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HANFORD STANDARD PILE

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Hanford Works
Richland, Washington

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Physics Section
Pile Technology Division

Technical Divisions

July 30, 1951

HANFORD WORKS
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ABSTRACT

The construction and diffusion length measurement of the standard pile erected for the exponential experiments are described. The techniques used for accurate flux measurement are given, and the importance of the potential errors discussed. The steps in the calculation of diffusion length from those measurements using the conventional thermal-source approximation and the fast-source theory are outlined and a comparison made of the diffusion lengths so calculated. It is concluded that generally the fast-source theory is preferable although only in the case a single-source was used rather than two or four matched sources did the diffusion length obtained from thermal-source theory differ appreciably from that obtained by fast-source calculations.

The value of the diffusion length of the graphite in the standard pile was found to be 54.4 ± 0.5 cm when corrected to a graphite density of 1.60 g/cc.

HANFORD STANDARD PILE

INTRODUCTION

The Hanford standard pile was erected in the spring of 1950 to serve as a combination standard and sigma pile for the exponential pile program which was planned. As a standard pile it was to furnish a constant thermal neutron flux against which all neutron detectors could be standardized during the course of the work. As a sigma pile it would provide information about the quality of the graphite being used in the exponential pile experiments and, also, since all graphite used had been tested in 305, provide a calibration of the 305 test pile.

PILE DESCRIPTION

1. Graphite Specifications

The bars of graphite (48" x 4-3/16" x 4-3/16") which were chosen for the standard pile had all been tested in four bar groups in the 305 pile and had reactivity values between 0.96 dih and 0.99 dih (average 0.974 dih per bar corrected for density). The bars had been weighed in pairs at the time of testing and only those pairs whose weight fell between 100# and 102# were selected for use. The bars were weighed individually as the pile was laid up, and with the exception of bars in the top two layers of the standard pile, the individual full length bar weights were between 49# 12 oz. and 51# 4 oz. (density 1.636-1.686). In the top two layers the bar weights varied between 49# and 52#. The average density of the pile was 1.658 g/cc. With the exception of a few bars, the graphite was all G.B.F. The graphite in the base of the standard pile was lower grade graphite (0.70 dih or better) which had been rejected for dimensional reasons. For use in the base, it was machined to four inches square to eliminate the irregularities.

2. Pile Layup

Since the concrete floor of the 101 pad room was smooth enough that a section eight feet square could be selected which had only 1/8 inch variation in height, no special concrete pad was laid on which to build the pile. Instead a 0.020" cadmium sheet was placed directly on the floor to provide known base

boundary conditions for the thermal neutrons, and a 1/4" felt pad was laid on top of the cadmium to help even out the irregularities in the floor. The base was built directly on the felt pad. Measurement of the lengths of the diagonals of each layer insured that the layer was not out of square, and the use of a plumb line insured the vertical alignment of the pile.

Typical layer plans of the pile are given in Figure I. It is to be noted that the bars are of varied lengths and the seams staggered to increase the stability of the pile and help remove any irregularities produced by the unevenness of the floor. The 24" bars in the pile were cut from 48" bars and thus are actually 1/32" short of 24", because of the saw kerf. Thus every other row in a given layer is 1/16" short of 8 feet, and the average size of the pile is actually 1/64" under 8 feet square. This 1/64" difference was neglected in all calculations. Layer E in the base has provisions for using a single source in the center of the base or matched sources located halfway between the axis of the pile and the center of the faces. The use of a single source is preferable when using the pile as a standard pile since it permits the other sources to be used elsewhere simultaneously; however, in diffusion length measurements the use of the matched sources increases the accuracy of the measurement by reducing the harmonic corrections. Layer twelve also contains a removable bar which may be replaced by a source bar for such measurements as standardization of foils. As can be seen in the face view of the pile in Figure II, every layer contains a 1-3/4" diameter cylinder of graphite which may be removed to measure the flux in that layer. Each measuring slot is designated by its layer number. Layer five has six extra slots so that a fairly extensive traverse of a quadrant of that layer may be obtained if desired. These are designated as 5-1, 5-2, 5-3, etc. starting from the normal slot. The diagonal lengths and average density of each of the layers is given in the appendix.

