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## CALIBRATION OF THE 305 PILE FOR GRAPHITE TESTING

### SUMMARY

The methods of calibrating the 305 pile for impurities and density differences in graphite are reviewed and calibration constants are calculated theoretically. The theoretical impurity calibration agrees with the actual calibrations within 15%. The theoretical density calibration is 30% to 40% smaller than the measured values and it displays a different dependence on graphite cross-section from that which has been reported previously. The discrepancy in this case is great enough to warrant more extensive calibrations. It is shown also that the density calibration obtained by previous methods may differ appreciably from the correction to be applied to normal graphite bars under test because the impurity cross-sections are not properly accounted for.

The relation between reactivity differences in the 305 tests and the  $k$  of the 105 piles is calculated and found to be

$$\Delta ih(105) = 1145 \Delta \rho + 432 (dih)$$

where  $dih$  is the 305 value corrected for density differences and 432 is an average of the measured calibration constants. This formula is applied to the 105-F and 105-H piles and found to predict a greater reactivity difference between the two piles than was actually observed.

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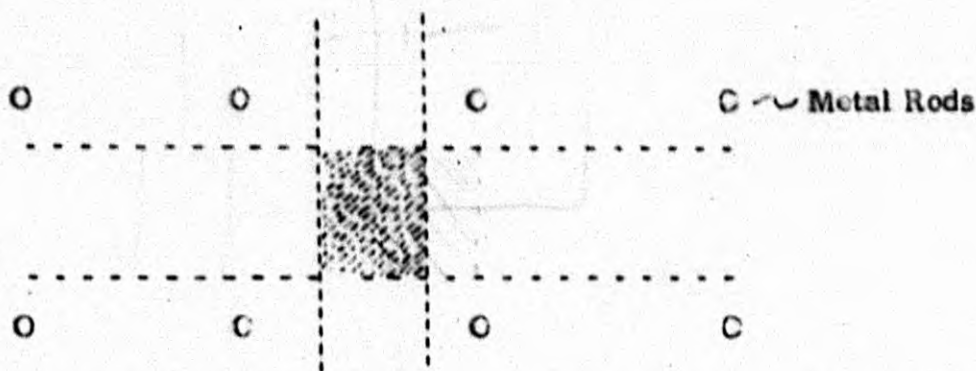
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THEORY

The lattice of the 305 pile is represented in Figure 1. The shaded square

Figure 1



represents a stringer of graphite which can be removed at will and replaced by graphite to be tested for purity. The testing procedure is to load two standard bars into the center of the stringer, measure the pile reactivity, replace the standards by two bars to be tested, again measure the pile reactivity; then take the resulting change in reactivity ( $\Delta k$ ) as a measure of the quality of the two test bars.

The effect of foreign bars inserted into this stringer is to change the  $k$  of the surrounding lattice cells, thereby changing the pile reactivity. The detailed analysis of the effect on  $k$  of foreign bars in the position shown would be difficult to perform. If we assume, however, that the foreign graphite is shared equally by the four adjacent lattice cells and is diffused homogeneously throughout the graphite of these cells, an approximate analysis can be made. As a matter of fact it becomes clear as the analysis proceeds that the same result is obtained if the foreign graphite is contained solely in one of the adjacent lattice cells, all others remaining undisturbed. This is in accord with Wheeler's "Principle of Equivalence" <sup>(1)</sup> and the analysis will be carried out on this basis. It is furthermore assumed that the presence of foreign graphite in the one cell does not effect the boundary conditions satisfied by the neutron flux. This is not strictly true but the difference is of the second order.

We consider now the effect on the  $k$  of a single lattice cell of changing the properties of the moderating graphite. The multiplication factor  $k$  is the product of four factors commonly designated  $f, p, \eta, \epsilon$ . Of these  $\eta$  and  $\epsilon$  depend only on the uranium in the cell leaving  $p$  and  $f$  dependent on the moderator properties. Then for changes in the cell graphite alone

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$$\frac{\Delta k}{k} = \frac{\Delta p}{p} + \frac{\Delta f}{f}$$

The resonance escape probability  $p$  is described by the formula<sup>(2)</sup>

$$p = e^{-1/T}, \quad T = \frac{N_1 V_1}{N_0 V_0} \left[ \frac{\sigma_{sl} \xi_1}{\rho_0 \int dE/E} \right]_{\text{eff}} \quad (2)$$

where the subscript "1" applies to graphite and "0" applies to uranium,

$N$  = number of atoms per cc

$V$  = volume of material per unit length of cell

$\sigma_{sl}$  = scattering cross-section of graphite

$\xi_1$  = average logarithmic energy loss for neutrons in graphite

$\left[ \rho_0 \int dE/E \right]_{\text{eff}}$  = effective cross-section for resonance capture in uranium.

Form (2)

$$\frac{\Delta p}{p} = \frac{1}{T} \frac{\Delta T}{T} = \frac{1}{T} \frac{\Delta N_1 V_1}{N_1 V_1} = \frac{1}{T} \frac{\Delta \rho_1 V_1}{\rho_1 V_1} \quad (3)$$

since any light element impurities will be present in such small quantities as not to change  $\sigma_{sl}$   $\xi_1$ , and  $N_1$  is proportional to graphite density  $\rho_1$ .

