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OPERATION HURRICANE GROUP REPORTS

(PART 29)

Measurements of the Neutron Dose at Various Distances

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1. Introduction

The purposes of the observations undertaken was to provide information regarding the dose of neutrons of several energy groups at various distances from "ground zero", and hence to deduce a value for lethal range as applied to the non-survival against neutron irradiation of unshielded human beings, for the Hurricane type of burst.

A subsidiary measurement of some interest was the measure of protection against fast neutrons afforded by a standard concrete structure.

In this work, no accurate theoretical prediction was possible owing to the considerable uncertainty regarding the proportion of "prompt" neutrons which would escape from the immediate vicinity of the explosion.

2. Instruments and Equipment

The equipment used in the several measurements was as follows:-

2.1 Fast Neutrons

The detecting instrument here was simply a cylindrical block of paraffin wax with a central cavity in which the thermal neutron flux due to incident fast neutrons is virtually independent of incident energy over a wide range of energies. This is, in effect, the energy insensitive fast neutron counter described by Hanson and McKibben (1), with the normal central boron trifluoride chamber replaced by various metal foils which give, by thermal neutron activation, an activity suitable for estimation as regards emission and half-life.

It is known that the boron trifluoride wax assembly has an efficiency of detection for thermally incident neutrons of about twenty per cent of the value for fast neutrons, and, as the number of thermal neutrons in this case was expected to be at least as great as the fast, it was decided to apply the usual cadmium difference technique. Accordingly, the units were erected in pairs, one with a complete outer lining of 0.010 in. thick cadmium sheet, the other unscreened. The whole was contained in an outer aluminium cylinder, as shown diagramatically in Figure 1.

The substances used were gold, tantalum, copper and antimony, and were assayed, after activation, by means of a Geiger glass-walled counting tube in a suitable concentric geometry, with standard probe, E.H.T. supply, and scaling units.

Gold, tantalum and copper were used in the form of high purity metal foil, thickness 0.005 in., and antimony as a layer of similar thickness sprayed at high temperature on to thin aluminium backing to

give a uniform and adhesive coat of metallic antimony, as determined by tests.

2.2 High Energy Group of Fast Neutrons

Various substances with an energy threshold for fast neutron activation were used. These substances - sulphur, selenium, and zirconium (oxychloride) - were powders, sealed as approximately five gramme units each in a lead-glass ampoule of about one millimetre wall-thickness. High purity materials were used, and spectroscopic tests for undesirable impurities were carried out.

The activities induced in these substances by neutron irradiation were subsequently separated chemically and estimated by counting in standard geometry using an end-window Geiger tube.

In this case, the activities due to thermal neutrons are not of interest, and were excluded, where likely to be relatively strong, by a layer of cadmium.

2.3 Thermal Neutrons

Here small foils of two suitable substances, indium and silver, were used. As both of these show resonance activation for neutrons of epi-cadmium-cut-off energy, cadmium screening was necessary. The induced activities were estimated by counting in standard end-window Geiger tube geometry, with the usual electronic accessories.

2.4 Neutron Penetration Through a Concrete Shelter

For this measurement the wax cylinder instruments were used, one pair mounted inside the concrete structure, and another at the same range outside, a short distance away.

2.5 Activation Data

The relevant neutron activation features of the materials used are as in Table I.

3. Procedure

3.1 Siting of Detectors

The three types of detector were sited at various points in a range of from 400 to 1,500 yd distance from ground zero, and of about 180 degrees in azimuth. Because of the topography and poor choice of sites, relatively few of the sites had a line-of-sight view of the target vessel.

The paraffin wax cylinders were arranged in pairs - with and without cadmium, mounted about 2 ft. above ground on stout 3 in.x $\frac{1}{4}$ in. steel pipes embedded 4 or 5 ft. in the earth, and protected against direct sunlight and heat flash by a small bivouac tent.

The other detectors - viz. the glass ampoule threshold type, and the "thermal" foils (0.86 in. diameter, thickness 0.005 in) were enclosed each in a 0.010 in. thick P.V.C. sack which was nailed to a wooden support, fixed about 18 in. above ground, to a steel tube embedded in the earth.

