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DETERMINATION OF THERMAL-NEUTRON
FLUX DISTRIBUTIONS IN THE BULK
SHIELDING REACTOR II BY COPPER
WIRE ACTIVATION TECHNIQUES

G. T. Chapman

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MARCH 1965

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ABSTRACT

The thermal-neutron flux distribution within the ORNL stainless steel Bulk Shielding Reactor II has been determined by exposing copper wires at selected locations in the core during reactor operation. The gamma-ray activity resulting from thermal-neutron activation of the copper was counted as a function of position along the wire, and the results were converted to estimates of thermal-neutron flux by the methods described in this report.

The method of analysis was checked by independently exposing gold and copper wires at a common location in the reactor. The thermal-neutron fluxes obtained from analysis of both sets of data were in agreement within ~ 3%. The method was further checked by comparing the results of a wire exposure with calculations of the distribution made by the PDQ reactor code. Agreement was good in statistically important regions.

Several CDC-1604A programs were written to facilitate processing of the wire data, and are included as an appendix.

I. INTRODUCTION

In measuring¹ the gamma-ray spectrum of the Bulk Shielding Reactor II (BSR II), a core composed of stainless steel fuel elements, it was found that most of the higher-energy gamma rays had resulted from thermal-neutron captures in the nuclides comprising the stainless steel fuel cladding and other portions of the core structure. In order to satisfactorily interpret the data it was necessary to determine the distribution of the capture gamma-ray sources by mapping the thermal-neutron flux distribution throughout the reactor core. This was done by inserting copper wires of length greater than the depth of the core in various locations in the core, with

1. G. T. Chapman et al., Neutron Phys. Div. Ann. Progr. Rept. Aug. 1, 1963, ORNL-3499, Vol. I, p. 93

the reactor operated at a nominal 2-W power level for controlled times, then removing the wires and measuring the gamma-ray activity resulting from thermal-neutron activation of the copper. The method used in converting the measured activity to thermal-neutron flux is the principal subject of this report.

Copper was chosen for the activation measurements for a number of reasons:

1. Its cross sections seems to follow a $1/v$ law over a large energy range, and there is no evidence of resonances near thermal energies. The magnitude of the cross section is sufficient to produce reasonable activities in a reactor flux without excessively long exposures, yet is not so great as to introduce large flux depressions.

2. Copper has only two naturally occurring isotopes: ^{63}Cu (69.1%) and ^{65}Cu (30.9%). The ^{63}Cu isotope has an (n,γ) cross section which is twice that of the ^{65}Cu at thermal-neutron energies, and its product nuclide (^{64}Cu) decays with a half-life of 12.8 hr, whereas ^{66}Cu , the product nuclide of ^{65}Cu , has a half-life of only 5.1 min. Thus, after just 1 hr, only one relatively simple decay scheme need be considered in measuring the activity. The fact that the two gamma rays occurring in the ^{64}Cu distribution are widely separated in energy, with the lower one (0.511 MeV) much greater in magnitude than the higher one (1.34 MeV), facilitated analysis of the copper activity.

3. Finally, copper requires no special handling or preparation and may be disposed of, in a manner consistent with health physics requirements, very soon after measurements are completed.

This report discusses only the methods developed for analyzing the data. The final results of the measurements will be reported later. In order to check the validity of the method of analysis, a gold wire and a copper wire were activated at the same location in the reactor. Since these two materials differ greatly in nuclear properties and since their diameters differed by a factor of 2, a comparison of the results of the two measurements should have been a satisfactory check. However, as an additional check, the experimental data were compared with a calculated distribution.

II. EXPERIMENTAL PROCEDURE

After the wires had been exposed in the reactor and then removed, the activity was allowed to decay for a minimum of 1 hr before the counting was started, in order to eliminate the activity resulting from the disintegrating ^{66}Cu nuclei. As can be seen in Fig. 1 showing the first 100 min of the measured decay curve compared with the expected decay curve for a natural mixture of ^{64}Cu ($T_{1/2} = 12.8$ h) and ^{66}Cu ($T_{1/2} = 5.1$ m) nuclei, the 1-hr waiting period was sufficient. Since the "two-component" curve matches the measured curve so well, the wire can be assumed to be of effectively pure copper, even though it was "off-the-shelf" material.

For counting, the wire was mounted on the scanning mechanism shown in Fig. 2. This mechanism moved the wire across the mouth of a collimator at an accurately controlled speed of 0.132 cm/sec. The photons resulting from the disintegration of the excited nuclei passed through the collimator (shown schematically in Fig. 3) and were detected by a 3-in.-diam by 3-in.-long NaI(Tl) crystal. The resulting counts were recorded by successively "opening" the individual channels of a 400-channel pulse-height analyzer² as the wire passed over the collimator opening. Since each channel was open for 1 sec (controlled by a 1-kc oscillator in the analyzer circuit) and since the speed of the wire was constant and known, each channel number corresponded directly to both the time elapsed since travel was initiated and the total distance traveled in that time. The analyzer could be operated remotely, and so the time that the counting was started and the time that it was stopped were both controlled by an arrangement of micro-switches mounted on the scanning device, as shown schematically in Fig. 4.

A brief explanation may aid in clarifying Fig. 4. The signal from the photomultiplier tube was first passed through a solid-state preamplifier, where the pulse shape was adjusted for compatibility with the amplifier. The power for the preamplifier was obtained through a dropping resistor from the same 1-kV supply used with the photomultiplier tube. The signal was then fed into a DD-2 amplifier³ with a built-in single-channel

2. Technical Measurement Corp., Model 401B.

3. E. Fairstein, Rev. Sci. Instr. 27, 476 (1956).

Fig. 1. Measured Decay Curve for a Sample of Activated Copper Wire Compared with the Theoretical Decay Curve for Daughters of the Two Stable Isotopes of Elemental Copper.

Fig. 2. View of the Wire Scanning Device Showing the Crystal Shield, Analyzer Control Switches, and Wire in Place.

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Fig. 3. Dimensions of the Collimator and Copper Wire.

Fig. 4. Block Diagram of the Electronics and Remote Control Used with the 400-Channel Analyzer for Scanning the Activated Wires.

analyzer (SCA). The window-width, ΔE , and the base line, E , of the single-channel analyzer were adjusted to pass only those pulses falling in the peak of the distribution corresponding to the desired gamma-ray energy. The positive output of the SCA was used to trigger a coincidence gate in the multichannel analyzer, and the negative output was used to monitor the count rate. The signal from the normal DD-2 output was fed into the normal input of the multichannel analyzer (PHA) through a length of HH-2000 coaxial cable, which delayed the signal about 0.75 μ sec. The analyzer, when operated in the coincidence mode, would then accept only those pulses that fell within the desired peak of the pulse-height distribution.

The multichannel analyzer could be operated remotely by appropriate connections through a multipin plug (J111). In order for the analyzer to be operated in the "accumulate" mode, both pins C and F had to be closed to ground (pin E). With switch S1 in the "local" position, pin C was closed to ground at 1 of S1a, the circuit from pin F to ground was broken at S1b regardless of the conditions of S2 and/or S3, and all functions of the analyzer were controlled at the analyzer control panel. With S1 in the "stop" position, only pin A was closed to ground (through 2 of S1a) and the analyzer was held in the stop mode to prevent an accidental destruction of the data. With S1 in the "remote" position, pin C was at ground at all times through 3 of S1a. Pin F was closed to ground through 3 of S1b only if the wire scanner had moved away from the end position, thus relieving the pressure on S2 and S3 and causing them to switch to the normally closed (NC) position. If either S2 or S3 was in the normally open (NO) position, which occurred when the wire scanner was at either end of the travel length, then the electrical path from pin F to ground was broken and the analyzer went into the "stop" mode.