The thermal utilization of the cell is given by

$$\frac{1}{T} - 1 = \frac{\bar{\phi}_1}{\bar{\phi}_0} \frac{E_1}{S_{\text{cell}}}$$

where  $\bar{\phi}$  is the average flux in the material and  $S$  is the total absorption cross-section for thermal neutrons per unit length of cell. The fractional change in  $f$  resulting from a change in the moderator is then

$$\frac{\Delta f}{f} = -(1-f) \frac{\Delta S_1}{S_1} \quad (4)$$

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since  $\bar{\rho}_1 / \bar{\rho}_0$  is insensitive to small changes in neutron cross-section.

The values of  $p$  and  $f$  for the normal lattice are approximately 0.868 and 0.904 respectively<sup>(3)</sup>, so  $1/T = 0.142$ ,  $1-f = 0.096$ , and

$$\frac{\Delta k}{k} = 0.142 \frac{\Delta \rho_1}{\rho_1} \frac{V_1}{V_1} - 0.096 \frac{\Delta S_1}{S_1} \quad (5)$$

The pile volume over which this change occurs is two bars long (11.3 lu) and the number of effective central cells for 305 weighted by  $\rho^2$  is 1573<sup>(6)(4)</sup>. Then if we take  $1\% k = 385$  ih and assume the mean square flux over the two bars to be equal to the maximum square flux, the above change in  $k$  produces a reactivity change of

$$\Delta R = 276.5 \Delta k = 0.0575 \Delta \rho_1 V_1 - 165.2 \Delta S_1 \text{ ih} \quad (6)$$

where the following constants have been used:  $k = 1.07$ <sup>(3)</sup>,  $V_1 = 456.7$ <sup>(3)</sup>,  $\rho_1 = 1.60$ , diffusion length in 305 graphite = 51 cm<sup>(3)(4)</sup>, scattering cross-section in graphite is 4.2b<sup>(5)</sup>, and absorption cross-section is 4.7 mb.

#### IMPURITY CALIBRATION

When the impurity calibration is made the first step is to remove a volume  $V_h$  of the normal graphite and replace it by a volume  $V_t$  of foreign graphite. The volume  $V_t$  is the bar volume minus the volume of the holes that have been drilled in it. For this change

$$\Delta \rho_1 V_1 = \rho_t V_t - \rho_1 V_h$$

$$\begin{aligned} \Delta S_1 &= (N_t \sigma_{at} + \sum_i N_{it} \sigma_{ait}) V_t - (N_1 \sigma_{a1} + \sum_i N_{i1} \sigma_{ai1}) V_h \\ &= S_t - S_{1h} \end{aligned}$$

where  $N_1$  is the number of graphite atoms per cc in the original graphite  
 $N_t$  is the number of graphite atoms per cc in the foreign graphite  
 $N_{i1}$  is the number of impurity atoms of cross-section  $\sigma_{ai1}$  per cc in the original graphite and

$N_{it}$  is the number of impurity atoms of cross-section  $\sigma_{ait}$  per cc in the foreign graphite.

$\rho_1$  is the density of the original graphite

$\rho_T$  is the density of the foreign graphite

$S_T$  is the total absorption cross-section per unit length of the foreign bars

$S_{lh}$  is the total absorption cross-section per unit length of the original graphite

The resulting change in reactivity is

$$\Delta R = 0.575 (\rho_T V_t - \rho_1 V_h) - 165.2 (S_t - S_{lh}) \quad (7)$$

As the next step an additional impurity of cross-section  $S_i$  per unit length is added to the test graphite and the change in reactivity relative to the original is again computed,

$$\Delta R' = 0.0575 (\rho_T V_t - \rho_1 V_h) - 165.2 (S_t - S_{lh} + S_i)$$

The difference in reactivity between the test graphite with holes and with impurities is then

$$\Delta ih = \Delta R' - \Delta R = - 165.2 S_i \quad (8)$$

In calibrating the 305 pile it has been the custom to express the impurity calibration constant as the ratio of reactivity change to total impurity cross-section introduced into the two test bars. If we denote this total cross-section by  $S'$  and introduce it into (8) we have

$$\Delta ih = - 0.679 S'_i \quad \text{since the length of the two bars is 243.5 cm.}$$

This compares favorably with measured values

$$\frac{\Delta ih}{S'_i} = - 0.535 \text{ ih/cm}^2 \quad (7), \quad - 0.588 \text{ ih/cm}^2 \quad (8)$$

This close agreement between the calculated and observed calibration constant gives us confidence in both the impurity calibration and in its interpretation.