In all three types of measurement one obtains primarily a series of counting-rates in the individual counting conditions used.

3.2 Collection of Samples

The irradiated samples were collected as and when the organisation for re-entry to the island permitted.

4. Calibration of Detectors

4.1 Paraffin Wax Cylinders

4.1.1 General Propoerties

These instruments, besides detecting fast neutrons, have a considerable sensitivity for neutrons incident as thermal neutrons. To discriminate between these two groups we may use the fact that cadmium is a strong absorber of thermal neutrons, and employ two cylinders at each point, one of them lined with cadmium sheet, the other unlined. Thus one will be sensitive to neutrons of all energies, the other to those of epi-cadmium energy. Because of difficulties of calculation for the sub-cadmium energy neutrons, we confine our attention to the very large energy range of neutrons extending to the cadmium out-off energy (cm. 0.3 ev) at the lower end, and assume that the instrument has a uniform sensitivity to all neutrons in this group. In Figure II the curve given by Hanson and McKibben(1) is reproduced and shows a drop in sensitivity at both ends of the group. Some crude measurements, not given here, using a six-inch BF_3 chamber in the eight-inch central cavity, showed no great difference in sensitivity for neutrons from antimony-beryllium (γ, n) (30 kev) and radium-beryllium (α, n) ($\sim$ 5 Mev) sources.

There seemed to be a possibility that a considerable proportion of the activity of the foils in the paraffin wax cylinders might be due to activation by neutrons incident at resonance energies. If that were so, the density of activity would be relatively large on the inside and near the front edge of the foils. A comparison of the density variation along the foil for the Hurricane case and that of foils irradiated with neutrons incident at radium-beryllium energies was done by an empirical method of selective screening against beta radiation. No difference was apparent, and in addition no difference of emission between outside and inside was found in either case, so that it seems that the neutrons incident at resonance energies made no unduly large contribution to the epi-cadmium activities. This factor, if present, would be of different importance for the various foils used.

4.1.2 Gold Calibration

A primary calibration has been done in which one obtains the relation between counting rate of the activity induced in gold foils and strength of the beam of fast neutrons from a radium-beryllium source, incident on the front of the cylindrical paraffin wax unit. A correction for the small source distance has been estimated using indium foils in which a relatively strong In^{116} activity is induced.

A similar calibration of the other foils used - tantalum, antimony and copper - is not possible by this method, as their induced activities are very much small than that of gold. These substances were in fact chosen to cover a wide range of fast neutron yield, there being a considerable uncertainty in the expected figure. The calibration of these foils is further complicated by the existence of resonance activation at epi-thermal neutron energies, as in Table II.

The cross-calibration of gold with copper, and copper with antimony was done by irradiating foils at the same position in a block of paraffin wax in which a radium-beryllium source was placed, to give a high thermal neutron density with, however, a proportion of fast neutrons. Tantalum and copper foils were irradiated at the centre of G.L.E.E P. and a

comparison thus effected. In all cases the counting conditions were identical with those in the original Hurricane measurements, and a weak radium D source, similar in area and shape to the foils, was used as a standard.

The results from the paraffin wax cylinder calibrations yield an inverse square relation of the form

$$C = \frac{k}{(r + r_o)^2} \quad \text{with } r_o = 11.3 \pm 0.5 \text{ cm.}$$

where C is the counting rate of activity induced by the source at distance r cm. from the front face of the cylinder.

The weighted average of the two measurements for gold foils yields the relation

$C_s = \frac{2.08 \times 10^6}{(r + 11.3)^2} \pm 2\%$, where C_s is the initial count/minute from the activity induced by irradiating to "saturation" with the radius beryllium neutron source (output 2.53×10^6 neutron/sec. $\pm$ 3.2%) at range r cm. from the front of the wax cylinder.

This result may be expressed in the form - neutron flux to give unit initial count/minute, for saturation irradiation of gold foils

$(= \frac{1}{a}) = 5.81 \pm 3.8\%$ neutrons/cm^2/minute.

To deduce the calibration for the case of instantaneous irradiation at Hurricane, we compare the following relations.

$$\frac{C_I}{C_S} = \frac{\lambda\alpha \; F_I}{\alpha \; F_S}$$

where C_I = initial counting rate due to the total virtually instantaneous dose F_I

C_S = initial counting rate for saturation irradiation in flux F_S/unit time.