Six one-quarter inch square graphite rods separate the standard pile from the base to provide a slot into which a cadmium sheet can be inserted for correcting the diffusion length measurements for fast neutron effects when the thermal source approximation is used. The entire pile is covered with

Figure 1
LAYER PLANS

- - Keyway Slot
- - Source Hole

Figure 2

HANFORD STANDARD PILE

FRONT FACE

 - Removable Bar

⊕ —Removable Cylinder

Bars I-23—10.636 cm. A-J—10.160 cm.
NOTES:
2.54 cm. from $\frac{1}{2}$ of source top of Layer E

Bars 1-23 — 10.636 cm. A-J — 10.160 cm.

2.54 cm. from ϵ of source top of Layer E

0.022" cadmium to eliminate any reflection of thermal neutrons back into the pile from the room. Actually the pile is large enough and the walls far enough away that there is little cause for worry about this effect.

3. Flux Measurement Techniques

Since the flux measurement with foils is no better than the equipment used to count the foils, the first step was to establish a Geiger tube and scaler combination that was stable and required little maintenance. The final combination chosen was a Potter scaler and a R. C. L. thin-walled glass Geiger tube Mark I, Model 10. The Potter scaler has the convenience of the decade scale and, if set up carefully, will operate for weeks without maintenance. About 50% of the R. C. L. tubes used gave a satisfactory life* of 2×10^7 counts or better. This life is necessary if the tube is to be standardized and used profitably. The operation of the scaler and Geiger tube was checked daily with a uranium glass standard which gave a counting rate of approximately 7000 c/m. The standard was placed in a fixed position over the Geiger tube and 15 one-minute counts were taken. The statistical "chi squared" test was applied to the counts to determine if they had a probable statistical distribution. The counts were also plotted on a chart to show any day to day trends in the value of the standard counts. The 90% - 10% limits of the "chi squared" test proved to be fairly reliable indications of instrument or tube trouble. A somewhat less reliable but simpler test of the distribution also used was that approximately two thirds of the counts should deviate from the average by less than the square root of the average count, and that no counts should deviate by more than 2.58 times the square root of the average count from the average count.

The standardization of the counters was carried out with three indium foils exposed in a standard position in the standard pile each day and then counted on each of the counters. This eliminated any questions about differences of energy of the particles and differences of geometry between the glass standards and the foils which were to be counted. Counter factors derived in this manner were found to drift less than 1% per month normally. The daily counter

* Considered to be over when plateau slope exceed 7%/100 volts.

factor was taken to be the average over the past ten days.

The first indium foils used were 1" x 2 1/2" x approx. 0.006" selected within a weight range of $\pm 1/4\%$ of the average. These were exposed in a flat aluminum dish mounted in a specially milled head shown in Figure III. After exposure the foils were removed from this holder and formed around a cylindrical mandrel and slipped into an aluminum holder which was then placed over the Geiger tube. This procedure was subject to error in the proper positioning of the foil and, furthermore, the continued rolling and unrolling of the foil distorted it so that its life was usually about three exposures.

To avoid these difficulties later measurements were made with foils which were permanently mounted in cylindrical graphite holders (Figure IV) in which they could be calibrated in the standard pile. The direct calibration in the standard pile was much more accurate than the weighing and measuring techniques used with the flat foils. The foil holders were indexed and always irradiated and counted in a standard position. The cadmium ratio was obtained by surrounding the mounting with a complete cadmium shell (upper holder in Figure IV). Because of the thin shell of graphite included inside the enclosing cadmium shell, the cadmium cutoff was lowered a slight amount. This lowering was ignored in all calculations. A more important change in the sensitivity of the foil to fast neutrons occurs because the inner surface of the indium which is the side next to the Geiger tube during counting is shielded from most of the resonance neutrons by the rest of the indium. Only those fast neutrons which are slowed down to resonance in the graphite core of the holder, or those resonance neutrons which come in the ends of the cylinder have a chance of being captured on the inner surface of the indium. This lowers the sensitivity of such a foil to resonance energy neutrons by a factor of 0.68. If thermal neutron measurements are all that are desired, as is usually the case, this is an advantage of the cylindrical geometry.

Since measurement of thermal neutron flux with indium foils was both slow and subject to more errors in execution than with BF_3 proportional

Figure 3

FLAT FOIL HOLDER

Dish and lid are made of 2-S aluminum for measuring total neutron flux and of cadmium (0.020") for measuring "fast" flux.

P 12

Figure 4

CYLINDRICAL FOIL HOLDERS

Indium foils are permanently mounted inside graphite cylinders. Upper holder is cadmium (0.020") lined.

