KSU PILE STANDARDIZATION AND STUDY OF SLOWING DOWN AND DIFFUSION MODELS

by

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INTRODUCTION

In investigations concerned with neutrons and their behavior, there is often a need for accurate measurement of a laboratory standard of absolute thermal neutron flux. In 1941, Anderson and Fermi (3) outlined a method of determining an absolute thermal neutron flux in a laboratory pile, based on theoretical and semi-empirical considerations. Seren (35) seems to have been the first to do the experimental work in his calibration of the Argonne Standard Pile in 1943. This pile was dismantled in 1946 and Redman (32) recalibrated what is now the Argonne Standard Pile. In 1954, Hanford Laboratories (11) published a report on the standardization of indium foils and gold foils in the Hanford Standard Pile. It is reasonable to think that other piles have been standardized as this method of pile standardization has been outlined in many references (11, 16, 20, 30).

A standardized pile is a large stack of graphite in which a neutron source of known strength has been placed, and an absolute thermal neutron flux has been defined. The spatial distribution of the slowing down density, q, at indium resonance energy can be measured with cadmium-covered indium foils. Assuming no leakage of epithermal neutrons in the z direction of the assumed infinite column and no absorption of epithermal neutrons, absolute values can be assigned to this measured distribution of the slowing down density since the volume integral of this slowing down density must equal the known neutron emission rate of the source, Q_0. Empirically fitting the absolute slowing down density leads to an analytical expression which may be evaluated at thermal energy, and which then can

be used as a source term in the one velocity thermal diffusion equation. The solution to this equation is then taken to define the absolute flux. It is customary to use the neutron velocity of 2,200 meters per second (m/sec) in the calculation of the flux in a standard pile (20).

The confidence limits of such an absolute flux assignment are determined primarily by the accuracy of the source strength and the diffusion coefficient. It is reported by Hughes (20) that this method of flux assignment is within the error in the knowledge of the absolute source strength. Previous investigators (11, 35) seemed to have no question about uncertainty of the diffusion coefficient. However, recent measurements of the transport mean free path and the diffusion coefficient in graphite introduce additional uncertainty about assignments of absolute flux (6, 29)

The National Bureau of Standards (7) has made provision for producing a constant thermal neutron flux of 4,000 neutrons per square centimeter per second (n/cm^2-sec) in a particular moderating geometry. This calibration has been made to an accuracy of ± 2 per cent by the absolute counting of α particles from the $B^{10}(n,\alpha)$ Li (7) reaction. It has been verified to within the limits of experimental accuracy by a comparison with an independent calibration by Oak Ridge National Laboratories. The National Bureau of Standards invites the exchange of activated gold foils between it and other national laboratories for the purpose of intercomparison of absolute flux. This has not been done at Kansas State University; however intercomparisons have been completed with Hanford Laboratories, and with Argonne National Laboratory.

Glasstone and Edlund (15) have assumed that for the experimental determination of the diffusion length, extraneous sources to the thermal

diffusion equation emit only thermal neutrons. This development appears to be adequate for describing what happens to the thermal flux near a concentrated source. The method of assuming that the source emits epithermal neutrons of age zero, and allowing their distribution in space and energy to be determined by the Fermi age equation, leads to the more accurate expression of a distributed thermal source for use in the thermal diffusion equation.

Some work with this coupling of the Fermi age equation and the thermal diffusion equation in addition to pile standardization has been done. A group at Hanford (10) used this method in an investigation of the diffusion length. They concluded that generally this fast source theory was preferable, but only in the case of a single source did the diffusion length obtained from thermal source theory differ appreciably from that obtained from fast source theory. A paper by Anselone (4) at Hanford in 1954 outlines the use of the "method of images" in determining theoretically the distribution of thermal neutrons from fast sources in exponential piles. A publication by Wallace and LeCaine (42) has an extensive compilation of these coupled solutions for various geometries.

Previous work at Kansas State University leading to this work has been the determination of the Fermi age both from theory and experiment by Steichen (39) and the determination of diffusion length in the KSU pile by Kaiser (22).

THEORY

Thermal Neutron Diffusion

Extensive treatment of the theory of thermal neutron diffusion can be found in many references (2, 15, 24, 43). It will be considered sufficient for this work to outline the basic theory of neutron diffusion and point out the assumptions and approximations involved.

The rate of change of the number of thermal neutrons in an elemental volume equals the number which flow in through the boundary of the elemental volume plus the number produced by sources minus the number captured per unit time. The equation expressing this principle of continuity at a steady state condition is

$$- \nabla \cdot \vec{j} + S(\vec{r}) - \Sigma_a n(\vec{r}) v = 0, \tag{1}$$

where n is the density of the thermal neutrons, v is their representative velocity. Σ_a is the absorption cross section of the medium, and S is the number of thermal neutrons produced per unit time per unit volume. The net number of neutrons, $\vec{j}$, flowing in unit time through a unit area normal to the direction of flow is the neutron current given by Fick's law of diffusion, the characteristic assumption of elementary diffusion theory

$$\vec{j} = - D \nabla n v. \tag{2}$$

In this, D is the diffusion coefficient for the monoenergetic flux, having the dimensions of length.

Using Eq. 2 in Eq. 1 gives the thermal diffusion equation, Eq. 3. Since for monoenergetic neutrons the neutron flux, ϕ, is equal to nv, this equation will be written

$$D \nabla^2 \phi - \Sigma_a \phi + S = 0 \tag{3}$$

where an isotopic medium has been assumed.

The conditions for the justification of diffusion theory and the diffusion equation include the following considerations:

(a) Collisions between neutrons do not occur, making the probability of collisions proportional only to ϕ. This results in linear equations describing the neutron diffusion. Weinberg and Wigner (43) point this out as the most important mathematical property of the diffusion equation. This makes superposition of solutions possible.

(b) The neutron scattering is spherically symmetric or isotropic. The isotropic distribution allows the velocity vector to be treated as a scalar in the equation of continuity. This assumption places a limitation on the diffusion equation near sources, boundaries, and absorbers since near them, the scattering is not isotropic.

(c) The nuclei of the isotropic, homogeneous moderator are at rest and of such high mass number with respect to a neutron that they do not recoil appreciably under the impact of neutrons (43).

(d) The neutrons are monoenergetic for which scattering occurs without energy loss. This allows the diffusion equation to be energy independent.

(e) The fractional change in the neutron flux and the mean free path over a distance of two or three mean-free paths is small (15). It can be shown on the basis of transport theory that Fick's law is not valid if this condition does not hold (15). Thus in regions near a concentrated source, absorber or boundary where the flux changes rapidly or the mean-free path is discontinuous, the neutron current cannot be represented as being proportional to the gradient of the flux.

(f) The diffusion medium is a weak absorber so that the scattering cross section can represent the total cross section, and therefore $\Sigma_a / \Sigma_s << 1$. This is tied in with condition (e) in that if the absorption cross section is appreciable, the neutron density may vary substantially within a mean-free path.

(g) The diffusion coefficient is independent of position. This allows D to be factored out of the term for divergence of the current in Eq. 3 leaving $D\nabla^2\phi$ for $\nabla \cdot D\nabla\phi$.

(h) The general dimensions of the moderator are much larger than characteristic lengths such as the diffusion length in diffusion theory or the slowing down length in slowing down theory.

Neutron Slowing Down

The problem of neutron slowing down must be considered in order to determine the effective source to the thermal diffusion equation. The accurate theory here is quite complicated (43). For this treatment it will be sufficiently accurate to consider the slowing down process to be described by an approximate, continuous slowing down model given by

Fermi. It is based on the assumption of a functional relationship between a neutron's energy and its age, i.e., the time elapsed since its birth at a primary source.

The approximation is that for large neutron populations the neutrons lose energy in a continuous fashion rather than in discontinuous, discrete jumps as with a single neutron. This approximation cannot be valid in the event that a neutron may lose its entire energy in a single collision which is the case with moderators of low mass number.

The development of the Fermi age equation which describes the neutron slowing down process is given in considerable detail in a number of works (2, 15, 43). Assuming no capture of neutrons during slowing down, the Fermi age equation is

$$\nabla^2 q(\vec{r}, \tau) = \frac{\partial q(\vec{r}, \tau)}{\partial \tau} . \tag{4}$$

A new variable, the Fermi age has been introduced and is defined by

$$\tau(E_0, E) = \int_E^{E_0} \frac{D(E)\, dE}{\xi \Sigma_s(E) E} . \tag{5}$$

In the above expression, the slowing down density $q(\vec{r}, \tau)$ can be defined as the number of neutrons/cm^3 - sec which slow down past a given energy E, corresponding to the age τ, at a given point $\vec{r}$. E_0 is the energy of the source neutrons, E is the energy to which τ is measured and ξ is the average logarithmic energy decrement per collision. D is the diffusion coefficient, and Σ_s is the macroscopic scattering cross section.

Solutions for Particular Conditions

The solution to the Fermi age equation for a point neutron source emitting Q_0 monoenergetic neutrons per second in a finite parallelepiped of sides 2a, 2b, and 2c is derived in Appendix B, and given here as

$$q(x,y,z,\tau)=\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\sum_{0=1}^{\infty} Q_0 F_m(x)F_m(x_0)G_n(y)G_n(y_0)H_o(z)H_o(z_0)e^{-(\alpha_m^2+\beta_n^2+\gamma_o^2)\tau} \tag{6}$$

where

$$F_m(x) = \frac{1}{\sqrt{a}} \cos \alpha_m x \qquad \text{for m odd}$$

$$F_m(x) = \frac{1}{\sqrt{a}} \sin \alpha_m x \qquad \text{for m even}$$

$$F_m(x_0) = \frac{1}{\sqrt{a}} \cos \alpha_m x_0 \qquad \text{for m odd} \tag{7}$$

$$F_m(x_0) = \frac{1}{\sqrt{a}} \sin \alpha_m x_0 \qquad \text{for m even}$$

$$\alpha_m = \frac{m\pi}{2a} .$$

$G_n(y)$, $G_n(y_0)$, $H_o(z_0)$ are defined in the same manner, with the dimensions b and c corresponding to directions y and z, respectively. This solution will be referred to as the slowing down density in a finite pile from a fast source. It will be evaluated at the age corresponding to thermal energy and used as the distributed thermal neutron source in the thermal diffusion equation.

The one-dimensional solution to the Fermi age equation for a point source of monoenergetic neutrons at the origin of an infinite column of rectangular sides a and b is derived in Appendix A and given here as

$$q(z,\tau) = \frac{4Q_0}{ab\sqrt{4\pi\tau}} \sum_{j=1}^{\infty} \sum_{k=1}^{\infty} e^{-\pi^2\tau(j^2/a^2 + k^2/b^2)}\, e^{-z^2/4\tau} . \tag{8}$$

In this, z represents the distance from the source along the central Z axis of the infinite column, and j and k are summed over odd integers.

The $\sqrt{\tau}$ is often called the slowing down length or characteristic length. The quantity $2\sqrt{\tau}$ will be referred to as the Gaussian range and denoted by

$$r = 2\sqrt{\tau} . \tag{9}$$

Defining

$$c = \frac{4}{ab\sqrt{\pi}\, r} \sum_{j=1}^{\infty} \sum_{k=1}^{\infty} e^{-\frac{\pi^2 r^2}{4}(j^2/a^2 + k^2/b^2)}, \tag{10}$$

Eq. 8 becomes

$$q(z,\ \tau) = Q_0\, c\, e^{-z^2/r^2} . \tag{11}$$

A quantity which is proportional to the slowing down density may be measured with some accuracy with cadmium-covered indium foils. There are some correction factors that must be applied to this measured distribution which will be introduced in the analytical part of this work. The cadmium covering filters out most of the neutrons with energies of 0.4 ev and below so that the activation of the indium foil is due primarily to neutrons with an energy of 1.44 ev,

corresponding to the energy of the resonance cross section of indium.

From the solution to the Fermi age equation in the infinite column, Eq. 11, it can be seen that the natural logarithm of the activity of cadmium-covered indium foils plotted against z^2 should yield a straight line with a slope of $-1/r^2$. However, the neutrons from a Pu-Be source are not monoenergetic but have a wide energy distribution as shown in Fig. 1. Hence, it is not unreasonable to find a curved line for this plot in Fig. 14. This curve might be considered to represent the superposition of the solutions for an infinite number of sources, each having a different monoenergy and thus a different Gaussian range. Thus Eq. 11 should be written

$$q(z,\tau) = Q_0 \sum_{i=1}^{\infty} f_i \, C_i \, e^{-z^2/r_i^2} \tag{12}$$

where f_i represents the fraction of the Q_0 neutrons emitted per second that are in the i^{th} energy group and r_i represents the Gaussian range from the energy level of the i^{th} group to the energy level of 1.44 ev.

Another solution for such a source distribution shown for the Pu-Be source in Fig. 1 would be found from a numerical integration of the point kernel over the source spectrum (43),

$$q(\vec{r}, \tau) = \sum_{i=1}^{N} \int_0^{\tau} d\tau_s \; S_i(\tau_s) \, \Psi_i(\vec{r}) \, e^{-B_i^2 (\tau - \tau_s)} . \tag{13}$$

$S_i(\tau)$ is the amplitude of the i^{th} harmonic from a source of age τ_s. $\Psi_i(\vec{r})$ represents the wave function satisfying the age

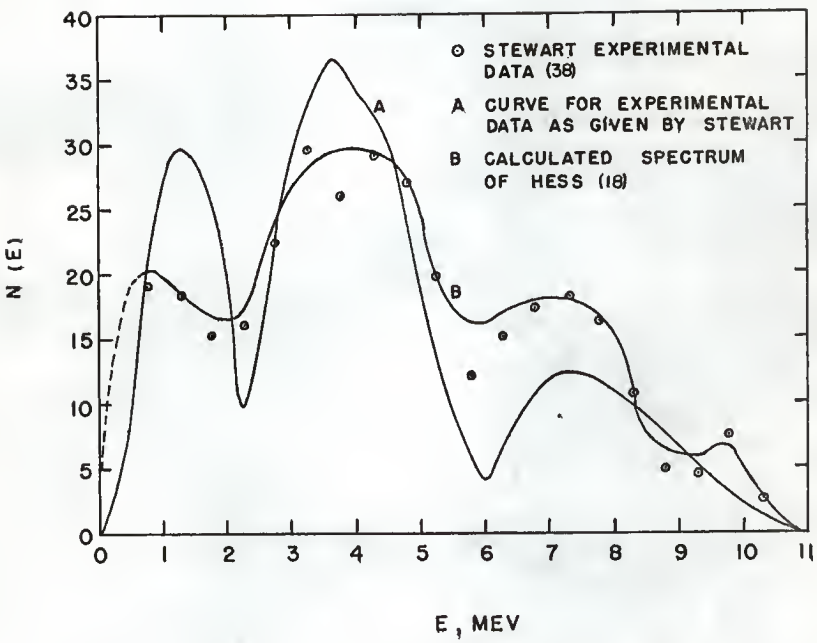


Fig. 1. Calculated and measured neutron energy spectrum for a Pu–Be neutron source.

equation and the boundary conditions, and B_i^2 represents the buckling of the distribution $\Psi_i(\vec{r})$.

An approximate fit of the quantity proportional to the slowing down density at indium resonance energy may be made with a finite number of the terms in Eq. 12.

$$q = Q_0 \sum_{i=1}^{N} f_i C_i e^{-z^2/r_i^2} \tag{14}$$

In terms of the experimental distribution, Eq. 14 is

$$A_{res} = \sum_{i=1}^{N} B_i e^{-z^2/r_i^2} \tag{15}$$

The f_i may be found from the experimentally determined amplitudes, B_i, and the constants C_i may be determined by Eq. 10. B_i is proportional to $f_i C_i$ and $\sum_{i=1}^{N} f_i = 1$. The combination of these relationships gives

$$f_i = \frac{B_i/C_i}{\sum_{i=1}^{N} B_i/C_i} \tag{16}$$

The result of this analysis gives an analytical expression, Eq. 14, for the absolute slowing down density to indium resonance energy if the absolute source strength Q_0 is known.

An experimentally determined Gaussian range to indium resonance energy may be extended to represent the Gaussian range to thermal energy by use of the definition of the age, Eq. 5, and by use of the relationship between age and Gaussian range, Eq. 9.

$$\tau(E_{oi},\ E_{th}) = \tau(E_{oi},\ E_{In}) + \tau(E_{In},\ E_{th}) \tag{17}$$

or

$$\frac{r^2_{th\text{-}i}}{4} = \frac{r^2_{In\text{-}i}}{4} + \int_{E_{th}}^{E_{In}} \frac{D}{\xi\,\Sigma_s}\,\frac{dE}{E} \tag{18}$$

Using the Gaussian ranges to thermal energy, the absolute expression for slowing down density, Eq. 14, gives the number of neutrons slowing down to thermal energy per unit volume per second, i.e.,

$$q_{th}(z) = Q_0 \sum_{i=1}^{N} f_i\, C_i\, e^{-z^2/r^2_{th\text{-}i}} \tag{19}$$

This extrapolation of the resonance energy Gaussian ranges to thermal energy assumes that the moderating process described by the age equation applies until the neutron energy corresponds to thermal energy. At this point slowing down stops and the neutron is considered to diffuse at a constant thermal energy.

The solution to the thermal diffusion equation in the infinite column of rectangular sides a and b, using as a source term Eq. 19, the expression for absolute slowing down density to thermal energy, is derived in Appendix A and given here as

$$\phi(z) = \sum_{i=1}^{N} \sum_{j,k=1}^{\infty} \frac{f_i Q_0 b_{jk}}{D\,a\,b}\, e^{-(\alpha_j^2+\beta_k^2)\frac{r^2_{th\text{-}i}}{4}}\, e^{\frac{r^2_{th\text{-}i}}{4b_{jk}}} \left\{ e^{-z/b_{jk}} \left[1 + \operatorname{erf}\left(\frac{z}{r_{th\text{-}i}} - \frac{r_{th\text{-}i}}{2b_{jk}} \right) \right] + e^{z/b_{jk}} \left[1 - \operatorname{erf}\left(\frac{z}{r_{th\text{-}i}} + \frac{r_{th\text{-}i}}{2b_{jk}} \right) \right] \right\} \tag{20}$$

where

$$\frac{1}{b_{jk}^2} = \frac{1}{L^2} + \frac{\pi^2 j^2}{a^2} + \frac{\pi^2 k^2}{b^2} = \kappa^2 + \alpha_j^2 + \beta_k^2 \tag{21}$$

and

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-u^2} \, du \tag{22}$$

It is evident that if the nuclear constants of the moderator are known, the absolute neutron flux along the Z axis may be defined from Eq. 20. Once this absolute flux is defined, various thermal neutron detectors can be standardized against it so that a normalization factor will convert from count rate to flux. Such detectors will be referred to as standardized detectors.

To correct for the fact that neutron measurements cannot actually be made in a column of infinite height, the experimental thermal measurements must be adjusted so that it appears that they were made in a pile of infinite height. Actually the neutron flux goes to zero at the upper extrapolated boundary, h, of the actual finite column. Actual pile measurements may be adjusted by the familiar fundamental mode end correction factor used in diffusion length measurements (11),

$$C_e = \left[1 - e^{-2(h-z)/b} \right]^{-1} \tag{23}$$

The solution to the diffusion equation in a finite medium of sides 2a, 2b, and 2c, using as a source term the distributed thermal source given by Eq. 6, is derived in Appendix B and given here as

$$\phi(x,y,z)=\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\sum_{0=1}^{\infty}\frac{Q_0 F_m(x)F_m(x_0)G_n(y)G_n(y_0)H_0(z)H_0(z_0)}{D(\alpha_m^2+\beta_n^2+\gamma_o^2+\kappa^2)}\, e^{-(\alpha_m^2+\beta_n^2+\gamma_0^2)\tau_{th}} \tag{24}$$

In this solution $F_m(x)$, $F_m(x_0)$, $G_n(y)$, $G_n(y_0)$, $H_o(z)$, $H_o(z_o)$ are given in Eqs. 7.

If the thermal diffusion equation in this geometry is sourced by a thermal point source the solution, derived in Appendix C, is

$$\phi(x,y,z)=\sum_{m}^{\infty}\sum_{n}^{\infty}\frac{Q_0}{D\gamma_{mn}}F_m(x)F_m(x_0)G_n(y)G_n(y_0)\frac{\sin h\,\gamma_{mn}(2c-z)\sin h\,\gamma_{mn}z_0}{\sin h\;2\gamma_{mn}\;c} \tag{25}$$

Some note should be made of the inaccuracy in the assumption of a physical point neutron source. The source to the age equation should actually be given by the distribution of first collisions (27). It would be introduced into the age equation as a function of the mean free path and the distance from the source location

$$f_i\,Q_0 = \frac{f_i\,Q_0\,e^{-z/\lambda_i}}{4\pi z^2} \tag{26}$$

In this equation, λ_i represents the first collision mean free path of the neutrons in the i^{th} energy group. λ_i may be determined according to an equation given on page 200 of Reference 43.

EXPERIMENTAL FACILITIES

General Pile Description

The Kansas State University Standard Graphite Pile, shown in Fig. 2, in which all measurements were made, consisted of a rectangular parallelepiped, 68 inches square and 100 inches high, resting on a concrete foundation. The column was constructed by stacking layers of machined reactor grade graphite blocks, approximately 4 inches in cross section and of various lengths. In stacking, the long dimension of the graphite blocks was altered by 90^0 cross-lapping from layer to layer. As seen in Fig. 2, certain of the graphite blocks were drilled to a diameter of 1.75 inches along the lengths of the blocks. For this work, in the effort to make a homogeneous, solid moderator, each of the fuel ports contained graphite cylinders measuring 1.625 inches in diameter with each being 22.68 inches in length, and of the same material as the graphite blocks.

The graphite cylinders rested on the bottoms of the fuel ports, leaving crescent shaped air gaps between the tops of the cylinders and the tops of the fuel ports. The distance between the tops of the cylinders and the tops of the fuel ports was 0.125 inches. The blocks along the central vertical axis of the column contained horizontal foil slots with a cross section of 1.281 inches by 0.343 inches. These slots were such that graphite foil stringers, shown in Fig. 3, containing indium foils with their covering material, could be placed at approximately 4-inch intervals up the central axis of the column. The density of the solid

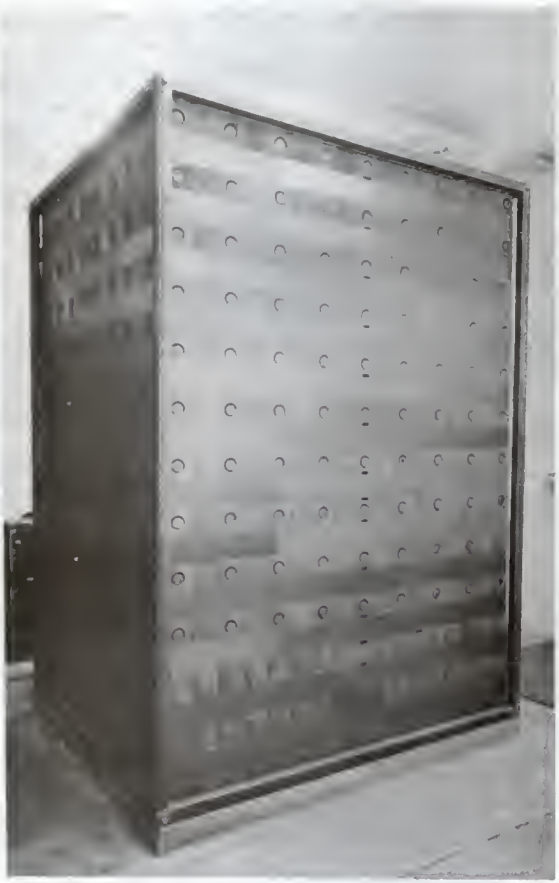


Fig. 2. KSU Standard Graphite Pile.

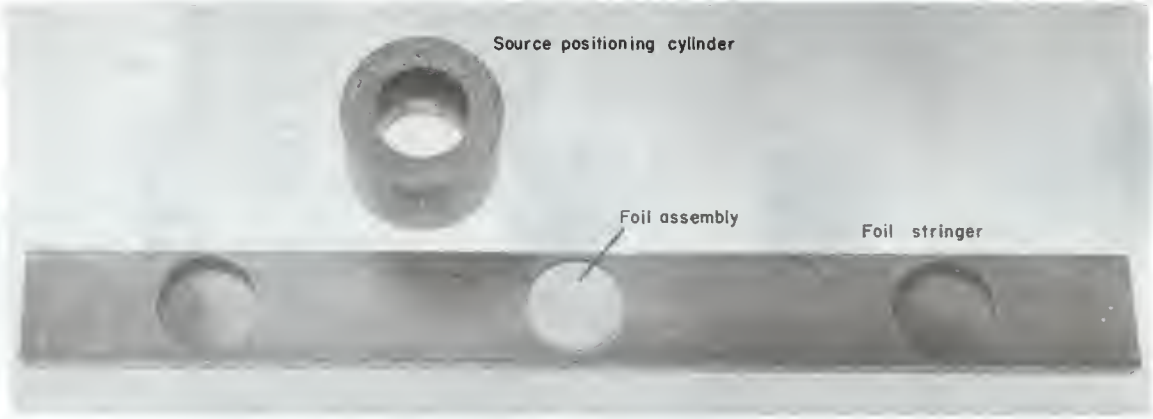


Fig. 3. Source positioning cylinder and foil stringer with foil assembly.

graphite blocks was 1.683 gm/cm^3. Steichen (39) calculated the percentage of air voids to be approximately 0.3 per cent. The resulting effective density of the pile was 1.678 gm /cm^3.

A summary of the physical specifications of the one curie Pu-Be neutron sources is given in Table 1.

A source was held in a graphite positioning cylinder, shown in Fig. 3, of inner diameter such that the sources fit snugly in the cylinders and of outer diameter such that the cylinders fit closely in the fuel ports of the graphite pile.

Standard Pile Configuration

For the standard pile analysis, a source in its graphite positioning cylinder, was located in the column in the bottom row of fuel ports (just above the pedestal) such that the central axis along the length of the source containers coincided with the horizontal central axis of the fuel port, and also so that the center of the source coincided with the vertical central axis of the pile. In this position, the center point of the source arrangement was 26 inches from the bottom, 74 inches from the top, and 34 inches from any side of the column.

A schematic diagram of the standard pile showing the various detector locations in relation to the source is shown in Fig. 4.

Finite Pile Configuration

For the finite pile analysis, a source was positioned in the plane of the fifth layer of fuel ports, in the same centering arrangement within the

Table 1. Summary of physical specifications of Plutonium-Beryllium neutron sources (8).

Source number	Grams Pu	Grams Be	Neutron emission rate (n/sec)
365	7.87	15.99	1.54×10^6
366	7.87	16.01	1.61×10^6
367	7.86	15.89	1.71×10^6
368	7.86	15.88	1.58×10^6
369	7.86	16.09	1.60×10^6

The inner container of each source is 0.85 inches in diameter, 0.90 inches in height, and is made of tantalum. The outside container of each source is 1.02 inches in diameter, 1.30 inches in height, and is made of stainless steel. All sources are sealed by welding. The melting point of tantalum is $5,425^0$ F. The melting point of 18-8 stainless steel is $2,600^0$ F.

The sources were calibrated by comparison to within ± 2 per cent of standards calibrated at the Los Alamos Scientific Laboratory. The absolute accuracy of the Los Alamos standard is reported as ± 5 per cent (7), thus giving an absolute accuracy of ± 7 per cent to the sources listed above.

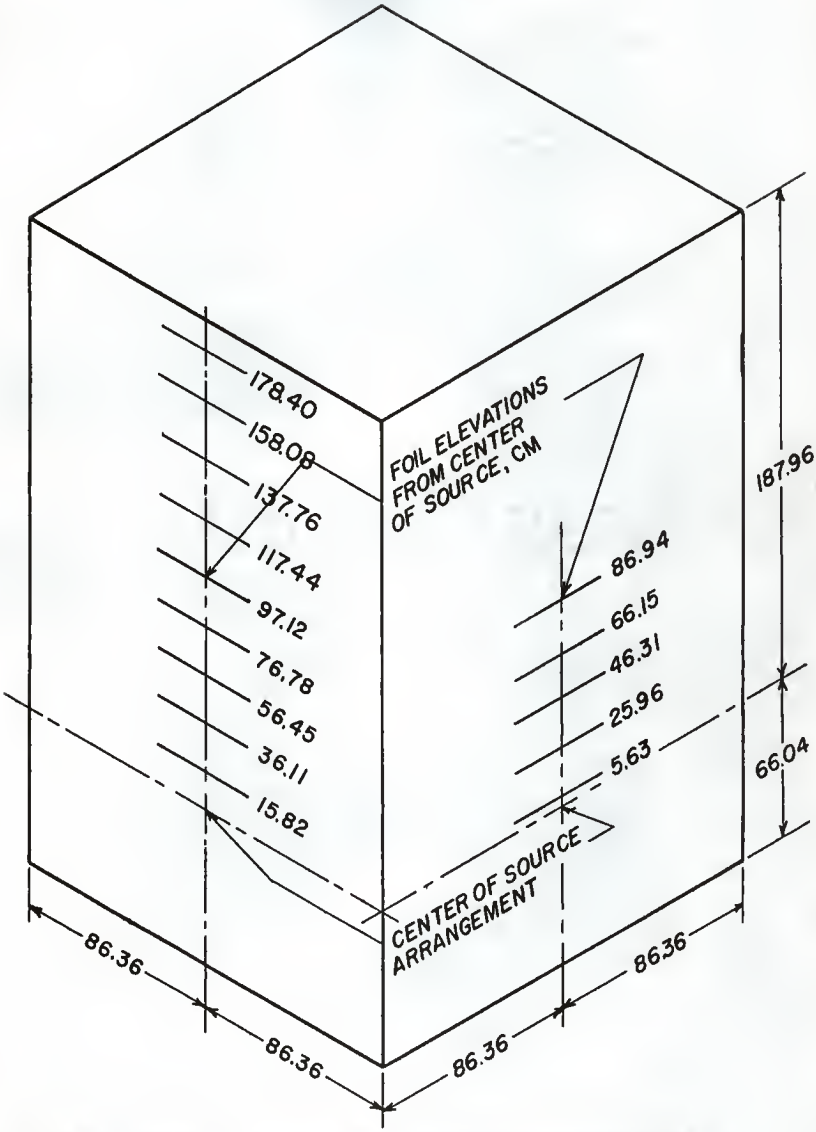


Fig. 4. Schematic diagram of KSU Standard Graphite Pile.

plane as was used with the standard pile arrangement. Cadmium sheets, approximately 0.020 inches thick were inserted in the plane separating the pedestal from the first row of fuel port blocks in order to create an artificial boundary at that point. Provision for this arrangement was made at the time of the original construction of the pile by inserting strips of 1100 aluminum alloy having a width of 0.50 inch and a thickness of 0.032 inch. The aluminum strips were spaced such that sheets of cadmium approximately 8 inches wide could be inserted easily.

The two uppermost layers of graphite were removed from the pile for the finite geometry measurements. This left the pile in such a state that it approximated a cube with sides of 68 inches, and with one source in the center of this cube. A schematic view of this pile arrangement is shown in Fig. 5.

Foil Counting Facilities

The indium foils, shown in Fig. 6, were 1.00 inches in diameter, had a thickness of approximately 0.005 inches, and weighed an average of 0.4592 gm, giving a mg/cm^2 thickness of 92.7. The foils were chosen such that their weights did not differ by more than one per cent.

The cadmium covers, shown in Fig. 6, were constructed by pressing them from a cadmium sheet. The covers had an inside diameter of slightly more than one inch and a wall thickness ranging from 0.021 inches to 0.022 inches. In addition to the cover, the foils were covered on both sides with cadmium disks of the same thickness as the covers, giving an overall average cadmium covering thickness of 0.043 inches.

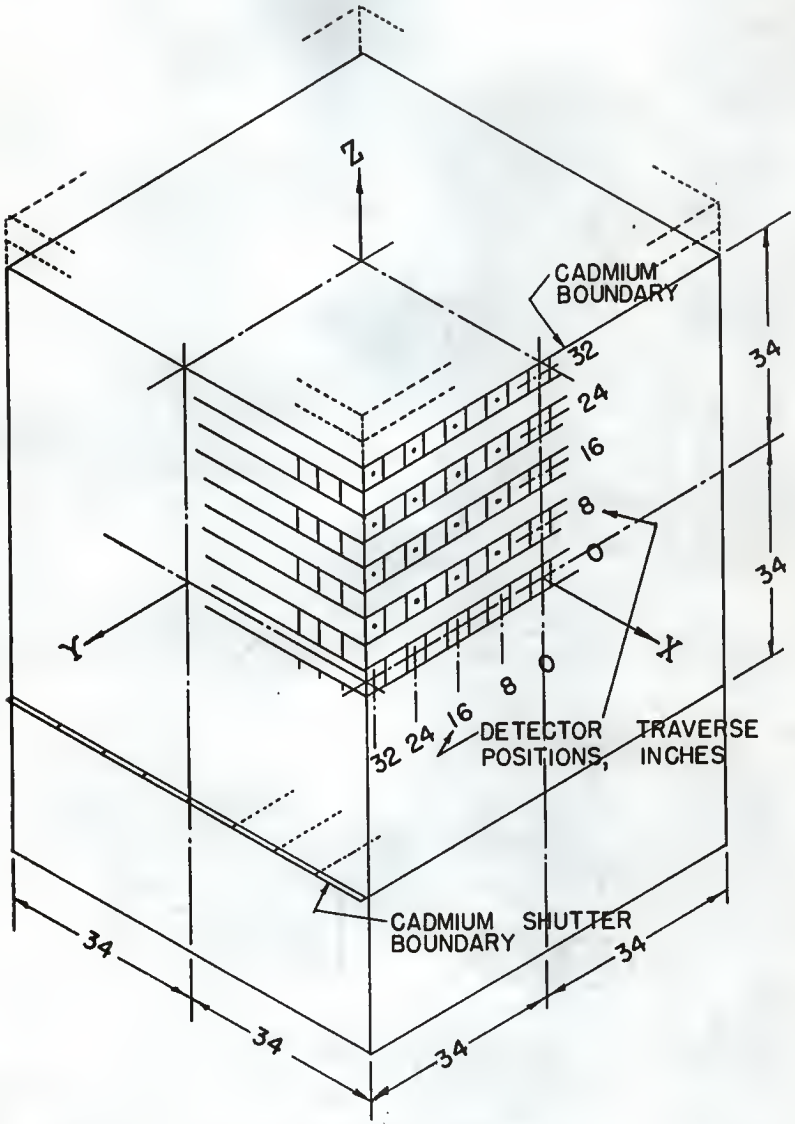


Fig. 5. Schematic diagram of finite pile.

Fig. 6. Cadmium covered foil assembly.

Aluminum covers were made in the same manner for the purpose of protecting and supporting the foil during bare foil measurements. Aluminum disks were inserted between the foil and the cover in order to duplicate the irradiation geometry used in the cadmium covered foil measurements.

The foil stringers, 0.125 inches by 0.325 inches by 12 inches, shown in Fig. 3, were constructed from the same material as the graphite blocks. The stringers were recessed so that the foils with their covering material could be positively positioned in the center of each stringer.

The foil counting system shown in Fig. 7 consisted of a B. J. Electronics Model DD7 continuous flow proportional counter, a Baird Atomic Model 255 proportional counter preamplifier, a Baird Atomic Model 132 scaler, and a Baird Atomic Model 322 timer. The KSU Nuclear Engineering Inventory No. of the scaler was 145, and the proportional counter, 369. The local identification of the preamplifier was KSU Nuclear Laboratory Inventory No. 10025. The proportional counter had a tungsten collector wire with a one half inch loop. The counting gas was Olin-Matheson P-10, a mixture of 10 per cent methane and 90 per cent argon.

The proportional counter was housed in a lead brick shield such that the minimum shield thickness at any point was at least 2 inches. A 0.020 inch thick aluminum tray was constructed to facilitate the removal and the positioning of the foil in the counter well.

The major portion of the foil counting system just described was due to the efforts of Steichen (39).

Fig. 7. Foil counting system

Neutron Probe Facilities

The counting system used in the neutron probe measurements is shown in Fig. 8. Measurements were made with both a BF_3 probe, Nuclear Engineering Inventory No. 97, and a Scintillation probe, N. E. No. 99. The BF_3 probe counting system consisted of a Nuclear Chicago Model NC-202 BF_3 neutron probe, a Nuclear Chicago Model 1062 preamplifier, a Baird Atomic Model 132 scaler, a John Fluke Model 400 BDA high voltage power supply, a B. J. Electronics Model DM1-D count rate meter, and an Esterline Angus Model A.W. strip chart recorder.

The scintillation probe counting system was identical except that a Nuclear Chicago, Model DS8-10, scintillation detector, was substituted for the NC-202 BF_3 probe and its Model 1062 preamplifier.

The basic detector portion of the DS8-10 scintillation probe had a transitorized preamplifier and a 10-stage photomultiplier with cesium antimony dynodes, housed in a container 9-1/4 inches long by 1 inch diameter. The SN-6 neutron probe portion had a thermal neutron crystal which was a phosphor of silver activated zinc sulfide, 95 per cent enriched with boron-10. It was attached at the end of an aluminum covered lucite light pipe, 42 inches long by 5/16 inch outside diameter.

The BF_3 probe active volume, with length of 1/2 inch and diameter of 3/16 inch, contained $B^{10}F_3$ gas at a pressure of 70 cm Hg and at an enrichment of 96 per cent. The Model 1062 transistorized preamplifier had a length of 6.25 inches and a diameter of 1.5 inches.

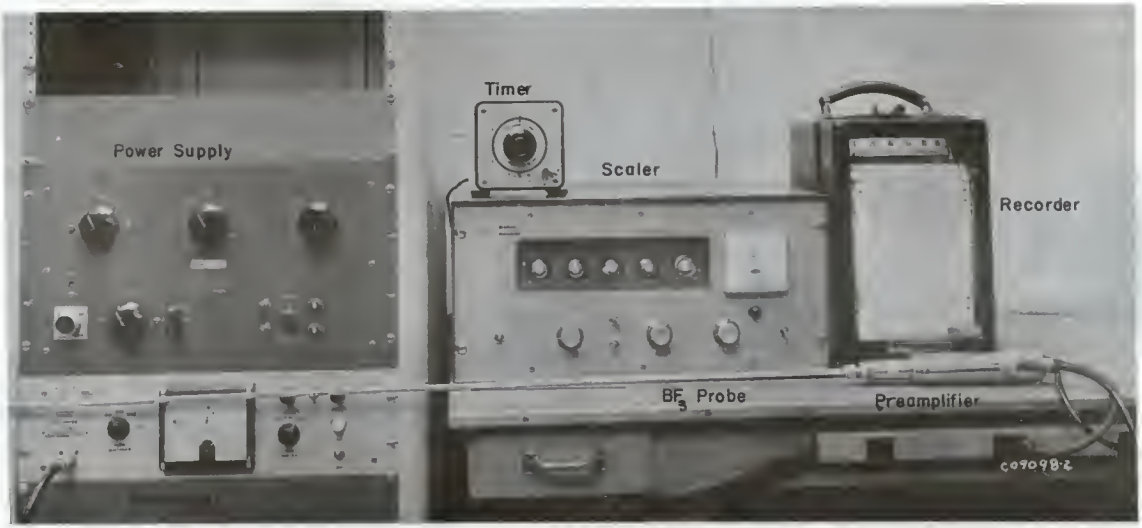


Fig. 8. Neutron probe counting system.