λ = decay constant of the induced activity
α = constant relating activity and flux

Thus neutron dose/unit initial count in the "flash" case

$$= \frac{F_I}{C_I} = \frac{1}{\lambda\alpha} \quad \text{and is for gold foils,}$$

$$\frac{2.69 \times 24 \times 60 \times 5.81 \pm 3.8\%}{0.6931} = 3.25 \times 10^4 \pm 3.8\% \text{ neutrons/cm}^2\text{/unit ct./min.}$$

4.1.3 Cross-Calibration of Remaining Materials - Copper, Antimony and Tantalum

Intercomparison of the activities induced in these materials by neutron irradiation was done in two ways. In one method the foils were placed simultaneously in a predominantly thermal neutron flux achieved in a block of paraffin wax in which a fast neutron source was located. In this case of tantalum, a much stronger flux was obtained at the centre of the Harwell G.L.E.E.P., and the comparison made with copper in the same position at a reduced power level.

The total activity ratios obtained are as follows:-

Substances	Location	Ratio of Initial Counting-Rates for Saturation Irradiation
Copper/Gold	Wax block	1.50×10^{-2} ± 5.2%
Antimony/Copper (Sb^{122})	Wax block	9.53 ± 2.4%
Antimony/Copper (Sb^{124})	Wax block	1.96 ± 2.4%
Tantalum/Copper	G.L.E.E.P.	5.58 ± 2.4%

In both these calibration methods, there will be some activity due to resonance energy neutrons, as will be the case also in the Hurricane conditions. Cadmium difference measurements for copper, tantalum and gold yield the following values for the ratio of resonance to thermal activation, in the location cited.

Substance	Ratio Resonance to Thermal Activation		
	in Wax Block	in Hurricane Cylinder	in G.L.E.E.P.
Gold	0.268 ± 0.016	0.110 ± 0.009	0.193 ± 0.007
Copper	0.0396 ± 0.0027		0.0512 ± 0.0014
Tantalum			0.575 ± 0.017

It is apparent that the corrections for the varying resonance contributions are quite considerable for gold, tantalum and antimony, and that there is some difficulty in estimating these from the limited data.

What we can do is to assume that the moderated neutrons in each location have a "$\frac{1}{E}$ flux" distribution at resonance energies, and that the resonance cross-section may be described on a Breit and Winger type model (see e.g. reference(7)). For "thin" foils and such a distribution of neutrons, we should expect the relative resonance/thermal activation ratios to be as indicated in the last column of Table II. The gold foils, however, are quite "black" for resonance energy neutrons (thickness 0.005 in. σ_R = 24,000 barns) and we may anticipate that the "effective" resonance integral will be smaller than would be the case for very thin foils. This is in agreement with the measured value of 2.98 for the resonance/thermal activity in tantalum relative to gold in G.L.E.E.P., whereas the theoretical thin foil ratio would be 1.81.

If we assume that the "self-shading" factor is independent of location we may deduce values of resonance/thermal ratios for tantalum in the wax block and Hurricane cylinder locations.

The corresponding ratio for the two antimony isotopes may be inferred on theoretical grounds from these tantalum values, using the information in Table II.

The copper foils have a little resonance activity, and some contribution from epithermal energy neutrons generally. The effect will presumably be very similar in the Hurricane cylinder and wax block locations - viz. ~ 0.04 of the thermal.

These assumptions lead to the following values of resonance/thermal activation ratios.

Substance	Resonance/Thermal Activation in the Location Cited		
	(a) Wax Block	(b) Hurricane Cylinder	(c) G.L.E.E.P.
Gold	0.268 ± 0.016//	0.110 ± 0.009//	0.193 ± 0.007//
Tantalum	0.798 ± 0.061	0.328 ± 0.030	0.575 ± 0.01//
Copper	0.0396 ± 0.0027//	0.04 ± 0.01	0.0512 ± 0.0014//
Antimony (Sb^{121})	0.837 ± 0.279	0.344 ± 0.115	
Antimony (Sb^{123})	1.041 ± 0.347	0.428 ± 0.143	

In the above the measured values are marked//, the others being obtained by the preceding assumptions.