P 12

counters, small aluminum walled counters were developed. The 3 1/2" long, 1/2" diameter counters were filled with pure enriched BF_3 . The total absorption cross section of the filled counter was 0.69 cm^2 as measured in the Test Pile. The counter was mounted inside a graphite cylinder as shown in Figure V, which fits into the test holes of the pile. Small coaxial cable used as the signal lead was led out of the pile through a milled slot in the graphite cylinder. The signal was fed through a cathode-follower type preamp into an Atomic Instrument A-1 amplifier model 204 C. The amplified pulses were counted on a Potter scaler. These instruments were checked for proper operation and stability in much the same way as were the Geiger tube assemblies. The BF_3 tube was positioned on the axis of layer two of the standard pile with source #3 in the center of layer E. Fifteen one-minute counts were taken and checked for proper distribution by application of the "chi squared" test. The average of the counts was used to calculate the counter factor of the set in terms of an arbitrarily assigned flux for that position.

4. Sources

Ten one-quarter gram Ra-Be sources canned in cylindrical capsules 16 mm in diameter and 9 mm in height were procured for the exponential program. The sources were made as nearly identical as possible and then by proper pairing of the sources, five half-gram sources were formed which had relative strengths of #1 = 1.008, #2 = 1.000, #3 = 1.005, #4 = 1.008, and #5 = 1.000. The paired sources were canned in an aluminum holder such as shown in Figure VI. This holder has a bail for easy handling by a pair of mechanical fingers, and slots top and bottom for assembly of the source with a long handled screw driver. When matching sources were desired, #1 and #4 were paired, and #2 and #5 were paired.

DIFFUSION LENGTH - THEORETICAL

1. Thermal-Source Theory

In C1-573⁽¹⁾ it was shown that the relationship between the thermal diffusion length and the thermal flux distribution in a sigma pile may be expressed by the equation

$$\nabla^2 n - \frac{n}{L^2} = 0 \quad (1)$$

Figure 5

SMALL BF_3 COUNTER

Showing a counter and mounting cap in the foreground and the mounted counter and graphite head in the background.

P 12

Figure 6

ALUMINUM SOURCE HOLDER AND DUMMY SOURCES

where n is the difference between the flux measured in the normal pile and the flux measured at the same position with a cadmium shutter interposed between the source and the nearest measurement position. The equation assumes that the shutter has no perturbing effects on the fast neutrons, but merely absorbs thermal neutrons. This relationship will hold also, of course, for the total thermal flux in regions of the pile which are far enough from the source that there is no production of thermal neutrons.

This equation has the solution

$$n = \sum_{j,k} C_{jk} (e^{-z/b_{jk}} - e^{-(2Z-z)/b_{jk}}) \cos \frac{j\pi x}{a} \cos \frac{k\pi y}{b} \quad (2)$$

(where the origin of the rectangular coordinate system is taken to be in the center of the source plane)

for a rectangular cross section pile of effective dimensions a and b in which the source to effective top-of-pile distance is Z , provided, the sources are distributed symmetrically about the $x-z$ and $y-z$ planes. The b_{jk} 's are defined by

$$\frac{1}{b_{jk}^2} = \frac{1}{L^2} + \pi^2 \left(\frac{j^2}{a^2} + \frac{k^2}{b^2} \right) \quad (3)$$

where L is the diffusion length of the graphite. The summation in equation(2) is to be taken over all odd positive values of the integers j and k

In order to evaluate C_{jk} the assumption is made that the thermal neutrons behave as if they originate from a point thermal source located at (X_i, y_i) , which leads to the equation

$$C_{jk} = Kb_{jk} \frac{1}{1 + e^{-2Z/b_{jk}}} \sum_i \cos \frac{j\pi x_i}{a} \cos \frac{k\pi y_i}{b}$$

where K is a constant

When this value of C_{jk} is inserted in the expression for n and the following simplifying assumptions are made:

(1) Z is nearly as large and a and b so that

(a) $1 + e^{-2Z/b_{jk}}$ is approximately unity

(b) $\frac{1 - e^{-2(Z-z)/b_{jk}}}{1 - e^{-2(Z-z)/b_{11}}}$ is approximately unity for z small