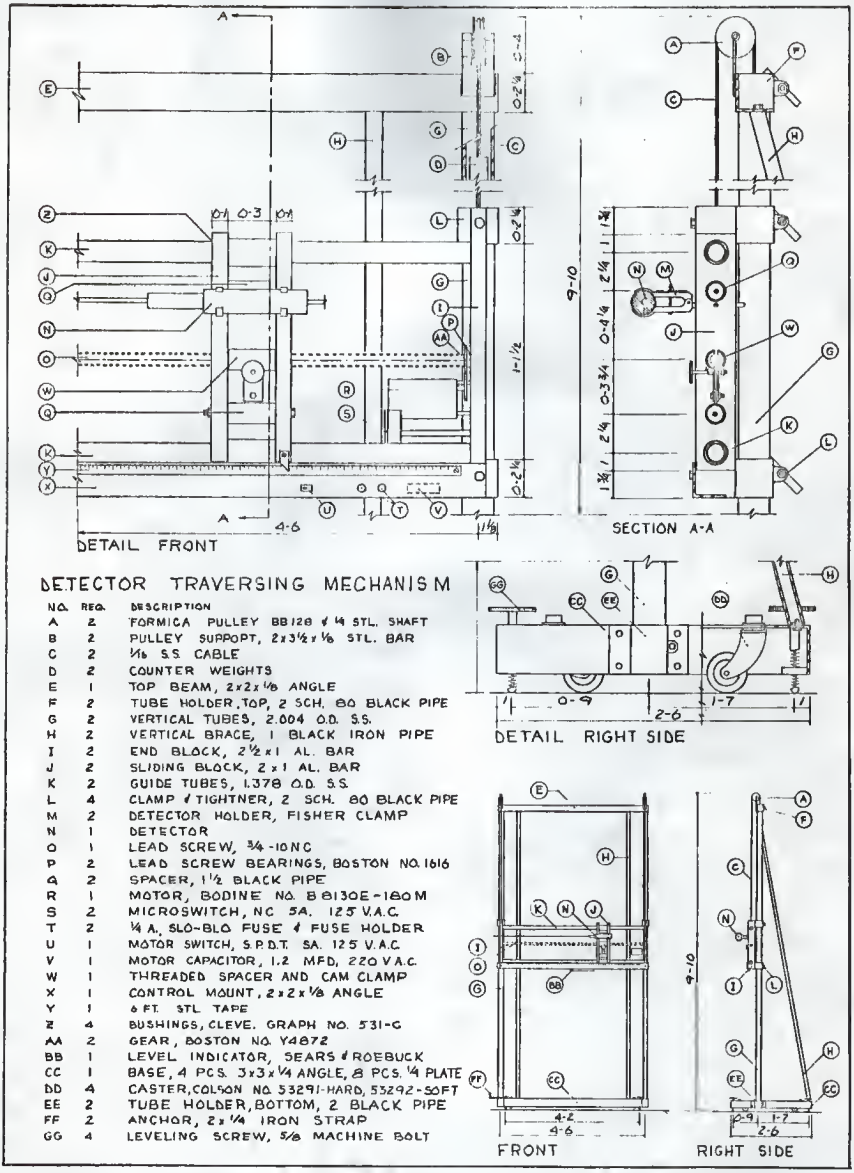
The BF_3 probe is shown with the counting system in Fig. 8; the scintillation probe is shown in Fig. 12.

Traversing Mechanism

For the purpose of supporting these two detectors in a variety of positions in the pile, a traversing mechanism was designed and built. A drawing of this mechanism is displayed as Fig. 9. Figures 10 and 11 include photographs of the complete assembly, and Fig. 12 shows a close-up view of the positioning device of the mechanism.

The mechanism was designed such that the detector could be positioned positively at any elevation between the limits of 19 inches and 101 inches. The detector could be positioned horizontally into the pile either by hand adjustment or motor powered adjustment. A cam action engaging device allowed the detector to be moved horizontally at the rate of one inch per minute by the motor and lead screw, or it allowed the detector to be positioned freely by hand. The mechanism was designed such that a maximum horizontal traverse of 40 inches was available.

The complete traversing mechanism could be moved to a different horizontal position on the face of the pile as a result of caster wheels mounted on the base. The base of the mechanism could be positioned firmly in a desired position with respect to the floor by use of the leveling screws at each corner of the base, which allowed the caster wheels to be raised from the floor.



DETECTOR TRAVERSING MECHANISM

NO.	REQ.	DESCRIPTION
A	2	FORMICA PULLEY BB128 ∅ 1/4 STL. SHAFT
B	2	PULLEY SUPPORT, 2x3½x⅛ STL. BAR
C	2	1/16 S.S. CABLE
D	2	COUNTER WEIGHTS
E	1	TOP BEAM, 2x2x⅛ ANGLE
F	2	TUBE HOLDER, TOP, 2 SCH. 80 BLACK PIPE
G	2	VERTICAL TUBES, 2.004 O.D. S.S.
H	2	VERTICAL BRACE, 1 BLACK IRON PIPE
I	2	END BLOCK, 2½x1 AL. BAR
J	2	SLIDING BLOCK, 2x1 AL. BAR
K	2	GUIDE TUBES, 1.378 O.D. S.S.
L	4	CLAMP ∅ TIGHTNER, 2 SCH. 80 BLACK PIPE
M	2	DETECTOR HOLDER, FISHER CLAMP
N	1	DETECTOR
O	1	LEAD SCREW, ¾-10 NC
P	2	LEAD SCREW BEARINGS, BOSTON NO. 1616
Q	2	SPACER, 1½ BLACK PIPE
R	1	MOTOR, BODINE NO. B 8130E-180M
S	2	MICROSWITCH, NC 5A. 125 V.A.C.
T	2	¼ A. SLO-BLO FUSE ∅ FUSE HOLDER
U	1	MOTOR SWITCH, S.P.D.T. 5A. 125 V.A.C.
V	1	MOTOR CAPACITOR, 1.2 MFD, 220 V.A.C.
W	1	THREADED SPACER AND CAM CLAMP
X	1	CONTROL MOUNT, 2x2x⅛ ANGLE
Y	1	6 FT. STL TAPE
Z	4	BUSHINGS, CLEVE. GRAPH NO. 531-G
AA	2	GEAR, BOSTON NO. Y4872
BB	1	LEVEL INDICATOR, SEARS ∅ ROEBUCK
CC	1	BASE, 4 PCS. 3x3x¼ ANGLE, 8 PCS. ¼ PLATE
DD	4	CASTER, COLSON NO. 53291-HARD, 53292-SOFT
EE	2	TUBE HOLDER, BOTTOM, 2 BLACK PIPE
FF	2	ANCHOR, 2x¼ IRON STRAP
GG	4	LEVELING SCREW, ⅝ MACHINE BOLT

Fig. 9. Traversing mechanism for graphite pile, assembly drawing.

Fig. 10. Traversing mechanism and standard pile.

Fig. 11. Traversing mechanism and finite pile.

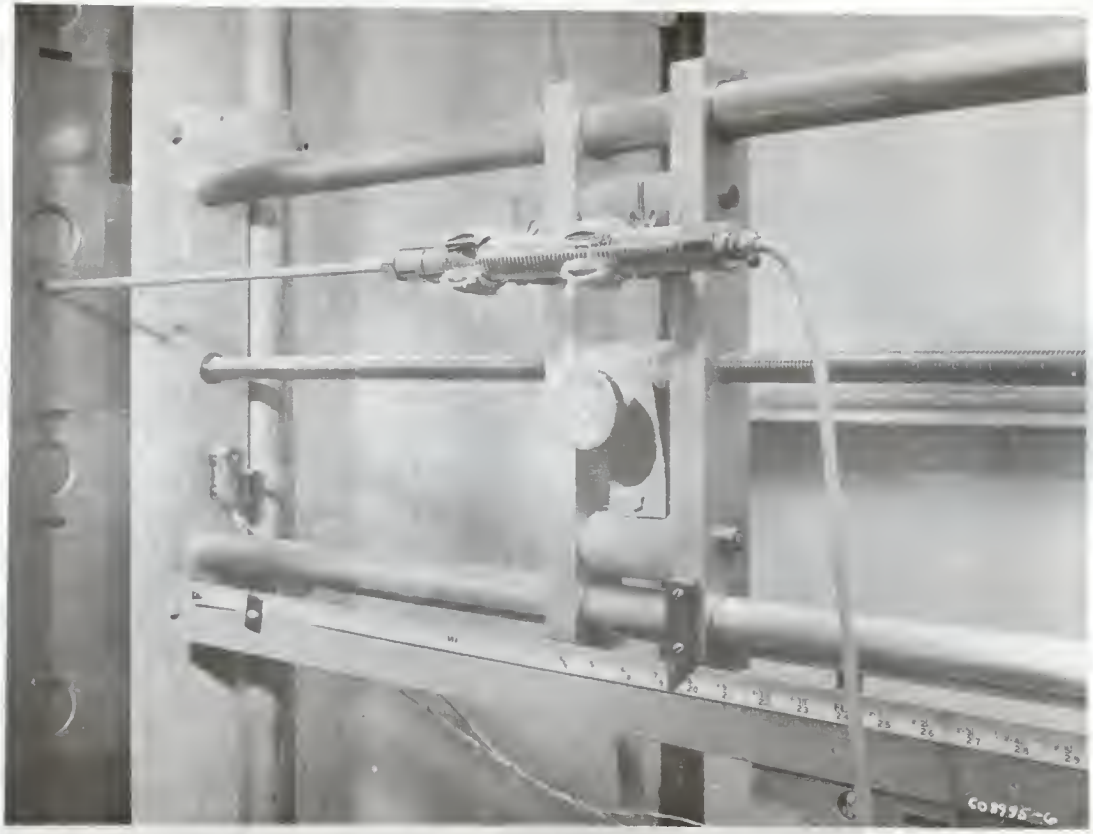


Fig. 12. Sliding assembly of traversing mechanism with scintillation probe.

In order to accommodate these neutron probes in a maximum number of positions and with the minimum amount of created void space, the three 1.652 inch diameter graphite cylinders, shown in Fig. 13, were drilled along their central axis to a diameter of 3/8-inch. Their use to accommodate a probe may be seen in Fig. 11.

EXPERIMENTAL PROCEDURE

Foil Measurements

All foil experiments were performed using one of the neutron sources described in Table 1. The source was placed in position in the pile as described in the section on experimental facilities. The foils in their appropriate covering material were placed in the foil stringer. The foil stringers were then placed in the pile such that the indium foils were centered on a line along the vertical axis of the column, directly above the center of the neutron source.

The foils were allowed to remain in the pile at least 7 hours until they reached equilibrium saturation activity with respect to the 54 minute half-life isotope. The foil nearest to the source was removed and a spare foil in an identical covering material was placed in the vacated position. The removed foil was allowed to "cool" for 3 minutes to assure the decay of the 13 second half-life isotope, and was then counted for a period of 27 minutes. At the end of the counting period, the foil second closest to the source was removed and the foil which had just been counted was immediately placed in the vacated position. This procedure was followed until all foils in the pile had been counted. A

Fig. 13. Special graphite cylinders for accommodation of neutron probes.

total of eleven sets of data using cadmium covered indium foils were taken using this procedure. Of these eleven trials, 5 were made counting the activity of the source side of the foil, and 6 were made counting the side of the foil away from the source. A total of 4 sets of data were taken using aluminum covered indium foils. Of these 4 trials, 2 were made on each side of the foil. The background count was taken for a period of 27 minutes before and after the counting periods for each of the sets of data. The data for cadmium covered indium foils were taken by Steichen (39).

The counter was operated at 1,950 volts, and with a pulse height sensitivity setting of 0.2. A number of trials were made by Steichen using various sensitivity settings, foil-collector wire spacings, and sizes of collector wire loops, to obtain an optimum operating plateau and minimum counter background.

The counting system was checked for stability before and after each trial with standard Ra-D-E source, Nuclear-Chicago Serial No. 2354. All foil data used in pile standardization were taken with the counting system in such a condition that the count rate from the standard Ra-D-E source was within 200 counts of 17,048 counts per minute.

Neutron Probe Measurements in Standard Pile

All experiments with the neutron probes were performed using one of the neutron sources described in Table 1. Probe measurements were made in both the foil slots and the fuel ports. Measurements in the fuel

ports were made using the special graphite cylinders described in the section entitled "EXPERIMENTAL FACILITIES."

Probe data for the standard pile analysis were taken such that 10,000 counts were obtained in each selected position. For the BF_3 probe, this was done with 7 series of runs getting 1,000 counts in each position, and one run getting 3,000 counts in each position. For the scintillation probe, this was done with a series of 10 runs, getting 1,000 in each selected position.

BF_3 probe data were taken at an operating voltage of 1,450 volts, and a pulse height sensitivity setting of 0.8. Scintillation probe data was taken at the same pulse height sensitivity but with an operating voltage of 11,000 volts.

Before each series of runs, 10 one-minute counts were taken in a standard position to check for proper distribution and counter reproducibility. All BF_3 probe measurements were taken at an operating condition such that a count rate of 1,764 $\pm$25 counts per minute was obtained at a position 15.82 cm directly above source number 368 in the standard pile configuration. All scintillation probe measurements were taken at an operating condition such that a count rate of 2533 $\pm$57 counts per minute was obtained in this same standard position. The variance reported on these count ranges is the standard deviation of a single observation.

The count rate meter and the strip chart recorder were used to monitor the counting during periods of operator absence, thus insuring that no erratic data were recorded.

Neutron Probe Measurements in Finite Pile

All measurements for the experiment in the finite geometry which compared the various source conditions to the thermal diffusion equation were made with the standardized BF_3 probe operating at the conditions described in the previous section.

The medium was mapped by means of the special graphite cylinders placed in the five hole by five hole array of fuel ports of the upper, northwest 1/8th of the finite medium (see Fig. 5). By selecting positions at 4-inch intervals along the horizontal traverse into the special graphite cylinders, 9 positions were available in each of 24 fuel ports, and 8 positions were available in the one fuel port containing the source, thus making a total of 224 positions to be counted for each pile mapping. This procedure resulted in a 3-dimensional mapping using a net dimension of 4 inches by 8 inches by 8 inches.

The data were taken such that in each position, either 1,000 counts were obtained or 10 minutes counting time had elapsed, depending on which condition was met first. Each selected position was counted for at least 2 minutes. Four complete traverses of the 224 positions were made to get the average at each position as reported in the results.

DATA PRESENTATION AND ANALYSIS

Pile Standardization Data Treatment

The raw data averages used in the standard pile analysis were corrected for background and tabulated in Table 2. All data used in the pile

standardization were based on source No. 368 used by Steichen, having an emission rate of 1.58×10^6 neutrons per second (see Table 1). It is important to note that A_{In}, the activity of an aluminum covered or bare indium foil and A_{CdInCd}, the activity of a cadmium covered indium foil, has always been reported in this work as the total counts over the 27 minute counting period.

The foil data may be adjusted to give activity at the time of removal by well known decay laws which results in the equation,

$$\begin{pmatrix} \text{Total counts in} \\ \text{27 minute counting} \\ \text{period} \end{pmatrix} = \int_{3\ \text{min}}^{30\ \text{min}} A_{Sat}\, e^{-\lambda_d t}\, dt. \qquad (27)$$

Using λ_d as $0.012815\ \text{min}^{-1}$ for the appropriate decay constant of indium, the saturation activity at the time of removal from the pile may be found from

$$A_{Sat} = \begin{pmatrix} \text{Total counts in 27 min-} \\ \text{ute counting period} \end{pmatrix} (0.0422). \qquad (28)$$

This may be considered to be the saturation activity since the foils were always irradiated for seven half-lives or more.

Column 2 of Table 2 lists the cadmium covered indium foil data as measured by Steichen in his determination of the age of neutrons from a Pu-Be source in graphite (39). Columns 4 and 5 list the counts per minute obtained from BF_3 probe measurements and scintillation probe measurements. The error quoted in all cases is the standard deviation of the mean. It includes only the statistical

Table 2. Summary of standard raw data.

z	A_{CdInCd}	A_{In}	A_{BF_3}	A_{Sc}
cm	total counts in 27 minute count period	total counts in 27 minute count period	counts per minute	counts per minute
5.63	35,199.0 ± 92.0	201,715 ± 3,367	1,856.00 ± 14.0	2,823.0 ± 19.0
15.82	27,668.0 ± 101.0	184,099 ± 604	1,764.00 ± 8.0	2,501.0 ± 18.0
25.96	18,543.0 ± 42.0	152,790 ± 368	1,528.00 ± 14.0	2,217.0 ± 25.0
36.11	10,752.0 ± 34.0		1,228.00 ± 10.0	1,716.0 ± 14.0
46.31	5,686.0 ± 35.0	89,840 ± 317	973.00 ± 8.2	1,341.0 ± 16.0
56.45	2,558.0 ± 12.0	62,977 ± 1,057	700.00 ± 6.1	948.9 ± 8.7
66.15	1,174.0 ± 8.0		515.90 ± 6.9	692.0 ± 6.1
76.78	468.5 ± 6.4	32,437 ± 286	371.60 ± 2.5	509.6 ± 4.2
86.94	209.8 ± 6.4	23,661 ± 116	272.90 ± 2.5	374.2 ± 4.3
97.12	93.1 ± 6.1		196.40 ± 2.2	256.7 ± 2.5
117.44		8,763 ± 148	100.40 ± 2.0	132.4 ± 1.8
137.76		4,287 ± 95	51.30	66.5 ± 1.1
158.08			24.63	32.0 ± 0.9
178.40			7.54	

error of the experimental data. Steichen's data for A_{CdInCd} were a combination of data taken with four sources and data taken with one source. The corrected activities for four source geometry were normalized to the one source geometry at 46.31 cm. Steichen felt that the four source data gave better statistics than the one source data at points far from the source. At these points, the correction for the finite size of the four sources became small.

The purpose of the foil measurements was to get quantities proportional to the thermal flux and the slowing down density at indium resonance energy. The activity due to thermal neutrons only was determined by means of a cadmium difference method. The foil was exposed to neutrons at a given position, first uncovered and then covered with a layer of cadmium 0.043 inches thick. Since cadmium absorbs the thermal neutrons, the activation of the cadmium covered indium foil was due primarily to epithermal neutrons while the uncovered indium foil activation was due to both thermal and epithermal neutrons. The difference in these two activations, the cadmium difference, after account was taken of the epithermal neutron absorption in the cadmium cover by the factor F_{cd} (40), was taken to be proportional to the thermal flux.

$$(nv)_{th} = K_{th} A_{th} = K^0_{th} F' (A_{In} - F_{Cd} A_{Cd\,In\,Cd}) \qquad (29)$$

In this expression, K_{th} is the constant of proportionality between flux and cadmium difference activation which standardizes the detector. F' is a term containing considerations of perturba-

tions and corrections introduced through experimental limitations and finite foils. K^0_{th} is the constant of proportionality which is independent of these corrections and perturbations.

The term F' may include the following considerations:

a) activation of indium by higher energy resonance neutrons

b) absorption of epithermal neutrons in the cadmium filter

c) finite size of source and detector

d) difference in foil weights and size

e) unequal activation of two sides of foil

f) flux depression in vicinity of foil

g) self-shielding of the center of the foil by its outer layers

h) mutual shadowing of neighboring foils

i) hardening of the neutron spectrum through the foil

j) obliquity of foil with respect to the source.

These correction factors are discussed further in Appendix H. Reasons for consideration or rejection of individual correction factors are given, and the correction factors (a) through (e) which were used in this work are discussed quantitatively. The standardization constants determined in this thesis may be used only in graphite since many of the neglected correction factors depend upon the diffusing medium.

As outlined in the theory, the slowing down density at indium resonance energy may be taken to be proportional to the activation of a cadmium covered indium foil.

$$q_{res} = K_{res} A_{res} = K^{o}_{res} F' A_{CdInCd} \tag{30}$$

F' again represents appropriate correction factors that may be applied to the foil activations.

It must be kept in mind that for a $1/v$ absorber such as indium in the thermal range and for a resonance absorber in the epithermal range, the foil activation is more correctly proportional to the density of thermal neutrons or to the density of resonance neutrons (16). Hence, for a foil of $1/v$ cross section, A_{th} is proportional to n_{th}, not $(nv)_{th}$, making K_{th} depend upon the energy distribution of the thermal neutrons. Thus, foils standardized in graphite for thermal flux cannot readily be extrapolated for use in any other medium where the energy distribution of the thermal neutrons may be different.

In the case of a slowing down density standardization, where A_{res} is proportional to n_{res} and q_{res}, the standardization constant for converting A_{res} to q_{res} cannot be directly used in media other than graphite (16) since

$$q_{res} = \frac{n_{res} v_{res} \xi}{\lambda} = K_{res} A_{res} \tag{31}$$

where λ represents the scattering mean free path. To convert from graphite to water, the slowing down density standardization constant in water would have to be expressed (16) as

$$K_{res}\,(\text{water}) = K_{res}\,(\text{graphite}) \frac{\lambda\,(\text{graphite})\xi\,(\text{water})}{\lambda\,(\text{water})\,\xi\,(\text{graphite})} \tag{32}$$

Table 3 presents the corrected foil activations A_{res} and A_{th} which are considered to be proportional to the slowing down density at indium resonance energy and the thermal neutron flux, respectively. The end correction factor given by Eq. 23 in the theory, which adjusts the finite pile measurements to make them appear as if they had been taken in an infinite pile, is given in Column 4 of Table 3. Columns 5, 6, and 7 give the adjusted infinite pile measurements with foils, the BF_3 probe and the scintillation probe. Perturbations of the thermal flux by the two probes have not been considered. The count rates from these two instruments have been assumed to be proportional to the thermal neutron density, so that they are subject to the restriction that the standardization constant found in graphite is not useable in a medium where the energy distribution of the thermal neutrons may be different. The thermal standardization constants for these detectors will be found from the relationships

$$(nv)_{th} = K_{th}\,(BF_3)\,R_{BF_3} \tag{33}$$

and

$$(nv)_{th} = K_{th}\,(Sc)\,R_{Sc} \tag{34}$$

where R signifies count rate.

Empirical Fit of Indium Resonance Date

It may be recalled from the theoretical development of the standard pile analysis that an empirical fit of the quantity proportional to the slowing down density at indium resonance was

Table 3. Summary of experimental measurements for standard pile analysis.

Distance from source	A_{res}	A_{th}	C_e	$A_{th}C_e$	$R_{BF_3}C_e$	$R_{Sc}C_e$
cm	Counts in 27 minute counting period	Counts in 27 minute counting period		Counts in 27 minute counting period	Counts/min.	Counts/min.
5.63	32,623.0 ± 92	164,820 ± 3,370	1.0000	164,820	1,856.0	2,823
15.82	26,738.0 ± 101	153,967 ± 612	1.0000	153,967	1,764.0	2,501
25.96	18,335.0 ± 42	132,239 ± 470	1.0000	132,239	1,528	2,217
36.11	10,817.0 ± 34		1.0000		1,228	1,716
46.31	5,673.0 ± 35	83,546 ± 319	1.0000	83,546	973.7	1,341
56.45	2,576.0 ± 12	60,109 ± 1,056	1.0000	60,109	700.0	948.9
66.15	1,159.0 ± 8		1.0000		515.9	692.0
76.78	470.7 ± 6.4	31,914 ± 286	1.0000	31,914	371.6	509.6
86.94	212.5 ± 6.4	23,415 ± 116	1.0000	23,415	272.9	374.2
97.12	92.9 ± 6.1		1.0030		197.0	257.5
117.44		8,763 ± 148	1.0110	8,859	101.5	133.9
137.76		4,287 ± 95	1.0400	4,458	53.35	69.2
158.08			1.1570		28.50	37.02
178.40			1.9608		14.78	

required in order to express the slowing down density in the analytical form of Eq. 14. An IBM-650 code was developed for this purpose of fitting the data with a function of Gaussian form. It is given in Appendix G.

This fit was made by a trial and error procedure which strived to minimize the sum of the weighted squares of the residuals between the experimental values and the values calculated from the empirical expression. Tables 4 and 5 summarize these efforts to fit empirically the resonance data. The effect of various correction factors applied to the resonance data, the effect of the number of terms used in the finite summation, and the effect of a weighting function were studied.

The best fit may be considered on the basis of two different criteria; one, that the sum of the weighted residuals squared be a minimum; or two, that the residual between the calculated and experimental value at any point should lie within the statistical standard deviation of the experimental measurement. A weighting function of unity allows the former criterion to be satisfied more satisfactorily. Scarborough (33) points out that the residuals squared are best weighted with the reciprocal of the standard deviation squared $1/\sigma^2$ This weighting function allows the latter criterion to be satisfied more completely.

A consideration of interest was the necessary number of terms needed in Eq. 14 to fit adequately the resonance data. Since the fit was made to only ten data points, there was some limitation on the number of terms which could be used, each term having two parameters.

Table 4. Summary of resonance data fits.

Distance from source in cm			5.63	15.82	25.96	36.11	46.31	56.45	66.15	76.78	86.94	97.12	
Experimental deviations			±92	±101	±42	±34	±35	±12	±8	±6.4	±6.4	±6.1	
Data	No. of terms	Weight function	Residuals between experimental values and calculated values										Sum of squares of residuals
Raw	3	1	(-4.3)	(12.3)	-43.0	93.7	-107.7	34.3	(-1.2)	19.5	(4.6)	(1.5)	2.40×10^4
G	3	1	(-5.6)	(18.1)	-47.5	89.3	-105.0	37.3	(0.2)	18.3	(3.3)	(0.3)	2.35×10^4
W	3	1	(-4.0)	(11.3)	(-29.7)	49.8	- 62.2	24.5	9.4	7.4	-7.0	(-4.1)	8.17×10^3
R	3	1	(37.0)	(-66.4)	(5.1)	81.8	- 99.6	56.6	(-3.1)	(-1.8)	-11.8	(-1.6)	2.58×10^4
GW	3	1	(-3.3)	(9.2)	(-26.5)	47.8	- 63.5	24.2	11.0	7.9	-6.7	(-4.4)	7.94×10^3
GR	3	1	(37.2)	(-67.5)	(5.8)	81.6	- 99.6	56.5	(-2.6)	(-2.1)	-11.8	(-1.9)	2.59×10^4
RW	3	1	(14.4)	(-30.9)	(21.4)	(17.7)	- 63.8	49.6	15.6	-6.7	-19.4	(-6.1)	9.17×10^3
GWR	3	1	(13.0)	(-31.1)	(23.5)	(15.5)	- 64.6	48.3	16.1	(-6.2)	-18.0	(-4.9)	9.08×10^3
GWR	4	1	(15.8)	(-37.2)	(24.9)	(22.4)	- 66.8	41.8	14.9	(-2.8)	-15.2	(-2.8)	9.43×10^3
GWR	2	1	(-56.5)	(30.9)	102.1	(-16.3)	-150.0	19.2	55.2	52.4	18.1	(4.6)	4.39×10^4
GWR	1	1	289.5	110.0	391.0	141.0	-312.0	-366.0	-355.0	-250.0	-159.0	-82.0	7.21×10^5
GWR	3	$1/\sigma^2$	(-27.3)	(-29.5)	(33.6)	(-7.2)	-110.3	(12.2)	(1.9)	(-2.5)	-7.8	(5.5)	1.51×10^4
GWR	4	$1/\sigma^2$	(-10.7)	(-37.4)	(26.4)	(-8.0)	-101.0	15.0	(2.6)	(-2.6)	-8.4	(6.8)	1.28×10^4

Key to data treatment: G Geometry correction factor considered
W Weight correction factor considered
R Higher resonance absorption by indium foil correction factor considered
( ) Residual lies within experimental standard deviation

Table 5. Study of amplitudes and ranges of resonance fits.

Data treatment	No. of terms	Weight function	Values of ranges, amplitudes and fractions												
			1st term			2nd term			3rd term			4th term			
			r_1	B_1	f_1	r_2	B_2	f_2	r_3	B_3	f_3	r_4	B_4	f_4	$\Sigma f_i r_i^2/4$
Raw	3	1	16.70	4,711	0.015	33.25	28,223	0.686	50.85	3,442	0.299				384.2
G	3	1	16.85	4,787	0.015	33.25	28,238	0.685	50.56	3,516	0.300				382.1
W	3	1	16.21	4,583	0.013	33.42	28,183	0.698	50.44	3,395	0.289				379.6
R	3	1	26.39	10,546	0.128	36.95	22,455	0.750	63.88	703	0.122				402.4
GW	3	1	16.07	4,488	0.012	33.31	28,280	0.692	50.06	3,566	0.296				378.1
GR	3	1	26.48	10,713	0.131	36.96	22,448	0.749	63.76	700	0.120				400.6
RW	3	1	26.50	10,328	0.128	37.05	22,446	0.758	63.13	684	0.114				396.5
GWR	3	1	26.61	10,495	0.131	37.05	22,445	0.755	63.48	673	0.114				397.2
GWR	4	1	24.38	5,335	0.050	34.00	22,914	0.579	44.65	5,269	0.302	97.09	101	0.069	488.6
GWR	2	1	31.56	22,574	0.572	47.79	5,937	0.428							386.7
GWR	1	1	34.30	33,217	1.000										294.1
GWR	3	$1/\sigma^2$	27.31	11,112	0.149	36.94	21,756	0.722	65.44	695	0.129				411.9
GWR	4	$1/\sigma^2$	24.79	5,250	0.048	33.90	23,108	0.545	44.69	5,128	0.277	113.08	100	0.129	708.0

Key to data treatment: G Geometry correction factor considered
W Weight correction factor considered
R Higher resonance absorption by indium foil correction factor considered.

A fit of the data with one term was considered poor since the residual was much greater than the standard deviation at all experimental points. A fit with two terms was clearly an improvement since the sum of the weighted squares of the residuals decreased by over a factor of ten. The weighted three-term fit of the data corrected for geometry, higher resonance absorption and foil weights, was considered to be the best fit. The residuals of this fit were within or near the standard deviation of the experimental data for all points but one. The fit at 46.31 cm was consistently poor no matter what manner of fit was used. It may be seen from either the individual residuals or the sum of the weighted residuals squared that a fit with four terms did not give an improvement over a fit using three terms. Inspection of the fourth term in the fit reveals the effort of the machine to suppress the fourth term by giving it a small amplitude and a slope tending towards zero, the slope being equal to the reciprocal of the square of the Gaussian range associated with this term.

Consideration of the difference in foil weights had a noticeable improving effect upon the empirical fit. Little improvement was gained from using the correction factors for finite detector and source. The use of the correction factor for absorption of neutrons by the higher resonances of indium markedly changed the various amplitudes, B_i, the Gaussians ranges, r_i, and the fractional contributions, f_i.

Using the parameters of the appointed best fit, the expression for the indium resonance data distribution was

$$A_{res} = 11,112\ e^{-\left(\frac{z}{27.31}\right)^2} + 21,756\ e^{-\left(\frac{z}{36.94}\right)^2} + 695\ e^{-\left(\frac{z}{65.44}\right)^2} \qquad (35)$$

From Eq. 14, the absolute slowing down density to indium resonance energy was

$$\frac{q_{res}}{Q_0}\,10^6 = 1.314\ e^{-\left(\frac{z}{27.31}\right)^2} + 2.572\ e^{-\left(\frac{z}{36.94}\right)^2} + 0.824\ e^{-\left(\frac{z}{65.44}\right)^2} \qquad (36)$$

The IBM-650 program required initial estimates of the fitting parameters which were found from a "stripping-off" procedure. Shown in Fig. 14 are the three "stripped-off" curves which have been superimposed to give the empirical fit of the experimental points.

DISCUSSION AND RESULTS

Standardization Constants

Table 6 lists the values of absolute flux and slowing down density in the Kansas State University Standard Pile, using a source with an emission rate of 1.58×10^6 neutrons per second. The absolute slowing density was determined from Eq. 36. The absolute thermal flux was obtained from the computer code described in Appendix D which numerically evaluated the absolute flux defined by Eq. 20. This code used the empirically determined parameters f_i and r_i after r_i had been extended to thermal energy by Eq. 18. Figures 15 and 16 show the absolute flux and the absolute slowing down density to indium resonance energy. Superimposed upon these calculated curves are

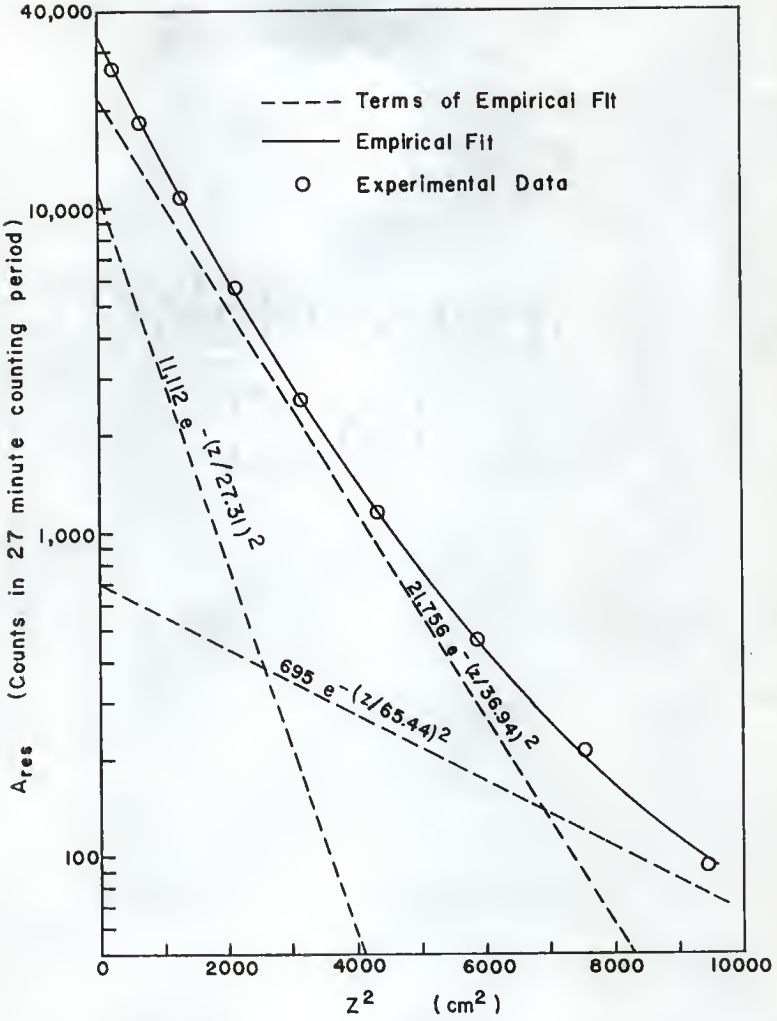


Fig. 14. Indium resonance distribution as empirically fit by three terms of Gaussian form.

Table 6. Summary of standardization constants and standard pile flux.
$Q_o = 1.58 \times 10^6$ n/sec.

Distance from source	q_{res}	$(nv)_{th}$	$K_{res}(foil)=\frac{q_{res}}{A_{res}}$	$K_{th}(foil)=\frac{(nv)_{th}}{A_{th}C_e}$	$K_{th}(BF_3)=\frac{(nv)_{th}}{A_{BF_3}C_e}$	$K_{th}(Sc)=\frac{(nv)_{th}}{A\ C_e}$
cm	n/cm^3-sec	n/cm^2-sec	Density per count in 27 minute counting period	Flux per count in 27 minute counting period	Flux per count per minute	Flux per count per minute
5.63	6.090	2,233.	0.00016903	0.01355	1.2031	0.7910
15.82	4.990	2,058.	0.00016088	0.01337	1.1667	0.8229
25.96	3.432	1,768.	0.00016136	0.01337	1.1571	0.7975
36.11	2.021	1,430.	0.00016106		1.1645	0.8333
46.31	1.040	1,101.	0.00015803	0.01318	1.1307	0.8210
56.45	0.4842	822.1	0.00016205	0.01368	1.1744	0.8664
66.15	0.2173	609.4	0.00016168		1.1812	0.8806
76.78	0.08768	434.02	0.00016058	0.01361	1.1685	0.8520
86.94	0.03836	312.7	0.00015562	0.01335	1.1458	0.8356
97.12	0.01841	225.0	0.00017078		1.1421	0.8738
117.44		117.2		0.01323	1.1547	0.8753
137.76		61.32		0.01376	1.1494	0.8861
158.08		32.15			1.1281	0.8684
178.40		16.89			1.1428	
Average Standardization Constant :			0.00016130 ± 0.00000122	0.01346 ± 0.00070	1.1578 ± 0.0055	0.8465 ±0.0088

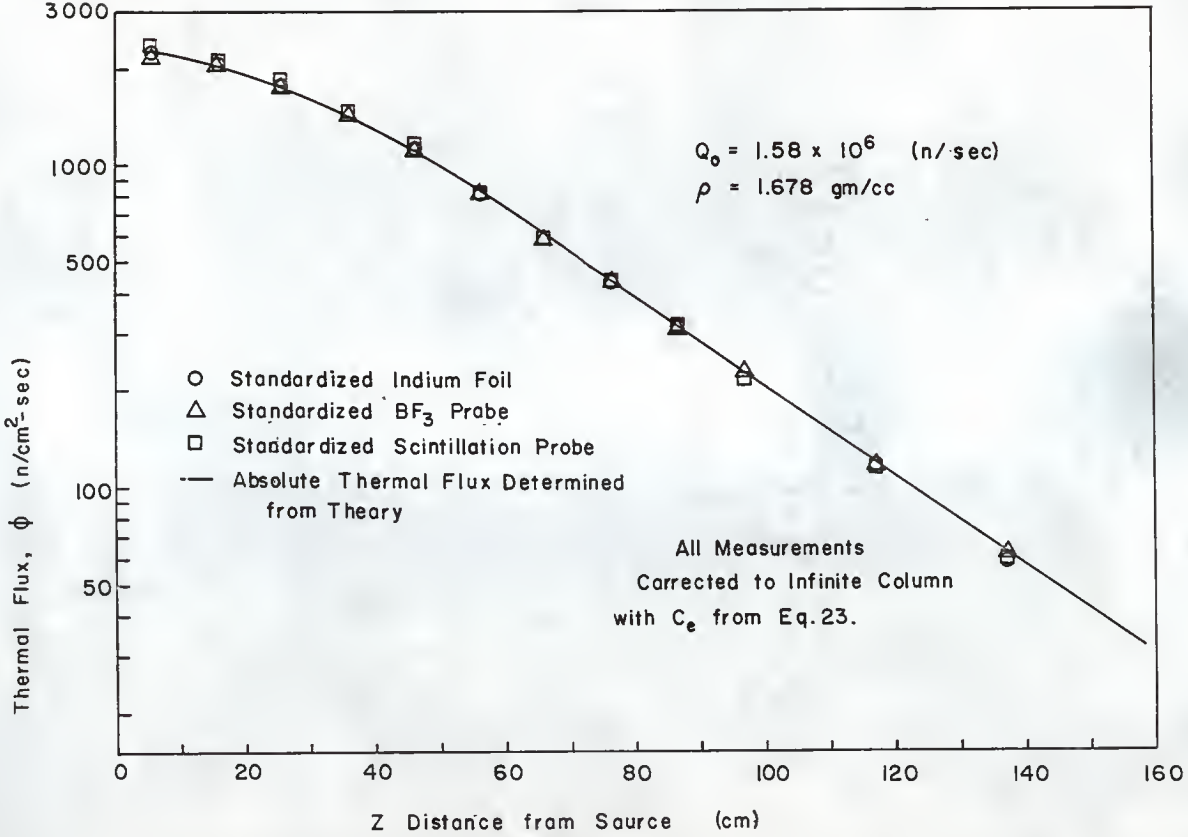


Fig. 15. Thermal flux in KSU Standard Pile.

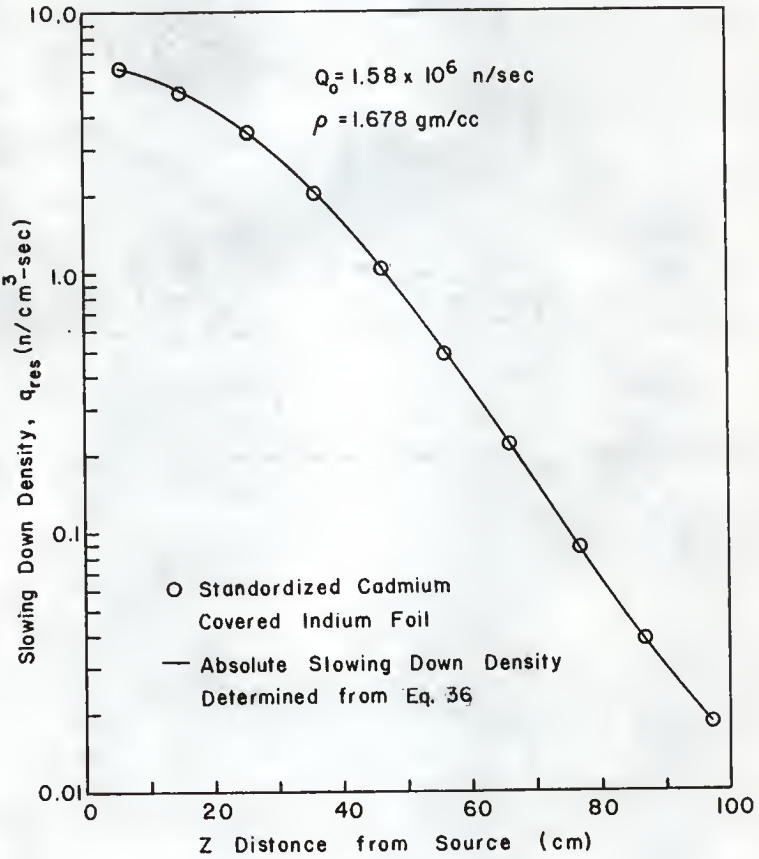


Fig. 16. Slowing down density to indium resononce energy in KSU Stondord Pile.

points showing absolute quantities as determined by detectors which have been standardized according to this thesis.