From these ratios we may now derive the correction factors to be applied to the total activity ratios to obtain the proper Hurricane cylinder ratios, as follows.

Consider a substance, X, which has been calibrated via copper in some location other than the Hurricane cylinder, and define the following quantities:-

ρj, σj are the mean activating densities of thermal and resonance neutrons, respectively in the calibration location j, where j = H, w and L, for Hurricane cylinder, wax block and G.L.E.E.P., respectively.

T_X, T_{Cu}, T_{Au} are the saturated activation constants (count/minute per unit ρ) for the materials X, Cu, and Au respectively.

R_X, R_{Cu}, R_{Au} are similar quantities per unit σ.

For convenience we introduce quantites $Kij = \dfrac{R_i \sigma_j}{T_i \rho_j}$

for material i in location j, and we note that the k's have been measured or calculated above.

In addition we know the quantites, experimentally determined:-

$$K_{x,j} = \frac{T_x \rho_j + R_x \sigma_j}{T_{Cu}\rho_j + R_{Cu}\sigma_j} = \frac{T_x [1 + k_{x,j}]}{T_{Cu}[1 + k_{Cu,j}]} \quad \text{(where j = L or W)}$$

$$\text{and } K^1 = \frac{T_{Cu}\ \rho_w + R_{Cu}\ \sigma_j}{T_{Au}\ \rho_w + R_{Au}\ \sigma_w} = \frac{T_{Cu}[1 + k_{Cu,\ w}]}{T_{Au}[1 + k_{Au,\ w}]}$$

What we require is the ratio of total saturated activities ϕ_x, Au, induced in materials x and Au, were they irradiated in the same flux, in the Hurricane cylinder.

$$\text{Viz. } \phi_{x,\,Au} = \frac{T_x \rho_H + R_x \sigma_j}{T_{Au} \rho_H + R_{Au} \sigma_H} = \frac{T_x [1 + k_x, H]}{T_{Au} [1 + k_{Au}, H]}$$

$$= K' K_{x,j} \frac{[1, + k_x, H] [1 + k_{Cu}, j] [1 + k_{Au}, w]}{[1 + k_{Au}, H] [1 + k_x, j] [1 + k_{Cu}, w]}$$

The values of $\phi_{x,Au}$ obtained thus are shown below, where also the corresponding factor for the simple copper case is given.

Substance x	Calibration Location	$\phi_{x,\,Au}$	Corrected ratio of total activity of substance to that of gold, if both were irradiated to "saturation" in the Hurricane cylinder in the same flux of fast neutrons
Cu	Wax block		0.01717 ± 5.3%
Ta	G.L.E.E.P.		0.0815 ± 6.3%
Sb^{122}	Wax block		0.120 ± 18.5%
Sb^{124}	Wax block		0.0235 ± 20.6%

To obtain the corresponding ratios for the case of a flash of neutrons, these figures must be multiplied by $\frac{\lambda \text{ substance}}{\lambda \text{ gold}}$ where the λ's are disintegration constants.

Substance	$\frac{\lambda \text{ substance}}{\lambda \text{ gold}}$	Ratio to gold (total) activity for the same "flash" dose of neutrons, in the Hurricane cylinder detector
Copper	5.01 ± 0.5 %	0.0859 ± 5.3%
Tantalum	2.53×10^{-3} ± 1.4%	1.916×10^{-3} ± 6.5%
Antimony (Sb^{122})	0.996 ± 1.5%	0.120 ± 18.5%
Antimony (Sb^{124})	4.67×10^{-2} ± 2.8%	0.00110 ± 20.6%

Combining these figures with the gold calibration figure obtained in Section 4.1.2, we may now evaluate the "flash" neutron dose to give unit initial counting rate to be as follows:-

Substance	Neutron "flash" dose ($cm.^{-2}$) per unit initial (total) count/minute
Gold	$3.25 \times 10^4 \pm 3.8\%$
Copper	$3.78 \times 10^5 \pm 6.5\%$
Tantalum	$1.70 \times 10^7 \pm 7.5\%$
Antimony(Sb^{122})	$2.72 \times 10^5 \pm 18.9\%$
Antimony(Sb^{124})	$2.96 \times 10^7 \pm 20.9\%$

These figures, refer, of course, to a parallel beam condition.