(2) Flux measurements are made on the axis of the pile ($x = 0$, $y = 0$),

The equation may be rearranged into the form

$$n \left[1 - e^{-2(Z-z)/b_{11}} \right]^{-1} \left[\frac{\sum_i \sum_{jk} b_{jk} e^{-z/b_{jk}} \cos \frac{j\pi x_i}{a} \cos \frac{k\pi y_i}{b}}{b_{11} e^{-z/b_{11}} \sum_i \cos \frac{j\pi x_i}{a} \cos \frac{k\pi y_i}{b}} \right]^{-1} = K b_{11} e^{-z/b_{11}} \quad (5)$$

where the summation is now over all odd positive harmonics above the 1,1 harmonic. The first factor in brackets is known as the end correction, C_e , and the second factor in brackets is the harmonic correction, C_h .

In the case of a single source located on the axis of the pile ($x_i = 0$, $y_i = 0$) the harmonic correction becomes

$$C_h = \left[1 + \frac{\sum_{jk} b_{jk} e^{-z/b_{jk}}}{b_{11} e^{-z/b_{11}}} \right]^{-1} \quad (6)$$

In the case of a multiple source arrangement of two sources at $(\pm a/4, 0)$ or four sources located at $(\pm a/4, 0)$ and $(0, \pm b/4)$ several of the harmonics cancel and some take a negative sign so that the expanded harmonic correction can be written as

$$C_h = \left[1 - \frac{b_{33} e^{-z/b_{33}} + 2b_{35} e^{-z/b_{35}} + b_{55} e^{-z/b_{55}} - 2b_{17} e^{-z/b_{17}} - 2b_{19} e^{-z/b_{19}}}{b_{11} e^{-z/b_{11}}} \right]^{-1} \quad (7)$$

The diffusion length is calculated from equation (5) by evaluating b_{11} from a least-squares fit of the logarithms of the corrected values of n versus the position, z . From b_{11} and the effective dimensions of the pile, the diffusion length, L , can be calculated by equation (3). The effective dimensions, a and b , are the physical dimensions of the pile plus twice the extrapolation distance, which may be measured as outlined in the appendix or taken to be the theoretical value, $0.71 \lambda_{tr}$. The harmonic and end corrections are evaluated by first guessing a value of L and calculating the $b_{jk}'s$ from equation (3) and using these $b_{jk}'s$ in the trial correction terms. The b_{11} thus obtained may be used to recalculate the $b_{jk}'s$ and the correction terms may be recalculated, and a new b_{11} derived. This may be repeated until satisfactory agreement is attained between the b_{11} used in the correction terms and that determined from (5). Since a change of 1 cm in the b_{11} used in the correction terms changes the calculated b_{11} by only 0.05 cm or less, one or two trials are usually sufficient.

2. Fast-Source Theory

It was pointed out in a recent paper (BNL-77)⁽²⁾ that the assumption of a point thermal source to evaluate C_{jk} might cause considerable discrepancy in the value of the diffusion length. It was suggested that a better solution is obtained by combining the thermal diffusion equation

$$\nabla^2 n - \frac{n}{L^2} + \frac{q}{D} = 0$$

with Fermi's age equation

$$\nabla^2 q = \frac{dq}{d\tau}$$

τ being the age to thermal of source neutrons. The thermal neutron distribution for a point fast neutron source as given by the solution to these equations is

$$n = \sum_{jk} \frac{A}{j_k} \cos \frac{j\pi x}{a} \cos \frac{k\pi y}{b} \left[e^{-z/b_{jk}} \left(1 + \operatorname{erf} \left(\frac{z}{2\sqrt{\tau}} - \frac{\sqrt{\tau}}{b_{jk}} \right) \right) + e^{z/b_{jk}} \left(1 - \operatorname{erf} \left(\frac{z}{2\sqrt{\tau}} + \frac{\sqrt{\tau}}{b_{jk}} \right) \right) \right]$$

where

$$A_{jk} = \left(\frac{Qe^{\tau/L^2}}{Dab} \right) b_{jk} \cos \frac{j\pi x_i}{a} \cos \frac{k\pi y_i}{b} \quad (10)$$

where b_{jk} is defined as previously, D is the diffusion coefficient and Q is the source strength. (2)(3)