Columns 4 through 7 of Table 6 list the standardization constants of the various detectors as they were determined in the standard pile analysis. The average standardization constant is listed at the bottom of each column.

Figures 17 show the variation of the measured standardization constants for each detector as a function of the distance from the source. Since the spectrum is harder near the source, a non-random distribution of these constants would indicate a possible energy dependence in the assumed thermal neutron detectors. It can be seen from Figs. 17 that the distributions appear to be random with respect to the average for all detectors except the scintillation probe. The standardization constant distribution of the scintillation probe suggests that the scintillation probe has an appreciable sensitivity for neutrons of epithermal energies. In order to determine a more reliable standardization constant for the scintillation probe, it would be necessary to use a cadmium difference technique such as that used with the indium foils.

Subsequent use of these standardization constants has been made with the average standardization constant.

The absolute flux or slowing down density in a graphite medium may be found from a particular standardized detector by merely multiplying its standardization constant by a properly measured quantity. In the case of the Kansas State University BF_3 probe or scintillation probe, this quantity is counts per minute, corrected for background. In the

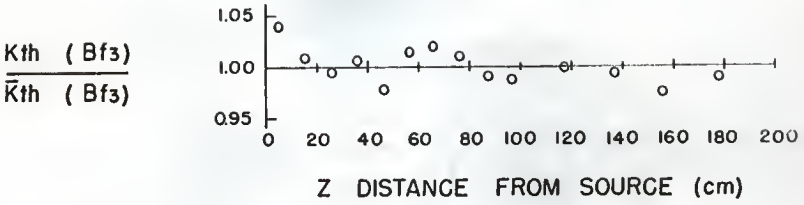


Fig. 17a. Distribution of BF_3 thermal standardization constants about average.

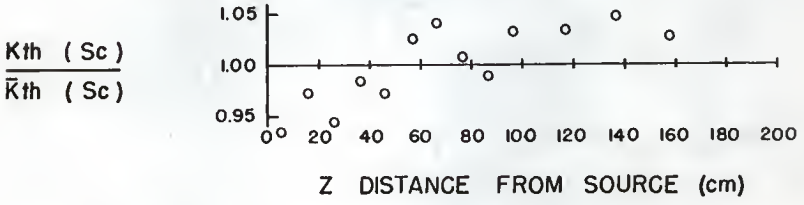


Fig. 17b. Distribution of scintillation probe thermal standardization constants' about overoge.

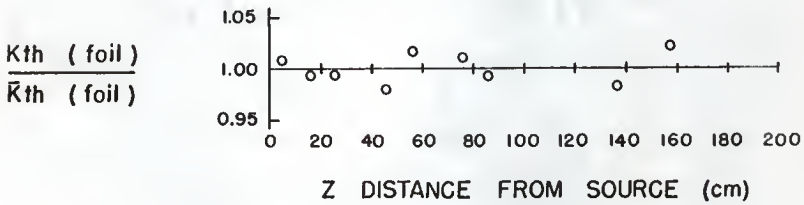


Fig. 17c. Distribution of foil thermol stondardizotion constonts obout overoge.

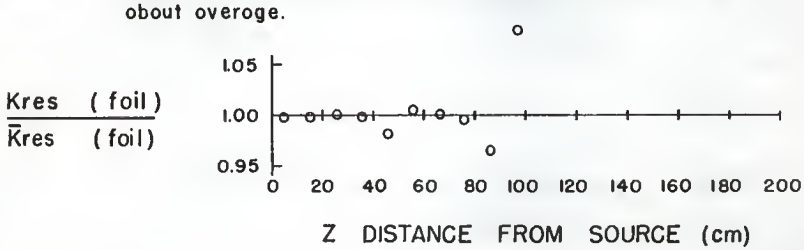


Fig. 17d. Distribution of foil resononce stondordizotion constonts about overoge.

case of KSU standard indium foils, the quantity is expressed in terms of total counts over the 27 minute counting period as explained in the experimental outline.

From Eq. 28, it was shown that for foil measurements this properly determined quantity could be the saturation activity at the time of foil removal from the pile if the standardization constant is used as K(foil)/0.0422.

Before a standardization constant may be used, it must be verified that the counting system reproducibility has not changed. This can be done by reproducing the counter stability check points described in the discussion of the experimental methods.

Confidence Limits on Flux Assignment

The deviation reported on each standardization constant is the standard deviation of the mean standardization constant. This deviation is a measure of the accuracy to which the detector was standardized. It is not a measure of the accuracy of the flux assignment, since as previously pointed out, the accuracy of the flux assignment depends upon the accuracy in the knowledge of the source strength and particular diffusion parameters.

Neutron Sources. The neutron sources, listed in Table 1, were prepared and calibrated by the Mound Laboratory. Their catalog (8) states that the sources were calibrated by comparison with standards calibrated at the Los Alamos Scientific Laboratory. Since the Los Alamos source has a relative absolute calibration ratio of 1.016, (7), compared with the National Bureau of Standards source, a KSU source strength

should be divided by 1.016. Table 1 explains the assignment of the confidence limit of ±7 per cent to KSU sources.

The Ra-Be (α, n) source number 38 at Argonne National Laboratories has a relative absolute calibration ratio of 1.049 compared with the Bureau of Standards source (7). To compare the KSU source with the Argonne source, the KSU source should be divided by 1.016/1.049. The Hanford source is not compared with NBS-I in Reference (7).

Diffusion Coefficient. A diffusion parameter of particular importance to an absolute determination of flux is the diffusion coefficient D; for as can be seen in Eqs. 20, 24, and 25, it serves to scale the value of the absolute flux. A dilemma arises when considering the best value to use for the diffusion coefficient of graphite as calculated values and experimental values may differ as much as 10 per cent (see Table 7).

D can be calculated, in principle, from expressions such as Eqs. 37, 38, 40 and 41 below (15).

$$D = \frac{1}{3\Sigma(1-\bar{\mu}_o)\left(1 - \frac{4}{5}\cdot\frac{\Sigma_a}{\Sigma} + \frac{\Sigma_a}{\Sigma}\cdot\frac{\bar{\mu}_o}{1-\bar{\mu}_o} + \ldots\right)} \tag{37}$$

In this expression, $\bar{\mu}_o$ is the average cosine of the scattering angle in the laboratory system, given by $2/3A$ where A is the atomic weight.

For weak absorbers where $\Sigma_a/\Sigma_s << 1$, this equation reduces to

$$D = \frac{1}{3\Sigma_s(1 - \bar{\mu}_o)} \tag{38}$$

Table 7. Summary of graphite diffusion parameters.

Density	σ_a	σ_s	λ_{tr}	D	References
gm/cm^3	millibarns, mb	barns	cm	cm	
1.60	3.73	4.8		0.886	(5, 21, 44)
1.60	3	4.8		0.778	(12)
1.60			2.58 ± .02	0.860	(6)
1.60			2.55 ± .09	0.850	(29)
	4.5	4.8			(30)
1.62				0.903	(15)
				0.90	(43)
1.60	4.65		2.74	0.913	(20)
1.60	4.8	4.8	2.75	0.917	(14)
1.60	4.8			1.040	(24)
	3.80 ± 0.04 mb including impurities 3.51 ± 0.06 mb without impurities				(26)

Defining the transport mean free path as

$$\lambda_{tr} = \frac{1}{\Sigma_s(1-\bar{\mu}_o)} \quad , \tag{39}$$

the diffusion coefficient becomes

$$D = \frac{\lambda_{tr}}{3} \tag{40}$$

From a development of the significance of the diffusion length for monoenergetic neutrons in a weak absorber (15)

$$D = \Sigma_a L^2 \, , \tag{41}$$

where Σ_a is evaluated at the mean energy of the thermal spectrum (43).

An often quoted value of D is calculated from Eq. 40 where λ_{tr} is calculated from Eq. 39. Σ_s appears to be known with some certainty as 0.385 cm^{-1} (21); and $(1 - \bar{\mu}_o)$ is calculated as 0.944, (12). This results in a λ_{tr} in the range from 2.71 cm to 2.75 cm and corresponding diffusion coefficients in the range from 0.903 cm to 0.917 cm, respectively. This has been the range of D values used in previous pile standardizations (11, 35).

It has not been feasible to calculate adequately D from Eq. 41; for until recently, accurate direct measurements of Σ_a were difficult to make.

Direct measurements of D thus λ_{tr} made since 1955, (6, 29), by pulsed source techniques disagree somewhat with the calculated values outlined above. These two independent measurements of λ_{tr}

have been reported as 2.55 ± 0.09 and 2.58 ± 0.02, both disagreeing considerably with the values for λ_{tr} calculated above.

Amaldi (2) claims that one cannot rely on the values of the diffusion parameters computed from scattering and absorption cross sections of the atoms of the medium. He points out that these various relationships for the diffusion parameters are useful however, since they provide the possibilities of checking in detail the fulfillment of the assumptions underlying their derivation.

From transmission experiments, one measures Σ_s not λ_{tr}. λ_{tr} is found from Σ_s by involvement of $\overline{\mu}_o$, the calculation of which depends upon the angular distribution of the scattered neutrons and this depends in a rather complicated way upon the molecular structure of the medium.

Singwi and Kothari (36), in pointing out this discrepancy between the calculated λ_{tr} and the measured λ_{tr}, offer no conclusion as to the best value to use. They say that the theory in the case of graphite is still in an unsatisfactory state and that a better theoretical calculation must await a better model for the vibrational spectrum of graphite. They suggest that a direct measurement of the angular distribution of the scattered neutrons in the thermal energy group would be valuable.

On the basis of this review and from communication with the Critical Mass Physics Section of Hanford Laboratories (9), it was felt that the most reasonable value of the diffusion coefficient would be found from the directly measured values of λ_{tr}. Thus D was taken as $2.58/3 = 0.860$ cm at a graphite density of 1.60 gm/cm^3.

A paper by P. F. Nichols (26) gives a direct measurement of the graphite absorption cross section in the Physical Constants Testing Reactor. The reactor grade graphite (GAF) tested had a 2200 m/sec cross section of $\sigma_a = 3.80 \pm 0.04$ mb including all impurities. Using this and the diffusion length measured in the KSU pile of 55.3 ± 0.3 cm, a diffusion coefficient of 0.828 cm is obtained from Eq. 41, thus further indicating that the diffusion coefficient obtained from Eq. 38 may be an overestimate.

Table 7 lists a summary of the diffusion parameters of graphite.

Age. In the finite pile flux calculations, the Fermi age measured by Steichen (39) has been used, whereas in the standard pile absolute flux calculations, a combination of Gaussian ranges has been used instead of a Fermi age. In either case, to evaluate the source for the thermal diffusion equation, the Fermi age or a Gaussian range to indium resonance must be extended to represent the age or range at thermal energy by Eq. 17 which resulted from Fermi's slowing down theory

$$\tau(E_{oi}, E_{th}) = \tau(E_{oi}, E_{In}) + \int_{E_{th}}^{E_{In}} \frac{D}{\xi \Sigma_s} \frac{dE}{E} \tag{42}$$

where

$$r^2_{th\text{-}i} = 4\tau(E_{oi}, E_{th}). \tag{43}$$

Using the following diffusion parameters appropriate to this work,

$D = 0.860$ cm $\qquad E_{In} = 1.44$ ev

$\Sigma_s = 0.385\ cm^{-1} \qquad E_{th} = 0.025$ ev

$\xi = 0.158$

the age integral above has a value of 57.3 cm^2.

The Reactor Handbook (30) gives an estimated age from indium resonance energy to thermal energy of 53 cm^2. Weinberg and Wigner (43) estimate the age from resonance to thermal as 39 cm^2 by means of

$$\tau(E_{th}) = \tau(E_{In}) + \int_{E_{th}}^{E_{In}} \frac{dE}{3E \sum_j (\xi_j \Sigma_j) \sum_j \left[\Sigma_j (1 - \bar{\mu}_{oj})\right]} \qquad (44)$$

A study of the slowing down of neutrons in graphite by Duggal and Martelly (13) of France states that the most probable value of the effective slowing down age between indium resonance and thermal equilibrium is 49 cm^2. This value of 49 cm^2 was used for this work since it seemed to lie in between the extreme values and it agreed quite well with that given by the Reactor Handbook (30).

Thermalization theory (43) was not applicable in this case since there were no heavy absorbers such as uranium to harden the spectrum.

The age of neutrons from a Pu-Be neutron source to indium resonance energy as measured by Steichen (39) was taken as 419 cm^2 at a graphite density of 1.6 gm/cm^3. This number was the result of an experimental determination of 422 and a theoretical calculation of 416. Extrapolating this age to thermal energy with the estimated age difference of 49 cm^2 gave the age of neutrons from a Pu-Be source to

thermal energy as 468 cm^2. At the effective density of the KSU pile of 1.678 gm/cm^3, the age was 381 cm^2 to indium resonance and 426 cm^2 to thermal.

To extend any indium resonance Gaussian range to the thermal Gaussian range, the expression

$$\frac{r^2_{th\text{-}i}}{4} = \frac{r^2_{In\text{-}i}}{4} + (49)^2 \qquad (45)$$

was used.

Diffusion Length. The diffusion length was experimentally determined to be 52.76 ± 0.30 cm by Kaiser (22) at the effective density of the KSU pile. At a density of 1.6 gm/cm^3 this would be 55.33 ± 0.30 cm. This number is the result of the average of ten determinations of diffusion length, each determination getting 1,000 counts with the BF_3 probe in each of 13 selected pile positions. The model from which the diffusion length was determined assumed a thermal point source.

It would be a difficult task to propagate the errors of each individual parameter to give the confidence limits in the standard pile flux as determined by Eq. 20. Considering the uncertainty in the diffusion coefficient to be ±5 per cent, (estimated from the difference between 0.860 and 0.910), the uncertainty in the thermal flux, considering only the effect of the source strength and the diffusion coefficient, amounts to ±12 per cent. Error in the diffusion length (55.33 ± 0.30), or estimated error in the age (39) or a Gaussian range should have a small effect on the flux compared with the effect of the error in the source strength or the diffusion coefficient. A study of the variation of standard

flux with variation of diffusion length is presented in Fig. 18.

Intercalibration with Argonne Standard Pile and Hanford Standard Pile

Table 8 presents standardization constants of KSU gold foils as determined from the irradiation of the bare foils in known flux positions of the Argonne Standard Pile and the Hanford Standard Pile. The foils were irradiated for approximately two half-lives and then sent to Kansas State University where the saturation activity of the foils was determined by use of the KSU standard foil counting system described in the section on experimental facilities. On the basis of the saturation activity of the foil and the knowledge of the flux to which the bare foil was exposed, a standardization constant was determined for the foil according to

$$K_{th}\,(g\,f) = \frac{(nv)_{th}}{A_{sat}} \tag{46}$$

The results of the subsequent use of these foils in the KSU Standard Pile may be seen in Table 9.

It must be pointed out that the pile at Hanford was standardized with a diffusion coefficient of 0.910 cm (11) and the pile at Argonne was standardized with a diffusion coefficient of 0.903, (32, 35). The KSU pile was standardized on the basis of a diffusion coefficient of 0.860 cm since, as previously pointed out, this was thought to be a better estimate of the diffusion coefficient for graphite. To intercalibrate the fluxes of the various standard piles on the basis of a consistent diffusion coefficient, the Argonne flux was multiplied by

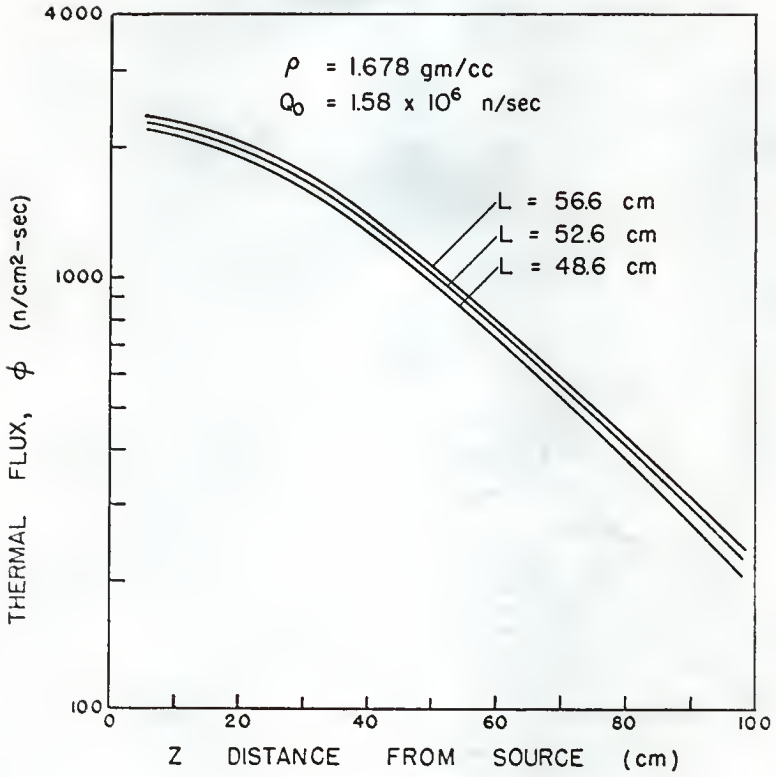


Fig. 18. Effect of diffusion length variation on KSU Standard Pile flux.

Table 8. Summary of Gold foil standardization constants found from bare foil irradiation in standard piles at Argonne and Hanford.

Foil identification		Standardizing conditions			Saturation activity determined from KSU standard counter	Standardization constant
Top	Bottom	Laboratory	Distance from source (cm)	Absolute flux (n/cm^2-sec)	(counts/sec)	(flux/counts/sec)
KSU-1		Argonne	15.75	6,611	50.247 ± 0.199	164.3 ± 0.8
KSU-2		Argonne	36.75	4,497	26.251 ± 0.142	171.3 ± 0.9
KSU-1	HAN	Hanford	10.64	8,565	62.116 ± 0.313	137.9 ± 0.7
KSU-2	HAN	Hanford	31.91	6,149	36.835 ± 0.183	166.9 ± 0.8

Table 9. Intercalibration of KSU Standard Pile flux with standard pile flux at Hanford and Argonne by use of standardized gold foils.

Foil identification		Exposure condition in KSU Standard Pile		Flux determined from standardized foil	Flux from standardized foil using consistent diffusion coefficients	Discrepancy with KSU standard flux
Top	Bottom	Distance from source (cm)	KSU standard flux (n/cm^2-sec)	(n/cm^2-sec)	(n/cm^2-sec)	
KSU-1		25.96	1,768	1,520	1,596	-9.7 %
KSU-2		46.11	1,101	1,049	1,101	0.0 %
KSU-1	HAN	25.96	1,768	1,471	1,557	-11.9 %
KSU-2	HAN	46.11	1,101	978.7	1,036	-5.9 %
KSU-1		15.82	2,058	1,866	1,960	-4.8 %
KSU-2		36.11	1,430	1,326	1,392	-2.7 %

0.903/0.860 and the Hanford flux was multiplied by 0.910/0860. Such an adjustment led to the flux listed in Column 6 of Table 9 which was the flux to be compared with the KSU assigned value of the absolute flux.

One cause of the unsatisfying intercomparison was the assumption expressed in Eq. 46 that the thermal flux is proportional to the saturation activity of a bare gold foil. Since gold has its peak cross section at an epithermal energy, a considerable portion of the activation of the foil near the source was due to epithermal neutrons. The epithermal content of the fluxes in the intercalibrated cases was not necessarily the same since a KSU neutron source has a different energy spectrum and since the irradiations took place at different distances from the source. The correct procedure for the intercalibration of standard pile fluxes would be the exchange of both bare and cadmium covered gold foils since the thermal flux is more correctly proportional to the cadmium difference saturation activity.

The most reliable intercomparisons made with this bare foil exchange are those made at the positions fartherest from the source, even though at these points there is still an epithermal flux contribution.

Theoretical Standardization of BF_3 Neutron Probe

A theoretical standardization constant for the BF_3 neutron detector was determined according to a development by Price (28). Based on the manufacturer's specifications for the BF_3 probe described in the

section on experimental facilities, the theoretical standardization constant of the probe was calculated to be 0.872 neutron flux per count per minute. The standardization constant determined from this thesis was 1.1578. Considering the average of 1.1578 and 0.872 to be correct, this amounts to a discrepancy between the two of 28 per cent with the theoretical standardization constant giving the lower flux.

All assumptions made in the theoretical calculation appear to be reasonably correct. However, experience at Kansas State University with the construction of BF_3 neutron detectors (25) indicates that such important specifications as the gas pressure and the active volume are difficult to determine accurately. Perhaps the specifications given by the manufacturer were meant to be nominal.

Scintillation Probe Standardization

The standard pile analysis gave a standardization constant of 0.8465 neutron flux per count per minute for the scintillation probe. The instrument manufacturer assigned a sensitivity of 0.014 counts per second per unit neutron flux to the probe. Expressing the standardization constant of 0.8465 in terms of counts per second per unit neutron flux results in a sensitivity of 0.0197. Considering the average of 0.0197 and 0.014 to be correct, a 34 per cent discrepancy appears to be involved with the manufacturer's assigned sensitivity giving the higher flux.

It must be pointed out that the manufacturer's assignment of the sensitivity was based on a calibration with the Argonne Standard Pile. In order to compare the KSU standard flux with the flux indication from an Argonne standardized detector, the detector indication must be ad-

justed in order to base the comparison on consistent diffusion coefficients. Such a consideration would decrease the manufacturer's assigned value of the sensitivity from 0.014 to 0.0133, giving a larger 39 per cent discrepancy with the KSU assigned sensitivity value of 0.0197.

Inspection of Table 6 or Fig. 17 reveals that the scintillation probe gave the least reliable standardization constant of the various detectors. The lower standardization constants near the source suggest that a standardization using a cadmium difference technique would give more reliable results for the scintillation probe.

The Use of Gaussian Ranges and the Fermi Age to Describe Slowing Down

Steichen (39) has shown that the age from a polyenergetic neutron source may be theoretically represented by

$$\tau = \sum_{i=1}^{N} f_i \tau_i \tag{47}$$

where f_i represents the fractional contribution of τ_i, the age from the i^{th} energy group of the source to an energy such as indium resonance energy. Writing τ_i in terms of r_i according to the defining equation of r_i, Eq. 47 may be written as

$$\tau = \sum_{i=1}^{N} f_i \frac{r_i^2}{4} \tag{48}$$

This value of the age, hereafter referred to as the equivalent age, has been calculated for each of the empirical fits and tabulated in Column 16 of Table 5. Inspection of this column reveals that even though the equivalent ages are near 381 cm^2. Steichen's (39) value of the age to indium resonance, they could not be used to determine accurately the age. Steichen shows that the value of the Fermi age is determined to a great degree by the extrapolation to infinity of the measured resonance distribution beyond the last measured point at 97.12 cm. This variation of the equivalent ages with choice of empirical fit may be a result of the different extrapolations beyond 97.12 cm given by various empirical fits.

It was of interest to study the variation of the calculated standard pile flux that resulted from different choices of the indium resonance data fit given in Table 5. Two different fits were used to calculate the standard pile flux. One was the appointed best fit which had an equivalent age of 411.9 cm^2. The other was a three term fit of the indium resonance data corrected for geometry and foil weights, but not corrected for neutron absorption by higher energy indium resonances. This latter fit had an equivalent age of 378.1 cm^2. Even though the equivalent ages and the individual terms of the two fits were different, the small difference in the calculated fluxes was difficult to show clearly in a plot of the two fluxes. The maximum difference was a little greater than 2 per cent.

Use of the three Gaussian ranges allows a more accurate description of the slowing down density than does the use of the Fermi age.

As can be seen from the form of Eq. 8, use of the Fermi age to describe the slowing down distribution would yield a straight line on Fig. 14. The use of three Gaussian ranges, however, provides an adequate description of the actual measured slowing down distribution.

Further, it must be stated that the use of the three Gaussian ranges to determine the slowing down to thermal energy will allow a more accurate description of the thermal neutron flux than will the use of the Fermi Age. This conclusion has not been explicitly demonstrated but it follows from the fact that a more accurate description of the slowing down of neutrons to thermal energy will allow a more accurate source boundary condition to the thermal diffusion equation.

Study of Source Boundary Condition in Finite Pile

Table 10 is a summary of flux calculations in the study of the source boundary condition to the thermal diffusion equation in the finite pile geometry. Column 2 lists the flux using fast point source theory as obtained from the computer code described in Appendix E which numerically evaluates Eq. 24. Column 3 lists the flux using thermal point source theory as obtained from the computer code described in Appendix F which numerically evaluates Eq. 25. Column 4 lists the experimental absolute flux determined by the standardized BF_3 probe. All measurements and calculations were made with a source having a strength of 1.71×10^6 neutrons per second.

Figures 20 are isometric plots of the flux values in Table 10. The absolute flux is plotted along the vertical axis as a function of

Table 10. Study of the flux from two assumed source boundary conditions for the thermal diffusion equation in a finite pile. $Q_0 = 1.71 \times 10^6$ n/sec.

Distance from source			Thermal flux from fast point source	Thermal flux from thermal point source	Thermal flux from standardized BF_3 probe
X	Y	Z			
inches			n/cm^2-sec	n/cm^2-sec	n/cm^2-sec
0	0	0	2,238.0		
4			2,162.0	13,150.0	2,432.0
8			1,951.0	5,356.0	2,190.0
12			1,647.0	2,879.0	1,794.0
16			1,304.0	1,716.0	1,423.0
20			966.0	1,061.0	1,115.0
24			659.4	650.5	666.9
28			391.6	363.2	389.8
32			154.3	139.1	167.6
0	8	0	1,951.0	5,356.0	2,094.0
4			1,886.0	4,594.0	2,037.0
8			1,706.0	3.177.0	1,820.0
12			1,445.0	2,101.0	1,508.0
16			1,150.0	1,377.0	1,115.0
20			855.4	896.5	842.6
24			586.8	569.6	585.6
28			349.9	320.9	338.7
32			138.2	123.8	136.4
0	16	0	1,304.0	1,716.0	1,335.0
4			1,263.0	1,615.0	1,298.0
8			1,150.0	1,373.0	1,159.0
12			982.7	1,078.0	982.4
16			790.8	799.9	771.7
20			596.7	566.9	578.0
24			414.5	378.3	404.4
28			249.8	222.6	257.0
32			99.29	87.41	100.3
0	24	0	659.4	650.5	621.7
4			640.5	629.5	511.3
8			586.8	565.8	566.5
12			507.7	474.6	482.2
16			414.5	378.5	396.0
20			317.7	283.0	300.7
24			224.2	196.5	219.0
28			136.8	118.2	132.5
32			54.74	47.33	54.74
0	32	0	154.3	126.3	147.1
4			150.1	134.8	142.8
8			138.2	125.9	133.4
12			120.5	106.2	113.4
16			99.29	86.61	94.42
20			76.87	67.36	68.31
24			54.75	47.25	52.33
28			33.64	28.60	32.53
32			13.53	11.58	14.39

Table 10 (cont.)

Distance from source X	Y	Z	Thermal flux from fast point source	Thermal flux from thermal point source	Thermal flux from standardized BF_3 probe
inches			n/cm^2-sec	n/cm^2-sec	n/cm^2-sec
0	0	8	1,951.0	5,356.0	2,148.0
4			1,886.0	4,594.0	2,062.0
8			1,706.0	3,177.0	1,815.0
12			1,445.0	2,101.0	1,516.0
16			1,150.0	1,377.0	1,188.0
20			855.4	896.5	861.4
24			586.8	564.6	605.5
28			349.9	320.8	339.2
32			138.2	123.8	148.2
0	8	8	1,706.0	3,177.0	1,775.0
4			1,650.0	2,889.0	1,721.0
8			1,495.0	2,258.0	1,536.0
12			1,271.0	1,623.0	1,266.0
16			1,015.0	1,130.0	1,012.0
20			759.3	764.0	747.4
24			523.3	492.5	514.9
28			313.2	283.8	318.7
32			124.0	110.3	126.4
0	16	8	1,149.0	1,373.0	1,162.0
4			1,114.0	1,312.0	1,105.0
8			1,015.0	1,127.0	1,002.0
12			870.7	909.9	896.7
16			703.3	689.3	692.9
20			532.8	496.3	528.0
24			371.8	334.7	371.9
28			224.8	198.5	224.0
32			89.52	78.25	91.62
0	24	8	586.8	565.8	564.4
4			570.2	541.0	542.4
8			523.3	491.3	498.0
12			453.9	417.4	434.2
16			371.8	335.2	362.4
20			285.9	253.3	273.5
24			202.4	176.6	192.6
28			123.8	106.9	122.5
32			49.63	42.69	49.94
0	32	8	138.2	125.9	128.86
4			134.5	121.8	128.32
8			124.0	111.3	119.75
12			108.3	96.36	103.08
16			89.52	78.03	84.44
20			69.50	60.43	66.96
24			49.63	42.84	47.53
28			30.56	26.19	29.99
32			12.30	10.52	13.89

Table 10 (cont.)

Distance from source X	Y	Z	Thermal flux from fast point source	Thermal flux from thermal point source	Thermal flux from standardized BF_3 probe
inches			n/cm^2-sec	n/cm^2-sec	n/cm^2-sec
0	0	16	1,304.0	1,716.0	1,330.0
4			1,263.0	1,615.0	1,269.0
8			1,150.0	1,373.0	1,167.0
12			982.7	1,078.0	992.5
16			790.8	799.9	774.3
20			596.5	566.9	594.4
24			419.5	378.3	412.4
28			249.8	222.6	252.4
32			99.29	87.41	103.7
0	8	16	1,149.0	1,373.0	1,118.0
4			1,114.0	1,312.0	1,092.0
8			1,015.0	1,127.0	1,010.0
12			870.7	909.9	870.7
16			703.3	689.3	696.7
20			53.28	496.3	529.3
24			37.18	334.7	365.6
28			224.8	198.5	224.30
32			89.52	78.25	92.43
0	16	16	790.8	799.9	753.4
4			767.9	772.3	767.9
8			703.3	690.2	686.9
12			608.2	576.8	597.4
16			496.2	457.8	482.5
20			480.1	341.2	367.9
24			268.0	235.7	274.1
28			163.4	141.7	166.8
32			65.41	56.37	66.69
0	24	16	414.5	378.5	398.3
4			403.4	365.8	385.9
8			371.8	334.4	359.4
12			324.6	290.7	310.7
16			268.0	234.8	255.3
20			208.0	181.3	198.9
24			148.4	128.6	148.20
28			91.34	78.90	91.85
32			36.77	31.48	39.02
0	32	16	99.26	86.61	94.94
4			96.75	84.95	90.52
8			89.52	74.81	87.22
12			78.64	66.14	77.32
16			65.82	57.40	63.48
20			51.15	43.31	49.32
24			36.77	31.66	36.41
[illegible]			22.76	19.82	22.15
[illegible]			9.02	7.896	10.74

Table 10 (cont.)

Distance from source X	Y	Z	Thermal flux from fast point source	Thermal flux from thermal point source	Thermal flux from standardized BF_3 probe
inches			n/cm^2-sec	n/cm^2-sec	n/cm^2-sec
0	0	24	659.4	650.5	650.0
4			640.5	679.5	630.2
8			586.8	565.8	578.4
12			507.7	474.6	502.3
16			414.5	378.5	413.6
20			317.7	283.0	317.7
24			224.2	196.5	227.6
28			136.8	118.2	142.6
32			54.74	47.33	61.80
0	8	24	586.8	565.8	554.1
4			570.2	541.0	553.7
8			523.3	491.3	517.3
12			453.9	417.4	445.5
16			371.8	335.2	363.6
20			285.9	253.3	277.9
24			202.4	176.6	197.1
28			129.3	106.9	120.6
32			49.63	42.69	53.29
0	16	24	414.5	378.5	405.9
4			403.4	365.8	386.4
8			371.8	334.4	349.7
12			324.5	290.7	313.5
16			268.0	234.8	265.4
20			208.0	181.3	205.5
24			148.4	128.6	144.5
28			91.34	78.90	93.53
32			36.77	31.48	38.71
0	24	24	224.2	196.5	215.2
4			218.5	189.3	207.7
8			202.4	175.3	196.7
12			178.1	154.6	168.3
16			148.3	128.0	144.3
20			116.3	100.2	110.2
24			83.75	71.77	82.53
28			51.92	44.84	54.10
32			20.99	18.18	24.02
0	32	24	54.75	47.25	52.60
4			53.42	45.21	51.27
8			49.63	41.95	47.04
12			43.86	37.11	44.00
16			36.77	32.30	37.11
20			28.98	24.25	29.23
24			20.99	17.65	21.40
28			13.07	11.53	14.33
32			5.30	4.67	7.56

Table 10 (concl.)

Distance from source X : Y : Z			Thermal flux from fast point source	Thermal flux from thermal point source	Thermal flux from standardized BF_3 probe
inches			n/cm^2-sec	n/cm^2-sec	n/cm^2-sec
0	0	32	154.3	139.1	149.4
4			150.1	134.8	149.1
8			138.2	125.9	138.1
12			120.5	106.2	121.9
16			99.29	86.61	95.63
20			76.87	67.36	74.66
24			54.75	47.25	54.42
28			33.64	28.60	34.13
32			13.53	11.58	14.47
0	8	32	134.9	125.9	126.06
4			134.5	121.8	128.28
8			124.0	111.3	122.73
12			108.3	96.36	100.8
16			89.52	78.03	83.99
20			69.50	60.43	68.66
24			49.63	42.84	51.52
28			30.56	26.19	28.13
32			12.30	10.52	13.69
0	16	32	99.29	86.61	99.10
4			96.75	84.95	88.90
8			89.52	74.81	84.50
12			78.64	66.14	76.80
16			65.42	57.40	65.57
20			51.15	43.31	50.51
24			36.77	31.66	35.95
28			22.76	19.82	23.62
32			9.195	7.90	10.08
0	24	32	54.75	47.25	52.74
4			53.42	45.21	47.91
8			49.63	41.95	47.27
12			43.86	37.11	40.81
16			36.77	32.30	35.31
20			28.98	24.25	27.73
24			20.99	17.65	20.64
28			13.07	11.53	12.09
32			5.297	4.67	5.89
0	32	32	13.53	11.58	12.39
4			13.21		12.64
8			12.31	10.53	13.35
12			10.92		11.61
16			9.195	7.90	8.949
20			7.279		8.660
24			5.297	4.67	5.708
28			3.304		4.006
32			1.343	1.22	1.424

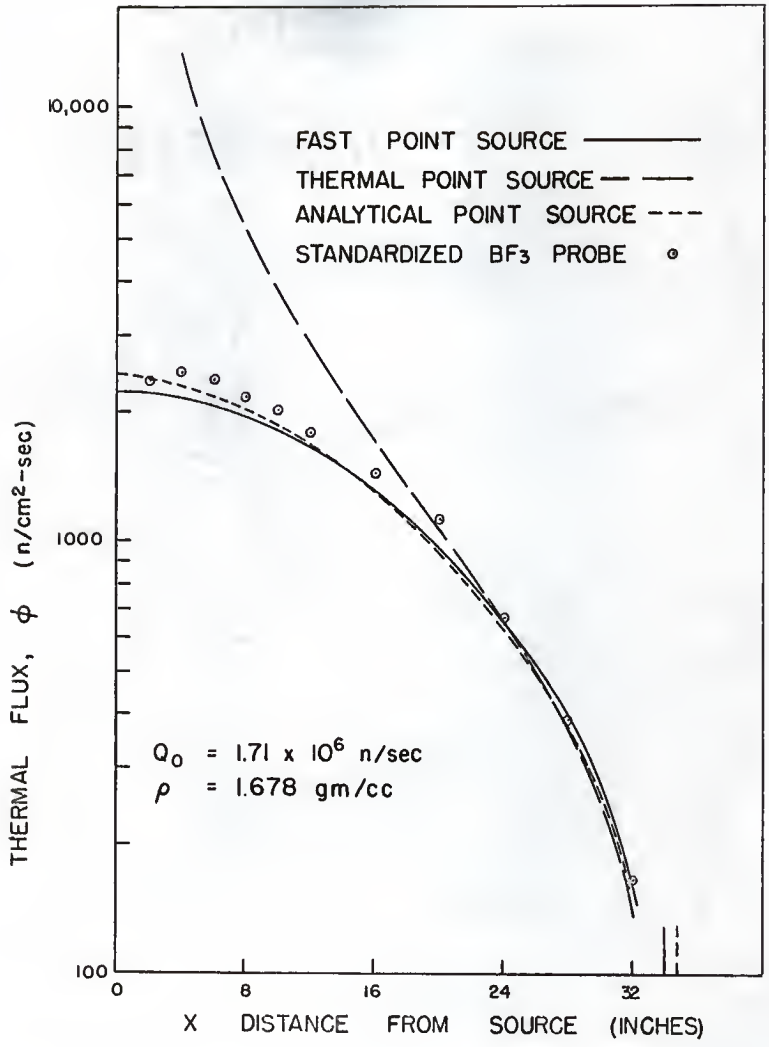


Fig. 19. Thermal flux study in finite pile.

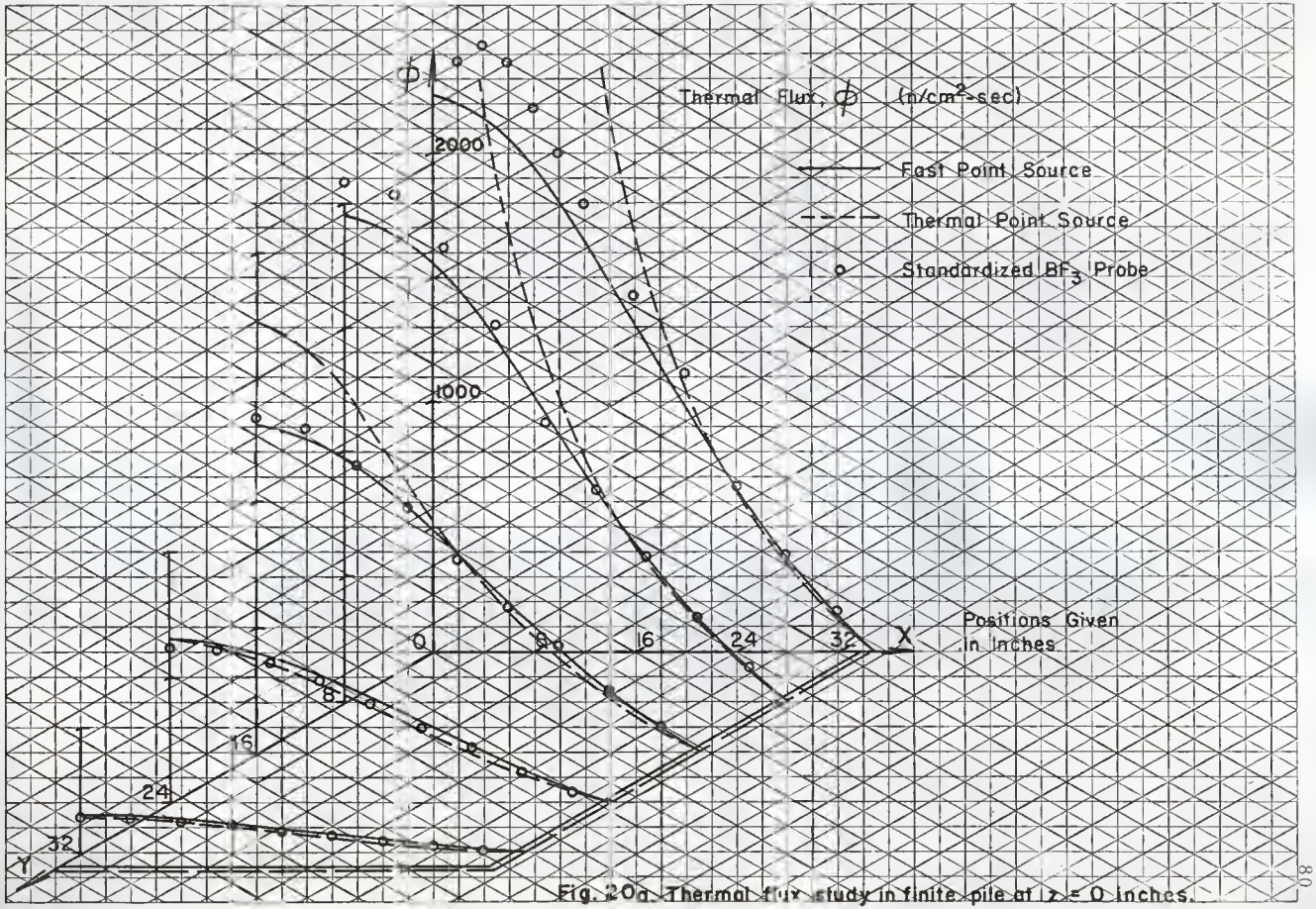


Fig. 20a. Thermal flux study in finite pile at z = 0 inches.

