream thermocouples; $x = 7.154'$

$$(5.3) \quad T_L = T_1 + 0.884 \Delta T_w$$

The K' value used in this study may now be defined as follows:

$$(6) \quad K' = \frac{dQ_L / dx}{T_G - T_L} \quad \text{KW/TB-FT-}^\circ\text{C}$$

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The k' value used at the old piles may be similarly defined:

$$(7) \quad k' = \frac{dQ_{FT}/dx}{T_G - T_L} \quad \text{CHU/TB-FT-MR-}^\circ\text{C}$$

The units of expression (6) include the total heat generated per foot of tube, and those of (7) include only 6.55 per cent of the total which may be assumed to correspond to the heat that is transferred to a foot of tube from the graphite only. The conversion factor from one system of units to the other is 124.14 ($k' = 124.14 \text{ K}'$). Both unit systems are shown on Figure 3.

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ABBREVIATIONS USED:

CHU Centigrade Heat Units; $1 \text{ CHU} = 9/5 \text{ BTU}$

FT Foot

GPM Gallons per Minute per Tube

HR Hour

K' Lattice Conductance Factor; $\text{KW/TB-FT-}^\circ\text{C}$

k' Lattice Conductance Factor; $\text{CHU/TB-FT-HR-}^\circ\text{C}$

KW Kilowatts

Q_t Total Heat Produced along a Tube

Q_x Accumulated Heat from Front of Pile to a Point x Feet from Pile Center

T_G Temperature measured by Graphite Thermocouple

T_i Inlet Water Temperature

T_L Local Water Temperature

TB Tube

x Distance from Pile Center; Feet

ΔT_L Local Water Temperature above Inlet

ΔT_w Water Temperature Rise for a Tube

ΔT_x Water Temperature above Inlet for a Point x Feet from Pile Center

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Figure 4

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Figure 5

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Figure 6

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Figure 10

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