This equation may be used in two different ways to calculate the diffusion length. First, it may be used as suggested in BNL-77 to calculate a correction to the harmonics derived from the thermal source theory. This method can be used when the thermal fluxes are obtained by the cadmium shutter technique. This calculated correction to the thermal source theory harmonics reduces them by the factor (2)

$$f = 1/2 e^{\tau/L^2} \left[\left(1 + \operatorname{erf} \left(\frac{z}{2\sqrt{\tau}} - \frac{\sqrt{\tau}}{b_{jk}} \right) \right) + e^{2s/b_{jk}} \left(1 - \operatorname{erf} \left(\frac{s}{2\sqrt{\tau}} + \frac{\sqrt{\tau}}{b_{jk}} \right) \right) \right] \quad (11)$$

where s is the source to cadmium shutter distance. The correction is seen to depend on the harmonic being corrected, through b_{jk} , on the diffusion length of the graphite, through L and b_{jk} , and on the energy of the source neutrons, through τ . Since the correction factor is only a slowly varying function of the diffusion length, the inclusion of L and b_{jk} offers little difficulty; however, it is somewhat more sensitive to age variation so the age must be selected from the literature or measured with some care. (2) BNL-77 reports ranges ($\tau = 2\sqrt{\tau}$) from the literature and from their measurements for Ra-Be and Po-Be sources. In the case of Ra-Be sources it takes at least three ranges to describe the source spectrum, which means that the correction factor for the harmonics is the sum of three terms like that given in equation (11).

Measurement of the ranges of neutrons emitted by a Ra-Be source by the method described in CP-704 gave 33% with $r_{th} = 31$ cm, 59% with $r_{th} = 43$ cm, and 8% with $r_{th} = 64$ cm which is in good agreement with other published data. (4)(5) The small differences make only negligible uncertainties in the correction factors.

A second and somewhat more straightforward appearing method of using equation (10) is to treat it exactly as was done in the case of the thermal source equation. Reduce it to the form

$$n = \frac{1}{C_h} e^{-z/b_{11}} \quad \text{or} \quad n \cdot C_h = e^{-z/b_{11}} \quad (12)$$

by dividing and multiplying the right hand side of the equation by $e^{-z/b_{11}}$ and defining the harmonic correction as $e^{-z/b_{11}}$ divided by the right hand side of equation (10). This harmonic correction is only a slowly varying function of the diffusion length as was the correction derived from the thermal source theory. The calculation of the fast source theory harmonic correction, however, is much more laborious because of the presence of the age term, especially in the case of a multi-range source such as Ra-Be.

Equation (10) was derived for a pile of infinite height; therefore, the value of n required is the measured value of the total thermal neutron flux multiplied by the end correction. The end correction necessary will be just that given in the section on thermal source theory.

DIFFUSION LENGTH - EXPERIMENTAL

Several sets of measurements of the neutron distribution were made with and without the cadmium shutter using different measurement techniques, flat foils, cylindrical foils, and BF_3 counters, and using a single source in the center of the base as well as four sources distributed at positions $(\pm a/4, 0)$ and $(0, \pm a/4)$.

Typical harmonic correction factors which must be applied to the flux measurements made at each slot are given in Table I for both the fast-source and thermal-source theory as applied to single-source and four-source measurements. (The four-source corrections also would apply to two sources at $(\pm a/4, 0)$). It is to be noted that the four-source corrections are much smaller than the single-source corrections and are less sensitive to the theory used in their calculation. The corrections listed under the heading Total Thermal Flux were calculated from the fast-source theory as in equation (12). The end correction listed in the last column is seen to be negligible below layer 12 and small below layer 20.

The value of the diffusion length calculated from each of the sets of measurements (and corrected to a graphite density of 1.60 g/cc.) is tabulated

in Table II. In the case of the values listed under Cadmium Shutter Technique, the thermal flux was taken as the difference of the no-shutter and shutter measurements of the flux with a bare detector. The Total Thermal Flux values of the diffusion length were calculated from flux values which were the difference between the same no-shutter values and the no-shutter cadmium covered detector values. (In the case of indium foil detectors the cadmium covered detector values were first multiplied by 1.080 to correct for the capture of "fast" neutrons by the cadmium).⁽⁶⁾

Set "1" is not included since it was the first measurement made and showed internal inconsistencies probably resulting from faulty technique. Set "2" was measured with indium foils (only one foil per position) exposed in a flat geometry, and then formed into cylinders for counting. For this reason it is felt to be less reliable than the other sets.

Sets 3, 4, 7, and 8 were measured with indium foils (2 to 3 foils per position) permanently mounted in graphite cylinders. Sets 5, 6, 9, and 10 were measured with the small, low cross-section BF_3 's.