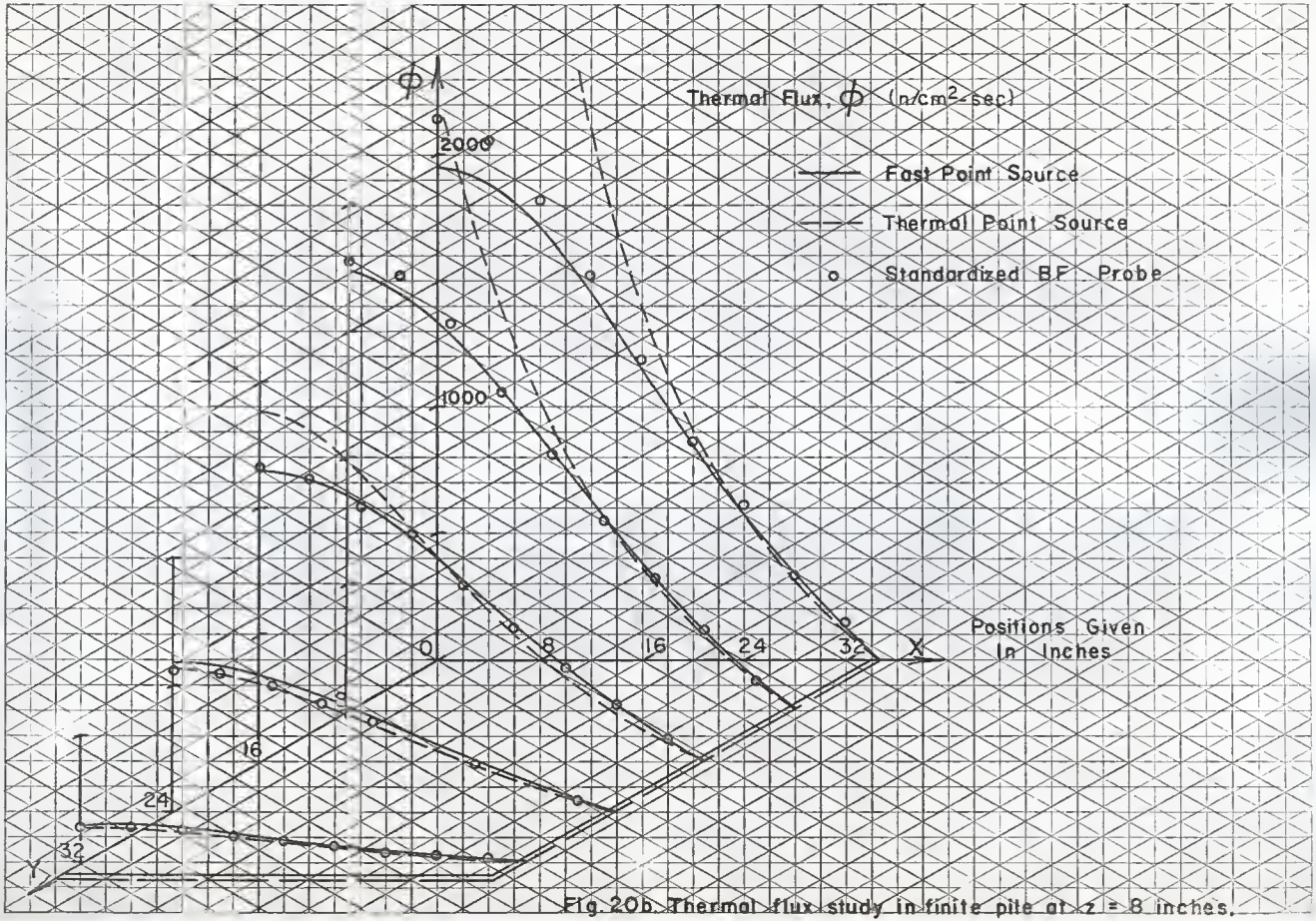


Fig. 20b. Thermal flux study in finite pile at z = 8 inches.

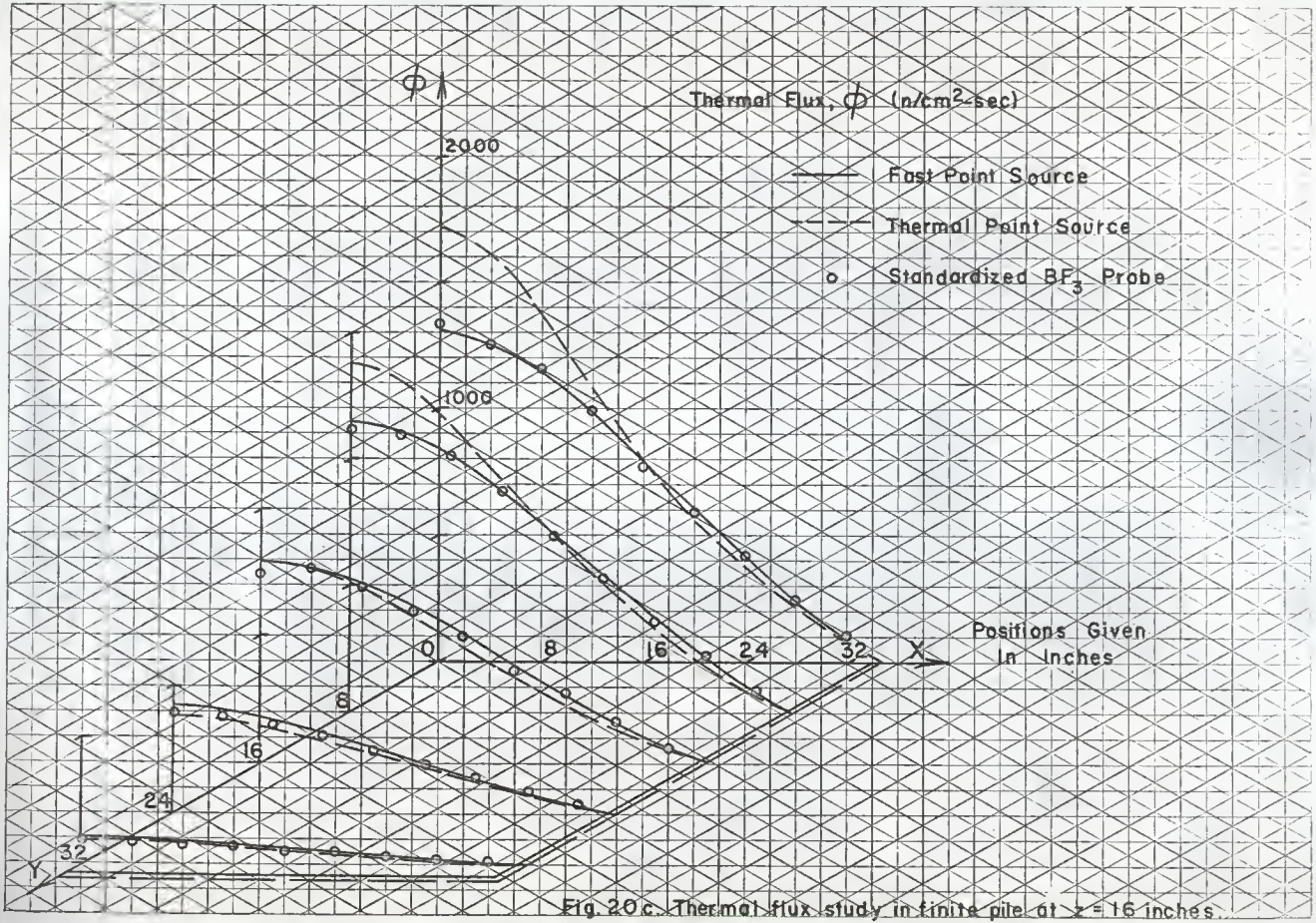


Fig. 20c. Thermal flux study in finite pile at z = 16 inches.

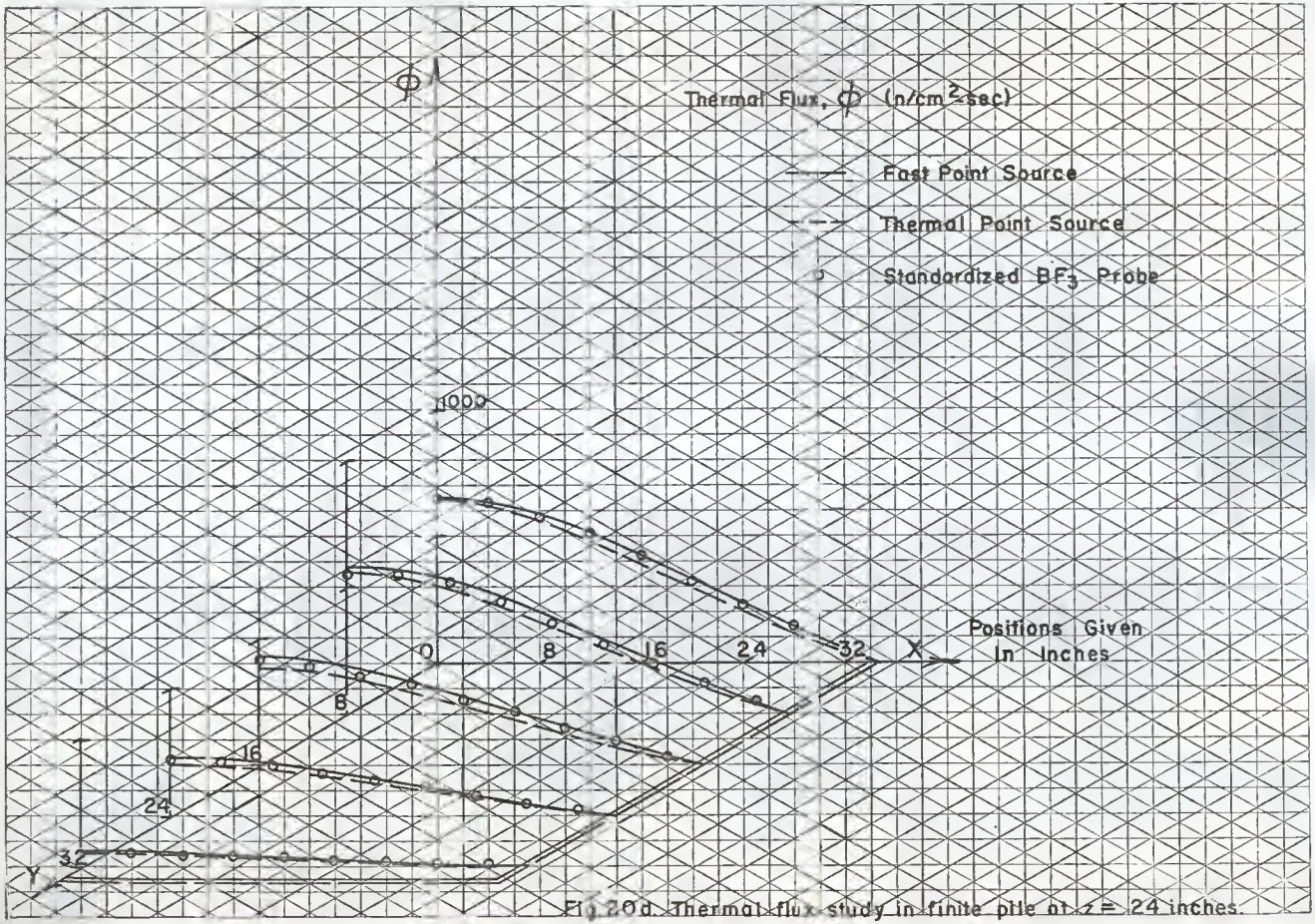


Fig. 20d. Thermal flux study in finite pile at z = 24 inches.

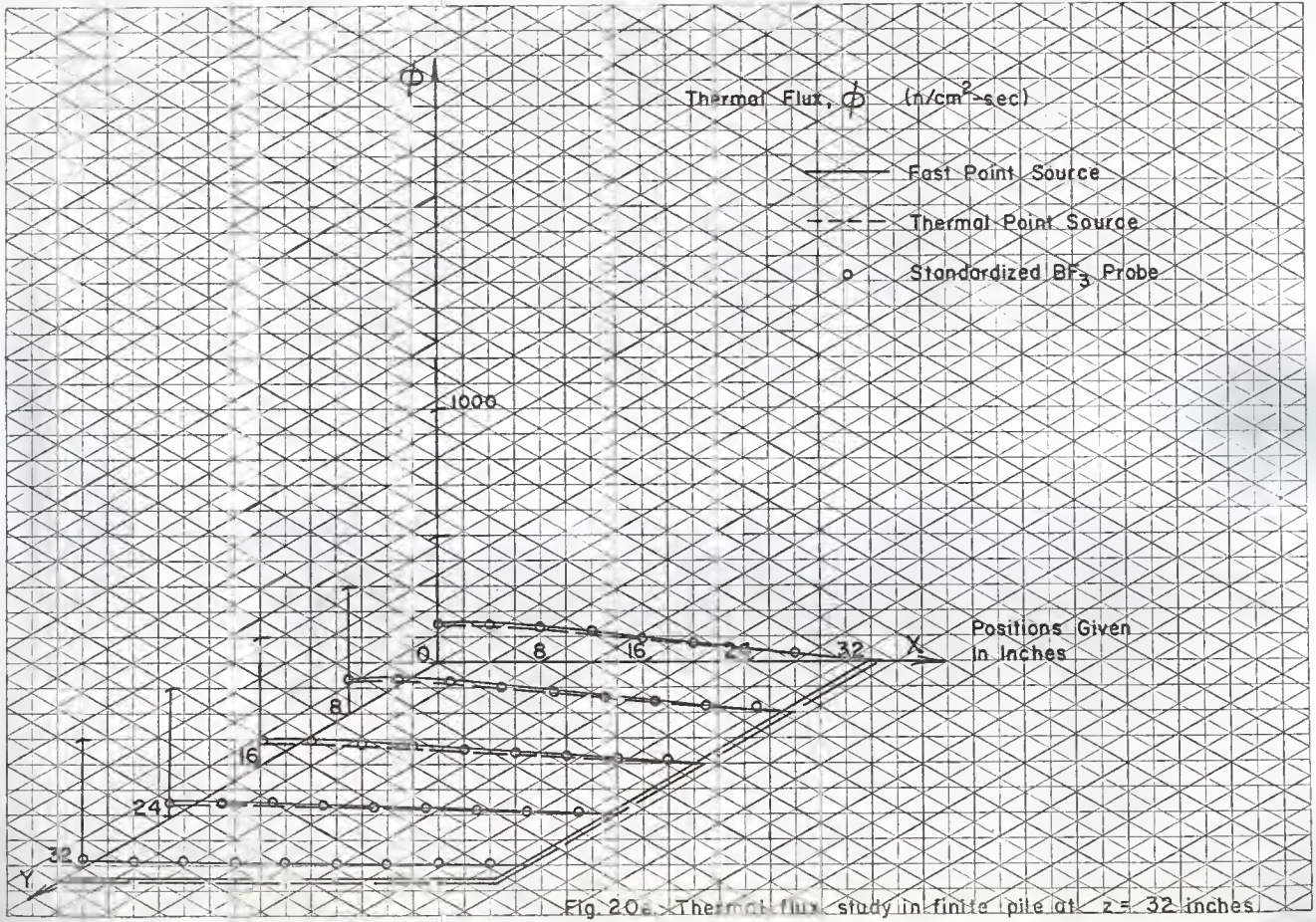


Fig. 20c. Thermal flux study in finite pile at z = 32 inches.

x, y and z with each figure representing a different z level in the finite pile. Figure 19 is a semi-logarithmic plot of the flux as a function of x alone, z and y being zero. Figure 19 clearly shows the difference between the flux from fast source theory and the flux from thermal source theory. The fast source calculations used the single value of the age of neutrons from a Pu-Be source to thermal energy. Figure 19 shows the effect of using the three range groups, or an analytical source expression, determined from the standard pile analysis instead of the single value of the age. This curve, calculated by Eq. 24, resulted from the superposition of the flux contributions from three different monoenergetic sources, each source having its respective Gaussian range and fractional contribution determined empirically from Eq. 36 and extended to thermal energy by Eq. 45. It can be seen that the breaking up of the source into three energy groups by the use of Gaussian ranges does give an improved effect.

Studies of the variation of the flux in fast source theory and thermal source theory with the variation of various parameters are given in Figs. 21 through 23. Graphs showing the variation of flux with variation of source strength or diffusion coefficient are not given, since both of these parameters are merely scaling coefficients to the flux.

The values of the source strength and the diffusion coefficient do not affect the various plots in Figs. 19 and 20 with respect to each other since they were all based on consistent values.

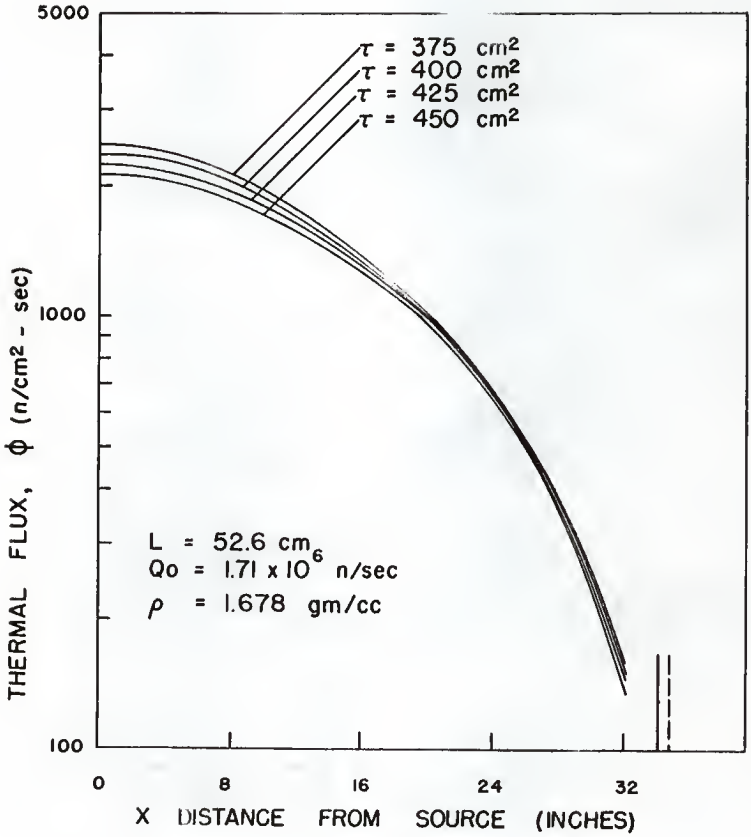


Fig. 21. Effect of variation of Fermi age on thermal flux from fast point source in finite pile.

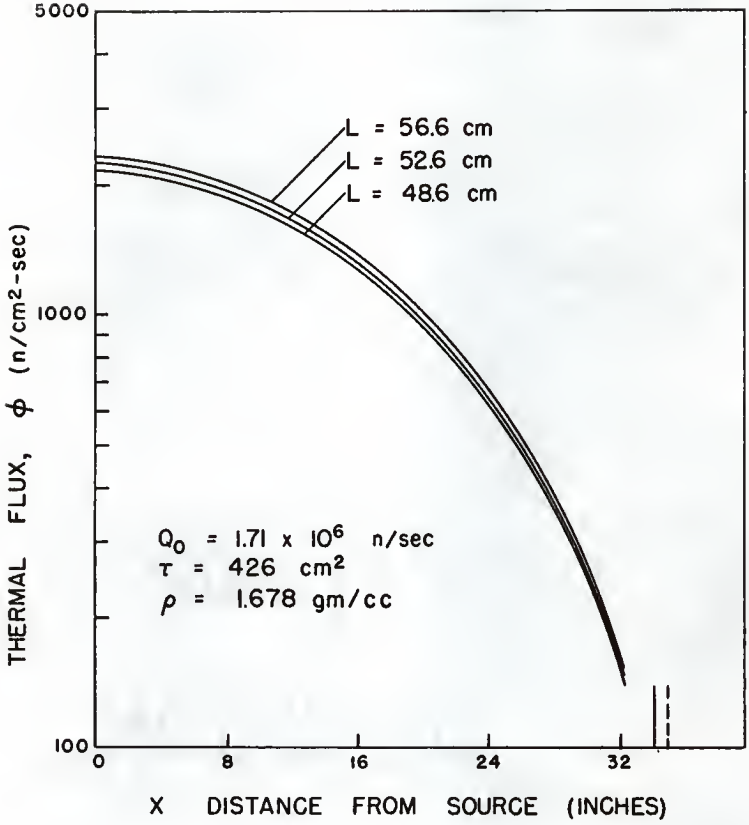


Fig. 22. Effect of variation of diffusion length on thermal flux from fast point source in finite pile.

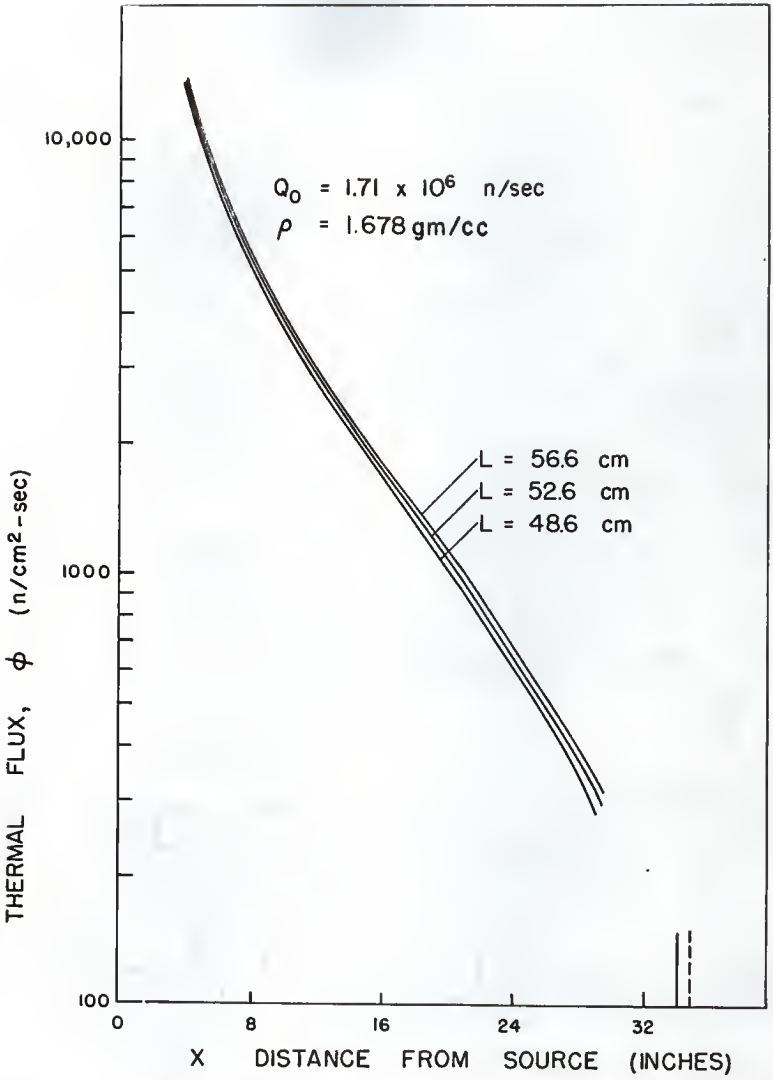


Fig. 23. Effect of voriotion of diffusion length on thermol flux from thermol point source in finite pile.

Suggestions for Further Work

The IBM-650 program which calculates the thermal flux from fast point source theory in finite geometry offers interesting possibilities for research with superposition of fluxes. Sources may be placed at various positions in the pile and the absolute flux may be determined experimentally with the standardized detectors. This experimental absolute flux may be compared with the superimposed fluxes determined from machine calculations of the flux from individual sources.

It is evident that there is still uncertainty in defining the absolute flux. An independent calculation of absolute flux could be made with the absolute counting of beta particles from indium foils. A recent outline for such work is References (17) and (23).

An approximate method for an absolute flux determination using a water medium has been outlined by Reference 1. The method assumes:

(a) The count rate of a thermal neutron detector such as the BF_3 probe, is directly proportional to the thermal flux at all points in the water medium.

(b) The water medium is infinite and spherical geometry can be used. Reference (30) considers the water volume necessary to approximate infinity.

(c) Neutron capture occurs only at thermal energies.

(d) Σ_a for water is accurately known.

(e) Q_0 is accurately known.

Since leakage from the "infinite medium" is negligible, the only loss of neutrons is due to capture at thermal energies. It can then be written in spherical coordinates that

$$Q_0 = \int_{\text{all space}} \Sigma_a \, \phi(r) \, 4\pi r^2 \, dr \tag{49}$$

From the assumption that $\phi = KR(r)$ where r is the count rate, K may be written as

$$K = \frac{Q_0}{\int_0^\infty 4\pi \Sigma_a \, R(r) \, r^2 \, dr} \tag{50}$$

K may be experimentally determined and the integral may be evaluated numerically.

Some work may be done in attempting to tie up the foil standardizations in graphite with the absolute flux in other media such as water or paraffin. A first approximation, ignoring any difference in the energy of the thermal neutron spectrum in graphite and water for example, would require the determination of K^0_{th}, the standardization constant independent of perturbing effects introduced in the section on data analysis. This is necessary since many of the perturbations depend upon the moderating properties of the medium.

It is felt by this author that a complete systematic study of the foil correction factors would be desirable. In addition to the contribution of helping to make possible the use of the standardized foils in media other than graphite, this study would be necessary in determining the absolute value of an unperturbed flux from absolute beta counting of foils.

An interesting addition to this work might be the comparison of the standard pile flux with the flux obtained from the finite pile solu-

tions which would use the standard pile in its finite dimensions. It may be recalled that in the standard pile analysis, the pile was assumed to have an infinite height. A difficulty of interest that would arise would be the definition of the boundary condition at the lower face of the pile, which rests on concrete.

In the discussion of the results it was stated that the use of Gaussian ranges to determine the slowing down to thermal would allow a more accurate description of the thermal neutron flux than would the use of the Fermi age. A standard pile flux calculation using Steichen's value of the age instead of the three Gaussian ranges would show this difference in thermal flux.

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APPENDICES

APPENDIX A

Solutions to the Fermi Age Equation and the Thermal Diffusion Equation for the Standard Pile Analysis

The geometry for the standard pile solution is shown in Fig. 24.

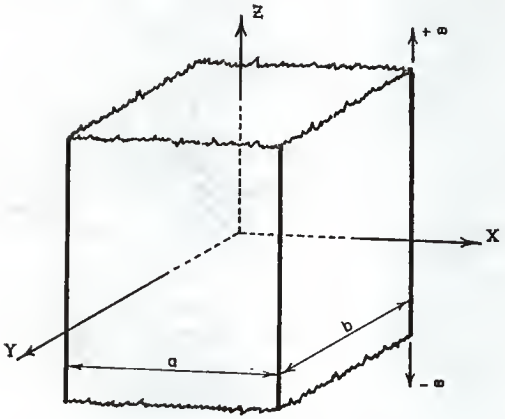


Fig. 24. Geometry for the standard pile solution.

The equations solved were the Fermi age equation

$$\nabla^2 q = \frac{\partial q}{\partial \tau} \tag{A-1}$$

and the thermal diffusion equation

$$D\nabla^2\phi - \Sigma_a \phi + S = 0 \tag{A-2}$$

The Fermi age equation was subjected to the boundary conditions that $q = 0$ at $x = \pm a/2$, $y = \pm b/2$, and $q \to 0$ as $|z| \to \infty$.

The source condition was that all source neutrons entered the system at $x = y = z = 0$, at an age $\tau = 0$.

This condition was written into the Fermi age equation in the form

$$\nabla^2 q = \frac{\partial q}{\partial \tau} - Q_0 \, \delta(\tau) \, \delta(x) \, \delta(y) \, \delta(z). \tag{A-3}$$

The boundary conditions to the thermal diffusion equation were that $\phi = 0$ at $x = \pm a/2$, $y = \pm b/2$, and $\phi \to 0$ as $|z| \to \infty$. The source condition was that $S = q(x, y, z, \tau_{th})$.

Q_0, q and ϕ were expressed as double Fourier series satisfying the boundary conditions

$$\phi = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \phi_{mn}(z) \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{b} \tag{A-4}$$

$$q = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} q_{mn}(z) \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{b} \tag{A-5}$$

and

$$Q_0 \, \delta(\tau) \, \delta(x) \, \delta(y) \, \delta(t) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} Q_{mn}(z) \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{b} \tag{A-6}$$

where m and n are summed over odd integers. Each side of Eq. A-6 was multiplied by orthogonal functions and then was integrated over the range of orthogonality which resulted in

$$Q_0 \, \delta(\tau) \, \delta(x) \, \delta(y) \, \delta(z) = \frac{4Q_0}{ab} \, \delta(\tau) \, \delta(z) \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{b} \tag{A-7}$$

Substitution of Eqs. A-5 and A-7 into the age equation, Eq. A-3 gave

$$\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\left[-\frac{\partial q_{mn}}{\partial \tau}+\frac{\partial^2 q_{mn}}{\partial z^2}-\left(\frac{m^2\pi^2}{a^2}+\frac{n^2\pi^2}{b^2}\right)q_{mn}+\frac{4Q_0}{ab}\,\delta(\tau)\,\delta(z)\right]=0\,. \tag{A-8}$$

Taking the Fourier transform of the equation for a particular m and n and letting

$$\alpha_m = \frac{m\pi}{a} \tag{A-9}$$

and

$$\beta_n = \frac{n\pi}{b} \tag{A-10}$$

led to

$$\frac{\partial \bar{q}(\omega)}{\partial \tau}+(\alpha_m^2+\beta_n^2+\omega^2)\,\bar{q}(\omega)=\frac{4Q_0}{ab}\,\delta(\tau) \tag{A-11}$$

where $\bar{q}(\omega)$ represents the Fourier transform of $q_{mn}(z)$.

The solution to this differential equation was

$$\bar{q}(\omega)=\frac{4Q_0}{ab}\,e^{-(\alpha_m^2+\beta_n^2+\omega^2)\tau}\,. \tag{A-12}$$

Taking the inverse transform of Eq. A-12 and substituting it into Eq. A-5 gave the slowing down density along the z axis as

$$q(z)=\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{4Q_0\,e^{-(\alpha_m^2+\beta_n^2)\tau}}{ab\sqrt{4\pi\tau}}\,e^{-z^2/4\tau}\,. \tag{A-13}$$

Substitution of Eqs. A-4 and A-5 into the thermal diffusion equation, Eq. A-2, and designating $\frac{\Sigma_a}{D}$ as κ^2 gave

$$\sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \left[\frac{\partial^2 \phi_{mn}}{\partial z^2} - (\alpha_m^2 + \beta_n^2 + \kappa^2)\, \phi_{mn} + \frac{q_{mn}}{D} \right] = 0. \qquad \text{(A-14)}$$

Taking the Fourier transform of Eq. A-14 for a particular m and n and designating the Fourier transforms of ϕ_{mn} and q_{mn} by $\overline{\phi}(\omega)$ and $\overline{q}(\omega)$, respectively, gave

$$\overline{\phi}(\omega) = \frac{\overline{q}(\omega)}{D(\alpha_m^2 + \beta_n^2 + \omega^2)} . \qquad \text{(A-15)}$$

Taking the inverse transform of Eq. A-15 by means of the convolution theorem (42), after Eq. A-12 had been used to express $\overline{q}(\omega)$ gave

$$\phi_{mn} = \frac{2Q_0 b_{mn} e^{-(\alpha_m^2 + \beta_m^2)\tau}}{Dab\sqrt{4\pi\tau}} \int_{-\infty}^{\infty} e^{-z'^2/4\tau} e^{-|z-z'|/b_{mn}} dz' \qquad \text{(A-16)}$$

where

$$b_{mn} = \frac{1}{\sqrt{\alpha_m^2 + \beta_n^2 + \kappa^2}} . \qquad \text{(A-17)}$$

Glasstone and Edlund (15), on pages 185 to 187, give the development showing how the integral in Eq. A-16 may be expressed in terms of the error function

$$erf(t) = \frac{2}{\sqrt{\pi}} \int_0^t e^{-u^2} du . \qquad \text{(A-18)}$$

Writing Eq. A-16 in terms of the error function and substituting it into Eq. A-4 gave the thermal flux along the z axis as

$$\phi(z) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{Q_0 b_{mn}}{Dab} e^{\kappa^2 \tau} \left[e^{-z/b_{mn}} \left\{ 1 + erf\left(\frac{z}{2\sqrt{\tau}} - \frac{\sqrt{\tau}}{2b_{mn}} \right) \right\} \right.$$

$$\left. + e^{z/b_{mn}} \left\{ 1 - erf\left(\frac{z}{2\sqrt{\tau}} + \frac{\sqrt{\tau}}{2b_{mn}} \right) \right\} \right] \qquad (A\text{-}19)$$

If difficulty has been encountered in following this solution, it may be helpful to study References (37) and (42).

APPENDIX B

Finite Pile Solution to the Thermal Diffusion Equation Using the Distributed Thermal Source Found from the Solution to the Fermi Age Equation.

The geometry for this finite pile solution is shown in Fig. 25.

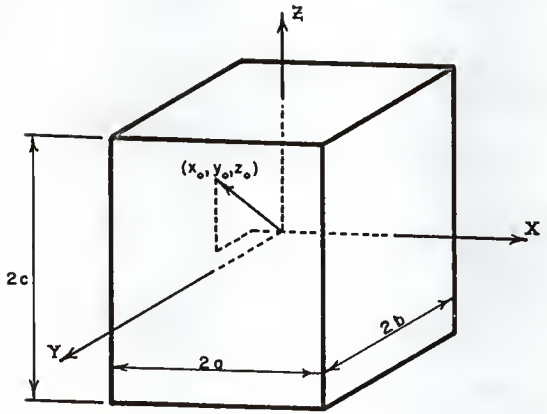


Fig. 25. Pile geometry for fast point source in finite pile.

The equations solved were the Fermi age equation

$$\nabla^2 q = \frac{\partial q}{\partial \tau} \tag{B-1}$$

and the thermal diffusion equation

$$D\nabla^2\phi - \Sigma_a \phi + S = 0. \tag{B-2}$$

The Fermi age equation was subjected to the boundary conditions that $q = 0$ at $x = \pm a$, $y = \pm b$, and $z = \pm c$. The source condition was that all source neutrons entered the system at $x = x_0$, $y = y_0$,

and $z = z_0$; and at $\tau = 0$.

The boundary conditions to the thermal diffusion equation were that $\phi = 0$ at $x = \pm a$, $y = \pm b$, and $z = \pm c$. The source condition was that $S = q(x, y, z, \tau_{th})$.

By assuming that the variables of q were separable,

$$q(x, y, z, \tau) = M(x, y, z)\, N(\tau) \tag{B-3}$$

the age equation could be written

$$\frac{1}{M} \nabla^2 M = \frac{1}{N} \frac{dN}{d\tau} = -B^2 \tag{B-4}$$

Solutions satisfying the boundary conditions and the two independent differential equations were

$$M(x,y,z) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \sum_{o=1}^{\infty} A'_{mno}\ F_m(x)\, G_n(y)\, H_o(z) \tag{B-5}$$

where

$$F_m(x) = \frac{1}{\sqrt{a}} \cos \alpha_m x$$

$$F_m(x) = \frac{1}{\sqrt{a}} \sin \alpha_m x \tag{B-6}$$

$$\alpha_m = \frac{m\pi}{2a}$$

and

$$N(\tau) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \sum_{o=1}^{\infty} A''_{mno}\ e^{-B^2_{mno}\,\tau} \tag{B-7}$$

where

$$B^2_{mno} = \alpha_m^2 + \beta_n^2 + \gamma_o^2 . \tag{B-8}$$

$G_n(y)$, and $H_o(z)$ are similar to $F_m(x)$ except that b and β replace a and α, respectively, for the y direction; and c and γ are used for the z direction.

To evaluate A_{mno} in the resulting expression for q,

$$q = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \sum_{o=1}^{\infty} A_{mno} F_m(x) G_n(y) H_o(z) e^{-B^2_{mno} \tau} \tag{B-9}$$

the source condition that

$$q(x, y, z, 0) = Q_0 \delta(x - x_0) \delta(y - y_0) \delta(z - z_0) \tag{B-10}$$

was used. Expressing Eq. B-10 with the use of Eq. B-9, multiplying both sides of the result by orthonormal functions, and integrating over the range of orthonormality led to the expression for A_{mno},

$$A_{mno} = Q_0 F_m(x_0) G_n(y_0) H_o(z_0). \tag{B-11}$$

The expression for the slowing down density evaluated at thermal energy was then

$$q(x, y, z, \tau_{th}) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \sum_{o=1}^{\infty} Q_0 F_m(x) F_m(x_0) G_n(y) G_n(y_0) H_0(z) H_0(z_0) e^{-B^2_{mno} \tau_{th}} \tag{B-12}$$

Assuming that ϕ could be represented by the same orthonormal set used for q, a solution for the thermal diffusion was

$$\phi(x, y, z) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \sum_{o=1}^{\infty} C_{mno} F_m(x) G_n(y) H_o(z). \tag{B-13}$$

Substitution of this expression and the expression for slowing down density evaluated at thermal energy, Eq. B-12, into the thermal diffusion equation yielded

$$C_{mno} = \frac{Q_0 F_m(x_0) G_n(y_0) H_o(z_0)}{D(\alpha_m^2 + \beta_n^2 + \gamma_o^2 + \kappa^2)} \quad e^{-B^2_{mno} \tau_{th}} \tag{B-14}$$

where

$$\kappa^2 \equiv \Sigma_a / D. \tag{B-15}$$

The thermal flux was then

$$\phi(x, y, z) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \sum_{o=1}^{\infty} \frac{Q_0 F_m(x) F_m(x_0) G_n(y) G_n(y_0) H_0(z) H_0(z_0)}{D(\alpha_m^2 + \beta_n^2 + \gamma_o^2 + \kappa^2)} e^{-B^2_{mno} \tau_{th}} \tag{B-16}$$

APPENDIX C

Finite Pile Solution to the Thermal Diffusion Equation using a Point Source of Thermal Neutrons.

The solution using a point source emitting only thermal neutrons could have been determined by merely using τ_{th} as zero in Eq. B-15. However, it was found that such an expression converged quite slowly. The thermal diffusion equation was re-solved using the geometry shown in Fig. 26.

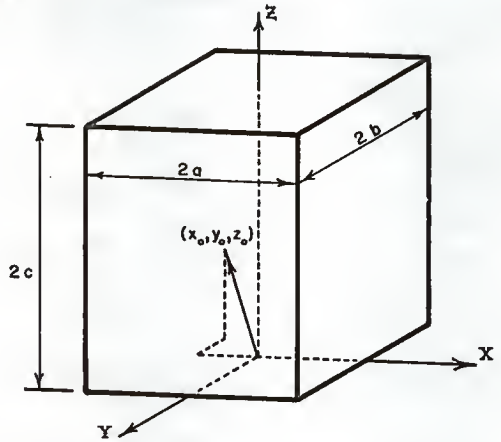


Fig. 26. Pile geometry for thermal point source in finite pile.

The boundary conditions to the thermal diffusion equation were that $\phi = 0$ at $x \pm a$, $y \pm b$, and $z = 0$, $2c$. The point thermal neutron source was considered to be in the $z = z_0$ plane at $x = x_0$, and $y = y_0$. The source was introduced through the boundary

conditions that

$$\phi_1 (z_0) = \phi_2 (z_0) \tag{C-1}$$

and

$$-D \left| \frac{d\phi_1}{dz} - \frac{d\phi_2}{dz} \right|_{z_0} = Q_0 \tag{C-2}$$

where ϕ_1 was considered to be the flux of the region below the $z = z_0$ plane and ϕ_2 was the flux of the region above the z_0 plane.