With the semiautomatic method described above it was found that eight to ten wires could be exposed and scanned in a period of 8 hr, with two people required for operation. This period included the normal reactor check-out time at the start of the day, the required 1-hr decay time, and at least three calibration checks during the scanning of the wires.

III. THEORY

The theory for converting the data recorded in each channel of the analyzer to thermal-neutron flux as a function of position along the wire was the following:

1. Assume, for the present, that a wire has been exposed to mono-energetic neutrons in the water between the fuel plates. After the wire is removed from the flux, the activity in the wire will continue to decay, and at some subsequent time, t , in a small volume of the wire it will be

$$A(t) = v \Sigma \bar{\phi} (1 - e^{-\lambda t}) e^{-\lambda t} , \quad (1)$$

where

$A(t)$ = activity at time t (d/sec),

v = volume (cm^3),

Σ = macroscopic absorption cross section for the wire material (cm^{-1}),

$\bar{\phi}$ = average neutron flux along the diameter of the wire (neutrons $\text{cm}^{-2} \text{sec}^{-1}$),

λ = decay constant (sec^{-1}),

T = exposure time (sec),

t = decay time (sec).

The average flux in the wire is expected to be somewhat lower in magnitude than the flux in the water before the wire was inserted. This "flux depression," which is discussed in detail in the literature,⁴⁻⁶ requires the application of the factor

$$f = \bar{\phi} / \phi , \quad (2)$$

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4. R. V. Meghreblian and D. K. Holmes, pp 244,260 in Reactor Analysis, McGraw-Hill, New York, 1960.
 5. R. J. Royston, The Absorption of Neutrons by a Small, Strongly Absorbing Rod, AERE T/M 117 (1954).
 6. Reactor Physics Constants, ANL-5800, Sect. 5.2, p 387 (1958).

where f is a function of the wire radius a and the absorption cross section Σ and Φ is defined as the unperturbed neutron flux.

Since the wire moves constantly while the activity is being measured, the volume of wire passing a given point in a time τ sec ($\tau \ll t$) is

$$v = \tau s u \text{ cm}^3, \quad (3)$$

where s = cross-sectional area of the wire (cm^2) and u = wire speed (cm/sec).

The initial assumption that the wires would be exposed to mono-energetic neutrons is not, of course, valid for reactor neutrons. Therefore, since it is desired to measure the thermal-neutron flux in the reactor, a multiplication by the ratio of the number of thermal neutrons, Φ_{th} , to the number of neutrons of all energies, $\Phi(E_n)$, is required. This ratio,

$$R_n = \frac{\Phi_{th}}{\Phi(E_n)}, \quad (4)$$

will be shown in a later section to be comparable to the cadmium ratio for the particular wire material and the neutron energy spectrum in the reactor.

By substituting Eqs. 2, 3, and 4 into Eq. 1,

$$A(t) = \frac{\tau s u}{R_n} \bar{\Sigma}_{th} f \Phi_{th}(x) (1 - e^{-\lambda T}) e^{-\lambda t}, \quad (5)$$

where $\bar{\Sigma}_{th}$ = the macroscopic thermal-neutron cross section for the wire material averaged over a maxwellian distribution (cm^{-1}), $\Phi_{th}(x)$ = the unperturbed thermal-neutron flux in the water (neutrons/cm^2), and all other terms have been defined.

2. The experimental data consisted of the total number of counts recorded in τ seconds in a particular analyzer channel corresponding to a given location, x , along the wire. To facilitate the interpretation, assume that the wire is stopped and that it consists of a line of point isotropic gamma-ray sources coincident with the axis. During the time τ

seconds, there will be recorded in channel i a total number of counts, C , corresponding to the number of gamma rays emitted in small volume v at x . The length of line sources visible through the collimator is 2ξ , where ξ is the distance measured from the collimator axis. There is some point, ξ_1 , where the "edge" of the collimator will start shadowing the sources so that the number of gamma rays passing through the collimator from sources at $\xi > \xi_1$ will be monotonically reduced and approach zero at $\xi = \xi_2$. Thus the effective solid angle for the line of sources is

$$\Omega' = \int_{-\xi}^{+\xi} \rho(\xi) \Omega(\xi) d\xi, \quad (6)$$

where $\rho(\xi)$ = the collimator "self-shadowing" factor for a constant distance from the shield (see Sect. IV), and $\Omega(\xi)$ = the solid angle subtended by a circular area (collimator aperture at the crystal) from a point source at ξ . Since both $\rho(\xi)$ and $\Omega(\xi)$ are even functions, and thus their product is an even function, Eq. 6 may be written as

$$\Omega' = 2 \int_0^{\xi} \rho(\xi) \Omega(\xi) d\xi. \quad (7)$$

The number of nuclei disintegrating per second, $[A(\xi)]$, will give rise to $A(\xi)\eta$ photons emitted per unit solid angle per disintegration. Of these, only $\nu\eta A(\xi)$ photons will leave the wire without having at least one collision in the wire, resulting in either an absorption or energy degradation. Thus the total number of photons passing through the collimator per second from the source at ξ is

$$N_\gamma = A(\xi) \eta \nu \rho(\xi) \Omega(\xi). \quad (8)$$

If the crystal is against the collimator exit aperture and if the radius of the crystal is equal to or greater than the radius of the exit aperture, then Eq. 8 also gives the number of uncollided photons incident on the crystal surface. Of these only ϵ photons will have at least one

interaction in the crystal, with a probability p that the total photon energy will be given up in the crystal, thus causing a pulse with the appropriate magnitude to be recorded in the peak of the pulse-height distribution. The total counts recorded in channel i due to the length of wire $u\tau$ passing the collimator in τ second therefore is:*

$$C_i(x) = \frac{2}{u\tau} \int_0^{\xi} A(\xi) \eta \nu \rho(\xi) \Omega(\xi) \epsilon p \tau d\xi, \quad (9)$$

where $C_i(x)$ = counts recorded in channel i due to photons originating in the small volume of wire at x , and all other terms have been defined. If the activity does not vary greatly over the distance $u\tau$, Eq. 9 may be written as

$$C_i(x) = \frac{2 A(x, t) \eta \nu \epsilon p \Omega'}{u}, \quad (10)$$

where Ω' is defined in Eq. 7 and the explicit dependence of the activity A on the decay time and distance along the wire is shown. Solving Eq. 10 for the activity and equating the results to Eq. 5 gives

$$\frac{u C_i(x)}{2 \eta \nu \epsilon p \Omega'} = \frac{\tau s u}{R_n} \bar{\Sigma}_{th} f \Phi_{th}(x) (1 - e^{-\mu T}) e^{-\lambda t}, \quad (11)$$

from which is obtained

$$\Phi_{th}(x) = \frac{C_i(x) R_n}{2 \eta \nu \epsilon p \Omega' \tau s \bar{\Sigma}_{th} f (1 - e^{-\mu T}) e^{-\lambda t}}. \quad (12)$$

3. The methods used to approximate or otherwise determine the appropriate values for application in Eq. 12 were the following:

*Actually, ν , $\rho(\xi)$, ϵ , and p are all functions of the photon energy, but here this dependence is neglected since the discussions are concerned with monoenergetic photons.