Table I
HARMONIC AND END CORRECTIONS*

Cadmium Shutter Technique						Total Thermal Flux		Correction C _e
Thermal Theory				Fast Theory		Fast Theory		
		C _h	C _h	C _h	C _h	C _h	C _h	
Slot	z(cm.)	Single Source	Four Sources	Single Source	Four Sources	Single Source	Four Sources	
2	59.77	0.624	1.110	0.704	1.063	0.738	1.164	1.000
3	70.41	0.686	1.074	0.752	1.043	0.762	1.109	1.000
4	81.04	0.738	1.050	0.793	1.030	0.792	1.073	1.000
5	91.68	0.782	1.034	0.828	1.020	0.821	1.049	1.000
6	102.31	0.819	1.024	0.857	1.014	0.847	1.033	1.000
7	112.95	0.850	1.017	0.880	1.010	0.873	1.022	1.000
8	123.59	0.876	1.012	0.902	1.007	0.890	1.017	1.000
9	134.22	0.897	1.008	0.919	1.005	0.914	1.012	1.000
10	144.86	0.915	1.006	0.933	1.004	0.929	1.008	1.000
12	166.13	0.942	1.003	0.954	1.002	0.953	1.003	1.002
14	187.40	0.961	1.002	0.968	1.001	0.971	1.000	1.004
16	208.68	0.973	1.001	0.979	1.000	0.983	1.000	1.014
18	229.95	0.982	1.000	0.988	1.000	0.992	1.000	1.044
20	251.22	0.988	1.000	0.993	1.000	0.999	1.000	1.146
22	272.49	0.992	1.000	0.994	1.000	1.000	1.000	1.640

* Corrections calculated for $b_{11} = 38.029$ cm ($L = 52$ cm), $a = 247.72$ cm

Fast source correction calculated assuming Ra-Be source emits neutrons of ranges 31, 43, 64, in the ratio of 0.33 to 0.59 to 0.08.

Table II
DIFFUSION LENGTH
 (Corrected to = 1.60 g/cc)

Set	Sources	Cadmium Shutter Technique		Total Thermal Flux Fast-Source Theory
		Thermal-Source Theory	Fast-Source Theory	
5	1	56.3	54.4	54.7
6	1	56.2	54.2	55.0
10	1	--	--	53.4
Ave.		56.2	54.3	54.4
9	2	--	--	55.1
2	4	52.9	53.9	53.5
3	4	54.1	55.1	54.4
4	4	53.9	54.9	54.3
7	4	54.3	54.9	54.6
8		--	--	54.8
Ave.		53.8	54.7	54.4

These results show a pronounced discrepancy between the one-source and four-source values of the diffusion length in the case of the thermal-source theory, which is not evident in either of the fast-source theory calculations. This is some evidence of the inadequacy of the thermal-source theory. The difference between the diffusion lengths calculated by fast-source theory from the total thermal flux and the cadmium shutter measurement seems to indicate that the fast theory may over-correct slightly in the case of the cadmium shutter measurement, possibly due to some perturbing effect of the shutter on the fast flux. Sets #7 and 8 were carefully measured on successive days to check the effect of the 1/4" gap above the base on the measurements. In set #7 the gap was left open while in set #8 the gap was filled with graphite shims. The flux measurements of the two sets were within statistics ($\frac{\sqrt{n}}{n} \sim 0.5\%$) of each other, indicating there was no measureable perturbation effect produced by the 1/4" gap.

From these measurements, it was concluded that thermal-source theory should be used only when split sources are used and in general the extra nuisance of the cadmium shutter technique is as much trouble as the extra complexity of the fast-source equations which have much more general application.

The value of the diffusion length was concluded to be $54.4 \text{ cm} \pm 0.5 \text{ cm}$ (corrected to a graphite density of 1.60 g/cc) accepting the "Total Thermal Flux" calculations as the most reliable.

REFERENCES

(1)	C. L. 573	Manual on Graphite Testing
(2)	B. N. L. -77	A Review of Graphite Testing Procedures and Their Applications to the B. N. L. Reactor, J. Chernick and I. Kaplan.
(3)	(C. P. A.-6)	Production of Neutrons by Uranium, H. L. Anderson and E. Fermi.
(4)	C. P. -704	Report on Argonne Standard Pile, L. Seren.
(5)	A. N. L. -4174	Report for April, May and June, 1948.
(6)	Phys. Rev.
May, 1950	A Correction to be Applied to the Activity of Neutron Activated Cadmium Covered Indium Foils, Kunstadter.