Assuming that the variables of ϕ were separable,

$$\phi (x, y, z) = F(x)\, G(y)\, H(z) \tag{C-3}$$

the thermal diffusion equation written without a source term,

$$\nabla^2 \phi - \kappa^2 \phi = 0 \tag{C-4}$$

could be written as

$$\frac{1}{F} \frac{d^2 F}{dx^2} + \frac{1}{G} \frac{d^2 G}{dy^2} + \frac{1}{H} \frac{d^2 H}{dz^2} - \kappa^2 = 0. \tag{C-4}$$

A solution for the region above the z_0 plane that satisfied the boundary conditions and the diffusion equation was

$$\phi(x, y, z) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} A_{mn}\, F_m(x)\, G_n(y)\, H_{mn}(z) \tag{C-6}$$

where

$$F_m(x) = \frac{1}{\sqrt{a}} \cos \alpha_m x \qquad \text{for m odd}$$

$$= \frac{1}{\sqrt{a}} \sin \alpha_m x \qquad \text{for m even} \tag{C-7}$$

$$\alpha_m = \frac{m\pi}{2a}$$

and

$$H_{mn}(z) = \sinh \gamma_{mn}(2c - z) \tag{C-8}$$

where

$$\gamma_{mn}^2 = \alpha_m^2 + \beta_n^2 + \kappa^2 \tag{C-9}$$

$G_n(y)$ is similar to $F_m(x)$ except that b, n, and β replace a, m, and α, respectively.

Expanding the source term in a similar two-dimensional set in x and y,

$$Q_0\, \delta(x - x_0)\, \delta(y - y_0) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} Q_{mn}\, F_m(x)\, G_n(y), \tag{C-10}$$

multiplying both sides by the orthonormal functions and integrating over the range of orthonormality gave

$$Q_0\, \delta(x - x_0)\, \delta(y - y_0) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} Q_0\, F_m(x_0)\, G_n(y_0) \tag{C-11}$$

Using the boundary conditions, Eq. C-1 and Eq. C-2 with Eq. C-11 led to the evaluation of A_{mn} for the region above the z_0 plane,

$$A_{mn} = \frac{Q_0\, F_m(x_0)\, G_n(y_0) \sinh \gamma_{mn}(z_0)}{D\gamma_{mn} \sinh 2\gamma_{mn} C} \tag{C-12}$$

The expression for the thermal flux in the region above the plane of the source was then

$$\phi(x, y, z) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{Q_0}{D\gamma_{mn}} F_m(x)\, F_m(x_0)\, G_n(y)\, G_n(y_0) \frac{\sinh \gamma_{mn} z_0 \sinh \gamma_{mn}(2c - z}{\sinh 2\gamma_{mn} C} \tag{C-13}$$

APPENDIX D

Description and Explanation of the IBM-650 Computer Program used to Calculate the Flux in the Standard Pile

This computer program was written to calculate the thermal neutron flux along the central axis of the KSU Standard Pile. The program was written in SOAP II and floating point. The object program and the logic diagram are given in this section.

$$\phi(z) = \sum_{i=1}^{N} \sum_{j,k=1}^{\infty} \frac{3 f_i Q_0 b_{jk}}{\lambda_{tr} ab} e^{-(\alpha_j^2 + \beta_k^2)\frac{r_{th-i}^2}{4}} e^{\frac{r_{th-i}^2}{4b_{jk}}} \left\{ e^{-\frac{z}{b_{jk}}} \left[1 + \operatorname{erf}\left(\frac{z}{r_{th-i}} - \frac{r_{th-i}}{2b_{jk}} \right) \right] + e^{z/b_{jk}} \left[1 - \operatorname{erf}\left(\frac{z}{r_{th-i}} + \frac{r_{th-i}}{2b_{jk}} \right) \right] \right\} \tag{D-1}$$

where $$\left(\frac{1}{b_{jk}} \right)^2 = \frac{1}{L^2} + \frac{\pi^2 j^2}{a^2} + \frac{\pi^2 k^2}{b^2} = \kappa^2 + \alpha_j^2 + \beta_k^2 \tag{D-2}$$

and $$\operatorname{erf}(t) = \frac{2}{\sqrt{\pi}} \int_0^t e^{-u^2} du. \tag{D-3}$$

The program was set up to sum the infinite series j and k by summing over odd integers j, holding k constant, until the contribution of a term of the series became less than a specified precision. Index k was then increased by two and the summation on index j repeated until the precision specification was met.

This summation process was repeated in such a manner that contributions from all possible combinations of odd j and k that were greater than a specified precision were included in the summation.

Input data consisted of diffusion parameters, numerical constants and geometrical specifications. The positions along the central z axis at which the flux was to be calculated were read into drum storage locations starting with 1001. The program had a capacity for 100 flux positions. The Gaussian ranges were read into drum storage locations 0101, 0102, and 0103. The corresponding fractional contributions of each Gaussian term were read into drum locations 0104, 0105, and 0106, respectively. Table 11 lists other input data required for program use.

Table 11. Input data required for use of the IBM-650 program which calculates the flux in the standard pile.

Symbol	Explanation	Drum storage location
1	Identification number 1	0041
3	Identification number 3	0969
4	Identification number 4	0389
ZERO	0.00	0226
ONE	1.00	0250
TWO	2.00	0212
THREE	3.00	0340
FOUR	4.00	0407
A	Width of pile in x direction (cm)	0369
B	Width of pile in y direction (cm)	0469
PI	π	0259
SQPI	$\sqrt{\pi}$	0350
Q	Source strength (n/sec)	0572
KAPP2	Reciprocal of diffusion length squared (cm^{-2})	0158
LMBDA	Transport mean free path (cm)	0025
INDXA	Number of Gaussian range groups	0114
INDXC	Number of flux points	0202
PREC	Specified precision of last term in summation	0047

Other symbols corresponding to terms in the program print out and the logic diagram are given as follows:

FRAC = f_i, the fractional contribution of the i^{th} Gaussian range

TURM = The part of the solution which depends on a particular j and k

SUM 1 = Summation of TURMS

E = $f_i \; e^{r^2_{th-i} \; \kappa^2}$ (SUM 1)

F = $\sum_{i=1}^{N} E_i$

The machine yielded an answer card having a capacity of eight words, a word being a ten digit number and a sign. Provision was made for printing out partial answers for checking purposes, thus making it necessary to identify partial answer cards by the use of an identification number which was always printed in the word 1 location of the answer card. Table 12 lists the identification number and the answer card content of the various print outs. If the partial answer print outs are not needed, they may be eliminated by use of the one word load cards listed in Table 13.

Table 12. Answer identification table for various answer print outs for the standard pile flux.

Word 1	Word 2	Word 3	Word 4	Word 5	Word 6	Word 7	Word 8
1	J	K	R	Z	TURM	SUM 1	
3	FRAC	SUM 1	SUM 2	E			
4	Z					F	FLUX

Table 13. One word load cards used for eliminating unnecessary answer print outs for standard pile flux program.

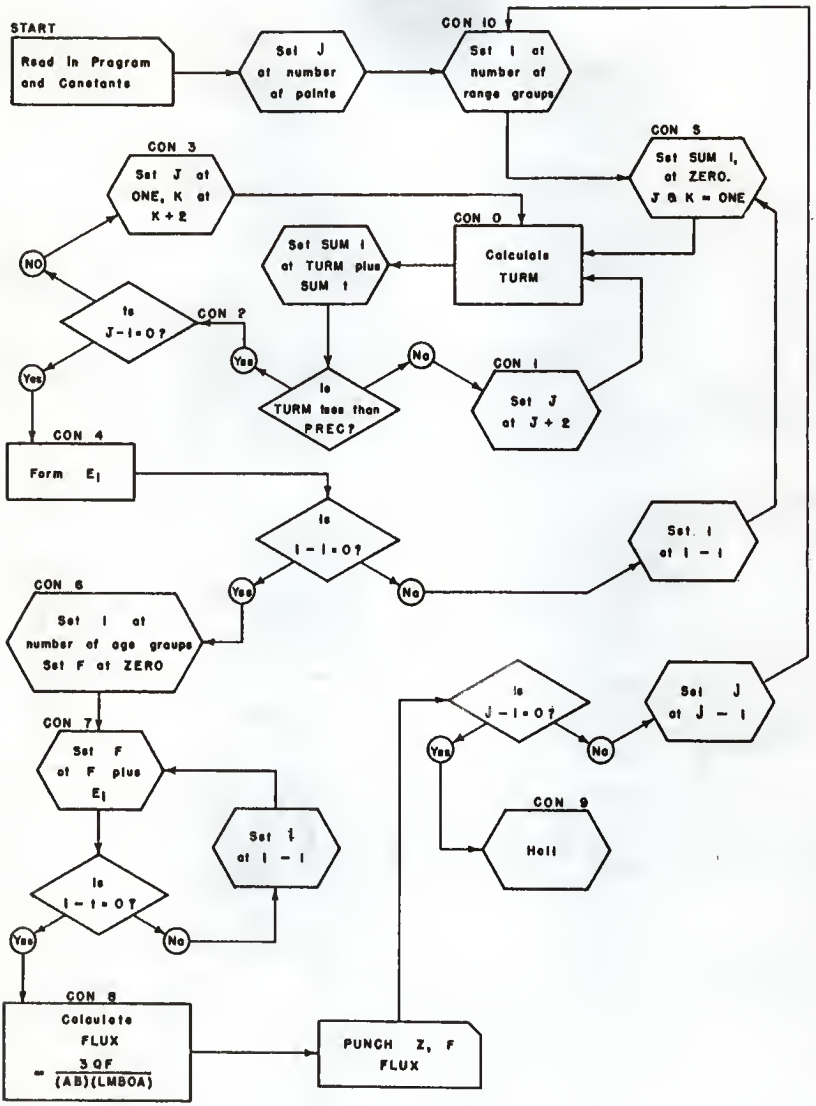
Print out identification :	Instruction address :	Instruction
1	0435	60 0152 0357
3	0263	50 0001 0183

Table 14. Computer precision study for standard pile flux.

PREC :	Flux at z = 5.63 cm	Convergence time	Flux at z = 158.08 cm	Convergence time
10^{0}	2259.4 n/cm^2-sec		32.361 n/cm^2-sec	
10^{-1}	2273.9	49 sec	32.758	17 sec
10^{-2}	2275.1	62	32.758	17
10^{-3}	2275.3	89	32.768	29
10^{-4}	2275.3	114	32.768	35

Table 14 presents a study showing the flux values as a function of the specified accuracy of the last term in the finite series.

LOGIC DIAGRAM – APPENDIX D



STANDARD PILE FLUX

							1	0000	00 0000	0000
							2	0000	00 0000	0000
							3	0000	00 0000	0000
							4	0000	00 0000	0000
							5	0000	00 0000	0000
							6	0000	00 0000	0000
							7	0000	00 0000	0000
							8	0000	00 0000	0000
							9	0000	00 0000	0000
							10	0000	24 0003	0006
							11	0006	20 0011	0014
							12	0014	67 0011	0015
							13	0015	30 0019	0022
							14	0022	60 0019	0023
							15	0023	39 0026	0076
							16	0076	32 0029	0005
							17	0005	39 0019	0060
							18	0069	32 0072	0049
							19	0049	39 0019	0119
							20	0119	32 0122	0099
							21	0099	39 0019	0169
							22	0169	32 0172	0149
							23	0149	39 0019	0219
							24	0219	32 0222	0199
							25	0199	39 0019	0269
							26	0269	32 0272	0249
							27	0249	31 0004	0007
							28	0007	39 0004	0054
							29	0054	21 0004	0057
							30	0057	39 0004	0154
							31	0154	21 0004	0157
							32	0157	60 0011	0065
							33	0065	46 0018	0319
							34	0018	60 0027	0027
							35	0027	34 0004	0304
							36	0204	21 0004	0319
							37	0319	65 0004	0003
							38	0272	10 0000	0051
							39	0222	24 9998	6850
							40	0172	31 8575	8349
							41	0122	25 9137	1248
							42	0072	17 1562	0047
							43	0029	54 3020	0045
							44	0026	69 0600	0044
							45	0050	24 0053	0056
							46	0056	69 0009	0012
							47	0012	24 1977	0030
							48	0030	24 1978	0031
							49	0031	24 1979	0032
							50	0032	24 1980	0033
							51	0033	24 1981	0034
							52	0034	24 1982	0035
							53	0035	24 1983	0036
							54	0036	24 1984	0053
							55	0009	00 0000	0000
							56	0150	24 0153	0156
							57	0156	46 0059	0010
							58	0010	45 0064	0153
							59	0064	31 0060	0001
							60	0001	32 0024	0001
							61	0001	39 0254	0304
							62	0304	21 0008	0061
							63	0061	60 0068	0073
							64	0073	34 0008	0058
							65	0058	32 0008	0085
							66	0085	39 0254	0354
							67	0354	33 0000	0135
							68	0135	44 0039	0040
							69	0039	46 0042	0040
							70	0042	32 0008	0185
							71	0185	21 0008	0061
							72	0040	60 0008	0153
							73	0053	01 0000	0153
							74	0254	50 0000	0050
							75	0024	10 0000	0051
							76	0200	24 0203	0206
							77	0206	60 0053	0113
							78	0013	39 0016	0066
							79	0066	21 0020	0123
							80	0123	34 0159	0209
							81	0209	39 0062	0112
							82	0112	39 0016	0116
							83	0116	21 0070	0173
							84	0173	34 0062	0162
							85	0162	39 0115	0165
							86	0165	39 0016	0166
							87	0166	21 0220	0223
							88	0223	34 0115	0215
							89	0215	39 0118	0168
							90	0168	39 0016	0166
							91	0216	21 0170	0273
							92	0273	34 0118	0218
							93	0218	39 0071	0121
							94	0121	39 0016	0266
							95	0266	21 0220	0323
							96	0323	34 0071	0171
							97	0171	39 0074	0124
							98	0124	39 0016	0316
							99	0316	32 0220	0047
							100	0047	32 0172	0097
							101	0097	32 0120	0147
							102	0147	32 0078	0197
							103	0197	32 0228	0247
							104	0247	32 0250	0077
							105	0077	21 0082	0235
							106	0235	39 0016	0136
							107	0132	21 0086	0089
							108	0089	39 0086	0136
							109	0136	23 0090	0043
							110	0043	39 0090	0140
							111	0140	21 0044	0297
							112	0297	39 0044	0094
							113	0094	21 0048	0051
							114	0051	60 0250	0055
							115	0055	34 0048	0098
							116	0098	21 0002	0155
							117	0155	60 0250	0205
							118	0205	33 0002	0203
							119	0159	70 5230	7849

	6LR	0100	0110			
	6LR	1000	1100			
	6LR	1951	1960	READ		
	6LR	1977	1985	PRINT		
	SYN	R	0104	GAUSSRANGE		
	SYN	FRAC	0107	FRACTION R		
	SYN	E	0110	FLUX PART		
	SYN	START	1999			
	SYN	Z	1000			
EOQEA	STO	AAA1		E TO X		
	ATL	AAA2		SUBROUTINE		
	RAM	AAA2				
	STL	AAA3		X FOR CALC		
	RAU	AAA3				
	FMP	AAA16				
	FAD	AAA15				
	FMP	AAA3				
	FAD	AAA14				
	FMP	AAA3				
	FAD	AAA13				
	FMP	AAA3				
	FAD	AAA12				
	FMP	AAA3				
	FAD	AAA11				
	FMP	AAA3				
	FAD	AAA10				
	STU	AAA4				
	FMP	AAA4				
	STU	AAA4				
	FMP	AAA4				
	STU	AAA4				
	RAU	AAA2				
	BMI	AAA5	AAA6			
AAA5	RAU	AAA10				
	FDV	AAA4				
	STU	AAA4	AAA6			
	RAL	AAA4	AAA1			
AAA6	10	0000	0051			
AAA11	24	9998	6850			
AAA12	31	8575	8349			
AAA13	25	9137	1248			
AAA14	17	1562	0047			
AAA15	54	3020	0045			
AAA16	69	0600	0044			
EOQCL	STD	ZZZ1		CLEAR		
	LOD	ZZZ10		PUNCH		
	STD	1977		ROUTINE		
	STD	1978				
	STD	1979				
	STD	1980				
	STD	1981				
	STD	1982				
	STD	1983				
	STD	1984	ZZZ1			
ZZZ10	00	0000	0000			
EOOAU	STO	SEXT		SQUARE	1	
	BMI	SERR		ROOT	2	
	NZE		SEXT	SUB	3	
	STU	8A		ROUTINE	4	
	FAD	810			5	
	FMP	8HAF	8B		6	
B8	STU	88AV	8A8		7	
8A8	RAU	8A		8 CAPT A	8	
	FDV	88AV			9	
	FAD	88AV			10	
	FMP	8HAF			11	
	FSB	98AV			12	
	NZU		8R		13	
	BMI		8R		14	
	FAD	88AV			15	
	STU	88AV	8A8		16	
8R	RAU	86AV	SEXT		17	
BERR	HLT	0000	SEXT		18	
8HAF	80	0000	0050		19	
810	10	0000	0051		20	
ERF	STO	EXIT		ERROR		
	RAU	A1		FUNCTION		
	FMP	X		SUBROUTINE		
	STU	A1X1				
	FDV	A1				
	FMP	A2				
	FMP	X				
	STU	A2X2				
	FDV	A2				
	FMP	A3				
	FMP	X				
	STU	A3X3				
	FDV	A3				
	FMP	A4				
	FMP	X				
	STU	A4X4				
	FDV	A4				
	FMP	A5				
	FMP	X				
	STU	A5X5				
	FDV	A5				
	FMP	A6				
	FMP	X				
	FAD	A5X6				
	FAD	A4X4				
	FAD	A3X3				
	FAD	A2X2				
	FAD	A1X1				
	FAD	ONE				
	STU	TERM1				
	FMP	TERM1				
	STU	TERM2				
	FMP	TERM2				
	STU	TERM4				
	FMP	TERM4				
	STU	TERM8				
	FMP	TERM8				
	STU	TERM				
	RAU	ONE				
	FDV	TERM				
	STU	TEMP				
	RAU	ONE				
	FSB	TEMP	EXIT			
A1	70	5230	7849			

```
A2          42   2820      1249                     120   0062   42 2820 1249
A3          92   7052      7248                     121   0115   92 7052 7248
A4          15   2014      3047                     122   0118   15 2014 3047
A5          27   6567      2047                     123   0071   27 6567 2047
A6          43   0638      0046                     124   0074   43 0638 0046
REPET       STD  EXET                 SUBROUTINE    125   0300   24 0253 0256
            RAU  PI                   TO FIND       126   0256   60 0259 0063
            FMP  J                    TURM FOR      127   0063   39 0366 0416
            FDV  A                    PARTICULAR    128   0416   34 0369 0419
            STU  ALPH                 J AND K       129   0419   21 0174 0127
            FMP  ALPH                               130   0127   39 0174 0224
            STU  ALPH2                              131   0224   21 0028 0081
            RAU  PI                                 132   0081   60 0259 0113
            FMP  K                                  133   0113   39 0466 0516
            FDV  B                                  134   0516   34 0469 0519
            STU  BETA                               135   0519   21 0274 0177
            FMP  BETA                               136   0177   39 0274 0324
            FAD  ALPH2                              137   0324   32 0028 0255
            FAD  KAPP2                              138   0255   32 0158 0285
            STU  TEMP1                              139   0285   21 0190 0093
            RAU  ONE                                140   0093   60 0250 0305
            FDV  TEMP1                              141   0305   34 0190 0240
            LDD            E00AU                    142   0240   69 0143 0150
            STU  BJK                  FORM BJK      143   0143   21 0148 0151
            RAU  R      A                           144   0151   60 2104 0309
            FDV  TWO                                145   0309   34 0212 0262
            FDV  BJK                                146   0262   34 0148 0198
            STU  ROVER                              147   0198   21 0052 0355
            RAU  Z      C                           148   0355   60 7000 0405
            FDV  R      A                           149   0405   34 2104 0404
            STU  ZOVER                              150   0404   21 0208 0111
            FAD  ROVER                              151   0111   32 0052 0079
            STU  X                                  152   0079   21 0016 0569
            LDD            ERF                      153   0569   69 0322 0200
            STU  ERFX                               154   0322   21 0126 0129
            RAU  ONE                                155   0129   60 0250 0455
            FSB  ERFX                               156   0455   33 0126 0303
            STU  PAR1                               157   0303   21 0258 0161
            RAU  ZOVER                              158   0161   60 0208 0163
            FSB  ROVER                              159   0163   33 0052 0179
            STU  X                                  160   0179   21 0016 0619
            BMI  SUB1      SUB2                     161   0619   46 0372 0373
SUB1        RAM   8003                              162   0372   67 8003 0229
            RAU   8002                              163   0229   60 8002 0037
            STU  X                                  164   0037   21 0016 0669
            LDD            ERF                      165   0669   69 0422 0200
            RAL   8003                              166   0422   65 8003 0279
            RSU   8002                              167   0279   61 8002 0087
            FAD  ONE       SUB3                     168   0087   32 0250 0227
SUB2        LDD            ERF                      169   0373   69 0176 0200
            FAD  ONE       SUB3                     170   0176   32 0250 0227
SUB3        STU  PAR2                               171   0227   21 0182 0335
            RAU  Z      C                           172   0335   60 7000 0505
            FDV  BJK                                173   0505   34 0148 0248
            STU  TEMP1                              174   0248   21 0190 0193
            RAL   8003                              175   0193   65 8003 0201
            LDD            E00EA                    176   0201   69 0454 0000
            RAU   8002                              177   0454   60 8002 0213
            FMP  PAR1                               178   0213   39 0258 0308
            STU  RAP1                               179   0308   21 0312 0265
            RSL  TEMP1                              180   0265   66 0190 0045
            LDD            E00EA                    181   0045   69 0298 0000
            RAU   8002                              182   0298   60 8002 0207
            FMP  PAR2                               183   0207   39 0182 0232
            FAD  RAP1                 TURM FOR      184   0232   32 0312 0139
            FMP  BJK                  PARTICULAR    185   0139   39 0148 0348
            STU  TURM      EXET       J AND K       186   0348   21 0152 0253
START       LDD  INDXC                SET IRC AT    187   1999   69 0203 0555
            RAC   8001     CON10      NMBR OF Z     188   0555   88 8001 0211
CON10       LDD  INDXA                SET IRA AT    189   0211   69 0114 0017
            RSA   8001     CON5       NMBR OF R     190   0017   81 8001 0423
CON5        LDD  ZERO                 SET SUM1      191   0423   69 0226 0329
            STD  SUM1                 AT ZERO       192   0329   24 0282 0385
            LDD  ONE                                193   0385   69 0250 0353
            STD  J                    SET J AT 1    194   0353   24 0366 0719
            STD  K         CON0       SET K AT 1    195   0719   24 0466 0769
CON0        LDD            REPET      FIND TURM     196   0769   69 0472 0300
            RAU  TURM                               197   0472   60 0152 0257
            FAD  SUM1                 ADD TURM      198   0257   32 0282 0359
            STU  SUM1                 TO SUM1       199   0359   21 0282 0435
            LDD            E00CL                    200   0435   69 0038 0050
            LDD  1                    PRINT         201   0038   69 0041 0144
            STD   1977                PARTIAL       202   0144   24 1977 0080
            LDD  J                    ANSWERS       203   0080   69 0366 0819
            STD   1978                FOR           204   0819   24 1978 0131
            LDD  K                    CHECKING      205   0131   69 0466 0869
            STD   1979                              206   0869   24 1979 0332
            LDD  R      A                           207   0332   69 2104 0307
            STD   1980                              208   0307   24 1980 0083
            LDD  Z      C                           209   0083   69 7000 0403
            STD   1981                              210   0403   24 1981 0084
            LDD  TURM                               211   0084   69 0152 0605
            STD   1982                              212   0605   24 1982 0485
            LDD  SUM1                               213   0485   69 0282 0535
            STD   1983                              214   0535   24 1983 0186
            PCH   1977                              215   0186   71 1977 0277
            RAU  TURM                 TEST          216   0277   60 0152 0357
            FSB  PREC                 PRECISION     217   0357   33 0060 0137
            BMI  CON2      CON1       OF TURM       218   0137   46 0298 0091
CON1        RAU  J                    SET J AT      219   0091   60 0366 0221
            FAD  TWO                  J PLUS 2      220   0221   32 0212 0189
            STU  J         CON0                     221   0189   21 0366 0769
CON2        RAU  J                    TEST          222   0290   60 0366 0271
            FSB  ONE                  PRECISION     223   0271   33 0250 0327
            NZE  CON3      CON4       OF TURM       224   0327   45 0130 0181
CON3        RAU  ONE                  SET J AT 1    225   0130   60 0250 0655
            STU  J                                  226   0655   21 0366 0919
            RAU  K                    SET K AT      227   0919   60 0466 0321
            FAD  TWO                  K PLUS 2      228   0321   32 0212 0239
            STU  K         CON0                     229   0239   21 0466 0769
CON4        RAU  R      A                           230   0181   60 2104 0409
            FMP  R      A                           231   0409   39 2104 0504
            FDV  FOUR                               232   0504   34 0407 0457
            FMP  KAPP2                              233   0457   39 0158 0358
            RAL   8003                              234   0358   65 8003 0315
            LDD            E00EA                    235   0315   69 0268 0000
            RAU   8002                STORE FLUX    236   0268   60 8002 0377
            FMP  SUM1                 CONTRIBU      237   0377   39 0282 0382
            STU  SUM2                 TION FROM     238   0382   21 0236 0289
            FMP  FRAC   A             PARTICULAR    239   0289   39 2107 0507
            STU  E      A             R             240   0507   21 2110 0263
            LDD            E00CL                    241   0263   69 0566 0050
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           LDD  3                                242   0566   69 0969 0522
           STD   1977               PRINT        243   0522   24 1977 0180
           LDD  FRAC   A            PARTIAL      244   0180   69 2107 0160
           STD   1978               ANSWERS      245   0160   24 1978 0231
           LDD  SUM1                FOR          246   0231   69 0282 0585
           STD   1979               CHECKING     247   0585   24 1979 0432
           LDD  SUM2                             248   0432   69 0236 0339
           STD   1980                            249   0339   24 1980 0133
           LDD  E      A                         250   0133   69 2110 0313
           STD   1981                            251   0313   24 1981 0134
           PCH   1977                            252   0134   71 1977 0427
           AXA   0001               SET R AT     253   0427   50 0001 0183
           NZA  CON5      CON6      NEW R        254   0183   40 0423 0187
  CON6     LDD  INDXA                            255   0187   69 0114 0067
           RSA   8001                            256   0067   81 8001 0473
           LDD  ZERO                             257   0473   69 0226 0379
           STD  F         CON7      SUM          258   0379   24 0482 0635
  CON7     RAU  E      A            CONTRIBU     259   0635   60 2110 0365
           FAD  F                   FROM EACH    260   0365   32 0482 0459
           STU  F                   R            261   0459   21 0482 0685
           AXA   0001                            262   0685   50 0001 0141
           NZA  CON7      CON8                   263   0141   40 0635 0095
  CON8     RAU  F                                264   0095   60 0482 0237
           FMP  THREE                            265   0237   39 0340 0390
           FDV  A                                266   0390   34 0369 1119
           FDV  B                                267   1119   34 0469 1169
           FMP  Q                                268   1169   39 0572 0622
           FDV  LMBDA               DETERMINE    269   0622   34 0025 0075
           STU  FLUX                FLUX         270   0075   21 0230 0233
           LDD            EOOCL                  271   0233   69 0286 0050
           LDD  4                                272   0286   69 0389 0092
           STD   1977               PRINT Z      273   0092   24 1977 0280
           LDD  Z      C            F AND FLUX   274   0280   69 7000 0453
           STD   1978                            275   0453   24 1978 0281
           LDD  F                                276   0281   69 0482 0735
           STD   1983                            277   0735   24 1983 0336
           LDD  FLUX                             278   0336   69 0230 0283
           STD   1984                            279   0283   24 1984 0287
           PCH   1977                            280   0287   71 1977 0477
           SXC   0001               SET Z AT     281   0477   59 0001 0333
           NZC  CON10     CON9      NEW Z        282   0333   48 0211 0337
  CON9     HLT                                   283   0337   01 0387 0387
  1        00    1000     0000      IDENTIFI     284   0041   00 1000 0000
  3        00    3000     0000       CATION      285   0969   00 3000 0000
  4        00    4000     0000      NUMBERS      286   0389   00 4000 0000
  ZERO     00    0000     0000                   287   0226   00 0000 0000
  ONE      10    0000     0051                   288   0250   10 0000 0051
  TWO      20    0000     0051                   289   0212   20 0000 0051
  THREE    30    0000     0051                   290   0340   30 0000 0051
  FOUR     40    0000     0051                   291   0407   40 0000 0051
  PI       31    4159     0051                   292   0259   31 4159 0051
  A        17    6230     0053      PILE SIZE          0369   17 6230 0053
  B        17    6230     0053      PILE SIZE          0469   17 6230 0053
  SQPI     17    7245     3951      ROOT OF PI         0350   17 7245 3951
  Q        16    1000     0057      SOURCE STR         0572   16 1000 0057
  KAPP2    35    9250     0047      KAPPA SQD          0158   35 9250 0047
  LMBDA    24    6000     0051      MN FR PATH         0025   24 6000 0051
  INDXA    00    0000     0003      NMBR OF R          0114   00 0000 0003
  INDXC    00    0000     0014      NMBR OF Z          0202   00 0000 0014
  R01      30    5400     0052       RANGE             0101   30 5400 0052
  R02      39    3900     0052       GROUPS            0102   39 3900 0052
  R03      66    8500     0052                         0103   66 8500 0052
  FRAC1    12    8000     0050                         0104   12 8000 0050
  FRAC2    63    1000     0050      RANGE              0105   63 1000 0050
  FRAC3    24    1000     0050      FRACTIONS          0106   24 1000 0050
  PREC     10    0000     0047      PRECISION          0060   10 0000 0047
  Z1       56    3000     0051      Z VALUES           1001   56 3000 0051
  Z2       15    8200     0052                         1002   15 8200 0052
  Z3       25    9600     0052                         1003   25 9600 0052
  Z4       36    1100     0052                         1004   36 1100 0052
  Z5       46    3100     0052                         1005   46 3100 0052
  Z6       56    4500     0052                         1006   56 4500 0052
  Z7       66    1500     0052                         1007   66 1500 0052
  Z8       76    7800     0052                         1008   76 7800 0052
  Z9       86    9400     0052                         1009   86 9400 0052
  Z10      97    1200     0052                         1010   97 1200 0052
  Z11      11    7440     0053                         1011   11 7440 0053
  Z12      13    7760     0053                         1012   13 7760 0053
  Z13      15    8080     0053                         1013   15 8080 0053
  Z14      17    8400     0053                         1014   17 8400 0053
```

APPENDIX E

Description and Explanation of the IBM-650 Computer Program Used to Calculate the Fast Point Neutron Source in a Finite Pile.

This computer code was written to calculate from theoretical considerations, the thermal flux in a finite pile due to a point source of epithermal neutrons. The program was written in SOAP II and floating point. The object program and a logic diagram are given in this section.

The solution to be programmed was

$$\phi(x,y,z) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \sum_{o=1}^{\infty} \frac{Q_0 F_m(x) F_m(x_0) G_n(y) G_n(y_0) H_o(z) H_o(z_0) e^{-(\alpha_m^2 + \beta_n^2 + \gamma_o^2)\tau_{th}}}{D(\alpha_m^2 + \beta_n^2 + \gamma_o^2 + 1/L^2)} \tag{E-1}$$

where

$$F_m(x) = \frac{1}{\sqrt{a}} \cos \alpha_m x \qquad \text{for m odd} \tag{E-2}$$

$$F_m(x_0) = \frac{1}{\sqrt{a}} \sin \alpha_m x \qquad \text{for m even}$$

and $$\alpha_m = \frac{m\pi}{2a}$$

$F_n(x_0)$, $G_n(y)$, $G_n(y_0)$, $H_o(z_0)$, and $H_o(z_0)$ are written in a similar manner. The geometry for this solution is shown in Fig. 25.

The program was set up to sum the infinite series by the process of summing over index o, holding m and n constant, until the contribution of a term became less than a specified precision. Index n

was then increased by unity and the summation on index o repeated until the precision specification was met. This summation process was repeated in such a manner that contributions from all possible combinations of m, n and o that were greater than a specified precision were included in the summation.

Input data consisted of various diffusion parameters, numerical constants, and geometrical specifications. Data were read into the machine with the program deck on one-word load cards. Each one-word load card contained the numerical value of a particular constant and its specified machine storage location. Table 15 lists the input data required for program use.

Table 15. Input data required for use of the IBM-650 program which calculates the thermal flux from a fast point source in a finite pile.

Symbol	Explanation	Drum Storage location
2	Identification number 2	0450
4	Identification number 4	0500
6	Identification number 6	0550
7	Identification number 7	0173
TWO	2.00	0151
ONE	1.00	0350
ZERO	0.00	0080
PI	π	0098
A	Half width of pile in x-direction (cm)	0254
B	Half width of pile in y-direction (cm)	0354
C	Half width of pile in z-direction (cm)	0454
D	Diffusion coefficient (cm)	0457
Q	Source strength (n/sec)	0160
XINIT	Initial value of x (cm)	0102
YINIT	Initial value of y (cm)	0256
ZINIT	Initial value of z (cm)	0168
XO	Source location in x-direction (cm)	0397
YO	Source location in y-direction (cm)	0447
ZO	Source location in z-direction (cm)	0547

Table 15. (concl.)

Symbol	Explanation	Drum storage location
DELX	Increment in x (cm)	0958
DELY	Increment in y (cm)	0170
DELZ	Increment in z (cm)	0282
XMAX	Maximum value of x (cm)	0456
YMAX	Maximum value of y (cm)	0968
ZMAX	Maximum value of z (cm)	0330
TAU	Fermi age (cm^2)	0126
K2	Reciprocal of diffusion length squared (cm^{-2})	0226
BETSQ	Lateral buckling in y-direction (cm^{-2})	0202
GAMSQ	Lateral buckling in z-direction (cm^{-2})	0242
PREC	Specified precision of term in summation	0064

Other symbols corresponding to terms in the program print out and the logic diagram are given as follows:

$$FX = a F_m(x) F_m(x_0)$$

$$FY = b G_n(y) G_n(y_0)$$

$$FZ = c H_o(z) H_o(z_0)$$

$$\text{CONSTANT or CONST} = \frac{e^{-(\alpha_m^2 + \beta_n^2 + \gamma_o^2)}}{(\alpha_m^2 + \beta_n^2 + \gamma_o^2 + \kappa^2)}$$

M, N, and O = Summation indices in the x, y, and z directions.

INDXM, INDXN, and INDXO = Summation indices for testing the oddness or evenness of M, N, and O.

The program calculated the flux at the initial values of x, y, and z. The coordinates were then varied according to specified increments in a particular manner in order to give a three-dimensional mapping of the flux in the region.

The machine yielded an answer card having a capacity for eight words, a word being a ten digit number and a sign. Provision was made for printing out partial answers for checking purposes, thus making it necessary to identify partial answer cards by use of an identification number which was always printed in the word 1 location. Table 16 lists the identification number and the answer card content of the various print outs. If the partial answer print outs are not needed they may be eliminated by use of the one word load cards listed in Table 17.

Table 16. Answer identification table for various answer print outs for thermal flux from fast point source in finite pile.

Word 1	Word 2	Word 3	Word 4	Word 5	Word 6	Word 7	Word 8
2	M	N	O	SUM 1	SUM 2	SUM 3	
4	M	N	O	SUM 1	SUM 2	SUM 3	
6	M	N	O	SUM 1	SUM 2	SUM 3	
7	XO	YO	ZO	X	Y	Z	FLUX

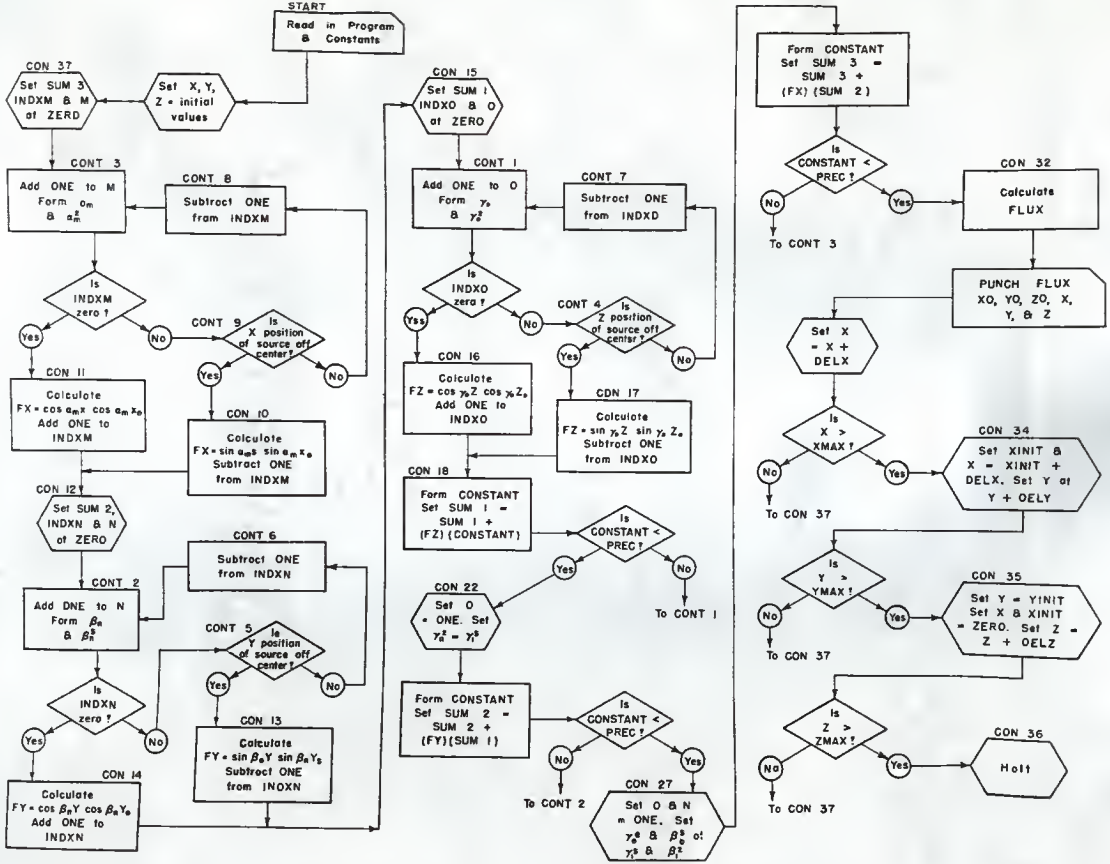
Table 17. One-word load cards used for eliminating unnecessary answer print outs for fast point source flux in finite pile.

Print out identification	Instruction address	Instruction
2	0441	46 1077 0651
4	0541	46 1127 0401
6	0591	46 1177 0101

Table 18. Computer precision study for fast point source flux in finite pile.

PREC	Flux at x = 10.16 cm, y = 0.00, z = 0.00	Flux at x = 80.00 cm, y = 80.00, z = 80.00	Convergence time
10^{0}	2151.4 n/cm^2-sec	2.033 n/cm^2-sec	
10^{-1}	2153.0	2.214	
10^{-2}	2153.1	2.207	3 min 21 sec

Table 18 presents a study showing the flux value as a function of the specified accuracy of the last term in the infinite series.