Decay Time and Distance. — In all cases the decay time and distance along the wire were adjusted to the center of the analyzer channel currently "open." Since the time required to bring the reactor to the nominal 2-W power level was short compared with the length of time that the wires were exposed in the reactor, the time distribution of the neutron flux was assumed to be that shown in Fig. 5. It is seen from the figure that the total exposure time is

$$T = T_2 - T_1 \text{ sec} , \quad (13)$$

and the total decay time through one-half the counting period for channel i is

$$\begin{aligned} t &= (T_3 - T_2) + T_1 + 0.5 \tau \\ &= (T_3 - T_2) + \tau(i + 0.5) \text{ sec} , \end{aligned} \quad (14)$$

since τ was constant for all channels. The distance the wire has traveled at this time is

$$x = u \tau(i + 0.5) \text{ cm} , \quad (15)$$

where i may take on values from 0 to 399 in Eqs. 14 and 15.

The initial processing of the data consisted of converting the data to

$$C'_i(x) = \frac{C_i(x)}{\tau(1 - e^{-\lambda t}) e^{-\lambda t}} \quad (16)$$

by means of the Fortran-63 program WIREDAT, written for a CDC-1604A computer. This allowed an intermediate inspection of the data for correct alignment and consistency. A second program, WIREDAT2, performed an averaging over a 1-cm wire length if desired and accomplished the conversion to thermal-neutron flux. Listings of both programs are in the Appendix.

Fig. 5. Assumed Time Distribution of the Neutron Flux and Wire Activity.

Flux Depression Factor. — The flux depression factor, f , is discussed explicitly and in detail in refs. 4, 5, and 6. It was found, however, that the numerical values of the escape probability, P_0 , calculated by Case, deHoffman, and Placzek⁷ agreed with the values of f for long cylindrical rods given in refs. 2 and 3, as shown in Fig. 6. (This is probably the result of the neutron scattering in the absorbing materials being neglected in the latter references.) Based on this it was assumed that, to a first approximation, the escape probabilities discussed in ref. 7 could be used for f . Such an approximation should not be too bad for small-diameter gold and copper wires since the cross sections for these materials are predominantly absorption cross sections at neutron energies near thermal.

The Probability of Photons Escaping Without a Collision. — The escape probability, P_0 , mentioned earlier is a function only of the attenuation properties of the material and the radius of the wire. Since gamma-ray interactions are also functions of the attenuation properties and geometry of the material, the escape probabilities⁷ might equally as well be used to give the probability that a gamma ray born in the wire with a given energy will escape without undergoing a collision. However, due to the relatively small size of the wires used in the experiment compared with the mean free path of the characteristics gamma ray, this factor, v , was taken to be unity (to an accuracy of about 2%).

Solid Angle and Collimator. — As was mentioned earlier, the contributions from sources located beyond a certain distance ξ_1 would be reduced because of self-shadowing by the collimator. This shadowing results in an effective reduction of the solid angle subtended by the exit aperture of the collimator. In a previous report,⁸ a method of correcting the solid angle for cylindrical collimators was described. Since the collimator used in this experiment was conical, it was necessary to extend the method to conical collimators having the source at a distance less than the distance to the apex of the cone.

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7. K. M. Case, F. deHoffmann, and G. Placzek, Introduction to the Theory of Neutron Diffusion, Vol. I, p 17, Los Alamos Scientific Laboratory (1953).
 8. G. T. Chapman, Neutron Phys. Div. Ann. Progr. Rept. Aug. 1, 1963, ORNL-3499, Vol. I, p 188.

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Fig. 6. First-Approximation Flux Depression Factors for Long Slim Cylinders.

Figure 7 shows a right-conical collimator truncated at a length l and with radii r_1 at the entrance (source) aperture and r_2 at the exit (crystal) aperture. It will be noticed that r_2 is greater than r_1 . For any isotropic source located on the line between 0 and ξ_1 , the solid angle subtended by the exit aperture at the location of the source is $\Omega(\xi)$ as tabulated in ref. 9. However, at any distance greater than ξ_1 , some of the photons emitted into the solid angle $\Omega(\xi)$ are intercepted by the edge of the entrance aperture and never reach the exit aperture. Thus the solid angle is reduced and only the hatched area in the figure is illuminated by the photons. The self-shadowing factor is defined as the ratio of the illuminated area to the total exit aperture area.

For any displacement less than or equal to ξ_1 the total exit aperture area is illuminated and the self-shadowing factor is

$$\rho(\xi \leq \xi_1) = 1, \quad (17)$$

but for ξ greater than ξ_1 the illuminated area becomes

$$\begin{aligned} A(\xi > \xi_1) = & \frac{\pi}{2} (r_1^2 \beta^2 + r_2^2) - r_1 \beta (\beta - 1) \xi \left[1 - h_1^2(\xi) \right]^{\frac{1}{2}} \\ & - r_2^2 \sin^{-1} h_2(\xi) - r_1^2 \beta^2 \sin^{-1} h_1(\xi), \end{aligned} \quad (18)$$

where

$$\begin{aligned} \beta &= 1 + \frac{l}{z}, \\ h_1(\xi) &= \frac{\beta - 1}{2\beta r_1} \frac{\xi^2 + \xi_1 \xi_2}{\xi}, \\ h_2(\xi) &= \frac{\beta - 1}{2r_2} \frac{\xi^2 - \xi_1 \xi_2}{\xi}, * \end{aligned}$$

9. A. V. H. Masket and W. C. Rodgers, Table of Solid Angles, TID-14975 (July 1962).

* ρ , h_1 , h_2 , and A are all functions of z , the distance from the collimator entrance, but this distance was held constant for this experiment.

Fig. 7. Geometry of a Conical-Shaped Collimator with the Source Located off the Collimator Axis.

$$\xi_1 = \frac{\beta r_1 - r_2}{\beta - 1}$$

= point at which shadowing first occurs,

$$\xi_2 = \frac{\beta r_1 + r_2}{\beta - 1}$$

= point at which the source becomes "invisible" through collimator;

and the self-shadowing factor* becomes

$$\rho(\xi > \xi_1) = \frac{A(\xi > \xi_1)}{\pi r_2^2} . \quad (19)$$

In order to perform the integration indicated in Eq. 7, it was desirable to have an analytic expression for $\Omega(\xi)$. It was found that, for small displacements from the collimator axis, an applicable expression was

$$\Omega(\xi) = \Omega(0)(1 - k X^2) , \quad (20)$$

where

$\Omega(0)$ = solid angle subtended by the collimator aperture from a point at the collimator axis,

k = constant,

$X = \xi/r_2$

= normalized displacement.

A simple linear least-squares fit to the values given in ref. 9 for the geometry of the collimator used gave a k value of 0.1755. The calculated values are compared with the published values in Fig. 8. The integration

*By setting $r_1 = r_2$, the equations discussed here reduce to those previously reported (ref. 9) for a straight collimator.

Fig. 8. Calculated Values of the Solid Angle for All Displacements Compared with the Exact Values.

$$\Omega(\xi) = \int_0^{\xi_2} \rho(\xi') \Omega(\xi') d\xi' \quad (21)$$

was performed on the CDC-1604A computer using Eqs. 19 and 20. A listing of the program (LOMEGO) is given in the Appendix.

Intrinsic Crystal Efficiency. — The intrinsic crystal efficiency, ϵ , is defined as the fraction of those photons of a given energy incident on the crystal face that have at least one interaction in the crystal to produce a measurable pulse. If the photons are collimated into the face of the crystal so that the average path length through the crystal does not differ greatly from the length of the crystal, this efficiency may be taken as

$$\epsilon = 1 - e^{-\mu L} \quad , \quad (22)$$

where $\mu = \mu(E_\gamma)$ = total gamma-ray absorption coefficient (cm^{-1}) and L = crystal length.