APPENDIX

A EFFECT OF DISPLACEMENT OF SOURCES

When two or four distributed sources are used to reduce harmonics they should be matched in strength and placed at $(\pm \frac{a}{4}, 0)$ and/or $(0, \pm \frac{a}{4})$ in a square pile for the simplest mathematical treatment. It was the custom in early pile measurements, both sigma and exponential, to place the sources at 1/4 the physical pile width from the axis, ignoring the extrapolation distance. The difference in the harmonic corrections as calculated from thermal theory produced by this misplacement (by approximately 1 cm) in an eight foot square pile can be seen in Table III. This difference in harmonic corrections results in a difference of approximately 0.3 cm in diffusion length when measurements are taken 70 - 200 cm from the source. In smaller piles the effect would be even larger. If the extrapolation distance is also ignored in calculating L from b_{11} in equation (3), the two errors being nearly the same size and of opposite sign nearly cancel each other.

Table III
HARMONIC CORRECTIONS

<u>Slot</u>	<u>z(cm)</u>	<u>Two Sources</u> <u>at $(\pm \frac{a}{4}, 0)$</u>	<u>Two Sources</u> <u>at $(\pm \frac{a}{4}, -1, 0)$</u>
2	59.77	1.110	1.097
3	70.41	1.074	1.064
4	81.04	1.050	1.042
5	91.68	1.034	1.028
6	102.31	1.024	1.018
7	112.95	1.017	1.012
8	123.59	1.012	1.008
9	134.22	1.008	1.005
10	144.86	1.006	1.003
12	166.13	1.003	1.001
14	187.40	1.002	1.000
16	208.68	1.001	1.000
18	229.95	1.000	1.000
20	251.22	1.000	1.000
22	272.49	1.000	1.000

B EFFECTIVE SIZE OF PILE

The effective size of the pile can be measured by a horizontal traverse of the pile. From the thermal source approximation, equation (2), a horizontal traverse should be fit by a curve of the form

$$n = \sum_i \sum_{jk} K b_{jk} e^{-z/b_{jk}} \cos \frac{j\pi x}{a} \cos \frac{j\pi x_i}{a} \cos \frac{k\pi y_i}{b} \quad (13)$$

for a traverse along the x axis ($y = 0$). In the fast source theory description of the same traverse the b_{jk} 's which appears as the coefficient of the exponential in equation (13) are reduced by the factor f of equation (11).

This equation can be reduced to form

$$n = A \cos \frac{\pi x}{a} + B \cos \frac{3\pi x}{a} + C \cos \frac{5\pi x}{a} \quad (14)$$

Where for the case of a single source in the center of the base of a square pile ($x_i = 0, y_i = 0$),

$$A = b_{11} e^{-z/b_{11}} + b_{13} e^{-z/b_{13}} + b_{15} e^{-z/b_{15}} + b_{17} e^{-z/b_{17}} + \dots$$

$$B = b_{13} e^{-z/b_{13}} + b_{33} e^{-z/b_{33}} + b_{35} e^{-z/b_{35}} + \dots$$

$$C = b_{15} e^{-z/b_{15}} + b_{35} e^{-z/b_{35}} + b_{55} e^{-z/b_{55}} + \dots$$

For the case of four sources distributed in the base at $(\pm \frac{a}{4}, 0)$ and $(0, \pm \frac{a}{4})$, the values of the coefficients are

$$A = b_{11} e^{-z/b_{11}} + b_{17} e^{-z/b_{17}} + \dots$$

$$B = -b_{33} e^{-z/b_{33}} - b_{35} e^{-z/b_{35}} + \dots$$

$$C = -b_{35} e^{-z/b_{35}} - b_{55} e^{-z/b_{55}} + \dots$$

From a least squares fit of a horizontal traverse of the neutron flux by an equation of the form of equation (14), one can determine the size, a , and the

appropriateness of the theory from the ratio of A to B and C.

The thermal neutron distribution across layer three (70 cm above the source plane) was measured twice by the cadmium shutter technique, once with cylindrically mounted indium foils, and once with the 3 inch BF_3 counters. The least squares fit of the foil data gave a 97.75 inch, and of the BF_3 counter data $a = 97.75$ inch. When the theoretical value of the extrapolation distance, 0.71λ , is added to both sides, the theoretical width is found to be 97.52", in very good agreement with average of the two measured values.