LOGIC DIAGRAM – APPENDIX E

```
                                      THERMAL
                                      FLUX FROM
                                       FAST
                                       POINT
                                      SOURCE IN
                                       FINITE
                                        PILE
         BLR  1951     1960                        1   0000   00 0000 0000
         BLR  1977     1985                        2   0000   00 0000 0000
         SYN  START    1999                        3   0000   00 0000 0000
         SYN  X        1000                        4   0000   00 0000 0000
EDDEA    STD  AAA1              E TO THE X         5   0000   24 0003 0006
         STL  AAA2              SUB                6   0006   20 0011 0014
         RAM  AAA2              ROUTINE            7   0014   67 0011 0015
         STL  AAA3              X FOR CALC         8   0015   20 0019 0022
         RAU  AAA3                                 9   0022   60 0019 0023
         FMP  AAA16                               10   0023   39 0026 0076
         FAD  AAA15                               11   0076   32 0029 0005
         FMP  AAA3                                12   0005   39 0019 0069
         FAD  AAA14                               13   0069   32 0072 0049
         FMP  AAA3                                14   0049   39 0019 0119
         FAD  AAA13                               15   0119   32 0122 0099
         FMP  AAA3                                16   0099   39 0019 0169
         FAD  AAA12                               17   0169   32 0172 0149
         FMP  AAA3                                18   0149   39 0019 0219
         FAD  AAA11                               19   0219   32 0222 0199
         FMP  AAA3                                20   0199   39 0019 0269
         FAD  AAA10                               21   0269   32 0272 0249
         STU  AAA4                                22   0249   21 0004 0007
         FMP  AAA4                                23   0007   39 0004 0054
         STU  AAA4                                24   0054   21 0004 0057
         FMP  AAA4                                25   0057   39 0004 0104
         STU  AAA4                                26   0104   21 0004 0107
         RAU  AAA2                                27   0107   60 0011 0065
         BMI  AAA5     AAA6                       28   0065   46 0018 0319
AAA5     RAU  AAA10                               29   0018   60 0272 0027
         FDV  AAA4                                30   0027   34 0004 0154
         STU  AAA4     AAA6                       31   0154   21 0004 0319
AAA6     RAL  AAA4     AAA1                       32   0319   65 0004 0003
AAA10     10  0000     0051                       33   0272   10 0000 0051
AAA11     24  9998     6850                       34   0222   24 9998 6850
AAA12     31  2575     8349                       35   0172   31 2575 8349
AAA13     25  9137     1248                       36   0122   25 9137 1248
AAA14     17  1562     0047                       37   0072   17 1562 0047
AAA15     54  3020     0045                       38   0029   54 3020 0045
AAA16     69  0600     0044                       39   0026   69 0600 0044
EDDCR    STD  EXIT              COSINE            40   0050   24 0053 0056
         RAU  8002              SUB               41   0056   60 8002 0115
         BMI  NEGAT    REDUC    ROUTINE           42   0115   46 0068 0369
NEGAT    FAD  TWOPI                               43   0068   32 0021 0047
         BMI  NEGAT                               44   0047   46 0068 0001
         FSB  ONEPI    COSIO                      45   0001   33 0204 0031
REDUC    FSB  TWOPI                               46   0369   33 0021 0097
         BMI           REDUC                      47   0097   46 0100 0369
         FAD  ONEPI    COSIO                      48   0100   32 0204 0031
COSIO    STU  THETA                               49   0031   21 0036 0039
         RSU  FPONE                               50   0039   61 0042 0147
         STU  TERMM                               51   0147   21 0002 0055
         STU  FUNKT                               52   0055   21 0010 0013
         STL  ENN      NEGST                      53   0013   20 0017 0020
EDDSR    STD  EXIT              SINE              54   0150   24 0053 0106
         RAU  8002              SUB               55   0106   60 8002 0165
         BMI  NEGAV    REDUO    ROUTINE           56   0165   46 0118 0419
NEGAV    FAD  TWOPI                               57   0118   32 0021 0197
         BMI  NEGAV                               58   0197   46 0118 0051
         FSB  ONEPI    SINET                      59   0051   33 0204 0081
REDUO    FSB  TWOPI                               60   0419   33 0021 0247
         BMI           REDUO                      61   0247   46 0200 0419
         FAD  ONEPI    SINET                      62   0200   32 0204 0081
SINET    STU  THETA                               63   0081   21 0036 0089
         RSU  8003                                64   0089   61 8003 0297
         STU  TERMM                               65   0297   21 0002 0105
         STU  FUNKT                               66   0105   21 0010 0063
         LDD  FPONE                               67   0063   69 0042 0045
         STD  ENN      NEGST                      68   0045   24 0017 0020
NEGST    RAU  ENN                                 69   0020   60 0017 0071
         FAD  FPONE                               70   0071   32 0042 0469
         STU  NPONE                               71   0469   21 0024 0077
         FAD  FPONE                               72   0077   32 0042 0519
         STU  ENN                                 73   0519   21 0017 0070
         RSU  TERMM                               74   0070   61 0002 0157
         FMP  THETA                               75   0157   39 0036 0086
         FMP  THETA                               76   0086   39 0036 0136
         FDV  NPONE                               77   0136   34 0024 0074
         FDV  ENN                                 78   0074   34 0017 0067
         STU  TERMM                               79   0067   21 0002 0155
         RAM  FUNKT                               80   0155   67 0010 0215
         STL  FMAG                                81   0215   20 0569 0322
         RAM  TERMM                               82   0322   67 0002 0207
         RAU  8002                                83   0207   60 8002 0265
         FDV  FMAG                                84   0265   34 0569 0619
         FSB  SIZE8                               85   0619   33 0372 0299
         BMI  ENUFF                               86   0299   46 0052 0103
         RAU  FUNKT                               87   0103   60 0010 0315
         FAD  TERMM                               88   0315   32 0002 0079
         STU  FUNKT    NEGST                      89   0079   21 0010 0020
ENUFF    RAL  FUNKT    EXIT                       90   0052   65 0010 0053
SIZE8     10  0000     0043                       91   0372   10 0000 0043
TWOPI     62  8318     5351                       92   0021   62 8318 5351
ONEPI     31  4159     2751                       93   0204   31 4159 2751
FPONE     10  0000     0051                       94   0042   10 0000 0051
EDDCL    STD  ZZZ1              CLEAR             95   0250   24 0153 0156
         LDD  ZZZ10             PUNCH             96   0156   69 0009 0012
         STD  1977              ROUTINE           97   0012   24 1977 0030
         STD  1978                                98   0030   24 1978 0131
         STD  1979                                99   0131   24 1979 0032
         STD  1980                               100   0032   24 1980 0033
         STD  1981                               101   0033   24 1981 0034
         STD  1982                               102   0034   24 1982 0035
         STD  1983                               103   0035   24 1983 0186
         STD  1984     ZZZ1                      104   0186   24 1984 0153
ZZZ10     00  0000     0000                      105   0009   00 0000 0000
NEW      STD  EXINS             SUBROUTINE       106   0300   24 0203 0206
         RAU  ALPH2             FOR              107   0206   60 0059 0113
         FAD  BETA2             CONSTANT         108   0113   32 0016 0043
         FAD  GAM2                               109   0043   32 0046 0073
         FMP  TAU                                110   0073   39 0126 0176
         RSL  8003                               111   0176   66 8003 0083
         LDD           EDDEA                     112   0083   69 0236 0000
         STL  TEMP1                              113   0236   20 0041 0044
         RAU  ALPH2                              114   0044   60 0059 0163
         FAD  BETA2                              115   0163   32 0016 0093
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          FAD GAM2                            116    0093    32 0046 0123
          FAD K2                              117    0123    32 0226 0253
          STU TEMP2                           118    0253    21 0008 0061
          RAU TEMP1                           119    0061    60 0041 0095
          FDV TEMP2     EXINS                 120    0095    34 0008 0203
START     LDD XINIT                SET X Y Z  121    1999    69 0102 0205
          STD X                   AT INITIAL  122    0205    24 1000 0303
          LDD YINIT                VALUES     123    0303    69 0256 0109
          STD Y                               124    0109    24 0062 0365
          LDD ZINIT                           125    0365    69 0160 0121
          STD Z         CON37                 126    0121    24 0124 0127
CON37     LDD ZERO                SET SUM 3   127    0127    69 0080 0133
          STD SUM3                INDXM AND   128    0133    24 0286 0139
          STD M                   M AT ZERO   129    0139    24 0092 0145
          STD INDXM     CONT3                 130    0145    24 0048 0101
CONT3     RAU M                   ADD ONE     131    0101    60 0092 0347
          FAD ONE                 TO M        132    0347    32 0350 0177
          STU M                               133    0177    21 0092 0195
          FMP PI                              134    0195    39 0098 0148
          FDV TWO                             135    0148    34 0151 0201
          FDV A                   FORM ALPHA  136    0201    34 0254 0304
          STU ALPHA               AND ALPHA   137    0304    21 0058 0111
          FMP ALPHA               SQUARED     138    0111    39 0058 0108
          STU ALPH2                           139    0108    21 0059 0112
          RAU INDXM               TEST M FOR  140    0112    60 0048 0353
          NZE CONT9     CON11     EVEN OR OD  141    0353    45 0306 0257
CON11     RAU X                               142    0257    60 1000 0255
          FMP ALPHA               FORM COS    143    0255    39 0058 0158
          RAL  8003               ALPHA X     144    0158    65 8003 0415
          LDD           EDDCR                 145    0415    69 0218 0050
          STL TEMP1                           146    0218    20 0041 0094
          RAU XO                              147    0094    60 0397 0251
          FMP ALPHA               FORM COS    148    0251    39 0058 0208
          RAL  8003               ALPHA XO    149    0208    65 8003 0465
          LDD           EDDCR                 150    0465    69 0268 0050
          RAU  8002                           151    0268    60 8002 0227
          FMP TEMP1                           152    0227    39 0041 0091
          STU FX                  FORM FX     153    0091    21 0096 0349
          RAU INDXM               ADD ONE TO  154    0349    60 0048 0403
          FAD ONE                 INDXM       155    0403    32 0350 0277
          STU INDXM     CON12                 156    0277    21 0048 0301
CONT9     RAU XO                  TEST SORCE  157    0306    60 0397 0213
          NZU CON10     CONT8     X POSITION  158    0213    44 0117 0318
CONT8     RAU INDXM                           159    0318    60 0048 0453
          FSB ONE                 RESET       160    0453    33 0350 0327
          STU INDXM     CONT3     INDXM       161    0327    21 0048 0101
CON10     RAU X                               162    0117    60 1000 0305
          FMP ALPHA               FORM SINE   163    0305    39 0058 0258
          RAL  8003               ALPHA X     164    0258    65 8003 0515
          LDD           EDDSR                 165    0515    69 0368 0150
          STL TEMP1                           166    0368    20 0041 0144
          RAU XO                              167    0144    60 0397 0351
          FMP ALPHA               FORM SINE   168    0351    39 0058 0308
          RAL  8003               ALPHA XO    169    0308    65 8003 0565
          LDD           EDDSR                 170    0565    69 0418 0150
          RAU  8002                           171    0418    60 8002 0377
          FMP TEMP1                           172    0377    39 0041 0141
          STU FX                  FORM FX     173    0141    21 0096 0399
          RAU INDXM                           174    0399    60 0048 0503
          FSB ONE                 SUBT ONE    175    0503    33 0350 0427
          STU INDXM     CON12     FROM INDXM  176    0427    21 0048 0301
CON12     LDD ZERO                SET SUM2    177    0301    69 0080 0183
          STD N                   INDXN AND   178    0183    24 0336 0189
          STD SUM2                N AT ZERO   179    0189    24 0142 0245
          STD INDXN     CONT2                 180    0245    24 0198 0401
CONT2     RAU N                               181    0401    60 0336 0191
          FAD ONE                 ADD ONE     182    0191    32 0350 0477
          STU N                   TO N        183    0477    21 0336 0239
          FMP PI                              184    0239    39 0098 0248
          FDV TWO                             185    0248    34 0151 0451
          FDV B                               186    0451    34 0354 0404
          STU BETA                FORM BETA   187    0404    21 0358 0161
          FMP BETA                AND BETA    188    0161    39 0358 0408
          STU BETA2               SQUARED     189    0408    21 0016 0669
          RAU INDXN               TEST N FOR  190    0669    60 0198 0553
          NZE CONT5     CON14     EVEN OR OD  191    0553    45 0356 0307
CON14     RAU Y                               192    0307    60 0062 0167
          FMP BETA                FORM COS    193    0167    39 0358 0458
          RAL  8003               BETA Y      194    0458    65 8003 0615
          LDD           EDDCR                 195    0615    69 0468 0050
          STL TEMP1                           196    0468    20 0041 0194
          RAU YO                              197    0194    60 0447 0501
          FMP BETA                FORM COS    198    0501    39 0358 0508
          RAL  8003               BETA YO     199    0508    65 8003 0665
          LDD           EDDCR                 200    0665    69 0518 0050
          RAU  8002                           201    0518    60 8002 0527
          FMP TEMP1                           202    0527    39 0041 0241
          STU FY                  FORM FY     203    0241    21 0146 0449
          RAU INDXN               ADD ONE TO  804    0449    60 0198 0603
          FAD ONE                 INDXN       205    0603    32 0350 0577
          STU INDXN     CON15                 206    0577    21 0198 0551
CONT5     RAU YO                  TEST SORCE  207    0356    60 0447 0263
          NZU CON13     CONT6     Y POSITION  808    0263    44 0217 0568
CONT6     RAU INDXN                           209    0568    60 0198 0653
          FSB ONE                 RESET       810    0653    33 0350 0627
          STU INDXN     CONT2     INDXN       211    0627    21 0198 0401
CON13     RAU Y                               212    0217    60 0062 0267
          FMP BETA                FORM SINE   213    0267    39 0358 0558
          RAL  8003               BETA Y      214    0558    65 8003 0715
          LDD           EDDSR                 215    0715    69 0618 0150
          STL TEMP1                           216    0618    20 0041 0244
          RAU YO                              217    0244    60 0447 0601
          FMP BETA                FORM SINE   218    0601    39 0358 0608
          RAL  8003               BETA YO     219    0608    65 8003 0765
          LDD           EDDSR                 220    0765    69 0668 0150
          RAU  8002                           221    0668    60 8002 0677
          FMP TEMP1                           222    0677    39 0041 0291
          STU FY                  FORM FY     223    0291    21 0146 0499
          RAU INDXN                           224    0499    60 0198 0703
          FSB ONE                 SUBT ONE    225    0703    33 0350 0727
          STU INDXN     CON15     FROM INDXN  226    0727    21 0198 0551
CON15     LDD ZERO                SET SUM1    227    0551    69 0080 0233
          STD SUM1                INDXO AND   228    0233    24 0386 0289
          STD O                   O AT ZERO   229    0289    24 0192 0295
          STD INDXO     CONT1                 230    0295    24 0298 0651
CONT1     RAU O                               231    0651    60 0192 0497
          FAD ONE                 ADD ONE     232    0497    32 0350 0777
          STU O                   TO O        233    0777    21 0192 0345
          FMP PI                              234    0345    39 0098 0348
          FDV TWO                             235    0348    34 0151 0701
          FDV C                               236    0701    34 0454 0504
          STU GAMMA               FORM GAMMA  237    0504    21 0658 0211
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        FMP GAMMA               AND GAMMA    238  0211  39 0658 0708
        STU GAM2                SQUARED      239  0708  21 0046 0549
        RAU INDXO               TEST D FOR   240  0549  60 0298 0753
        NZE CONT4     CON16     EVEN OR OD   241  0753  45 0406 0357
CON16   RAU Z                                242  0357  60 0124 0129
        FMP GAMMA               FORM COS     243  0129  39 0658 0758
        RAL  8003               GAMMA Z      244  0758  65 8003 0815
        LDD           EOOCR                  245  0815  69 0718 0050
        STL TEMP1                            246  0718  20 0041 0294
        RAU ZO                               247  0294  60 0547 0751
        FMP GAMMA               FORM COS     248  0751  39 0658 0808
        RAL  8003               GAMMA ZO     249  0808  65 8003 0865
        LDD           EOOCR                  250  0865  69 0768 0050
        RAU  8002                            251  0768  60 8002 0827
        FMP TEMP1                            252  0827  39 0041 0341
        STU FZ                  FORM FZ      253  0341  21 0196 0599
        RAU INDXO               ADD ONE TO   254  0599  60 0298 0803
        FAD ONE                 INDXO        255  0803  32 0350 0877
        STU INDXO     CON18                  256  0877  21 0298 0901
CONT4   RAU ZO                  TEST SORCE   257  0406  60 0547 0313
        NZU CON17     CONT7     Z POSITION   258  0313  44 0317 0818
CONT7   RAU INDXO                            259  0818  60 0298 0853
        FSB ONE                 RESET        260  0853  33 0350 0927
        STU INDXO     CONT1     INDXO        261  0927  21 0298 0651
CON17   RAU Z                                262  0317  60 0124 0179
        FMP GAMMA               FORM SINE    263  0179  39 0658 0858
        RAL  8003               GAMMA Z      264  0858  65 8003 0915
        LDD           EOOSR                  265  0915  69 0868 0150
        STL TEMP1                            266  0868  20 0041 0344
        RAU ZO                               267  0344  60 0547 0851
        FMP GAMMA               FORM SINE    268  0851  39 0658 0908
        RAL  8003               GAMMA ZO     269  0908  65 8003 0965
        LDD           EOOSR                  270  0965  69 0918 0150
        RAU  8002                            271  0918  60 8002 0977
        FMP TEMP1                            272  0977  39 0041 0391
        STU FZ                  FORM FZ      273  0391  21 0196 0649
        RAU INDXO                            274  0649  60 0298 0903
        FSB ONE                 SUBT ONE     275  0903  33 0350 1027
        STU INDXO     CON18     FROM INDXO   276  1027  21 0298 0901
CON18   LDD           NEW       FORM TAU     277  0901  69 0554 0300
        STU CONST               TERM FOR     278  0554  21 0407 0261
        FMP FZ                  M N D        279  0261  39 0196 0246
        FAD SUM1                ADD TO       280  0246  32 0386 0363
        STU SUM1                SUM1         281  0363  21 0386 0339
        RAU CONST                            282  0339  60 0407 0311
        FSB PREC                TEST         283  0311  33 0064 0441
        BMI CON22     CONT1     PRECISION    284  0441  46 0394 0651
CON22   LDD           EOOCL                  285  0394  69 0597 0250
        LDD 2                                286  0597  69 0450 0953
        STD  1977               PRINT 2      287  0953  24 1977 0130
        LDD M                   PARTIAL      288  0130  69 0092 0395
        STD  1978               ANSWERS      289  0395  24 1978 0181
        LDD N                   FOR          290  0181  69 0336 0389
        STD  1979               CHECKING     291  0389  24 1979 0082
        LDD D                                292  0082  69 0192 0445
        STD  1980                            293  0445  24 1980 0283
        LDD SUM1                             294  0283  69 0386 0439
        STD  1981                            295  0439  24 1981 0084
        LDD SUM2                             296  0084  69 0142 0495
        STD  1982                            297  0495  24 1982 0085
        LDD SUM3                             298  0085  69 0286 0489
        STD  1983                            299  0489  24 1983 0436
        PCH  1977                            300  0436  71 1977 1077
        LDD ONE                 SET D AT 1   301  1077  69 0350 1003
        STD D                                302  1003  24 0192 0545
        LDD GAMSQ                            303  0545  69 0242 0333
        STD GAM2                             304  0333  24 0046 0699
        LDD           NEW       FORM TAU     305  0699  69 0152 0300
        STU CONST               TERM FOR     306  0152  21 0407 0060
        RAU SUM1                M N D        307  0060  60 0386 0491
        FMP FY                  ADD TO       308  0491  39 0146 0296
        FAD SUM2                SUM2         309  0296  32 0142 0719
        STU SUM2                             310  0719  21 0142 0595
        RAU CONST               TEST PRECI   311  0595  60 0407 0361
        FSB PREC                SION         312  0361  33 0064 0541
        BMI CON27     CONT2                  313  0541  46 0444 0401
CON27   LDD           EOOCL                  314  0444  69 0647 0250
        LDD 4                   PRINT 4      315  0647  69 0600 1053
        STD  1977               PARTIAL      316  1053  24 1977 0180
        LDD M                   ANSWERS      317  0180  69 0092 0645
        STD  1978               FOR          318  0645  24 1978 0231
        LDD N                   CHECKING     319  0231  69 0336 0539
        STD  1979                            320  0539  24 1979 0132
        LDD D                                321  0132  69 0192 0695
        STD  1980                            322  0695  24 1980 0383
        LDD SUM1                             323  0383  69 0386 0589
        STD  1981                            324  0589  24 1981 0134
        LDD SUM2                             325  0134  69 0142 0745
        STD  1982                            326  0745  24 1982 0135
        LDD SUM3                             327  0135  69 0286 0639
        STD  1983                            328  0639  24 1983 0486
        PCH  1977                            329  0486  71 1977 1127
        LDD ONE                 SET D AND    330  1127  69 0350 1103
        STD D                   N AT 1       331  1103  24 0192 0795
        STD N                                332  0795  24 0336 0689
        LDD GAMSQ                            333  0689  69 0242 0845
        STD GAM2                             334  0845  24 0046 0749
        LDD SETSQ                            335  0749  69 0202 0355
        STD SETA2                            336  0355  24 0016 0769
        LDD           NEW       FORM TAU     337  0769  69 0422 0300
        STU CONST               TERM FOR     338  0422  21 0407 0110
        RAU SUM2                M N D        339  0110  60 0142 0697
        FMP FX                               340  0697  39 0096 0346
        FAD SUM3                ADD TO       341  0346  32 0286 0413
        STU SUM3                SUM3         342  0413  21 0286 0739
        RAU CONST               TEST         343  0739  60 0407 0411
        FSB PREC                PRECISION    344  0411  33 0064 0591
        BMI CON32     CONT3                  345  0591  46 0494 0101
CON32   LDD           EOOCL                  346  0494  69 0747 0250
        LDD 6                   PRINT 6      347  0747  69 0550 1153
        STD  1977                            348  1153  24 1977 0230
        LDD M                   PARTIAL      349  0230  69 0092 0895
        STD  1978               ANSWERS      350  0895  24 1978 0281
        LDD N                   FOR          351  0281  69 0336 0789
        STD  1979               CHECKING     352  0789  24 1979 0182
        LDD D                                353  0182  69 0192 0945
        STD  1980                            354  0945  24 1980 0433
        LDD SUM1                             355  0433  69 0386 0839
        STD  1981                            356  0839  24 1981 0184
        LDD SUM2                             357  0184  69 0142 0995
        STD  1982                            358  0995  24 1982 0185
        LDD SUM3                             359  0185  69 0286 0889
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         STO   1983                                    360   0889   24 1983 0536
         PCH   1977                                    361   0536   71 1977 1177
         RAU   SUM3                                    362   1177   60 0286 0641
         FDV   A                                       363   0641   34 0254 0604
         FOV   8                                       364   0604   34 0354 0654
         FDV   C                                       365   0654   34 0454 0704
         FOV   0                                       366   0704   34 0457 0507
         FMP   0                                       367   0507   39 0160 0210
         STU   FLUX                    FORM FLUX       368   0210   21 0114 0367
         LDD                 EQDCL                     369   0367   69 0120 0250
         LOD   7               PRINT   7               370   0120   69 0173 0276
         STD   1977                                    371   0276   24 1977 0280
         LOO   XO              ANSWERS                 372   0280   69 0397 0600
         STD   1978            XO                      373   0600   24 1978 0331
         LOO   YO              YO                      374   0331   69 0447 0650
         STD   1979            ZO                      375   0650   24 1979 0232
         LOO   ZO              X                       376   0232   69 0547 0700
         STO   1980            Y                       377   0700   24 1980 0483
         LOO   X               Z                       378   0483   69 1000 1203
         STD   1981            FLUX                    379   1203   24 1981 0234
         LOO   Y                                       380   0234   69 0062 1015
         STD   1982                                    381   1015   24 1982 0235
         LOO   Z                                       382   0235   69 0124 1227
         STD   1983                                    383   1227   24 1983 0586
         LOO   FLUX                                    384   0586   69 0114 0417
         STO   1984                                    385   0417   24 1984 0037
         PCH   1977                                    386   0037   71 1977 1277
         RAU   X               CHANGE  X               387   1277   60 1000 0405
         FAD   DELX            UNTIL   PAST            388   0405   32 0958 0285
         STU   X               MAXIMUM X               389   0285   21 1000 1253
         FSB   XMAX                                    390   1253   33 0456 0533
         BM1   CON37   CON34                           391   0533   46 0127 0087
CON34    RAU   XINIT           OET  XINIT              392   0087   60 0102 0557
         FAD   DELX            AT  XINIT               393   0557   32 0958 0335
         STU   XINIT           PLUS OELX               394   0335   21 0102 0455
         STU   X                                       395   0455   21 1000 1303
         RAU   Y               CHANGE  Y               396   1303   60 0062 0467
         FAD   DELY            UNTIL   PAST            397   0467   32 0179 0797
         OTU   Y               MAXIMUM Y               398   0797   21 0062 1065
         FSB   YMAX                                    399   1065   33 0948 1045
         BM1   CON37   CON35                           400   1045   46 0127 0799
CON35    RAU   YINIT          SET  Y                  401   0799   60 0256 0461
         STU   Y               AT  YINIT               402   0461   21 0062 1115
         LOO   ZERO            SET XINIT               403   1115   69 0080 0583
         OTO   XINIT           AND X                   404   0583   24 0102 0505
         STO   X               AT  SOURCE              405   0505   24 1000 1353
         RAU   Z                                       406   1353   60 0124 0289
         FAD   DELZ            CHANGE  Z               407   0229   32 0238 0309
         STU   Z               UNTIL   PAST            408   0309   21 0124 1327
         FSB   ZMAX            MAXIMUM Z               409   1327   33 0330 0607
         BM1   CON37   CON36                           410   0607   46 0127 0511
CON36    HLT                                           411   0511   01 0561 0561
2        00  2000    0000      IDENTIFI                415   0450   00 2000 0000
4        00  4000    0000      CATION                  416   0500   00 4000 0000
6        00  6000    0000      NUMBER8                 417   0550   00 6000 0000
7        00  7000    0000                              418   0173   00 7000 0000
TWO      20  0000    0051                              419   0151   20 0000 0051
ONE      10  0000    0051                              420   0350   10 0000 0051
ZERO     00  0000    0000                              421   0080   00 0000 0000
PI       11  4161    0051                              422   0098   11 4161 0051
A        88  1100    0052      PILE  SIZE                    0254   88 1100 0052
B        88  1100    0052      PILE  SIZE                    0354   88 1100 0052
C        88  1100    0052      PILE  SIZE                    0454   88 1100 0052
D        82  0000    0050      DIFF  COEFF                   0457   82 0000 0050
Q        17  1000    0057      SOURCE  STR                   0160   17 1000 0057
XINIT    00  0000    0000      INITIAL                       0102   00 0000 0000
YINIT    00  0000    0000      VALUES  OF                    0256   00 0000 0000
ZINIT    00  0000    0000      X  Y  AND  Z                   0168   00 0000 0000
XO       00  0000    0000      SOURCE  POS                   0397   00 0000 0000
YO       00  0000    0000      SOURCE  POS                   0447   00 0000 0000
ZO       00  0000    0000      SOURCE  POS                   0547   00 0000 0000
DELX     10  1600    0053      CHANGES  IN                   0958   10 1600 0052
OELY     20  3200    0052      X  Y  AND  Z                  0170   20 3200 0052
DELZ     20  3200    0053                                    0282   20 3200 0052
XMAX     88  1100    0052      MAXIMUM                       0456   88 1100 0052
YMAX     88  1100    0052      VALUES                        0968   88 1100 0052
ZMAX     88  1100    0052      OF  X  Y  Z                   0330   88 1100 0052
TAU      42  6000    0053      EFOMI  ARE                    0126   42 6000 0053
K2       35  9250    0047      KAPPA  800                    0226   35 9250 0047
BETSQ    31  7840    0047      Y  BUCKLING                   0202   31 7840 0047
GAMSQ    31  7840    0047      Z  BUCKLING                   0242   31 7840 0047
PREC     10  0000    0049      PRECISION                     0064   10 0000 0049
```

APPENDIX F

Description and Explanation of the IBM-650 Computer Program Used to Calculate the Thermal Flux from a Thermal Point Neutron Source in a Finite Pile

This computer code was written to calculate from theoretical considerations, the thermal flux in a finite pile due to a point source of thermal neutrons. The program was written in SOAP II and floating point. The object program and a logic diagram are given in this section.

The solution programmed was

$$\phi(x,y,z) = \sum \sum \frac{Q_0}{D\gamma_{mn}} F_m(x)F_m(x_0)G_n(y)G_n(y_0)\frac{\sinh \gamma_{mn} z_0 \sinh \gamma_{mn}(2c-z)}{\sinh 2\gamma_{mn} c} \tag{F-1}$$

where

$$F_m(x) = \frac{1}{\sqrt{a}} \cos \alpha_m x \qquad \text{for m odd} \tag{F-2}$$

$$= \frac{1}{\sqrt{a}} \sin \alpha_m x \qquad \text{for m even}$$

and

$$\alpha_m = \frac{m\pi}{2a} .$$

$F_m(x_0)$, $G_n(y)$, and $G_n(y_0)$ are written in a similar manner. The geometry for this solution is shown in Fig. 26.

The program was set up to sum the infinite series in the same manner as the infinite series was summed in the computer program described in Appendix E. Input data required for use of this program are listed in Table 19.

Other symbols corresponding to terms in the program print out and the logic diagram are given as follows:

$$FX = aF_m(x)\, F_m(x_0)$$

$$FY = bG_n(y)\, G_n(y_0)$$

$$FZ = \frac{\sinh \gamma_{mn}(2c-z)\, \sinh \gamma_{mn} z_0}{\gamma_{mn} \sinh 2\gamma_{mn} c}$$

M and N = Summation indices in the x and y directions

INDXM and INDXN = Summation indices for testing the evenness or oddness of M and N.

Table 19. Input data required for use of the IBM-650 program which calculates the thermal flux from a thermal point source in a finite pile.

Symbol	Explanation	Drum Storage location
1	Identification number 1	0415
2	Identification number 2	0314
3	Identification number 3	0515
4	Identification number 4	0364
7	Identification number 7	0705
TWO	2.00	0182
ONE	1.00	0184
ZERO	0.00	0264
PI	π	0332
A	Half width of pile in x-direction (cm)	0785
B	Half width of pile in y-direction (cm)	1135
C	Half width of pile in z-direction (cm)	0900
D	Diffusion coefficient (cm)	0088
Q	Source strength (n/sec)	0291
XINIT	Initial value of x (cm)	0102
YINIT	Initial value of y (cm)	0356
ZINIT	Initial value of z (cm)	0268
XO	Source location in x-direction (cm)	0950
YO	Source location in y-direction (cm)	1050
ZO	Source location in z-direction (cm)	0016

Table 19. (concl.)

Symbol	Explanation	Drum Storage location
XMAX	Maximum value of x (cm)	0406
YMAX	Maximum value of y (cm)	0418
ZMAX	Maximum value of z (cm)	0414
DELX	Increment in x (cm)	0408
DELY	Increment in y (cm)	0370
DELZ	Increment in z (cm)	0226
K2	Reciprocal of diffusion length squared (cm^{-2})	0374
TOCEE	Height of pile in z-direction (cm)	0151
BETSQ	Lateral buckling in y-direction (cm^{-2})	0376
PREC	Specified precision of last term in summation	0178

This program had provision for printing out partial answers for checking purposes. Table 20 lists the identification number and the answer card content of the various print outs. If the partial answer print outs are not needed they may be eliminated by use of the one word load cards listed in Table 21. Table 22 presents a study showing the flux value as a function of the specified accuracy of the last term in the finite series.

Table 20. Answer identification table for various answer print outs for thermal flux from a thermal point source in a finite pile.

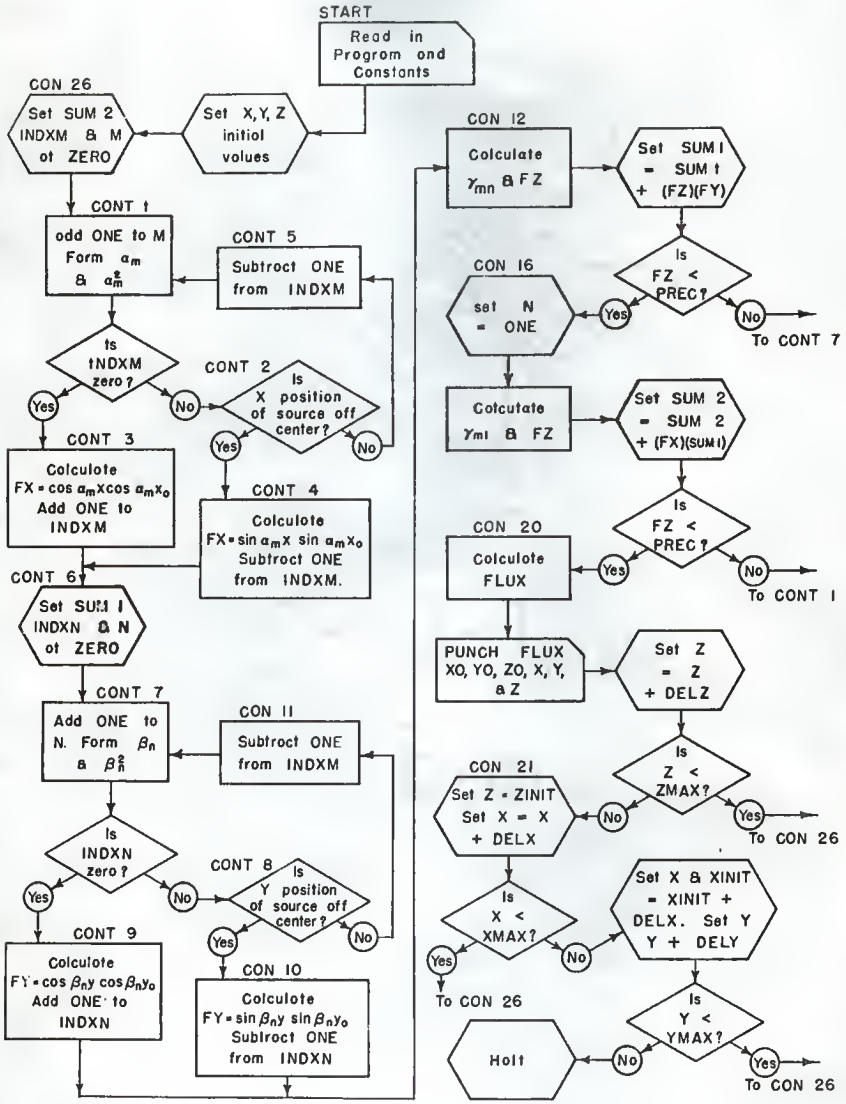
Word 1	Word 2	Word 3	Word 4	Word 5	Word 6	Word 7	Word 8
1	M	N	FY	FZ	SUM 1	SUM 2	
2	M	N	FY	FZ	SUM 1	SUM 2	
3	M	N	FX	FZ	SUM 1	SUM 2	
4	M	N	FX	FZ	SUM 1	SUM 2	
7	XO	YO	ZO	X	Y	Z	FLUX

Table 21. One word load cards used for eliminating unnecessary answer print outs for thermal point source in a finite pile.

Print out identification :	Instruction Address :	Instruction
1	0605	46 0258 1059
2	0258	69 0184 0587
3	0655	46 0308 0735
4	0308	60 0220 0425

Table 22. Computer precision study for thermal point source flux in finite pile.

PREC	Flux at x = 0 y = 0 and z = 20.32 cm	Convergence time	Flux at x = 0 y = 0 and z = 81.72 cm	Convergence time
10^{0}	4449.1 n/cm^2-sec		107.31 n/cm^2-sec	
10^{-1}	5202.2		126.16	
10^{-2}	5339.7		129.07	
10^{-3}	5363.3	approx. 5 min.	129.47	approx. 30 sec.