Correction of Window Distribution to a Gaussian Distribution. — Though not specifically mentioned in the previous discussion, the distribution of pulses in the window (ΔE) of the single-channel analyzer did not represent a Gaussian distribution below the channel containing the maximum counts and at the limits of the window width. This is shown graphically in Fig. 9. A correction,

$$g = \frac{\text{area of the equivalent Gaussian}}{\text{area of the distribution in the window}} \quad , \quad (23)$$

was applied by multiplying the counts in each channel (i) by g . The Gaussian corresponding to the measured distribution was obtained by a method suggested by Zimmerman.¹⁰ The general equation of a Gaussian distribution about x_0 with a standard deviation σ is

$$y(x) = \frac{1}{\sigma \sqrt{2\pi}} e^{-(x_0-x)^2/(2\sigma^2)} \quad . \quad (24)$$

10. W. Zimmerman, Rev. Sci. Instr. 32(9), 1063 (1961).

2-01-058-912R

Fig. 9. Measured and Corrected Distribution of Pulses in the Single-Channel Analyzer Window (ΔE).

$$Q(X) \equiv \frac{y(X_1)}{y(X_2)} = e^{-(1/2\sigma^2) \left\{ (X_0 - X_1)^2 - (X_0 - X_2)^2 \right\}}, \quad (25)$$

and if

$$X_1 = X - 1, \quad (26)$$

$$X_2 = X + 1,$$

where X is arbitrary, then Eq. 25 reduces to

$$Q(X) = e^{2(X - X_0)/\sigma^2}. \quad (27)$$

Then, upon taking the logarithms of both sides of Eq. 27,

$$\begin{aligned} \ln Q(X) &= \frac{2}{\sigma^2} (X - X_0) \\ &= -\frac{2}{\sigma^2} X_0 + \frac{2}{\sigma^2} X, \end{aligned} \quad (28)$$

which may be written as

$$Z(X) = A + b X, \quad (29)$$

where

$$Z(X) \equiv \ln Q(X),$$

$$A \equiv -\frac{2}{\sigma^2} X_0$$

$$= \text{constant},$$

$$b \equiv \frac{2}{\sigma^2}$$

$$= \text{constant}.$$

Equation 29 is linear in X and may be used to determine σ from the slope and the central value (X_0) of X from A and σ .

If $Q(X)$ is interpreted as the measured count in each channel* and X as the channel number with the analyzer operated in pulse-height analysis mode, a straight line will not necessarily result when the values are applied in Eq. 29, because of the nonuniformity of the measured distribution mentioned above. However, a portion of the distribution above X_0 will probably give a straight line. A simple least-squares fit to this portion will give the best values of A and B . Figure 9 shows the corrected Gaussian normalized to the experimental distribution for the 411.8-keV gamma ray from ^{197}Au .

Peak-to-Total Ratio. — The ratio, p , of the area under the peak of the pulse-height distribution to the total area under the distribution for a particular gamma-ray energy is a measure of the fraction of the total photons that deposited all their original energy in the crystal. This ratio is normally determined from the experimentally measured distribution as shown in Fig. 10. The area under the peak is again approximated as described above.

Probability, η , of Emission of Gamma Ray of Desired Energy per Disintegration per Unit Solid Angle. — Copper-64 and gold-197 decay according to the schemes given in Fig. 11, which are based on data in ref. 11. The gamma ray of interest in the ^{64}Cu measurements was that which originated with the annihilation of the positrons (β^+) in the copper. Since there are two such photons (0.511 MeV each) emitted in each annihilation and since a β^+ is emitted 19% of the time, the number of 0.511-MeV photons emitted per unit solid angle per disintegration is

$$\eta_{\text{Cu}} = \frac{0.19 \times 2}{4\pi} = 3.023 \times 10^{-2} \quad . \quad (30)$$

*A pulse-height channel (X) is not to be confused with a time channel (i).

11. K. Way et al. (Comp.), Nuclear Data Sheets, Vol. 5 (set 1), National Academy of Sciences of the National Research Council, Washington, 1962.

Fig. 10. Pulse-Height Distribution for 411.8-keV Gamma Rays.

2-01-058-914R

Fig. 11. Decay Schemes for ^{198}Au and ^{64}Cu . (Based on data in K. Way's tables.¹¹⁾)

An experiment¹² to determine the number of positrons escaping the copper without being annihilated was made by placing a sample of activated copper wire in an unactivated copper sleeve with an inside diameter comparable to the wire diameter. No distinction could be made between the number of 0.511-MeV gamma rays recorded with the bare wire and with the covered wire. Since any positrons which might have escaped from the wire would have been annihilated in the sleeve and thus have produced a greater number of gamma ray than those produced in the wire alone, it was assumed that essentially all the positrons were annihilated in the wire.

The 0.4118-MeV photons shown in the decay of ¹⁹⁸Au were measured to determine the activity of the gold wire. Two paths in the decay scheme give rise to a photon of this energy. One percent of the decays are to the 1.087-MeV level of stable ¹⁹⁸Hg, with a subsequent 82% probability of the transition to ground being through the 0.675-MeV level to cause the final emission of the 0.4118-MeV photon. The other path arises through the 99% of ¹⁹⁷Au decays that go directly to the 0.4118-MeV level of ¹⁹⁸Hg. The transmission from this level to the ground state is by the emission of the 0.4118-MeV photon. Consequently, the number of 0.4118-MeV photons emitted per unit solid angle per disintegrating ¹⁹⁷Au nucleus is

$$\eta_{Au} = \frac{0.01 \times 0.82 + 0.99}{4\pi} = 7.943 \times 10^{-2} \quad . \quad (31)$$

Neutron Cross Sections. — The thermal-neutron cross sections used¹³ for ⁶³Cu and ¹⁹⁷Au were 4.3 ± 0.2 barns and 98 ± 10 barns, respectively. When averaged over a Maxwellian distribution, the macroscopic absorption cross sections were 0.2234 cm^{-1} and 5.157 cm^{-1} , respectively.

Ratio of Thermal Neutrons to All Neutrons. — An approximation for R_n , the ratio of thermal neutrons to all neutrons, was obtained from the results of a PDQ calculation¹⁴ previously done for the design study of

12. M. S. Bokhari (ORNL), private communication.

13. D. J. Hughes and R. B. Schwartz, Neutron Cross Sections, BNL-325 2d ed., (July 1, 1958).

14. E. G. Silver (ORNL), private communication.

this reactor. It is emphasized that the following does not normalize the data to the calculations.

Experimentally, one would measure such a parameter as the cadmium ratio defined as¹⁵

$$R_c = \frac{\text{neutron flux measured with the bare detector}}{\text{neutron flux measured with the detector covered with cadmium}} \quad (32)$$

The numerator of Eq. 32 is a measure of the number of neutrons of all energies, while the denominator includes only those neutrons above a certain cutoff energy (about 0.4 eV for cadmium). From such measurements, the thermal-neutron flux can be obtained by the relation¹⁵

$$R_c - 1 = \frac{\text{thermal flux}}{\text{resonance flux}} \quad (33)$$

The previously mentioned PDQ calculations used four energy groups of neutrons: thermal, thermal to 0.6176 eV, 0.6176 to 9.118×10^3 eV, and above 9.118×10^3 eV. Figure 12 shows the spatial distributions obtained at the center of the reactor by a successive addition of the total neutrons of each group as a function of position. Also shown on the figure are the data obtained through the activation of a gold wire and a copper wire in comparable locations arbitrarily normalized to the calculations. The two sets of data have been corrected for the activation and decay times. It will be noticed that the copper-wire distribution matches, to a fair approximation, the shape of the calculated distribution for neutrons up to 0.6176 eV. This was taken to imply that the copper was sensitive only up to about this energy. It was not possible, however, to match the gold-wire data with either of the calculated groups. Based on these observations, a parameter R_{PDQ}^{Cu} , comparable to the defined cadmium ratio was obtained from the calculations for copper as explained in the following paragraphs. From the values determined for R_{PDQ}^{Cu} , another parameter, R_{PDQ}^{Au} ,

15. D. J. Hughes, Pile Neutron Research, p 62, Addison-Wesley, Cambridge, Mass., 1953.

was obtained for gold. In the discussion to follow, an attempt is made to follow a possible experimental procedure.