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DENSITY CALIBRATION

The procedure for this calibration is to take two standard size test bars of high density and observe the change in pile reactivity as graphite is removed from the bars to decrease their effective density. From (6) and (7) the change in pile reactivity resulting from an increase  $\Delta V_t$  per unit length in the volume of the test bars is

$$\begin{aligned} \Delta ih &= 0.0575 \rho_t \Delta V_t - 165.2 \Delta S_t = 0.0575 (1 - 0.144 \bar{\sigma}_{at}) \rho_t \Delta V_t \\ &= 0.0575 (1 - 0.144 \bar{\sigma}_{at}) V_t \Delta \rho_t = 6.51 (1 - 0.144 \bar{\sigma}_{at}) \Delta \rho_t \quad (9) \end{aligned}$$

where  $V_t = 113.12$  cc per unit length

$\Delta \rho_t =$  effective increase in density equivalent to volume increase  $\Delta V_t$

$$\Delta S_t = (N_t \sigma_{at} + \sum_i N_{it} \sigma_{ait}) \Delta V_t = N_t \bar{\sigma}_{at} \Delta V_t \times 10^{-27} \text{ cm}^2 / \text{cm}$$

$\bar{\sigma}_{at} =$  effective atomic cross-section of graphite in millibarns.

For  $\bar{\sigma}_{at} = 4.7$  and  $4.0$  (9) becomes  $\Delta ih = 2.1 \Delta \rho_t$  and  $2.76 \Delta \rho_t$  respectively. These constants are to be compared with 3.72 and 3.56 ih per gram/cc obtained by Weil <sup>(7)</sup> and West <sup>(8)</sup>. The agreement between these calculated and observed values is not very good. The calculation is less accurate than the previous one because it depends on the difference between two terms, neither of which is too well known, but even taking this into account the discrepancy seems too large.

It may be significant that equation (9) shows that the calibration constant should increase as the graphite purity increases, whereas West observed it to decrease <sup>(8)</sup>. This discrepancy would seem to justify a new density calibration.

GRAPHITE TESTING

When comparing test bars with standards, there are differences in both density and impurity cross-section. Then the difference in reactivity is

$$\Delta ih = 6.51 (1 - 0.144 \bar{\sigma}_{at}) \Delta \rho_t - 165.2 \Delta S_t \quad (10)$$

The density dependence of (10) is different from (9) in that the actual carbon cross-section  $\sigma_{al}$  replaces the effective cross-section  $\bar{\sigma}_{at}$ . The difference in total impurity cross section per unit length between the test bars and the standards is denoted by  $\Delta S_1$ .

The effect of changes in graphite quality on  $k$  in the 105 piles can be calculated by the method which resulted in equation (5),

$$\frac{\Delta k}{k} = 0.125 \frac{\Delta \rho}{\rho} - 0.092 \frac{\Delta S_1}{S_1}$$

$$\frac{\Delta S_1}{S_1} = \frac{\sigma_{al}}{\bar{\sigma}_{at}} \frac{\Delta \rho}{\rho} + \frac{\Delta (\sum N_i \sigma_{ai})}{N_1 \bar{\sigma}_{at}}$$

so that

$$\frac{\Delta k}{k} = (0.125 - 0.092 \frac{\sigma_{al}}{\bar{\sigma}_{at}}) \frac{\Delta \rho}{\rho} - 0.092 \frac{\Delta (\sum N_i \sigma_{ai})}{N_1 \bar{\sigma}_{at}} \quad (11)$$

In terms of the 305 measurements (10), this becomes

$$\frac{\Delta k}{k} = (0.125 - 0.092 \frac{\sigma_{al}}{\bar{\sigma}_{at}}) \frac{\Delta \rho}{\rho} + 0.0130 \text{ (dih)}$$

where (dih) is the 305  $\Delta$  ih corrected for density difference between standard and test bars.

Then if the density of the test bars is the same as the density of the 105 graphite, the increase in 105 pile reactivity corresponding to a given dih in 305 is

$$\Delta R = 526 \text{ (dih) inhours}$$

or if the measured impurity calibration constant is used

$$\Delta R = 432 \text{ (dih) inhours} \quad (12)$$

In order to estimate the validity of equation (12) we compute the difference in reactivity that it predicts between F and H piles. For H pile (10),  $\bar{\rho} = 1.669$ .

$\overline{(\text{dih})} = 0.936$ ; for F pile  $\overline{(\text{dih})} = 0.19^{(11)}$ . The cold clean reactivity of F at startup was estimated as  $660 \pm 5 \text{ ih}^{(12)}$ , that for H was estimated at  $850 \text{ ih}^{(13)}$ .

From (12) we get a predicted value of 323 ih for  $\Delta f = 0$ , 208 ih for  $\Delta \rho = -0.1$ , taking  $\sigma_{\text{al}} / \bar{\sigma}_{\text{at}} = 0.85$ . No figure for the density of F-graphite is available, but it is quite certain that  $|\Delta \rho| < 0.1$ . It appears then that the effect of 305 dih on 105 k is very seriously overestimated by (12). This may be the result of the wrong density correction being applied to the 305 data, an error in equation (11), or inaccurate evaluation of the cold, clean reactivity of the two piles. It is hoped that these sources of error can be investigated in the near future.

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