LOGIC DIAGRAM— APPENDIX F

```
                                 THERMAL
                                FLUX FROM
                                 THERMAL
                                  POINT
                                SOURCE IN
                                  FINITE
                                   PILE
         BLR  1951     1960     READ                1    0000    00 0000 0000
         BLR  1977     1985     PRINT               2    0000    00 0000 0000
         SYN  START    1999                         3    0000    00 0000 0000
         SYN  X        1000                         4    0000    00 0000 0000
E00SZ    STD  SNH02             SINH       001      5    0000    24 0003 0006
         LDD           E00LR    SUB        002      6    0006    69 0009 0012
         STU  SNH03             ROUTINE    003      7    0009    21 0014 0017
         RSU  FPONE                        004      8    0017    61 0020 0025
         FDV  SNH03                        005      9    0025    34 0014 0064
         FAD  SNH03                        006     10    0064    32 0014 0041
         FDV  FPTWO    SNH02               007     11    0041    34 0044 0003
E00LR    STD  EXP02                        008     12    0012    24 0015 0018
         STU  EXP03                        009     13    0018    21 0022 0075
         LDD  8007                         010     14    0075    69 8007 0031
         STD  EXP04                        011     15    0031    24 0034 0037
         RAC  0000                         012     16    0037    88 0000 0043
         RAU  EXP03                        013     17    0043    60 0022 0027
         BMI  EXP05    EXP06               014     18    0027    46 0030 0081
EXP06    FSB  LNTEN                        015     19    0081    33 0084 0011
         BMI  EXP07                        016     20    0011    46 0114 0065
         AXC  0001     EXP06               017     21    0065    58 0001 0081
EXP07    FAD  LNTEN    EXP08               018     22    0114    32 0084 0061
EXP05    SXC  0001                         019     23    0030    59 0001 0036
         FAD  LNTEN                        020     24    0036    32 0084 0111
         BMI  EXP05    EXP08               021     25    0111    46 0030 0061
EXP08    STU  EXP03                        022     26    0061    21 0022 0125
         STU  EXP09                        023     27    0125    21 0080 0033
         RAL  EXP04                        024     28    0033    65 0034 0039
         LDD  8007                         025     29    0039    69 8007 0045
         STD  EXP04                        026     30    0045    24 0034 0087
         RAC  8002                         027     31    0087    88 8002 0095
         LDD  FPONE                        028     32    0095    69 0020 0023
         STD  EXP10                        029     33    0023    24 0026 0029
         STD  EXP11    EXP12               030     34    0029    24 0032 0035
EXP12    RAU  EXP10                        031     35    0035    60 0026 0131
         FAD  EXP09                        032     36    0131    32 0080 0007
         STU  EXP10                        033     37    0007    21 0026 0079
         RAU  EXP11                        034     38    0079    60 0032 0137
         FAD  FPONE                        035     39    0137    32 0020 0047
         STU  EXP11                        036     40    0047    21 0032 0085
         RAU  EXP09                        037     41    0085    60 0080 0135
         FMP  EXP03                        038     42    0135    39 0022 0072
         FDV  EXP11                        039     43    0072    34 0032 0082
         STU  EXP09                        040     44    0082    21 0080 0083
         FDV  EXP10                        041     45    0083    34 0026 0076
         FSB  SIZES                        042     46    0076    33 0129 0005
         BMI           EXP12               043     47    0005    46 0008 0035
         RAU  EXP10                        044     48    0008    60 0026 0181
         AUP  EXP04    EXP02               045     49    0181    10 0034 0015
FPTWO    20   0000     0051                047     50    0044    20 0000 0051
LNTEN    23   0258     5151                049     51    0084    23 0258 5151
E00AU    STD  SEXT              SQUARE       1     52    0050    24 0053 0056
         BMI  SERR              ROOT         2     53    0056    46 0059 0010
         NZE           SEXT     SUB          3     54    0010    45 0164 0053
         STU  SA                ROUTINE      4     55    0164    21 0068 0021
         FAD  S10                            5     56    0021    32 0024 0001
         FMP  SHAF     SS                    6     57    0001    39 0004 0054
SS       STU  SSAV     SAS                   7     58    0054    21 0058 0161
SAS      RAU  SA                S CAPT A     8     59    0161    60 0068 0073
         FDV  SSAV                           9     60    0073    34 0058 0108
         FAD  SSAV                          10     61    0108    32 0058 0185
         FMP  SHAF                          11     62    0185    39 0004 0104
         FSB  SSAV                          12     63    0104    33 0058 0235
         NZU           SR                   13     64    0235    44 0089 0040
         BMI           SR                   14     65    0089    46 0042 0040
         FAD  SSAV                          15     66    0042    32 0058 0285
         STU  SSAV     SAS                  16     67    0285    21 0058 0161
SR       RAU  SSAV     SEXT                 17     68    0040    60 0058 0053
SERR     HLT  0000     SEXT                 18     69    0059    01 0000 0053
SHAF     50   0000     0050                 19     70    0004    50 0000 0050
S10      10   0000     0051                 20     71    0024    10 0000 0051
E00EA    STD  AAA1              E TO THE X         72    0100    24 0103 0106
         STL  AAA2              SUBROUTINE         73    0106    20 0211 0214
         RAM  AAA2                                 74    0214    67 0211 0115
         STL  AAA3              X FOR CALC         75    0115    20 0019 0122
         RAU  AAA3                                 76    0122    60 0019 0123
         FMP  AAA16                                77    0123    39 0126 0176
         FAD  AAA15                                78    0176    32 0179 0055
         FMP  AAA3                                 79    0055    39 0019 0069
         FAD  AAA14                                80    0069    32 0172 0049
         FMP  AAA3                                 81    0049    39 0019 0119
         FAD  AAA13                                82    0119    32 0222 0099
         FMP  AAA3                                 83    0099    39 0019 0169
         FAD  AAA12                                84    0169    32 0272 0149
         FMP  AAA3                                 85    0149    39 0019 0219
         FAD  AAA11                                86    0219    32 0322 0199
         FMP  AAA3                                 87    0199    39 0019 0269
         FAD  AAA10                                88    0269    32 0372 0249
         STU  AAA4                                 89    0249    21 0154 0057
         FMP  AAA4                                 90    0057    39 0154 0204
         STU  AAA4                                 91    0204    21 0154 0107
         FMP  AAA4                                 92    0107    39 0154 0254
         STU  AAA4                                 93    0254    21 0154 0157
         RAU  AAA2                                 94    0157    60 0211 0165
         BMI  AAA5     AAA6                        95    0165    46 0118 0319
AAA5     RAU  AAA10                                96    0118    60 0372 0077
         FDV  AAA4                                 97    0077    34 0154 0304
         STU  AAA4     AAA6                        98    0304    21 0154 0319
AAA6     RAL  AAA4     AAA1                        99    0319    65 0154 0103
AAA10    10   0000     0051                       100    0372    10 0000 0051
AAA11    24   9998     6850                       101    0322    24 9998 6850
AAA12    31   2575     8349                       102    0272    31 2575 8349
AAA13    25   9137     1248                       103    0222    25 9137 1248
AAA14    17   1562     0047                       104    0172    17 1562 0047
AAA15    54   3020     0045                       105    0179    54 3020 0045
AAA16    69   0600     0044                       106    0126    69 0600 0044
E00CL    STD  ZZZ1              CLEAR             107    0150    24 0153 0156
         LDD  ZZZ10             PUNCH             108    0156    69 0109 0062
         STD  1977              ROUTINE           109    0062    24 1977 0130
         STD  1978                                110    0130    24 1978 0231
         STD  1979                                111    0231    24 1979 0132
         STD  1980                                112    0132    24 1980 0133
         STD  1981                                113    0133    24 1981 0134
         STD  1982                                114    0134    24 1982 0335
         STD  1983                                115    0335    24 1983 0086
```

```
         STS  1984    ZZZ1                      116   0086   24 1984 0153
ZZZ10     00  0000    0000                      117   0109   00 0000 0000
ESOGR    STO  EXIT             COSINE           118   0200   24 0203 0206
         RAU  8002             SUBROUTINE       119   0206   60 8002 0215
         BMI  NEGAT   REDUC                     120   0215   46 0168 0369
NEGAT    FAD  TSOPI                             121   0168   32 0071 0097
         BMI  NEGAT                             122   0097   46 0168 0051
         FSB  ONEPI   COSIO                     123   0051   33 0354 0281
REDUC    FSB  TSOPI                             124   0369   33 0071 0147
         BMI          REDUC                     125   0147   46 0250 0369
         FAD  ONEPI   COSIO                     126   0250   32 0354 0281
COSIO    STU  THETA                             127   0281   21 0136 0139
         RSU  FPONE                             128   0139   61 0020 0175
         STU  TERMN                             129   0175   21 0180 0183
         STU  FUNKT                             130   0183   21 0038 0091
         STL  ENN     NEGST                     131   0091   20 0145 0048
EOOSR    STO  EXIT             SINE             132   0300   24 0203 0256
         RAU  8002             SUBROUTINE       133   0256   60 8002 0265
         BMI  NEGAV   REDUS                     134   0265   46 0218 0419
NEGAV    FAD  TWOPI                             135   0218   32 0071 0197
         BMI  NEGAV                             136   0197   46 0218 0101
         FSB  ONEPI   SINET                     137   0101   33 0354 0331
RESUO    FSB  TSOPI                             138   0419   33 0071 0247
         BMI          REDUD                     139   0247   46 0350 0419
         FAS  ONEPI   SINET                     140   0350   32 0354 0331
SINET    STU  THETA                             141   0331   21 0136 0189
         RSU   8003                             142   0189   61 8003 0297
         STU  TERMN                             143   0297   21 0180 0233
         STU  FUNKT                             144   0233   21 0038 0141
         LDD  FPONE                             145   0141   69 0020 0173
         STS  ENN     NEGST                     146   0173   24 0145 0048
NEGST    RAU  ENN                               147   0048   60 0145 0299
         FAD  FPONE                             148   0299   32 0020 0347
         STU  NPONE                             149   0347   21 0002 0105
         FAD  FPONE                             150   0105   32 0020 0397
         STU  ENN                               151   0397   21 0145 0098
         RSU  TERMN                             152   0098   61 0180 0385
         FMP  THETA                             153   0385   39 0136 0186
         FMP  THETA                             154   0186   39 0136 0236
         FDV  NPONE                             155   0236   34 0002 0052
         FDV  ENN                               156   0052   34 0145 0195
         STU  TERMN                             157   0195   21 0180 0283
         RAM  FUNKT                             158   0283   67 0038 0093
         STL  FMAG                              159   0093   20 0447 0400
         RAM  TERMN                             160   0400   67 0180 0435
         RAU   8002                             161   0435   60 8002 0143
         FSV  FMAG                              162   0143   34 0447 0497
         FSB  SIZES                             163   0497   33 0129 0155
         BMI  ENUFF                             164   0155   46 0158 0159
         RAU  FUNKT                             165   0159   60 0038 0193
         FAD  TERMN                             166   0193   32 0180 0207
         STU  FUNKT   NEGST                     167   0207   21 0038 0048
ENUFF    RAL  FUNKT   EXIT                      168   0158   65 0038 0203
SIZES     10  0000    0043                      169   0129   10 0000 0043
TSOPI     62  831B    5351                      170   0071   62 831B 5351
ONEPI     31  4159    2751                      171   0354   31 4159 2751
FPONE     10  0000    0051                      172   0020   10 0000 0051
OLDHI    STD  EXINS            SUBROUTINE       173   0450   24 0253 0306
         RAU  GAMMN            TO               174   0306   60 0209 0013
         FMP  ZO               DETERMINE        175   0013   39 0016 0066
         FSS  FPATE            FZ               176   0066   33 0469 0245
         BMI  SUB1    SUB3                      177   0245   46 0148 0349
SUS1     RAU  TSCEE                             178   014B   60 0151 0205
         FSB  Z                                 179   0205   33 0208 0485
         FMP  GAMMN                             180   0485   39 0209 0259
         FSB  FPATE                             181   0259   33 0469 0295
         BMI  SUB2    SUB6                      182   0295   46 019B 0399
SUB3     RAU  TOCEE                             183   0349   60 0151 0255
         FSB  Z                                 184   0255   33 020B 0535
         FMP  GAMMN                             185   0535   39 0209 0309
         FSS  FPATE                             186   0309   33 0469 0345
         BMI  SUB5    SUB4                      187   0345   46 0248 0449
SUS2     RAU  GAMMN                             188   0198   60 0209 0063
         FMP  ZO                                189   0063   39 0016 0116
         LSS          EOOBZ                     190   0116   69 0519 0000
         STU  TEMP1                             191   0519   21 0074 0127
         RAU  TSCEE                             192   0127   60 0151 0305
         FMP  GAMMN                             193   0305   39 0209 0359
         LSS          EOOBZ                     194   0359   69 0112 0000
         STU  TEMP2                             195   0112   21 0166 0569
         RAU  TOCEE                             196   0569   60 0151 0355
         FSB  Z                                 197   0355   33 0208 0585
         FMP  GAMMN                             198   0585   39 0209 0409
         LDD          EOOBZ                     199   0409   69 0162 0000
         FSV  TEMP2                             200   0162   34 0166 0216
         FDV  GAMMN                             201   0216   34 0209 0459
         FMP  TEMP1   EXINB                     202   0459   39 0074 0253
SUB4     RAU  ZO                                203   0449   60 0016 0121
         FSS  Z                                 284   0121   33 020B 0635
         FMP  GAMMN                             205   0635   39 0209 0509
         RAL   8003                             206   0509   65 8003 0067
         LDD          EOOEA                     207   0067   69 0070 0100
         RAU   8002                             208   0070   60 8002 0229
         FDV  TWO                               209   0229   34 0182 0232
         FSV  GAMMN   EXINB                     210   0232   34 0209 0253
SUB5     RAU  TOCEE                             211   0248   60 0151 0405
         FSS  Z                                 212   0405   33 0208 0685
         FMP  GAMMN                             213   0685   39 0209 0559
         LOO          EOOSZ                     214   0559   69 0212 0000
         STU  TEMP1                             215   0212   21 0074 0177
         RAU  ZO                                216   0177   60 0016 0171
         FSB  TOCEE                             217   0171   33 0151 0227
         FMP  GAMMN                             218   0227   39 0209 0609
         RAL   8003                             219   0609   65 8003 0117
         LOO          EOOEA                     220   0117   69 0120 0100
         RAU   8002                             221   0120   60 8002 0279
         FOV  GAMMN                             222   0279   34 0209 0659
         FMP  TEMP1   EXINS                     223   0659   39 0074 0253
SUB6     RAU  ZO                                224   0399   60 0016 0221
         FMP  GAMMN                             225   0221   39 0209 0709
         LDS          EOOSZ                     226   0709   69 0262 0000
         STU  TEMP1                             227   0262   21 0074 0277
         RAU  Z                                 228   0277   60 020B 0113
         FMP  GAMMN                             229   0113   39 0209 0759
         RSL   8003                             230   0759   66 8003 0167
         LDD          EOOEA                     231   0167   69 0170 0100
         RAU   8002                             232   0170   60 8002 0329
         FMP  TEMP1                             233   0329   39 0074 0124
         FSV  GAMMN   EXINB                     234   0124   34 0209 0253
FPATE     80  0000    0051                      235   0469   80 0000 0051
START    LSO  XINIT            SET X Y Z        236   1999   69 0102 0455
         STD  X                AT INITIAL       237   0455   24 1000 0303
```

```
          LDD YINIT                VALUES      238    0303    69 0356 0809
          STD Y                                239    0809    24 0312 0315
          LDD ZINIT                            240    0315    69 0268 0353
          STD Z         CON26                  242    0353    24 0208 0261
CON26     LDD ZERO                 SET SUM2    243    0261    69 0264 0217
          STD SUM2                 INDXM AND   244    0217    24 0220 0273
          STD M                    M AT ZERO   245    0273    24 0276 0379
          STD INDXM     CONT1                  246    0379    24 0282 0735
CONT1     RAU M                    ADD ONE     247    0735    60 0276 0381
          FAD ONE                  TO M        248    0381    32 0184 0311
          STU M                                249    0311    21 0276 0429
          FMP PI                               250    0429    39 0332 0382
          FDV T80                              251    0382    34 0182 0432
          FDV A                    FORM ALPHA  252    0432    34 0785 0835
          STU ALPHA                AND ALPHA   253    0835    21 0090 0243
          FMP ALPHA                SQUARED     254    0243    39 0090 0140
          STU ALPH2                            255    0140    21 0094 0547
          RAU INDXM                TEST M FOR  256    0547    60 0282 0187
          NZE CONT2     CONT3      EVEN OR OD  257    0187    45 0190 0191
CONT3     RAU X                                258    0191    60 1000 0505
          FMP ALPHA                FORM COS    259    0505    39 0090 0240
          RAL  8003                ALPHA X     260    0240    65 8003 0597
          LDD           E00CR                  261    0597    69 0500 0200
          STL TEMP1                            262    0500    20 0074 0327
          RAU X0                               263    0327    60 0230 0885
          FMP ALPHA                FORM COS    264    0885    39 0090 0290
          RAL  8003                ALPHA X0    265    0290    65 8003 0647
          LDD           E00CR                  266    0647    69 0550 0200
          RAU  8002                            267    0550    60 8002 0859
          FMP TEMP1                            268    0859    39 0074 0174
          STU FX                   FORM FX     269    0174    21 0028 0431
          RAU INDXM                ADD ONE TO  270    0431    60 0282 0237
          FAD ONE                  INDXM       271    0237    32 0184 0361
          STU INDXM     CONT6                  272    0361    21 0282 0935
CONT2     RAU X0                   TEST SOURC  273    0190    60 0230 0985
          NZU CONT4     CONT5      X POSITION  274    0985    44 0239 0340
CONT5     RAU INDXM                            275    0340    60 0282 0287
          FSB ONE                  RESET       276    0287    33 0184 0411
          STU INDXM     CONT1      INDXM       277    0411    21 0282 0735
CONT4     RAU X                                278    0239    60 1000 0555
          FMP ALPHA                FORM SINE   279    0555    39 0090 0390
          RAL  8003                ALPHA X     280    0390    65 8003 0697
          LDD           E00SR                  281    0697    69 0600 0300
          STL TEMP1                            282    0600    20 0074 0377
          RAU X0                               283    0377    60 0230 1035
          FMP ALPHA                FORM SINE   284    1035    39 0090 0440
          RAL  8003                ALPHA X0    285    0440    65 8003 0747
          LDD           E00SR                  286    0747    69 0650 0300
          RAU  8002                            287    0650    60 8002 0909
          FMP TEMP1                FORM FX     288    0909    39 0074 0224
          STU FX                               289    0224    21 0028 0481
          RAU INDXM                SUBT ONE    290    0481    60 0282 0337
          FSB ONE                  FROM INDXM  291    0337    33 0184 0461
          STU INDXM     CONT6                  292    0461    21 0282 0935
CONT6     LDD ZERO                 SET SUM1    293    0935    69 0264 0267
          STD N                    INDXN AND   294    0267    24 0270 0323
          STD SUM1                 N AT ZERO   295    0323    24 0326 0479
          STD INDXN     CONT7                  296    0479    24 0482 1085
CONT7     RAU N                                297    1085    60 0270 0225
          FAD ONE                  ADD ONE     298    0225    32 0184 0511
          STU N                    TO N        299    0511    21 0270 0373
          FMP PI                               300    0373    39 0332 0532
          FDV T80                              301    0532    34 0182 0582
          FDV B                                302    0582    34 1135 1185
          STU BETA                 FORM BETA   303    1185    21 0490 0293
          FMP BETA                 AND BETA    304    0293    39 0490 0540
          STU BETA2                SQUARED     305    0540    21 0144 0797
          RAU INDXN                TEST N FOR  306    0797    60 0482 0387
          NZE CONT8     CONT9      EVEN OR OD  307    0387    45 0590 0241
CONT9     RAU Y                                308    0241    60 0312 0317
          FMP BETA                 FORM COS    309    0317    39 0490 0640
          RAL  8003                BETA Y      310    0640    65 8003 0847
          LDD           E00CR                  311    0847    69 0700 0200
          STL TEMP1                            312    0700    20 0074 0427
          RAU Y0                               313    0427    60 0280 1235
          FMP BETA                 FORM COS    314    1235    39 0490 0690
          RAL  8003                BETA Y0     315    0690    65 8003 0897
          LDD           E00CR                  316    0897    69 0750 0200
          RAU  8002                            317    0750    60 8002 0959
          FMP TEMP1                            318    0959    39 0074 0274
          STU FY                   FORM FY     319    0274    21 0078 0531
          RAU INDXN                ADD ONE TO  320    0531    60 0482 0437
          FAD ONE                  INDXN       321    0437    32 0184 0561
          STU INDXN     CON12                  322    0561    21 0482 1285
CONT8     RAU Y0                   TEST SORCE  323    0590    60 0280 1335
          NZU CON10     CON11      Y POSITION  324    1335    44 0289 0740
CON11     RAU INDXN                            325    0740    60 0482 0487
          FSB ONE                  RESET       326    0487    33 0184 0611
          STU INDXN     CONT7      INDXN       327    0611    21 0482 1085
CON10     RAU Y                                328    0289    60 0312 0367
          FMP BETA                 FORM SIN    329    0367    39 0490 0790
          RAL  8003                BETA Y      330    0790    65 8003 0947
          LDD           E00SR                  331    0947    69 0800 0300
          STL TEMP1                            332    0800    20 0074 0477
          RAU Y0                               333    0477    60 0280 1385
          FMP BETA                 FORM SINE   334    1385    39 0490 0840
          RAL  8003                BETA Y0     335    0840    65 8003 0997
          LDD           E00SR                  336    0997    69 0850 0300
          RAU  8002                            337    0850    60 8002 1009
          FMP TEMP1                            338    1009    39 0074 0324
          STU FY                   FORM FY     339    0324    21 0078 0581
          RAU INDXN                            340    0581    60 0482 0537
          FSB ONE                  SUBT ONE    341    0537    33 0184 0661
          STU INDXN     CON12      FROM INDXN  342    0661    21 0482 1285
CON12     RAU ALPH2                            343    1285    60 0094 0499
          FAD BETA2                FORM        344    0499    32 0144 0271
          FAD K2                   GAMMA FOR   345    0271    32 0374 0201
          LDD           E00AU      M AND N     346    0201    69 0404 0050
          STU GAMMN                            347    0404    21 0209 0362
          LDD           OLOHI      DETERMINE   348    0362    69 0365 0450
          STU FZ                   FZ          349    0365    21 0320 0423
          RAU FZ                               350    0423    60 0320 0275
          FMP FY                   ADD FY      351    0275    39 0078 0128
          FAD SUM1                 TIMES FZ    352    0128    32 0326 0403
          STU SUM1                 TO SUM1     353    0403    21 0326 0529
          RAU FZ                               354    0529    60 0320 0325
          FSB PREC                 TEST FZ     355    0325    33 0178 0605
          BMI CON16                PRECISION   356    0605    46 0258 1059
          LDD           E00CL                  357    1059    69 0412 0150
          LDD 1                                358    0412    69 0415 0318
          STD  1977                PRINT       359    0318    24 1977 0330
          LDD M                    PARTIAL     360    0330    69 0276 0579
```

```
         STD  1978               ANSWERS     361   0579   24 1978 0631
         LDD  N                  FOR         362   0631   69 0270 0473
         STD  1979               CHECKING    363   0473   24 1979 0632
         LDD  FY                             364   0632   69 0078 0681
         STD  1980                           365   0681   24 1980 0333
         LDD  FZ                             366   0333   69 0320 0523
         STD  1981                           367   0523   24 1981 0234
         LDD  SUM1                           368   0234   69 0326 0629
         STD  1982                           369   0629   24 1982 1435
         LDD  SUM2                           370   1435   69 0220 0573
         STD  1983                           371   0573   24 1983 0286
         PCH  1977   CONT7                   372   0286   71 1977 1085
CON16    LDD         EDDCL                   373   0258   69 0711 0150
         LDD  2                              374   0711   69 0314 0417
         STD  1977               PRINT       375   0417   24 1977 0380
         LDD  M                  PARTIAL     376   0380   69 0276 0679
         STD  1978               ANSWERS     377   0679   24 1978 0731
         LDD  N                  FOR         378   0731   69 0270 0623
         STD  1979               CHECKING    379   0623   24 1979 0682
         LDD  FY                             380   0682   69 0078 0781
         STD  1980                           381   0781   24 1980 0383
         LDD  FZ                             382   0383   69 0320 0673
         STD  1981                           383   0673   24 1981 0284
         LDD  SUM1                           384   0284   69 0326 0729
         STD  1982                           385   0729   24 1982 1485
         LDD  SUM2                           386   1485   69 0220 0723
         STD  1983                           387   0723   24 1983 0336
         PCH  1977                           388   0336   71 1977 0527
         LDD  ONE                SET N AT 1  389   0527   69 0184 0587
         STD  N                              390   0587   24 0270 0773
         RAU  SETSO                          391   0773   60 0376 0831
         FAD  ALPH2              FORM GAMMA  392   0831   32 0094 0321
         FAD  KS                 FOR M       393   0321   32 0374 0251
         LDD         EDDAU       AND N       394   0251   69 0454 0050
         STU  GAMMN                          395   0454   21 0209 0462
         LDD         OLDHI       DETERMINE   396   0462   69 0465 0450
         STU  FZ                 FZ          397   0465   21 0320 0823
         RAU  SUM1                           398   0823   60 0326 0881
         FMP  FX                 ADD SUM1    399   0881   39 0028 0228
         FAD  SUM2               TIMES FX    400   0228   32 0220 1047
         STU  SUM2               TO SUM2     401   1047   21 0220 0873
         RAU  FZ                             402   0873   60 0320 0375
         FSB  PREC               TEST FZ     403   0375   33 0178 0655
         BMI  CON20              PRECISION   404   0655   46 0308 1109
         LDD         EDDCL                   405   1109   69 0512 0150
         LDD  3                              406   0512   69 0515 0368
         STD  1977                           407   0368   24 1977 0430
         LDD  M                  PRINT       408   0430   69 0276 0779
         STD  1978               PARTIAL     409   0779   24 1978 0931
         LDD  N                  ANSWERS     410   0931   69 0270 0923
         STD  1979               FOR         411   0923   24 1979 0732
         LDD  FX                 CHECKING    412   0732   69 0028 0981
         STD  1980                           413   0981   24 1980 0433
         LDD  FZ                             414   0433   69 0320 0973
         STD  1981                           415   0973   24 1981 0334
         LDD  SUM1                           416   0334   69 0326 0829
         STD  1982                           417   0829   24 1982 1535
         LDD  SUM2                           418   1535   69 0220 1023
         STD  1983                           419   1023   24 1983 0386
         PCH  1977   CONT1                   420   0386   71 1977 0735
CON20    LDD         EDDCL                   421   0308   69 0761 0150
         LDD  4                              422   0761   69 0364 0467
         STD  1977                           423   0467   24 1977 0480
         LDD  M                  PRINT       424   0480   69 0276 0879
         STD  1978               PARTIAL     425   0879   24 1978 1031
         LDD  N                  ANSWERS     426   1031   69 0270 1073
         STD  1979               FOR         427   1073   24 1979 0782
         LDD  FX                 CHECKING    428   0782   69 0028 1081
         STD  1980                           429   1081   24 1988 0483
         LDD  FZ                             430   0483   69 0320 1123
         STD  1981                           431   1123   24 1981 0384
         LDD  SUM1                           432   0384   69 0326 0929
         STD  1982                           433   0929   24 1982 1585
         LDD  SUM2                           434   1585   69 0220 1173
         STD  1983                           435   1173   24 1983 0436
         PCH  1977                           436   0436   71 1977 0577
         RAU  SUM2                           437   0577   60 0220 0425
         FDV  A                              438   0425   34 0785 1635
         FDV  B                              439   1635   34 1135 1685
         FDV  D                              440   1685   34 0088 0138
         FMP  D                  DETERMINE   441   0138   39 0291 0341
         STU  FLUX                FLUX       442   0341   21 0046 0549
         LDD         EDDCL                   443   0549   69 0152 0150
         LDD  7                              444   0152   69 0705 0358
         STD  1977               PRINT 7     445   0358   24 1977 0530
         LDD  XO                 ANSWERS     446   0530   69 0230 0533
         STD  1978                           447   0533   24 1978 1131
         LDD  YO                 XO          448   1131   69 0280 0583
         STD  1979               YO          449   0583   24 1979 0832
         LDD  ZO                 ZO          450   0832   69 0016 0619
         STD  1980               X           451   0619   24 1988 0633
         LDD  X                  Y           452   0633   69 1000 0453
         STD  1981               Z           453   0453   24 1981 0434
         LDD  Y                  FLUX        454   0434   69 0312 0565
         STD  1982                           455   0565   24 1982 1735
         LDD  Z                              456   1735   69 0208 0811
         STD  1983                           457   0811   24 1983 0486
         LDD  FLUX                           458   0486   69 0046 0599
         STD  1984                           459   0599   24 1984 0637
         PCH  1977                           460   0637   71 1977 0627
         RAU  Z                  CHANGE Z    461   0627   60 0208 0163
         FAD  DELZ               UNTIL PAST  462   0163   32 0226 0503
         STU  Z                  MAXIMUM Z   463   0503   21 0208 0861
         FSB  ZMAX                           464   0861   33 0414 0391
         BMI  CON26  CON21                   465   0391   46 0261 0395
CON21    RAU  ZINIT              SET Z AT    466   0395   60 0268 1223
         STU  Z                  INITIAL Z   467   1223   21 0208 0911
         RAU  X                              468   0911   60 1000 0755
         FAD  DELX               CHANGE X    469   0755   32 0408 1785
         STU  X                  UNTIL PAST  470   1785   21 1000 0553
         FSB  XMAX               MAXIMUM X   471   0553   33 0406 0683
         BMI  CON26  CON22                   472   0683   46 0261 0687
CON22    RAU  XINIT              RESET X     473   0687   60 0102 0257
         FAD  DELX               AND XINIT   474   0257   32 0408 1835
         STU  XINIT                          475   1835   21 0102 0805
         STU  X                              476   0805   21 1000 0603
         RAU  Y                  CHANGE Y    477   0603   60 0312 0517
         FAD  DELY               UNTIL PAST  478   0517   32 0370 1097
         STU  Y                  MAXIMUM Y   479   1097   21 0312 0615
         FSB  YMAX                           480   0615   33 0418 0445
         BMI  CON26  CON25                   481   0445   46 0261 0649
CON25    HLT                                 482   0649   01 0699 0699
```

1	00	1000	0000	IDENTIFI	483	0415	00	1000	0000
2	00	2000	0000	CATION	484	0314	00	2000	0000
3	00	3000	0000	NUMBERS	485	0515	00	3000	0000
4	00	4000	0000		486	0364	00	4000	0000
7	00	7000	0000		487	0705	00	7000	0000
TWO	20	0000	0051		488	0182	20	0000	0051
ONE	10	0000	0051		489	0184	10	0000	0051
ZERO	00	0000	0000		490	0264	00	0000	0000
PI	31	4161	0051		491	0332	31	4161	0051
A	88	1100	0052	PILE SIZE		0785	88	1100	0052
B	88	1100	0052	PILE SIZE		1135	88	1100	0052
C	88	1100	0052	PILE SIZE		0900	88	1100	0052
D	82	0000	0050	DIFF COEFF		0088	82	0000	0050
R	17	1000	0047	SOURCE STR		0201	17	1000	0047
XINIT	00	0000	0000	INITIAL X		0102	00	0000	0000
YINIT	00	0000	0000	INITIAL Y		0356	00	0000	0000
ZINIT	98	2700	0052	INITIAL Z		0268	98	2700	0052
XO	00	0000	0000	SOURCE POS		0950	00	0000	0000
YO	00	0000	0000	SOURCE POS		1050	00	0000	0000
ZO	88	1100	0052	SOURCE POS		0016	88	1100	0052
XMAX	88	1100	0052	MAXIMUM		0406	88	1100	0052
YMAX	88	1100	0052	VALUES OF		0416	88	1100	0052
ZMAX	17	6220	0053	X Y AND Z		0414	17	6220	0053
DELX	20	3200	0052	CHANGES IN		0406	20	3200	0052
DELY	20	3200	0052	X Y AND Z		0370	20	3200	0052
DELZ	10	1600	0052			0226	10	1600	0052
K2	35	9250	0047	KAPPA SQD		0374	35	9250	0047
TOCEE	17	6220	0053	PILE SIZE		0151	17	6220	0053
BETSQ	31	7840	0047	Y BUCKLING		0376	31	7840	0047
PREC	10	0000	0049	PRECISION		0178	10	0000	0049

APPENDIX G

Description and Explanation of the IBM-650 Computer Program Used for Fitting Empirically Experimental Data with the Sum of Several Terms of Gaussian Form

The computer code was written to fit empirically the experimental indium resonance activity with the sum of several Gaussian terms having adjustable parameters. The program was written in SOAP II and floating point form. The object program is listed and the logic diagram is given in this section.

This method of fit was not exact. There was no guarantee that the result of this fit would be the best; but in a practical approach to the problem of fitting a non-linear function, the result appeared to be adequate.

The criterion that the machine inspected was that the sum of the weighted squares of the residuals between the experimental data and calculated values should be made as small as possible. This was done through a trial and error process. Each of the fitting parameters was varied in turn by a specified increment, holding all other parameters constant, until such time that a specified increment could make no further reduction in the sum of the weighted squares of the residuals. This parameter was then stored as the best available estimate of the particular empirical parameter. When none of the parameters could be varied by the specified increment to give a smaller sum of the weighted squares of the residuals, the increments were refined and the trial and error process was repeated with the refined

increments. This procedure continued until the increments were less than a specified precision.

The second portion of the program calculated the fractional contributions of each range group according to Eq. 16 of the theory.

The data were empirically fit with a function of the form of Eq. 14 of the theory

$$\text{FLUX}_j = \sum_{i=1}^{N} B_i \, e^{-(z_j/r_i)^2}, \quad N \leqq 10 \tag{G-1}$$

As stated above, the best fit criterion was that

$$\text{ERROR} = \sum_{j=1}^{M} \frac{1}{W_j^2} \left(\sum_{i=1}^{N} B_i \, e^{-(z_j/r_j)^2} - \text{FLUX}_j \right)^2, \quad M \leqq 20 \tag{G-2}$$

be a minimum.

The program required, in addition to the experimental data and their respective positions, initial estimates for a specific number of parameters. The program had a capacity for up to 20 data points and 10 terms in the summation of Eq. G-1. These input data were read into the machine along with the program deck on one-word load cards. Each one-word load card contained a particular constant or initial value and its specified storage location. Table 23 lists the various input data needed for this program.

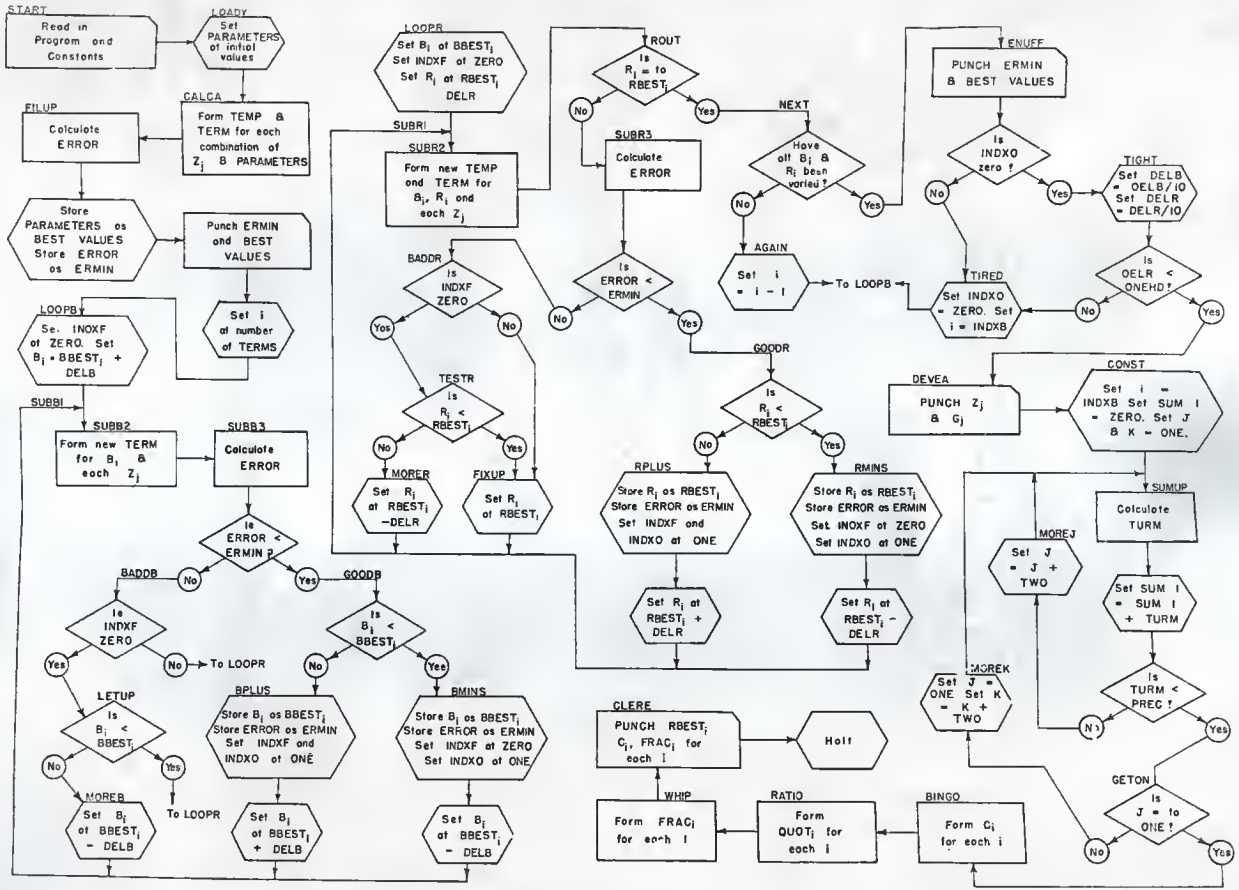
Table 23. Input data required for use of the IBM-650 program which empirically fits experimental data with several terms of Gaussian form.

Symbol	Explanation	Storage location
ZERO	0.00	0059
FPONE	1.00	0096
FPTWO	2.00	0260
FOUR	4.00	0743
TEN	10.00	0436
ONE	Index number 1	0292
EIGHT	Index number 8	0124
ONEHD	Desired precision of parameter increments	0354
PI	π	0290
SQPI	$\sqrt{\pi}$	0164
PREC	Desired precision in term of series summation	0126
A1	Pile width in x-direction (cm)	0405
A2	Pile width in y-direction (cm)	0211
DELB	Initial increment of the amplitude, B_i	0028
DELR	Initial increment of the Gaussian range, r_i(cm)	0198
INDXA	Number of data points	0077
INDXB	Number of Gaussian terms in empirical fit	0162
Z	Position of j^{th} data point (cm)	12(00+j)
FLUX	Experimental data at j^{th} point	12(20+j)
W	Weighting function of j^{th} piece of data	17(50+j)
	Initial estimate of B_i	13(00+i)
	Initial estimate of r_i (cm)	13(20+i)

The machine yielded an answer card having a capacity of 8 words, a word being a ten digit number and a sign. For the first answer punching operation the machine printed out the initial estimates of the fitting parameters on as many cards as was necessary to accomodate them. The amplitude and range of the first term were printed out in word locations 1 and 2, respectively. The amplitude and range of the second term were printed in word locations 3 and 4, respectively.

After a card was filled to its 8 word capacity it was punched and a new card began to be filled. This procedure continued until all fitting parameters had been punched out. Then a separate card was punched giving in the word 8 location, the value of the sum of the weighted squares of the residuals between the experimental data and the calculated value. Subsequent improvements in the parameters were printed out according to this procedure after each cycle of trying to vary each parameter. When the fitting parameters could not be further improved with the most refined increment specified, the punching out of the best fit parameters and their sum of the weighted squares of the residuals took place according to the procedure previously described. At this time the residual at each point was punched out along with the position of the point. The position of the last point and the associated residual were loaded into word locations 1 and 2, respectively. The position and the residual of the next to last point were loaded into word locations 3 and 4, respectively. This procedure continued until all the residuals and their identifying locations had been punched on as many cards as was necessary.

The machine then calculated the fractional contributions of each range group and printed it out in the word 5 location along with the respective Gaussian range in the word 7 location.