4.2 Calibration of Fast Neutron - Threshold Detectors

These were assayed by radio-chemical analysis by D. G. Vallis of team R.C.2, in whose report the details are given. The results are obtained, after applying the usual corrections for geometry, self-absorption and back-scatter, as disintegration rate per unit mass of irradiated material.

If we assume that these high energy neutrons are scattered elastically in a predominantly forward direction, we may relate the activity produced to the flux of the virtual beam of neutrons as follows:-

Number of initial disintegrating atoms/g., n_o

$$= \frac{\lambda N.m.p.}{M} \int_T^\infty F(E) \ \sigma(E) \ dE$$

where $F(E)dE$ is the number of neutrons/cm^2 which passed through the detector in the energy range dE, at E.

T is the energy threshold for the reaction.

$\sigma(E)$ is the cross-section for the reaction, at energy E.

N is Avagadro's Number, the number of molecules/g. molecule.

M is the Molecular weight of the substance.

λ is the decay constant of the resulting activity.

m is the number of atoms of the element of interest/molecule.

p is the fractional occurance of the target isotope in the element.

If now we can make a simplifying assumption regarding the form of $\sigma(E)$, we may obtain $\int_T^\infty F(E)dE$ as the total dose of neutrons with energy > threshold. In the case of sulphur, for example, we assume that $\sigma(E) = 0$ for $E < 3$ Mev, and $\sigma(E)$ = constant = 0.3 barns, for $E \geq 3$ Mev.

4.3 Calibration of Thermal Neutron Detectors

In the case of the thermal neutron measurement, we obtain, in our particular counting system, a counting rate from an unscreened foil due to activation by thermal and resonance energy neutrons, and also from an identically sited, cadmium screened foil, activated only by resonance energy neutrons. By a simple subtraction, the counting rate for thermal neutron activation is obtained, and is compared with that due to activation in a known density of thermal neutrons in the Harwell G.L.E.E.P. A uranium beta standard source was used throughout to check counter stability.

If we assume that conditions of thermal neutron density are parallel in the two places of measurement, i.e. Maxwellian distribution of velocities at the appropriate temperature, we may derive a thermal neutron flux ρV from a density ρ, where V = mean velocity = 2,480 metres/sec., at temperature 20°C.

The calibrations obtained from a known thermal neutron density in the Harwell G.L.E.E.P., are as follows:-

Foil	Active Isotope	Thermal Neutron Density to give Unit Initial ct/min. at Saturation Irradiation	Ratio of Resonance/ Thermal Activation in G.L.E.E.P.
Indium	In^{114}	$1.061 \times 10^{-3} \pm 6.5\%$	$1.68 \pm 11.6\%$
Silver	Ag^{110}	$9.16 \times 10^{-4} \pm 7.3\%$	$0.357 \pm 4.3\%$

5. Results

In general, the various activities studied were followed over many decay half-lives, except in the case of the long half-lives, in order to identify the particular activity.

5.1 The equivalent initial (at zero time) counting ratio for the various substances inserted in the wax cylinders are given in Table III, together with the nominal range from ground zero, and, for interest, the ratio of the activation by thermal to that by fast neutrons.

From these results, using the foil calibration figures of Section 4.1.3, we readily compute the dose of fast neutrons (i.e. all those of epi-cadmium-cut-off energy) at the various positions of the detectors. The results are given in Table IV, and graphically in Figure III.

5.2 The results for the threshold detectors for which a measurable activity was found by D. G. Vallis, are as follows:-

(a) P^{32} activity from S^{32} (n,p) P^{32} reaction.