If it is assumed that copper is sensitive only to 0.6176 eV, then the bare copper wire would "see" a total neutron flux,

$$\phi = \phi_{TH} + \phi_{RES} \quad , \quad (34)$$

where ϕ_{TH} = calculated spatial distribution for the thermal group, and ϕ_{RES} = calculated spatial distribution for the group THERMAL $\leq E_n \leq 0.6176$ eV, as shown in Fig. 12. Now

$$R_{PDQ}^{Cu} - 1 = \frac{\phi_{TH}}{\phi - \phi_{TH}} = \frac{1}{(\phi/\phi_{TH}) - 1} \quad (35)$$

by Eq. 33. From Eq. 35,

$$\frac{\phi}{\phi_{TH}} = \frac{R_{PDQ}^{Cu}}{R_{PDQ}^{Cu} - 1} = \frac{1}{R_n^{Cu}} \quad , \quad (36)$$

where R_{PDQ}^{Cu} refers to the ratio taken from the calculation* and R_n^{Cu} is defined by Eq. 4.

Having obtained $R_{PDQ}^{Cu} - 1$ for copper, the ratio of thermal neutrons to resonance neutrons (as defined by Eq. 33) may be obtained from the relation¹⁶

$$(R_{PDQ}^{Au} - 1) = \frac{RI_{Cu}}{RI_{Au}} \frac{CdD_{Au}}{CdD_{Cu}} (R_{PDQ}^{Cu} - 1) \quad , \quad (37)$$

where RI is the "resonance integral in the particular reactor neutron spectrum" and CdD, the "cadmium difference," is defined as the difference

*Since the neutron spectrum changes with location in the reactor, R_n and R_{PDQ} are functions of the position.

16. Reactor Physics Constants, ANL-5800, 2d ed. (July 1963).

Fig. 12. Shape of the Experimental (Normalized) and Calculated Neutron-Flux Distribution as Functions of Energy and Location in the Reactor.

between the activity induced in the detector by neutrons of all energies and the activity induced by thermal neutrons only. Thus

$$CdD = (\Sigma_a \phi_{TH} + \Sigma_a \phi_{RES}) - \Sigma_a \phi_{RES} = \Sigma_a \phi_{TH} \quad (38)$$

Since the wires used in the experiment were not of the same diameter and since the activities of the wires were a measure of the average neutron flux in the wire rather than the true, unperturbed neutron flux in the reactor, then for a unit length of the wires the ratio of the "cadmium differences" of the two wires may be written as

$$\frac{CdD_{Au}}{CdD_{Cu}} = \frac{\left(\frac{N \sigma_a^{TH}}{v f} \right)_{Au}}{\left(\frac{N \sigma_a^{TH}}{v f} \right)_{Cu}} \quad (39)$$

where

N = number of atoms/cm³,

σ_a^{TH} = microscopic absorption cross section at thermal-neutron energy,

f = flux depression factor (Eq. 2),

v = volume of wire per unit length of wire.

Finally, from Eqs. 39 and 37;

$$(R_{PDQ}^{Au} - 1) = \frac{RI_{Cu}}{RI_{Au}} \left(\frac{N \sigma_a^{TH}}{v f} \right)_{Au} \left(\frac{v f}{N \sigma_a^{TH}} \right)_{Cu} (R_{PDQ}^{Cu} - 1) \quad (40)$$

Use was made of a calculated spectrum¹⁴ to determine the approximate resonance integrals for the gold and copper. Briefly, the absorption cross section for copper was assumed to vary as $E_n^{-1/2}$ (E_n = neutron energy) up to about 34 eV. The same assumption was made for the gold cross section

below 1 eV. With these assumptions, the average cross section over an energy increment occurring in the spectrum calculation is

$$\begin{aligned}\bar{\sigma}_a(\Delta E) &= \frac{\int_{E_1}^{E_2} \sigma_a^{TH} (0.025)^{1/2} \frac{dE}{E^{1/2}}}{\int_{E_1}^{E_2} dE} \quad (41) \\ &= 2(0.025)^{1/2} \sigma_{TH}^a \frac{E_2^{1/2} - E_1^{1/2}}{E_2 - E_1},\end{aligned}$$

where E_2 and E_1 represent the upper and lower limits respectively of the energy increment.

Above 1 eV a numerical integration of the gold cross section as given in BNL-325¹³ was performed to obtain the average cross section. Thus

$$\bar{\sigma}_a(\Delta E) \simeq \frac{\sum_{n=1}^N \sigma_T(\epsilon_n) \left[1 - \frac{\sigma_s(\epsilon_n)}{\sigma_T(\epsilon_n)} \right] \Delta \epsilon_n}{E_2 - E_1}, \quad (42)$$

where

ϵ_n = neutron energy at the middle of the n th energy increment of width $\Delta \epsilon_n$ ($\Delta \epsilon_n < E_2 - E_1$),

$\frac{\sigma_s(\epsilon_n)}{\sigma_T(\epsilon_n)}$ = ratio of scattering to total cross section as given in BNL-325.

The neutron energy spectrum and the averaged cross sections are shown in Table 1. Another numerical integration of the flux-weighted averaged

Table 1. The Calculated Neutron Energy Spectrum and Averaged Cross Sections Used in Determining the Approximate Resonance Integrals for Copper and Gold

E_1 (eV)	E_2 (eV)	$\Phi(E_n)$, Neutron Flux per Unit Energy	$\bar{\sigma}_a^{Cu}$ (barns)	$\bar{\sigma}_a^{Au}$ (barns)
3.075×10^{-2}	3.756×10^{-2}	1.35×10^1	3.68	83.92
3.756×10^{-2}	4.587×10^{-2}	1.20×10^1	3.50	79.77
4.587×10^{-2}	5.603×10^{-2}	1.06×10^1	3.32	75.78
5.603×10^{-2}	6.843×10^{-2}	9.32×10^0	3.16	71.99
6.843×10^{-2}	8.358×10^{-2}	8.08×10^0	3.00	68.40
8.358×10^{-2}	1.021×10^{-1}	7.06×10^0	2.85	64.99
1.021×10^{-1}	1.247×10^{-1}	6.06×10^0	2.71	61.78
1.247×10^{-1}	1.523×10^{-1}	5.24×10^0	2.58	58.71
1.523×10^{-1}	1.860×10^{-1}	4.42×10^0	2.45	55.84
1.860×10^{-1}	2.272×10^{-1}	3.80×10^0	2.33	53.16
2.272×10^{-1}	2.775×10^{-1}	3.16×10^0	2.22	50.65
2.775×10^{-1}	4.140×10^{-1}	2.50×10^0	2.01	45.92
4.140×10^{-1}	6.176×10^{-1}	1.80×10^0	1.83	41.73
6.176×10^{-1}	9.214×10^{-1}	1.29×10^0	1.67	37.99
9.214×10^{-1}	1.375×10^0	8.89×10^{-1}	1.53	35.89
1.375×10^0	4.564×10^0	4.00×10^{-1}	1.19	68.06
4.564×10^0	1.016×10^1	1.53×10^{-1}	1.03	261.
1.016×10^1	1.515×10^1	9.79×10^{-2}	0.96	240.
1.515×10^1	3.372×10^1	5.51×10^{-2}	0.84	206.