The least squares equation which fit the two sets of data using the theoretical width were:

$$A_{th} = 19,545 \cos \frac{\pi x}{a} - 710 \cos \frac{3\pi x}{a} - 20 \cos \frac{5\pi x}{a} \quad (15)$$

for the foil data, and

$$A_{th} = 19,545 \cos \frac{\pi x}{a} - 642 \cos \frac{3\pi x}{a} - 153 \cos \frac{5\pi x}{a} \quad (16)$$

for the BF_3 data when the two sets are normalized to the same coefficient of the first cos term.

The ratio of the coefficient of the first term to the coefficient of the second term is $R_{1,2} = -27.5$ in equation (15) and $R_{1,2} = -30.4$ in equation (16).

The ratios of these coefficients as calculated from theory are $R_{1,2} = 18.0$ from thermal source theory and $R_{1,2} = 30.5$ from fast source theory. The measurements are seen to agree quite well with fast source theory. The theoretical ratios of the first to third coefficients are $R_{1,3} = -74$ from thermal source theory and $R_{1,3} = -188$ from fast source theory. The third coefficient is so small, however, that little can be concluded from the equations except an order of magnitude agreement.

As a more severe test of the fast source theory a horizontal traverse of the total thermal flux across layer three was measured with a single source in the center of the base. In this case, the theoretical coefficients of the cosine terms are calculated directly from equation (10). The ratio of the first to second coefficient is calculated to be $R_{1,2} = 5.87$. The least squares fit to the measured traverse using $a = 97.52''$ gave

$$n = 23,874 \cos \frac{\pi x}{a} + 4,407 \cos \frac{3\pi x}{a} + 523 \cos \frac{5\pi x}{a} \quad \text{which gives}$$

$$R_{1,2} = 5.42.$$

The 8% discrepancy between the calculated and measured ratios indicate some short comings in the fast-source theory as applied, perhaps due to edge effects. Since this may mean the single-source harmonic correction factors are in error by roughly 2%, it is preferable to use the split-source arrangement where the harmonic corrections are much smaller and less dependent on the theory.

Table IV

LAYER DETAILS

Layer No.	NW-SE Diag. 11° 3 3/4" Correct	NE-SW Diag. 11° 3 3/4" Correct	Difference	Density Grams/cc
1	11° 3 24/32"	11° 3 23/32"	1/32	1.661
2	--	--	--	1.657
3	11° 3 26/32"	11° 3 22/32"	4/32	1.660
4	11° 3 26/32"	11° 3 22/32"	4/32	1.657
5	11° 3 28/32"	11° 3 22/32"	6/32	1.653
6	11° 3 27/32"	11° 3 22/32"	5/32	1.660
7	11° 3 27/32"	11° 3 21/32"	6/32	1.658
8	11° 3 28/32"	11° 3 20/32"	8/32	1.659
9	11° 3 28/32"	11° 3 20/32"	8/32	1.659
10	11° 3 25/32"	11° 3 20/32"	5/32	1.656
11	11° 3 26/32"	11° 3 21/32"	5/32	1.659
12	11° 3 27/32"	11° 3 22/32"	5/32	1.657
13	11° 3 25/32"	11° 3 23/32"	2/32	1.659
14	11° 3 26/32"	11° 3 22/32"	4/32	1.660
15	11° 3 24/32"	11° 3 22/32"	2/32	1.656
16	11° 3 23/32"	11° 3 22/32"	1/32	1.660
17	11° 3 26/32"	11° 3 22/32"	4/32	1.660
18	11° 3 25/32"	11° 3 22/32"	3/32	1.661
19	11° 3 25/32"	11° 3 21/32"	4/32	1.660
20	11° 3 26/32"	11° 3 22/32"	4/32	1.664
21	11° 3 25/32"	11° 3 22/32"	3/32	1.661
22	11° 3 26/32"	11° 3 21/32"	5/32	1.655
23	--	--	--	1.651

Dimensions - Layer = 8' x 8' x 4 3/16"
Over-all = 8' x 8' x 8' -0 5/16"

Density - Average Layer = 1.658 g/cc

Note: In general the lengthwise layer measurements were within 1/16" of the given value of 8' -0".

1-27