LOGIC DIAGRAM – APPENDIX G

```
                                  EMPIRICAL
                                   FIT OF
                                  RESONANCE
                                    DATA
        SLR  1200      1780                       0000  00 0000 0000
        SLR  1951      1960                       0000  00 0000 0000
        SLR  1977      1985                       0000  00 0000 0000
        SYN  START     1999                       0000  00 0000 0000
        SYN  Z         1200      POSITION         0000  00 0000 0000
        SYN  FLUX      1220      ACTIVATION       0000  00 0000 0000
        SYN  G         1240      DEVIATION        0000  00 0000 0000
        SYN  S         1260      AMPLITUDE        0000  00 0000 0000
        SYN  SBEST     1270                       0000  00 0000 0000
        SYN  R         1280      RANGE            0000  00 0000 0000
        SYN  RBEST     1290                       0000  00 0000 0000
        SYN  SINIT     1300      INITIAL          0000  00 0000 0000
        SYN  RINIT     1310      ESTIMATES        0000  00 0000 0000
        SYN  TEMP      1320                       0000  00 0000 0000
        SYN  TERM      1500      SUM TERM         0000  00 0000 0000
        SYN  C         1720      CONSTANT         0000  00 0000 0000
        SYN  FRAC      1730      FRACTION         0000  00 0000 0000
        SYN  QUOT      1740                       0000  00 0000 0000
        SYN  W         1750      WEIGHT           0000  00 0000 0000
EODEA   STD  AAA1                E TO X           0000  24 0003 0006
        STL  AAA2                SUBROUTINE       0006  20 0011 0014
        RAM  AAA2                                 0014  67 0011 0015
        STL  AAA3                X FOR CALC       0015  20 0019 0022
        RAU  AAA3                                 0022  60 0019 0023
        FMP  AAA16                                0023  39 0026 0076
        FAD  AAA15                                0076  32 0029 0005
        FMP  AAA3                                 0005  39 0019 0069
        FAD  AAA14                                0069  32 0072 0049
        FMP  AAA3                                 0049  39 0019 0119
        FAD  AAA13                                0119  32 0122 0099
        FMP  AAA3                                 0099  39 0019 0169
        FAD  AAA12                                0169  32 0172 0149
        FMP  AAA3                                 0149  39 0019 0219
        FAD  AAA11                                0219  32 0222 0199
        FMP  AAA3                                 0199  39 0019 0269
        FAD  AAA10                                0269  32 0272 0249
        STU  AAA4                                 0249  21 0004 0007
        FMP  AAA4                                 0007  39 0004 0054
        STU  AAA4                                 0054  21 0004 0057
        FMP  AAA4                                 0057  39 0004 0104
        STU  AAA4                                 0104  21 0004 0107
        RAU  AAA2                                 0107  60 0011 0065
        BMI  AAA5      AAA6                       0065  46 0018 0319
AAA5    RAM  AAA10                                0018  60 0272 0027
        FDV  AAA4                                 0027  34 0004 0154
        STU  AAA4      AAA6                       0154  21 0004 0319
AAA6    RAL  AAA4      AAA1                       0319  65 0004 0003
AAA10    10  0000      0051                       0272  10 0000 0051
AAA11    24  9998      6850                       0222  24 9998 6850
AAA12    31  2575      8349                       0172  31 2575 8349
AAA13    25  9137      1248                       0122  25 9137 1248
AAA14    17  1562      0047                       0072  17 1562 0047
AAA15    54  3020      0045                       0029  54 3020 0045
AAA16    69  0600      0044                       0026  69 0600 0044
EOOCL   STD  ZZZ1                CLEAR            0050  24 0053 0056
        LDD  ZZZ10               PUNCH BAND       0056  69 0009 0012
        STD  1977                ROUTINE          0012  24 1977 0030
        STD  1978                                 0030  24 1978 0031
        STD  1979                                 0031  24 1979 0032
        STD  1980                                 0032  24 1980 0033
        STD  1981                                 0033  24 1981 0034
        STD  1982                                 0034  24 1982 0035
        STD  1983                                 0035  24 1983 0036
        STD  1984      ZZZ1                       0036  24 1984 0053
ZZZ10    00  0000      0000                       0009  00 0000 0000
TEMPP   STD  EGSIT               ROUTINE          0100  24 0103 0106
        RAU  Z       A           TO FORM          0106  60 3200 0055
        FMP  Z       A           RANGE            0055  39 3200 0150
        FDV  R       B           DEPENDENT        0150  34 5280 0080
        FDV  R       B           PART OF          0080  34 5280 0130
        RSL  8003                TERM             0130  66 8003 0037
        LDD            EODEA                      0037  69 0040 0000
        STL  TEMP    C EGSIT                      0040  20 7320 0103
TURMM   STD  EXXIT               ROUTINE          0200  24 0153 0156
        RAU  TEMP    C           TO FORM          0156  60 7320 0025
        FMP  S       B           TERM OF          0025  39 5260 0010
        STU  TERM    C EXXIT      SUM             0010  21 7520 0153
ERR     STD  EXIT                                 0250  24 0203 0206
        LDD  ZERO                ROUTINE          0206  69 0059 0062
        RAC  8001                TO FORM          0062  88 8001 0068
        STD  ERROR               SUM OF           0068  24 0021 0024
        LDD  INDXA               WEIGHTED         0024  69 0077 0180
        RAA  8001      READY     DEVIATIONS       0180  80 8001 0086
READY   LDD  INDXC               SQUARED          0086  69 0039 0042
        AXC  8001                                 0042  58 8001 0048
        LDD  ZERO                                 0048  69 0059 0112
        STD  ACCUM     DOONE                      0112  24 0115 0118
DOONE   RAU  TERM    C                            0118  60 7520 0075
        FAD  ACCUM                                0075  32 0115 0041
        STU  ACCUM                                0041  21 0115 0168
        LDD  INDXA                                0168  69 0077 0230
        SXC  8001                                 0230  59 8001 0136
        NZC  REPET     DIDIT                      0136  48 0089 0090
REPET   SMC  DIDIT     DOONE                      0089  49 0090 0118
DIDIT   RAU  ACCUM                                0090  60 0115 0369
        FSB  FLUX    A                            0369  33 3220 0047
        STU  G       A                            0047  21 3240 0043
        FMP  G       A                            0043  39 3240 0140
        FDV  W       A                            0140  34 3750 0300
        FAD  ERROR                                0300  32 0021 0097
        STU  ERROR                                0097  21 0021 0074
        SXC  0001                                 0074  59 0001 0280
        SXA  0001                                 0280  51 0001 0186
        NZA  READY     EXIT                       0186  40 0086 0203
PRINT   STD  EXET                ROUTINE          0350  24 0253 0256
        LDD            EOOCL     TO PRINT         0256  69 0109 0050
        LDD  INDXB               ANSWERS          0109  69 0162 0165
        RAS  8001      RESIT                      0165  82 8001 0071
RESIT   LDD  EIGHT                                0071  69 0124 0127
        RSA  8001      FILL                       0127  81 8001 0083
FILL    LDD  SBEST   B                            0083  69 5270 0073
        STD  1985    A                            0073  24 3985 0038
        LDD  RBEST   B                            0038  69 5290 0093
        STD  1986    A                            0093  24 3986 0139
        SXB  0001                                 0139  53 0001 0045
        AXA  0002                                 0045  50 0002 0001
        NZB  NEXTB     WHOPE                      0001  42 0204 0105
NEXTB   NZA  FILL      CARDZ                      0204  40 0083 0008
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CARDZ   PCH  1977                              119   0008   71 1977 0177
        LDD  RESIT     EOOCL                   120   0177   69 0071 0050
WHOPE   PCH  1977                              121   0105   71 1977 0227
        LDD            EOOCL                   122   0227   69 0330 0050
        LDS  ERMIN                             123   0330   69 0133 0236
        STD  1984                              124   0236   24 1984 0087
        PCH  1977      EXET                    125   0087   71 1977 0253
PRIME   STD  TIXE                ROUTINE       126   0400   24 0303 0306
        LDD  S      S            TO SET        127   0306   69 5260 0013
        STD  SBEST  S            BEST          128   0013   24 5270 0123
        LDD  R      S            VALUES OF     129   0123   69 5280 0183
        STD  RBEST  S            PARAMETERS    130   0183   24 5290 0143
        LDD  ERROR                             131   0143   69 0021 0174
        STD  ERMIN     TIXE                    132   0174   24 0133 0303
START   LDD  INDXB                             133   1999   69 0162 0215
        RAB  8001      LOADY                   134   0215   82 8001 0121
LOADY   LDD  SINIT  S            SET           135   0121   69 5300 0353
        STD  S      S            PARAMETERS    136   0353   24 5260 0063
        STD  SBEST  S            AT INITIAL    137   0063   24 5270 0173
        LDD  RINIT  S            ESTIMATES     138   0173   69 5310 0113
        STD  R      S                          139   0113   24 5280 0233
        STD  RBEST  S                          140   0233   24 5290 0193
        SXB  0001                              141   0193   53 0001 0299
        NZB  LOADY     SETUP                   142   0299   42 0121 0403
SETUP   RAU  INDXA                             143   0403   60 0077 0081
        RAA  8001                              144   0081   80 8001 0137
        LDD  INDXB                             145   0137   69 0162 0265
        RAS  8001                DETERMINE     146   0265   82 8001 0171
        MPY  8001                INDXC         147   0171   19 8001 0044
        STL  INDXC                             148   0044   20 0039 0092
        RAC  8001      CALCA                   149   0092   88 8001 0098
CALCA   LDD            TEMPP     CALCULATE     150   0098   69 0051 0100
        LDD            TURNN     TEMP AND      151   0051   69 0254 0200
        SXC  0001                TERM FOR      152   0254   59 0001 0060
        SXA  0001                ALL           153   0060   51 0001 0016
        NZA  CALCA     CALCB     COMBIN        154   0016   40 0098 0020
CALCB   LDD  INDXA               ATIONS        155   0020   69 0077 0380
        RAA  8001                OF R AND S    156   0380   80 8001 0286
        SXB  0001                              157   0286   53 0001 0142
        NZB  CALCA     FILUP                   158   0142   42 0098 0046
FILUP   LDD            ERR       DETERMINE     159   0046   69 0349 0250
        LDD            PRINE     INITIAL       160   0349   69 0002 0400
        LDD            PRINT     ERROR         161   0002   69 0155 0350
        LDD  INDXB                             162   0155   69 0162 0315
        RAB  8001                              163   0315   82 8001 0221
        LDD  INDXC                             164   0221   69 0039 0192
        RAC  8001      LOOPS                   165   0192   88 8001 0148
LOOPS   LDD  ZERO                              166   0148   69 0059 0212
        STD  INDXF                             167   0212   24 0365 0218
        RAU  SBEST  S            INCREASE S    168   0218   60 5270 0125
        FAD  DELS      SUBS1                   169   0125   32 0028 0205
SUBS1   STU  S      S                          170   0205   21 5260 0163
        LDD  8007                              171   0163   69 8007 0419
        STD  CTEMP                             172   0419   24 0322 0175
        LDD  8006                              173   0175   69 8006 0131
        STD  BTEMP                             174   0131   24 0084 0187
        LDD  INDXA                             175   0187   69 0077 0430
        RAA  8001      SUBS2                   176   0430   80 8001 0336
SUBS2   LDD            TURNN     FORM NEW      177   0336   69 0189 0200
        SXC  0001                TERM          178   0189   59 0001 0095
        SXA  0001                              179   0095   51 0001 0101
        NZA  SUBS2     SUBS3     DETERMINE     180   0101   40 0336 0255
SUBS3   LDD            ERR       ERROR         181   0255   69 0058 0250
        RAU  ERMIN               TEST ERROR    182   0058   60 0133 0237
        FSB  ERROR                             183   0237   33 0021 0147
        BMI  BADDS     GOODS                   184   0147   46 0450 0151
GOODS   LDD  BTEMP               HAVE          185   0151   69 0084 0287
        RAB  8001                IMPROVED S    186   0287   82 8001 0243
        LDD  CTEMP                             187   0243   69 0322 0225
        RAC  8001                              188   0225   88 8001 0181
        RAU  BBEST  S                          189   0181   60 5270 0275
        FSB  S      S                          190   0275   33 5260 0337
        BMI  SPLUS     SMINS                   191   0337   46 0190 0091
SPLUS   LDD            PRINE     SET S         192   0190   69 0293 0400
        LDD  FPONE               AT SBEST      193   0293   69 0096 0399
        STD  INDXF                             194   0399   24 0365 0268
        STD  INDXO                             195   0268   24 0271 0224
        RAU  SBEST  S            INCREASE S    196   0224   60 5270 0325
        FAD  DELS      SUBS1                   197   0325   32 0028 0205
SMINS   LDD            PRINE     SET S         198   0091   69 0094 0400
        LDD  ZERO                AT SBEST      199   0094   69 0059 0262
        STD  INDXF                             200   0262   24 0365 0318
        LDD  FPONE                             201   0318   69 0096 0449
        STD  INDXO                             202   0449   24 0271 0274
        RAU  SBEST  S            DECREASE S    203   0274   60 5270 0375
        FSB  DELS      SUBS1                   204   0375   33 0028 0205
BADDS   LDD  BTEMP               HAVE NOT      205   0450   69 0084 0387
        RAB  8001                IMPROVED S    206   0387   82 8001 0343
        RAU  INDXF                             207   0343   60 0365 0469
        NZU  LOOPR     LETUP                   208   0469   44 0223 0324
LETUP   LDD  BTEMP                             209   0324   69 0084 0437
        RAB  8001                              210   0437   82 8001 0393
        RAU  SBEST  S                          211   0393   60 5270 0425
        FSB  S      S                          212   0425   33 5260 0487
        BMI  MORES     LOOPS                   213   0487   46 0240 0223
MORES   LDD  BTEMP                             214   0240   69 0084 0537
        RAB  8001                              215   0537   82 8001 0443
        LDD  CTEMP                             216   0443   69 0322 0475
        RAC  8001                              217   0475   88 8001 0231
        RAU  SBEST  S            DECREASE S    218   0231   60 5270 0525
        FSB  DELS      SUBS1                   219   0525   33 0028 0205
LOOPR   LDD  ZERO                              220   0223   69 0059 0312
        STD  INDXF                             221   0312   24 0365 0368
        LDD  SBEST  S            SET S         222   0368   69 5270 0273
        STD  S      S            AT SBEST      223   0273   24 5260 0213
        RAU  RBEST  S                          224   0213   60 5290 0145
        FAD  DELR      SUBR1     INCREASE R    225   0145   32 0198 0575
SUBR1   STU  R      S                          226   0575   21 5280 0283
        LDD  CTEMP                             227   0283   69 0322 0625
        RAC  8001                              228   0625   88 8001 0281
        LDD  BTEMP                             229   0281   69 0084 0587
        RAB  8001                              230   0587   82 8001 0493
        LDD  INDXA                             231   0493   69 0077 0480
        RAA  8001      SUBR2     FORM NEW      232   0480   80 8001 0386
SUBR2   LDD            TEMPP     TEMP AND      233   0386   69 0239 0100
        LDD            TURNN     TERM          234   0239   69 0242 0200
        SXC  0001                              235   0242   59 0001 0248
        SXA  0001                              236   0248   51 0001 0304
        NZA  SUBR2     ROUT                    237   0304   40 0386 0108
ROUT    RAU  RBEST  S                          238   0108   60 5290 0195
        FSB  R      S                          239   0195   33 5280 0157
        NZU  SUBR3     NEXT      DETERMINE     240   0157   44 0061 0362
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SUBR3   LDD            ERR       ERROR        241   0061   69 0064 0250
        RAU  ERMIN                            242   0064   60 0133 0637
        FSB  ERROR               TEST ERROR   243   0637   33 0021 0197
        BMI  SADDR     GOODR                  244   0197   46 0500 0201
GOODR   LDD  BTEMP               HAVE         245   0201   69 0084 0687
        RAS   8001               IMPROVED     246   0687   82 8001 0543
        LDD  CTEMP               R            247   0543   69 0322 0675
        RAC   8001                            248   0675   88 8001 0331
        RAU  RBEST  B                         249   0331   60 5290 0245
        FSB  R      B                         250   0245   33 5280 0207
        BMI  RPLUS     RMINS                  251   0207   46 0110 0111
RPLUS   LDD            PRIME     SET R AT     252   0110   69 0263 0400
        LDD  FPONE               RBEST        253   0263   69 0096 0499
        STD  INDXF                            254   0499   24 0365 0418
        STD  INDXO                            255   0418   24 0271 0374
        RAU  RBEST  B            INCREASE R   256   0374   60 5290 0295
        FAD  DELR      SUBR1                  257   0295   32 0198 0575
RMINS   LDD            PRIME     SET R AT     258   0111   69 0114 0400
        LDD  ZERO                RBEST        259   0114   69 0059 0412
        STD  INDXF                            260   0412   24 0365 0468
        LDD  FPONE                            261   0468   69 0096 0549
        STD  INDXO                            262   0549   24 0271 0424
        RAU  RBEST  B            DECREASE R   263   0424   60 5290 0345
        FSB  DELR      SUBR1                  264   0345   33 0198 0575
SADDR   RAU  INDXF               HAVE NOT     265   0500   60 0365 0519
        NZU  FIXUP     TESTR     IMPROVED R   266   0519   44 0323 0474
TESTR   LDD  BTEMP                            267   0474   69 0084 0737
        RAB   8001                            268   0737   82 8001 0593
        RAU  RBEST  B                         269   0593   60 5290 0395
        FSB  R      B                         270   0395   33 5280 0257
        BMI  MORER     FIXUP                  271   0257   46 0160 0323
MORER   LDD  BTEMP                            272   0160   69 0084 0787
        RAB   8001                            273   0787   82 8001 0643
        LDD  CTEMP                            274   0643   69 0322 0725
        RAC   8001                            275   0725   88 8001 0381
        RAU  RBEST  B            DECREASE R   276   0381   60 5290 0445
        FSB  DELR      SUBR1                  277   0445   33 0198 0575
FIXUP   RAU  RBEST  B  SUBR1     SET R AT     278   0323   60 5290 0575
NEXT    SXB   0001               RBEST        279   0362   53 0001 0518
        NZB  AGAIN     ENUFF                  280   0518   42 0321 0372
AGAIN   RAU  CTEMP               REPEAT       281   0321   60 0322 0277
        SUP  INDXA               PROCEDURE    282   0277   11 0077 0431
        STU  CTEMP               FOR NEXT     283   0431   21 0322 0775
        RAU  BTEMP               RANGE        284   0775   60 0084 0289
        SUP  ONE                 GROUP        285   0289   11 0292 0247
        STU  BTEMP                            286   0247   21 0084 0837
        LDD  CTEMP                            287   0837   69 0322 0825
        RAC   8001                            288   0825   88 8001 0481
        LDD  BTEMP                            289   0481   69 0084 0887
        RAB   8001     LOOPB                  290   0887   82 8001 0148
ENUFF   LDD            PRINT                  291   0372   69 0875 0350
        RAU  INDXO                            292   0875   60 0271 0925
        NZU  TIRED     TIGHT                  293   0925   44 0079 0530
TIRED   LDD  INDXB               IMPROVED     294   0079   69 0162 0415
        RAB   8001               LAST TIME    295   0415   82 8001 0371
        LDD  INDXC               THROUGH      296   0371   69 0039 0342
        RAC   8001               DO AGAIN     297   0342   88 8001 0298
        LDD  ZERO                             298   0298   69 0059 0462
        STD  INDXO     LOOPB                  299   0462   24 0271 0148
TIGHT   RAU  DELS                REFINE       300   0530   60 0028 0333
        FDV  TEN                 INCREMENTS   301   0333   34 0436 0486
        STU  DELS                             302   0486   21 0028 0531
        RAU  DELR                             303   0531   60 0198 0453
        FDV  TEN                              304   0453   34 0436 0536
        STU  DELR                             305   0536   21 0198 0251
        FSB  ONEHO                            306   0251   33 0354 0581
        BMI  DEVEA     TIRED                  307   0581   46 0134 0079
DEVEA   LDD            EOOCL     PRINT        308   0134   69 0937 0050
        LDD  INDXA               DEVIATIONS   309   0937   69 0077 0580
        RAA   8001     RESET                  310   0580   80 8001 0586
RESET   LDD  EIGHT                            311   0586   69 0124 0327
        RBB   8001     STUFF                  312   0327   83 8001 0383
STUFF   LDD  Z      A                         313   0383   69 3200 0503
        STD   1985  B                         314   0503   24 5985 0088
        LDD  G      A                         315   0088   69 3240 0693
        STD   1986  B                         316   0693   24 5986 0339
        SXA   0001                            317   0339   51 0001 0495
        AXB   0002                            318   0495   52 0002 0301
        NZA  MOREG     FINIS                  319   0301   40 0404 0305
MOREG   NZB  STUFF     CARDS                  320   0404   42 0383 0158
CARDS   PCH   1977                            321   0158   71 1977 0377
        LDD  RESET     EOOCL                  322   0377   69 0586 0050
FINIS   PCH   1977     CONST                  323   0305   71 1977 0427
CONST   LDD  INDXB               DETERMINE    324   0427   69 0162 0465
        RAB   8001     SETJK     CONSTANT C   325   0465   82 8001 0421
SETJK   LDD  ZERO                             326   0421   69 0059 0512
        STD  SUM1                  BY         327   0512   24 0515 0568
        LDD  FPONE               SUMMING      328   0568   69 0096 0599
        STD  J                   INFINITE     329   0599   24 0052 0355
        STD  K         SUMUP     SERIES       330   0355   24 0208 0161
SUMUP   RAU  J                     UNTIL      331   0161   60 0052 0307
        FMP  J                   LAST TERM    332   0307   39 0052 0102
        FDV  A1                  SMALL        333   0102   34 0405 0455
        FDV  A1                  ENOUGH       334   0455   34 0405 0505
        STU  PART                             335   0505   21 0210 0313
        RAU  K                                336   0313   60 0208 0363
        FMP  K                                337   0363   39 0208 0258
        FDV  A2                               338   0258   34 0211 0261
        FDV  A2                               339   0261   34 0211 0311
        FAD  PART                             340   0311   32 0210 0987
        FMP  PI                               341   0987   39 0290 0340
        FMP  PI                               342   0340   39 0290 0390
        FMP  RBEST  B                         343   0390   39 5290 0440
        FMP  RBEST  B                         344   0440   39 5290 0490
        FDV  FOUR                             345   0490   34 0743 0793
        RSL   0003                            346   0793   66 8003 0351
        LDD            EDDEA                  347   0351   69 0454 0000
        RAU   8002                            348   0454   60 8002 0413
        STU  TURM                             349   0413   21 0618 0471
        FAD  SUM1                             350   0471   32 0515 0141
        STU  SUM1                             351   0141   21 0515 0668
        RAU  TURM                             352   0668   60 0618 0373
        FSB  PREC                             353   0373   33 0126 0553
        BMI  GETON     MOREJ                  354   0553   46 0356 0357
MOREJ   RAU  J                                355   0357   60 0052 0407
        FAD  FPTWO                            356   0407   32 0260 1037
        STU  J         SUMUP                  357   1037   21 0052 0161
GETON   RAU  J                                358   0356   60 0052 0457
        FSB  FPONE                            359   0457   33 0096 0423
        NZU  MOREK     BINGO                  360   0423   44 0477 0078
MOREK   RAU  K                                361   0477   60 0208 0463
        FAD  FPTWO                            362   0463   32 0260 1087
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        STU  K                                    363   1087   21 0208 0361
        LDD  FPONE                                364   0361   69 0096 0649
        STD  J          RUMUP                     365   0649   24 0052 0161
RINGO   RAU  RUM1                                 366   0078   60 0515 0569
        FMP  FOUR                                 367   0569   39 0743 0843
        FDV  A1                                   368   0843   34 0405 0555
        FDV  A2                                   369   0555   34 0211 0411
        FDV  SDPI                                 370   0411   34 0164 0214
        FDV  RBEST  B              CALCULATE      371   0214   34 5290 0540
        STU  C      B                 C           372   0540   21 5720 0473
        SXB   0001                                373   0473   53 0001 0129
        NZB  SETJK      FRACT                     374   0129   42 0421 0433
FRACT   LDD  ZERO                                 375   0433   69 0059 0562
        STD  DENOM                 DETERMINE      376   0562   24 0565 0718
        LDD  INDXB                 RANGE          377   0718   69 0162 0615
        RAB   8001      RATIO      GROUP          378   0615   82 8001 0521
RATIO   RAU  RBEST  B              FRACTION       379   0521   60 5270 0975
        FDV  C      B                             380   0975   34 5720 0070
        STU  QUOT   B                             381   0070   21 5740 0893
        FAD  DENOM                                382   0893   32 0565 0191
        STU  DENOM                                383   0191   21 0565 0768
        RXB   0001                                384   0768   53 0001 0524
        NZB  RATIO      GDWAN                     385   0524   42 0521 0128
GDWAN   LDD  INDXB                                386   0128   69 0162 0665
        RAB   8001      WHIP                      387   0665   82 8001 0571
WHIP    RAU  QUOT   B                             388   0571   60 5740 0545
        FDV  DENOM                                389   0545   34 0565 0715
        STU  FRAC   B                             390   0715   21 5730 0483
        RXB   0001                                391   0483   53 0001 0389
        NZB  WHIP       CLERE                     392   0389   42 0571 0943
CLERE   LDD  INDXB                                393   0943   69 0162 0765
        RAB   8001                                394   0765   82 8001 0621
        LDD  WRITE      EDOCL                     395   0621   69 0574 0050
WRITE   LDD  RBEST  B              PRINT          396   0574   69 5290 0993
        STD   1981                 RANGE          397   0993   24 1981 0184
        LDD  C      B              CONSTANT       398   0184   69 5720 0523
        STD   1982                 FRACTION       399   0523   24 1982 0085
        LDD  FRAC   B                             400   0085   69 5730 0533
        STD   1983                                401   0533   24 1983 0636
        PCH   1977                                402   0636   71 1977 0527
        SXB   0001                                403   0527   53 0001 0583
        NZB  WRITE      HALT                      404   0583   42 0574 1137
HALT    HLT                                       405   1137   01 1107 1107
ZERO     00   0000       0000                     406   0059   00 0000 0000
INDXA    00   0000       0010      NMBR OF Z      407   0077   00 0000 0010
INDXB    00   0000       0003      NMBR OF R      408   0162   00 0000 0003
EIGHT    00   0000       0008                     409   0124   00 0000 0008
FPONE    10   0000       0051                     410   0096   10 0000 0051
FPTWO    20   0000       0051                     411   0260   20 0000 0051
ONE      00   0000       0001                     412   0292   00 0000 0001
TEN      10   0000       0052                     413   0436   10 0000 0052
ONEMO    99   0000       0048                     414   0354   99 0000 0048
A1       17   6230       0053      PILE SIZE      415   0405   17 6230 0053
A2       17   6230       0053      PILE SIZE      416   0211   17 6230 0053
PI       31   4159       2651                     417   0290   31 4159 2651
FOUR     40   0000       0051                     418   0743   40 0000 0051
PSEC     10   0000       0046                     419   0126   10 0000 0046
S9PI     17   7245       3851                     420   0164   17 7245 3851
DELS     10   0000       0053      INITIAL        421   0028   10 0000 0053
DELR     10   0000       0051      INCREMENTS     422   0198   10 0000 0051
Z1       56   3000       0051                           1201   56 3000 0051
Z2       15   8200       0052                           1202   15 8200 0052
Z3       25   9600       0052                           1203   25 9600 0052
Z4       36   1100       0052                           1204   36 1100 0052
Z5       46   3100       0052                           1205   46 3100 0052
Z6       56   4500       0052                           1206   56 4500 0052
Z7       66   1500       0052                           1207   66 1500 0052
Z8       76   7800       0052                           1208   76 7800 0052
Z9       86   9400       0052                           1209   86 9400 0052
Z10      97   1200       0052                           1210   97 1200 0052
                                                        1221   32 6230 0055
                                   RESONANCE            1222   26 7380 0055
                                   DATA TO              1223   18 3350 0055
                                    BE FIT              1224   10 8170 0055
                                                        1225   56 7300 0054
                                                        1226   25 7600 0054
                                                        1227   11 5900 0054
                                                        1228   47 0700 0053
                                                        1229   21 2500 0053
                                                        1230   92 9000 0052
                                   WEIGHTING            1751   84 6400 0054
                                   FUNCTIONS            1752   10 2010 0055
                                                        1753   17 6400 0054
                                   RECIPROCAL           1754   11 5600 0054
                                       OF               1755   12 2500 0054
                                    STANDARD            1756   13 5000 0053
                                   DEVIATION            1757   64 0000 0052
                                   SQUARED              1758   41 0000 0052
                                                        1759   41 0000 0052
                                                        1760   37 2000 0052
                                   INITIAL              1301   69 5000 0053
                                   AMPLITUDES           1302   21 7560 0055
                                                        1303   11 1120 0055
                                   INITIAL              1311   65 4400 0052
                                   RANGES               1312   36 9400 0052
                                                        1313   27 3100 0052
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APPENDIX H

Consideration of Perturbations and Corrections Encountered in Experiments Using Finite Foils and Sources

In order to determine indium foil activations free from self-perturbations or experimental limitations, it is possible to consider the following:

(a) activation of indium by higher energy resonance neutrons

(b) absorption of epithermal neutrons in cadmium filter

(c) finite size of source and detector

(d) difference in foil weights or size

(e) unequal activation of two sides of foil

(f) flux depression in vicinity of foil

(g) self-shielding of the center of the foil by its outer layers

(h) mutual shadowing of neighboring foils

(i) hardening of the neutron spectrum through the foil

(j) obliquity of foil with respect to the source.

If there is need for an estimate of the absolute flux in medium or physical situation that differs from the standardizing medium or the standardizing physical situation, these factors should be considered. Factors (a) through (e) have been considered in this pile standardization.

Activation of Indium by Higher Energy Resonance Neutrons

This section considers the correction factor that must be applied to indium foil measurements made near high energy neutron sources, because of activation of the indium by resonance neutrons about 1.44 ev. (19, 41).

According to Hill, Roberts and McCammon, (19), at points close to a source of high energy neutrons in graphite, a good part of the foil activation is due to absorption of neutrons above an energy of 1.44 ev. Farther from the source, the perturbation due to higher resonances becomes less so that this correction factor becomes negligible.

The experimental technique for determining the correction factor to be applied to the measured activity of the cadmium covered indium foils consists of comparing the activity of indium foils covered by both cadmium and indium with the activity of foils covered by cadmium. Since the resonances of indium 115 above 1.44 ev are weak compared with the resonance at 1.44 ev, the self-shielding of the high energy resonances is small compared with that of the 1.44 ev resonance. Consequently, covering the foils with indium will have little effect on the activation by neutrons of higher energy, but will decrease the activation at 1.44 ev by a large factor.

At distances less than $\sqrt{\tau}$ from the source (41), the total activation of cadmium covered foils is

$$A_{CdInCd} = A_{1.44\ ev} + A_{higher\ energy}. \qquad (H\text{-}1)$$

At distances of two or three times $\sqrt{\tau}$ from the source, the activation by high energy neutrons is negligible so that the activation is

$$A_{CdInCd} = A_{1.44\ ev} \tag{H-2}$$

For the case in which the foils are covered with both indium and cadmium, Eqs. (H-1) and (H-2) can be written, respectively

$$A_{CdInInInCd} = g_0 A_{1.44\ ev} + A_{higher\ energy} \tag{H-3}$$

$$A_{CdInInInCd} = g_0 A_{1.44\ ev} \tag{H-4}$$

where g_0 is a shielding factor for the indium foils at the 1.44 ev resonance. Equations (H-2) and (H-4) may be used to obtain g_0 and then Eqs. (H-1) and (H-3) may be solved simultaneously to obtain $A_{higher\ energy}$ from known measured values of A_{CdInCd} and A_{CdInCd}.

Additional experimental measurements were made by enclosing the detecting indium foil on each side with similar indium foils in addition to the usual cadmium cover. Cadmium covered indium foil measurements made by Steichen (39) were used for the unshielded measurements after verifying that Steichen's measurements could be reproduced.

Table 24 lists the experimental results of foil measurements and the ratio of the indium foil activities when covered with indium plus cadmium to the activities when covered only with cadmium. Fig. 27 is a plot of this ratio.

Table 24. Summary of data and results on resonance correction factor.

Distance from source	A_{CdInCd} (39)	$A_{CdInInInCd}$	Ratio	Per cent correction to A_{CdInCd}
cm	counts in 27 minute counting period	counts in 27 minute counting period		
5.63	35,034 ± 92	15,101 ± 206	0.4310 ± 0.0060	6.73
15.82	27,536 ± 101	11,199 ± 73.3	0.4067 ± 0.0017	2.73
25.96	18,456 ± 42	7,325 ± 75.3	0.3969 ± 0.0042	0.82
36.11	10,706 ± 34	4,089 ± 63.0	0.3819 ± 0.0060	0.14
46.31	5,668 ± 35	2,230 ± 52.7	0.3934 ± 0.0096	
56.45	2,550 ± 32.9	1,104 ± 62.0	0.4329 ± 0.0250	
66.15	1,174 ± 27.8	470.4 ± 30.0	0.4008 ± 0.0271	
76.78	469 ± 26.2	178 ± 32.6	0.3795 ± 0.0725	

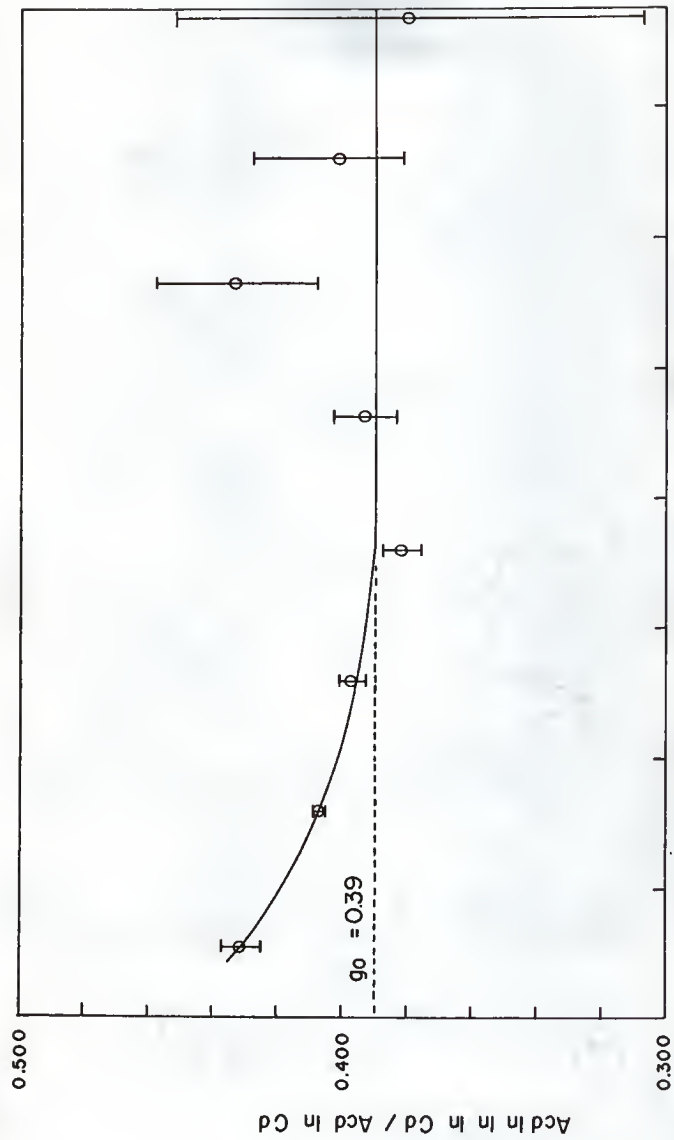

Fig. 27. Ratio of indium foil activities when covered with indium plus cadmium to the activities when covered with cadmium.

By assuming that the ratio will approach the constant shielding factor, g_0, at points away from the source, a line representing this shielding factor has been approximated. With this approximation, a correction factor has been determined and plotted in Fig. 28 along with the results of other work done with this correction factor (19, 41).

Absorption of Epithermal Neutrons in the Cadmium Filter

This correction factor, designated by F_{cd}, considers the absorption of epithermal neutrons in the cadmium foil covering. It is a function of both the thickness of the cadmium covering and the thickness of the foil. For the particular foils and covers used in this work, F_{cd} was 1.16. The graph from which it was obtained is available in many references, (2, 18, 28, 40).

This factor was measured by Tittle (40) by a technique that used successively different thicknesses of cadmium covering for a particular foil thickness, the correction factor being found from an extrapolation to zero cadmium thickness.

Finite Size of Source and Detector

To correct for the finite sizes of the source and detector, the following equation may be used for a circular source of radius a_1 and a circular detector of radius a_2,(41).

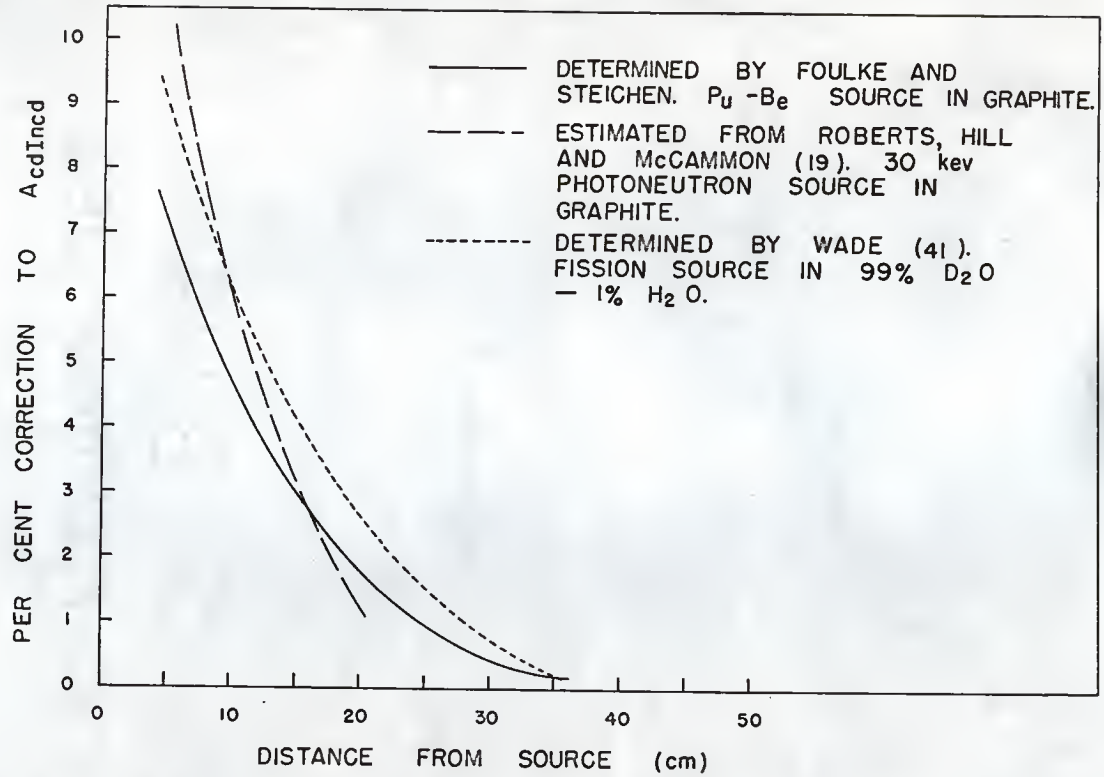

Fig. 28. Correction of indium foil activity for high energy neutron absorption.

$$A(r_0) - A_m(r_0) = -\left(\frac{a_1^2 + a_2^2}{4 r_0}\right)\left(\frac{d A}{d r}\right)_{r=o} \qquad \text{(H-5)}$$

$A_m(r_0)$ is the observed activity at the distance r_0 between the centers of the source and detector. $A(r_0)$ is the ideal activity of a point source.

Steichen (39) has determined this correction factor for resonance neutron measurements. It is given in Fig. 29. It was applied to the resonance measurements made in this work. This factor would vary with the diffusing medium.

Variation in Foil Weights or Sizes

Graves and Froman (16) point out that for thick foils, variation in weight has a small effect so long as the foil area is constant from foil to foil. They state that only the activity of a thin foil is proportional to the mass of the foil, and that a correction for variation of foil mass is difficult to make for a foil of sufficient thickness to be usable. They feel that it is better to control the manufacture of the foils such that the variation in weight from foil to foil is very small.

In the fitting of the resonance activations described in the analytical portion of the work, it was found that consideration of the variation of the foil weights improved the results of the resonance data fit considerably. The average foil weight was 0.4592 grams with a maximum deviation of one per cent by any foil.

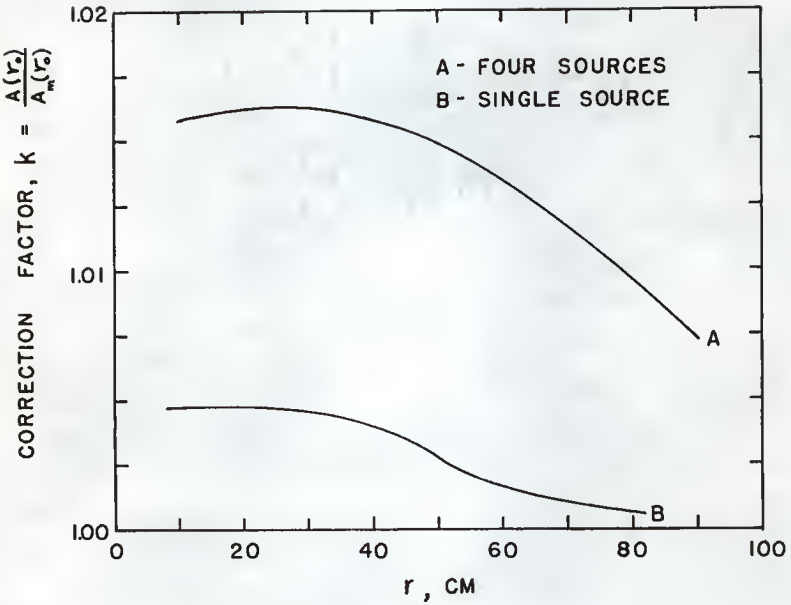

Fig. 29. Source and detector geometry correction factors for the single source and four source resonance distributions.

Unequal Activation of Two Sides of Foil

Since foils are seldom thin for neutrons or for the electrons produced by induced activation, the activity measured on different sides of the foil may be different. This difference depends upon the flux gradient in the neighborhood of the foil, (16). It is generally agreed (2, 16) that whenever the diffusion approximation is adequate to describe the neutron flux, the average of the measurements on both sides of a foil is proportional to the flux.

All foil data reported in this work is the average of measurements made on both sides of the foils.

Flux Depression in the Vicinity of the Foil

A flux detecting foil absorbs neutrons which would otherwise be able to scatter back and bolster the flux at the foil position. The magnitude of this flux depression depends upon the properties of the foil, the angular distribution of the neutrons in the foil vicinity, and the mean free path of neutrons in the surrounding medium (30).

This factor need not be considered when measurements with the standardized detector are made in the standardizing medium. If the standardized detector is used in other mediums, this factor may be easily determined from formulas given in various references, (28, 31, 34).

This correction for flux depression need not be considered for measurements of slowing down density at indium resonance energy. Absorption of an epithermal neutron does not remove a neutron which

could be scattered back to bolster the flux; since in order for the neutron to be scattered back to the detector position, the neutron must suffer an energy degrading collision. Thus the neutron may not have the resonance energy and would not be eligible to bolster the resonance energy flux.

Self-protection of the Foil by Its Outer Layers

This consideration takes into account the fact that atoms in internal layers of a thick detector are exposed to a neutron flux smaller than that impinging on the surface of the foil. The self-protection ratio is the ratio of the gross activation of the foil to the quantity calculated by multiplying the macroscopic cross section for activation by the surface flux (31). Determination of this self-protection ratio is outlined in reference (31).

This factor does not depend upon foil position and may be considered a constant for any medium and position. It is a function of only the foil material and thickness, and the nature of the flux. It would be necessary to apply this correction factor if a collimated flux were being measured. For the assumed isotropic flux in this work, this correction factor has not been considered.

Mutual Shadowing of Neighboring Foils

It is possible to irradiate resonance detectors near enough to each other to cause an effect by one foil upon the other. Approximate values for the fractional loss of resonance activations due to the presence of a neighboring foil are given in reference (30). For the particular

foils and foil spacings used in this work, the effect of one foil on the other was estimated to be negligible.

Hardening of the Neutron Spectrum through the Foil

The correction for the hardening of the spectrum arises from the fact that neutrons of lower energy are preferentially absorbed in the first few layers of a thick foil. Thus the neutrons reaching the internal layers of the detector will be of higher average energy and will be subject to different capture cross sections.

Amaldi (2) and Hughes (20) give complete discussions of this effect. It has not been considered in this work.

Obliquity of Foil with Respect to the Source

Even though the direction of most of the neutrons through the foil does not affect the activation directly, it does affect the correction factors that depend on foil thickness since the effective foil thickness is a function of obliquity, (20).

All experimental work in this paper was performed with the normal to the foil surface area facing the source. If need arises to irradiate the foil in a different manner, it might be of interest to experimentally determine the magnitude of this effect.

No effort to further systematize these foil correction factors has been made in this work. It might be desirable to have a more complete study of these factors. A determination of the absolute, unperturbed flux from absolute foil counting would require application of many of the factors introduced.

KSU PILE STANDARDIZATION AND STUDY OF SLOWING DOWN AND DIFFUSION MODELS

by

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AN ABSTRACT OF A THESIS

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The Kansas State University Graphite Pile was calibrated for absolute thermal neutron flux with a one curie Pu-Be neutron source, thus standardizing indium foils, a BF_3 probe and a scintillation probe. The sensitivities of these detectors to thermal and indium resonance neutrons are given.

Based on the neutron emission rate of the source, absolute values of the measured slowing down density at indium resonance energy were obtained from the volume integral of the slowing down density over a pile of assumed infinite height. The absolute thermal neutron flux was then obtained from the thermal diffusion equation using as a source condition the absolute slowing down density at indium resonance energy extended to the absolute slowing down density at thermal energy by use of Fermi slowing down theory.

The standardized detectors were used to test experimentally the validity of the diffusion equation in a finite pile geometry, using as a source condition to the thermal diffusion equation: (a) the solution to the Fermi age equation evaluated at thermal energy, (b) a thermal point neutron source, and (c) the analytical expression for the slowing down density at thermal energy as found from the standard pile measurements.

The techniques used in accurate foil activation measurements are discussed. Inconsistent values of various diffusion parameters for graphite are pointed out. IBM-650 programs are given to fit empirically the indium resonance foil activations, to calculate the thermal flux from a fast point source in an infinite column, to calculate the thermal flux from a fast point source in a finite medium, and to calculate the thermal flux from a thermal point source in a finite medium.