cross section between 3.085×10^{-2} eV and 3.372×10^1 eV gave the approximate resonance integral. Thus

$$RI = \sum_{i=1}^N \Phi(E_i) \bar{\sigma}(E_i) \Delta E_i$$

$$= 1.320 \times 10^3 \text{ barns for gold}$$

$$= 5.403 \times 10^0 \text{ barns for copper.}$$

(43)

Observing that the volume per unit length (v) of wire is numerically equal to the cross-sectional area of the wire as listed in Table 2 and using the value of the flux depression from that table, one can now

Table 2. The Constant Parameters Used in the Wire Analysis

Description of Parameter	Symbol	Numerical Value	
		Copper	Gold
Wire speed, cm/sec	u	1.32×10^{-1}	1.32×10^{-1}
Count time per channel, sec	τ	1.0	1.0
Wire radius, cm	a	1.03×10^{-1}	4.06×10^{-2}
Area, cm^2	s	3.32×10^{-2}	5.18×10^{-3}
Decay constant, sec^{-1}	λ	1.50×10^{-5}	2.97×10^{-6}
Photons. $\text{dis}^{-1} \cdot (\text{unit solid angle})^{-1}$	η	3.02×10^{-2}	7.93×10^{-2}
Positron annihilation probability		1.00	(not applicable)
Probability for photon escape from wire	v	1.00	1.00
Intrinsic efficiency of the crystal	ϵ	9.19×10^{-1}	9.54×10^{-1}
Peak efficiency of the crystal	p	3.11×10^{-1}	4.45×10^{-1}
Integrated solid angle, ^a cm/steradian	Ω'	1.69×10^{-1}	1.55×10^{-1}
Macroscopic absorption cross section, cm^{-1}	Σ_a	2.23×10^{-1}	5.14
Flux depression factor	f	9.71×10^{-1}	7.86×10^{-1}
Window correction	g	9.84×10^{-1}	9.56×10^{-1}
Total effect ^b	K	4.69×10^4	4.39×10^3

a. Entrance aperture corrected for penetration.

$$b. K = \frac{g}{2 \eta v \epsilon p \Omega' s \Sigma_a f} .$$

write the final expression for the ratio of thermal neutrons to resonance neutrons as measured by the gold wire relative to the ratio as measured by the copper wire:

$$(R_{PDQ}^{Au} - 1) = 0.745 (R_{PDQ}^{Cu} - 1) \quad . \quad (44)$$

The ratio of thermal neutrons to all neutrons as measured by the gold wire is

$$R_n^{Au} = \frac{R_{PDQ}^{Au} - 1}{R_{PDQ}^{Au}} \quad , \quad (45)$$

which of course implies the unrealistic condition that the resonance integrals are constant throughout all regions of the measurement. This divergence from reality, however, should not be important in the power-producing volume of the reactor and should become significant only near the edges of and external to the core of the reactor.

IV. RESULTS AND CONCLUSION

The values chosen for the many parameters discussed above are listed in Table 2 for gold and copper, along with the value computed for the "total effect" factor, K. A typical experimental curve obtained by multiplying the data by K and R_n is shown in Fig. 13. Each experimental point represents the arithmetic average of seven or eight measurements made over a 1-cm length of wire. The error bars reflect only the total counting error in 1 cm.

The calculated thermal-neutron distribution, normalized to 2 W of reactor power, is also shown in Fig. 13. The experimental data compare favorably with the calculation through the fuel-bearing region of the reactor and for some distance above that region. The copper-wire data begin to deviate from the calculation at about 44 cm, which may be due to the existence of structural materials in the actual reactor which were not considered in the calculation. The gold-wire data deviate from both the copper-wire data and the calculations at about 40 cm. This is quite

Fig. 13. A Comparison of the Distribution Measured Along the Reactor Center Line with the Gold and Copper Wires and a Calculated Distribution Using the PDQ-4 Reactor Program.

probably the result of assuming a constant resonance integral for gold even in this region, where the neutron energy spectrum is expected to change rapidly. This particular volume is not of much importance, however, in determining the power of the reactor.

It is difficult to quote an overall error for this system of estimating the reaction rates in a reactor from the activity induced in copper wires since the analysis utilizes values from published tabulations where errors are seldom quoted. However, the ratio of the thermal-neutron flux as determined by the gold-wire measurement to the thermal-neutron flux as determined by copper wire is 1.023 ± 0.121 within the reactor core. This suggests that the method is probably accurate to within $\pm 10\%$ or less. It is concluded, therefore, that the use of copper-wire activations in conjunction with a method of data interpretation such as the one presented here affords a convenient method for measuring neutron interaction rates in a reactor.

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Appendix
FORTRAN PROGRAMS

The three Fortran-63 programs used in the data analysis are listed in this section, with a brief discussion of each. The programs are compiled for use with the CDC-1604A computer at ORNL and use only standard I/O tapes.

Program WIREDAT

Program WIREDAT calculates the position along the wire and the total decay time corresponding to each channel. The input data are divided by the "open" time for each channel to give the count rate in the channel and its associated error and then by the product of $(1 - e^{-\lambda T}) e^{-\lambda t}$ as shown in Eq. 16 (Sect. III) to give the specific activity. The listed output shows both the count rate and the specific activity, along with the position. The specific activity and/or the count rate may be punched on cards for further use. The following definitions are pertinent:

Input Constants

XLAM = decay constant,

SPEED = wire scanning rate,

TI = total time each channel is open for counting,

ID = unique identification number for each wire,

TM1* = date and time the activation started,

TM2* = date and time the activation stopped,

TM3* = date and time the scanning started,

BPC = factor to correct for incomplete insertion of the
wire into the reactor,

POS = location of the wire in the reactor.

*See discussion of Subroutine TIME.

Control Characters

ICRD ≤ 1 results in the output of two decks of cards, the first containing the position and count rate and the second containing the position and the **specific activity**.

≥ 2 results in the output of one deck of cards containing the position and the specific activity,

IQUIT = -1 if program is to process another set of data with a different decay time, speed, and count time,

= 0 if program is to process another set of data with a different decay time, speed, and count time,

= +1 if the next set of data is the last set to be processed.

Subroutines

TMC (ID,SPEC,IRR) - This subroutine reads in a one-dimensional array containing the number of counts in each channel. The data were taken from the analyzer on punched paper tape at the BSF and converted to punched cards through the use of an external program supplied by W. Zobel of the BSF staff. TMC reads each card and checks it for word alignment. In addition, the identification number punched on each card is checked against the ID number above (see "Input Constants"). If no error is detected in the deck of cards, the set of data is processed; otherwise the set of data is rejected.

TIME (TX,SEC) - The times TM1, TM2, and TM3 (see "Input Constants") are read in as one word, each giving the number of elapsed days and the hour, minute, and second in 24-hr notation. TIME converts each number to the equivalent number of seconds. For example, assume that an exposure was started at 4:30:32 PM and was terminated at 6:42:20 PM. Assume further that the start of the scanning was delayed until 10:52:00 AM the following day. The appropriate numbers to be read in are

TM1: 00163032

TM2: 00184220

TM3: 01105200

Program WIREDAT2

Program WIREDAT2 averages the output of WIREDAT in 1-cm intervals through the whole length of the wire. SHAPE(I) is the product of R_n (see "Ratio of Thermal Neutrons to All Neutrons," Sect. III) and K (see Table 2, Sect. III) for each interval.

Program LOMEGO

Program LOMEGO calculates the integrated solid angle as given by Eq. 21. It is believed that the included comments will adequately explain the input required.

PROGRAM WIREDAT

```
C
C**** FOR USE IN REDUCING THE DATA TAKEN BY EXPOSING WIRES
C      IN THE REACTOR FOR NEUTRON FLUX MEASUREMENTS. THIS
C      PROGRAM GIVES THE SPECIFIC ACTIVITY AS A FUNCTION OF
C      POSITION ALONG THE WIRE.
C
C**** PROGRAM NUMBER 640206-0102(R0)/1604-63                                GTC-ORNL
C
C      DIMENSION SPEC(420),X(420),ERR(420)
C
C
103 READ INPUT TAPE 50,1001,XLAM,SPEED,TI
100 READ INPUT TAPE 50,1000, ID, TM1, TM2, TM3, BPC, POS, LCRD, IQUIT
    CALL TMC( ID, SPEC, IRR)
    IF(IRR)15,1,15
1   IOUT=1
    DO 2 J=1,400
        SPEC(J)=SPEC(J)/TI
        ERR(J)=SQRTF(SPEC(J))
2   X(J)=SPEED*TI*(FLOATF(J)-0.5)+BPC
101 WRITE OUTPUT TAPE 51,1002, ID, SPEED, POS, TI, BPC
102 IF(IOUT-1)3,3,4
3   WRITE OUTPUT TAPE 51,1003
    GO TO 5
4   WRITE OUTPUT TAPE 51,1004
5   L=1
6   LL=L+49
    WRITE OUTPUT TAPE 51,1005
    DO 7 J=L,LL
        J1=J-1 $ J2=J+49 $ J3=J+50
7   WRITE OUTPUT TAPE 51,1006, J1, X(J), SPEC(J), ERR(J), J2, X(J3),
1   SPEC(J3), ERR(J3)
    IF(LL-350)8,9,9
8   L=L+100
```

```
WRITE OUTPUT TAPE 51,1007
GO TO 6
9 IF(LCRD-IOUT)90,90,12
90 WRITE OUTPUT TAPE 52,1008,1D
M=1 $ MM=4
10 WRITE OUTPUT TAPE 52,1009,(X(J),SPEC(J),J=M,MM), 1D
IF(MM-400)11,12,12
11 M=M+4 $ MM=MM+4
GO TO 10
12 IF(IOUT-1)13,13,15
13 IOUT=IOUT+1
CALL TIME(TM1,T1)
CALL TIME(TM2,T2)
CALL TIME(TM3,T3)
DO 14 J=1,400
TD=T3-T2+T1*(FLOATF(J-1)+0.5)
TA=T2-T1+TD
EJ=EXP(-XLAM*TD)-EXP(-XLAM*TA)
SPEC(J)=SPEC(J)/EJ
14 ERR(J)=ERR(J)/EJ
GO TO 101
15 IF(IQUIT)103,100,16
16 STOP

C
C
C**** FORMAT STATEMENTS
C
C
1000 FORMAT( 16,3F10.0,F6.3,1A8,2I3)
1001 FORMAT(E12.4,2F8.4)
1002 FORMAT(65H1
1SCAN DATA/
239X,8HRUN NO. , 16,3X,14HSPEED (CM/SEC),F8.4/
338X,9HPOSITION ,1A8,3X,15HCOUNT TIME(SEC),F6.3/
441X,25HBACK-PLATE CORRECTION(CM),F8.4/)
```

WIRE


```
1003 FORMAT(50X,17HMEASURED ACTIVITY/)
1004 FORMAT(50X,17HSPECIFIC ACTIVITY/)
1005 FORMAT(8H    CHAN,8X,3HCMS,5X,10H CTS/SEC  ,
          111X,5HERROR,12X,4HCHAN,8X,3HCMS,5X,
          210H CTS/SEC  ,11X,5HERROR/)
1006 FORMAT(5X,13,6X,F6.2,3X,E12.5,6X,E12.5,10X,13,6X,
          1F6.2,3X,E12.5,6X,E12.5)
1007 FORMAT(1H1)
1008 FORMAT(72X,18)
1009 FORMAT(4(F6.2,E12.4),18)
```

C

C

END WIREDAT

SUBROUTINE TMC(ID,SPEC,IRR)

C

C**** FOR USE WHEN CHANNEL ZERO CONTAINS DATA OTHER THAN
C TIME.THIS PROGRAM READS CARDS PUNCHED VIA MARK IV
C AND RESHIFTS THE CHANNEL ZERO FROM THE LAST TO THE
C FIRST.THIS IS REQUIRED FOR DATA TAKEN IN THE MULTI-
C SCALER MODE ON THE TMC ANALIZER.

C PROGRAM NUMBER 640206-0101(R0)-1604/63

GTC-ORNL

C

DIMENSION DATA(420),SPEC(420)

C

IRR=0

KCRD=1

M=1

L=1

ML=10

1 READ INPUT TAPE 50,100,IID,ICHN,(DATA(J),J=L,ML),ICRD
IF(IID= ID)70,2,70

2 IF(KCRD-ICRD)71,3,71

3 NCHK=(ICRD-1)*10+1
IF(ICHN-NCHK)4,5,72

4 IF(ICHN)6,72,72

5 M=M+10

L=L+10

ML=ML+10

KCRD=KCRD+1

GO TO 1

6 IF(IRR)73,61,73

61 SPEC(1)=DATA(400)

DO 7 J=1,399

7 SPEC(J+1)=DATA(J)

GO TO 74

70 WRITE OUTPUT TAPE 51,170,ICRD,IID

GO TO 73

71 WRITE OUTPUT TAPE 51,171,ICRD,IID

GO TO 73
72 WRITE OUTPUT TAPE 51,172,ICRD,IID
73 IRR=1
GO TO 5
74 RETURN

C

C**** FORMAT STATEMENTS

C

100 FORMAT(16,16,10(F6.0),18)

170 FORMAT(39H

126H,I.D. NUMBER DOES NOT MATCH)

171 FORMAT(39H

118H,CARD OUT OF PLACE)

172 FORMAT(39H

117H,CARD PUNCH ERROR)

ERROR ON CARD,13,4H OF ,16,

ERROR ON CARD,13,4H OF ,16,

ERROR ON CARD,13,4H OF ,16,

C

END

SUBROUTINE TIME(TX,SEC)

C

C**** CALCULATES THE REQUIRED TIMES FOR DECAY CORRECTIONS.

C PROGRAM NUMBER 640206-0102(R0)-1604/63

GTC-ORNL

C

IDAY=TX/1000000.0

TEMP1=TX-(FLOATF(IDAY)*1000000.0)

Ihour=TEMP1/10000.0

TEMP2=TEMP1-(FLOATF(Ihour)*10000.0)

IMIN=TEMP2/100.0

TSEC=TEMP2-(FLOATF(IMIN)*100.0)

SEC=(FLOATF(IDAY)*86400.0)+(FLOATF(Ihour)*3600.0)

1 +(FLOATF(IMIN)*60.0)+TSEC

RETURN

C

END

PROGRAM WIREDAT2

```
C
C**** AVERAGES THE SATURATED ACTIVITY DATA OVER A ONE
C      CM LENGTH AND CONVERTS THE DATA TO THERMAL NEUTRON
C      FLUX.
C
C**** PROGRAM 640325-0100(R1)/1604(63)   GTC
C
C
      DIMENSION  X(500),DATA(500),SHAPE(500),XA(500),
1              DATAV(500),DATNOR(500)
C
C
1000 READ INPUT TAPE 50,100,NGPS
      READ INPUT TAPE 50,101,(SHAPE(I),I=1,NGPS)
1 READ INPUT TAPE 50,102,POS,XMIN,BPC,IDENT,NPTS,MOR
      READ INPUT TAPE 50,103,(X(I),DATA(I),I=1,NPTS)
      IF(BPC)2,4,2
2 DO 3 I=1,NPTS
3  X(I)=X(I)+BPC
4  TEMP=0.0 $ N=0 $ DIV=0.0 $ K1=1
      DO 11 I=1,NGPS
      A=XMIN+FLOATF(I-1) $ B=A+1.0
      IF(B-X(NPTS))6,5,5
5  B=X(NPTS)
6  K2=K1+9
      XA(I)=A+(B-A)/2.0
      DO 9 K=K1,K2
      IF(X(K)-A)9,7,7
7  IF(X(K)-B)8,10,10
8  TEMP=TEMP+DATA(K)
      N=N+1 $ DIV=DIV+1.0
9  CONTINUE
10 DATAV(I)=TEMP/DIV
    DATNOR(I)=DATAV(I)*SHAPE(I)
```

```
      TEMP=0.0 $ DIV=0.0 $ K1=K1+N $ N=0
11 CONTINUE
      L2=0
115 WRITE OUTPUT TAPE 51,104,POS,IDENT
      IF(NGPS-50)12,12,13
12 L1=1 $ L2=NGPS $ GO TO 14
13 L1=L2+1 $ L2=L1+49
14 WRITE OUTPUT TAPE 51,105
      IF(L2-NGPS)16,16,15
15 L2=NGPS
16 DO 17 I=L1,L2
17 WRITE OUTPUT TAPE 51,106,XA(I),DATAV(I),SHAPE(I),DATNOR(I),XA(I)
      IF(NGPS-L2)19,19,115
19 IF(MOR)1000,1,20
20 STOP

C
C
C**** FORMAT STATEMENTS
C
C
100 FORMAT(13)
101 FORMAT(8E10.4)
102 FORMAT(1A8,2F6.3,3I6)
103 FORMAT(4(F6.2,E12.4))
104 FORMAT(69H1
      1 NEUTRON FLUX/67H
      2 VERTICAL TRAVERSE//54H
      3 LOCATION ,1A8,6H RUN ,16)
105 FORMAT(86H0
      1ACTOR          FLUX          X//)
106 FORMAT(27X,F6.3,3(5X,E10.4),5X,F6.3)

C
C
      END WIREDAT2
```

THERMAL

X ACTIVITY F

PROGRAM LOMEGA

```

C
C**** CALCULATES THE REDUCED SOLID ANGLE FOR A LINE SOURCE
C      LOCATED ALONG THE DIAMETER OF THE COLLIMATOR ENTRANCE
C      APERTURE.
C**** THE ASSUMPTION IS MADE THAT, FOR SMALL DISPLACEMENTS
C      FROM THE COLLIMATOR AXIS, THE SOLID ANGLE MAY BE
C      OBTAINED FROM THE EQUATION
C              OMEGA(X) = OMEGO*(1.0-A*((X/R2)**E))
C      WHERE
C              X = DISTANCE FROM COLLIMATOR AXIS
C              R2 = COLLIMATOR RADIUS AT EXIT (DETECTOR)
C              OMEGO = SOLID ANGLE AT THE COLLIMATOR
C                   AXIS (SEE TID 14975)
C**** OTHER INPUT SYMBOLS
C              R1 = COLLIMATOR RADIUS AT ENTRANCE (SOURCE)
C              Z = DISTANCE FROM COLLIMATOR ENTRANCE
C              CL = COLLIMATOR LENGTH
C              XINC = INCREMENT OF DISPLACEMENT
C
C**** PROGRAM NUMBER 640203-0100(R1)/1604(63)
C
C      DIMENSION X(500),F1(500),F2(500),AX(500),RHO(500),
1      DELX(500),OMEGA(500)
C
100 READ INPUT TAPE 50,1000,R1,R2,CL,Z,XINC,OMEGO,E,A,IQUIT
   BETA1=1.0+(CL/Z) $ BETA2=BETA1-1.0
   AREA=3.1415927*(R2**2) $ ALPHA=1.5707963*(((R1*BETA1)**2)+(R2**2))
   RO=(BETA1*R1-R2)/BETA2 $ RM=(BETA1*R1+R2)/BETA2 $ R=RO*RM
   RB1=BETA2/(2.0*BETA1*R1) $ RB2=BETA2/(2.0*R2) $ RB3=R1*BETA1*BETA2
   RR1=(R1*BETA1)**2 $ RR2=R2**2 $ KLIM=RO/XINC
   DO 1 I=1,KLIM
     X(I)=XINC*FLOATF(I)
     AX(I)=AREA
1   RHO(I)=1.0

```

```
LIM=FLOATF(KLIM)+((2.0*R2)/(BETA2*XINC))    $    L=LIM+1
KK=KLIM+1    $    KK1=KK+1    $    X(KK)=R0    $    X(L)=RM
F1(KK)=1.0    $    F2(KK)=-1.0    $    F1(L)=1.0    $    F2(L)=1.00
DO 2 I=KK1,LIM
  K=I-KK
  X(I)=R0+FLOATF(K)*XINC
  F1(I)=RB1*(X(I)+(R/X(I)))
2  F2(I)=RB2*(X(I)-(R/X(I)))
  DO 3 I=KK,L
    AX(I)=ALPHA-RB3*X(I)*SQRTF(1.0-F1(I)**2)-RR1*ASINF(F1(I))
1    -RR2*ASINF(F2(I))
3  RHO(I)=AX(I)/AREA
  SUM=0.0
  DO 7 I=1,L
    IF(I-1)5,4,5
4  DELX(I)=XINC
  GO TO 6
5  DELX(I)=X(I)-X(I-1)
6  OMEGA(I)=OMEGO*(1.0-A*((X(I)/R2)**E))
  SUM=SUM+RHO(I)*OMEGA(I)*DELX(I)
7  CONTINUE
  WRITE OUTPUT TAPE 51,1001
  WRITE OUTPUT TAPE 51,1002,R1,R2,CL,Z,SUM
  K1=1    $    K2=50
8  WRITE OUTPUT TAPE 51,1003
9  IF(K2-L)11,11,10
10 K2=L
11 DO 12 I=K1,K2
12 WRITE OUTPUT TAPE 51,1004,X(I),AX(I),RHO(I),OMEGA(I),X(I)
  IF(K2-L)13,14,14
13 K1=K1+50    $    K2=K2+50
  WRITE OUTPUT TAPE 51,1005
  GO TO 8
14 IF(IQUIT)73,100,73
73 STOP
```


C

C**** FORMAT STATEMENTS

C

1000 FORMAT(4F8.4,F6.3,E12.6,2F7.4,13)

1001 FORMAT(70H1

COLLIMAT

10R SOLID ANGLE/64H

2 LINE SOURCE)

1002 FORMAT(48H0

R1=,F7.4,

110H R2=,F7.4/

248H

L=,F7.4,10H

3 Z=,F7.4/65H

INTEGRATED

4SOLID ANGLE=,E10.5)

1003 FORMAT(86H0

X

AREA

1 RHO OMEGA X/)

1004 FORMAT(29X,F6.4,3X,E10.4,2(6X,E10.4),2X,F6.4)

1005 FORMAT(1H1)

C

C

END LOMEGA

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