Site	Approximate Orientation (Relative to G.Z.)	Range from Ground Zero (ft.)	Disintegrations/min./ g. at Zero Time
TH26	E	1900	95 ± 48
TH22A	SE	2300	228 ± 132
TH42	N	2500(1) No Cadmium	73.2 ± 13.1
TH42	N	2500(2) With Cadmium	31.1 ± 9.3
TH18	SE	2850	16.3 ± 6.8
TH79	E	3150(1) No Cadmium	69.4 ± 20.2
TH79	E	3150(2) With Cadmium	31.2 ± 8.4
TH71	E	3350	173 ± 24
TH72	N	3700(1) No Cadmium	122 ± 11
TH72	N	3700(2) With Cadmium	114 ± 36
TH34	E	4050	36.8 ± 15.4
TH9	SE	4900	17.7 ± 14.8

Range (ft.)	Counting Rates at Zero Time				Equivalent Thermal Neutron Density (for Saturation Irradiation)
	Ct./min. Bare (i.e. Res. and Thermal)	Ct./min. with Cd. (i.e. Res. Only)	Ct./min. Difference (i.e. Thermal Only)	Ratio of Resonance/ Thermal Activation	
INDIUM (In^{114})					
1300	2390 ± 3%	1840 ± 2%	550 ± 3.6%	3.33 ± 4.1%	5.84×10^{-1} ± 7.5%
1600	3300 ± 3%	1580 ± 3%	1720 ± 4.2%	0.92 ± 4.2%	1.82 ± 7.8%
1850	942 ± 2%	777 ± 2%	165 ± 2.8%	4.71 ± 3.5%	1.75×10^{-1} ± 7.1%
2100	372 ± 4%	285 ± 2%	87 ± 4.5%	3.28 ± 4.9%	9.23×10^{-2} ± 7.9%
2300	241 ± 3%	199 ± 3%	42 ± 4.2%	4.74 ± 5.2%	4.46×10^{-2} ± 7.8%
2500	190 ± 3%	153 ± 3%	37 ± 4.2%	4.14 ± 5.2%	3.93×10^{-2} ± 7.8%
2850	81.6 ± 4%	67.8 ± 4%	13.8 ± 5.6%	4.91 ± 7.0%	1.46×10^{-2} ± 8.6%
3150	45.6 ± 4%	34.9 ± 4%	10.7 ± 5.6%	3.26 ± 7.0%	1.14×10^{-2} ± 8.6%
3700	61.2 ± 5%	35.4 ± 5%	25.8 ± 7.0%	1.37 ± 8.6%	2.74×10^{-2} ± 9.6%
4050	4.2 ± 8%	2.3 ± 25%	1.9 ± 26%	1.21 ± 36%	2.0×10^{-3} ± 27%
SILVER (Ag^{110})					
1200	196 ± 5%				
1300	178 ± 5%	58.5 ± 5%	119.5 ± 7.0	0.49 ± 8.6%	1.10×10^{-1} ± 10.1%
1600		50.3 ± 7%			

With the assumptions of Section 3.2, we may derive

$\int_{\text{threshold}}^{\infty} F(E)\ \sigma\ (E)dE = \frac{Mn_0}{\lambda N m_p}$ and assuming a step-function cross-section

at energy ~ 3 Mev, an approximate value of total dose of neutrons of greater than this energy, at each point of measurement. These figures are given in Table V, and graphically in Figure IV.

(b) From the other materials, the only measurable activities found after the delays in recovery and chemical separation were as follows:-

(1) Yttrium^{90} from Zr^{90} (n,p)reaction.

Range (ft.)	Count/min./g. at Zero Time
1900	638 ± 116 (No Cadmium)
1900	650 ± 140 (With Cadmium)

The cadmium here is incidental, and we may take a weighted average of 698 ± 63 from which we get the value, for the integral

$\int_{\text{zirconium threshold}}^{\infty} F(E)\ \sigma_{Zr}\ (E)dE$, of 2.18 × 10^9 ± 9.0%

(2) Phosphorus^{32} from Cl^{35} (n,α) reaction.

The one result obtained was a count/min./g. of 22.6 ± 1.2 from a sample, cadmium covered, at range 1900 ft.

This gives a value of $\int_{\text{chlorine threshold}}^{\infty} F(E)\ \sigma_{Cl}\ (E)dE$ of 1.32 × 10^8 ± 5.3%

Without an assumption of an effective constant σ above a definite threshold, it is not possible to deduce the fast neutron dose.

5.3 Thermal Neutron Measurements

The results for the indium and silver foils are as follows:-

The figures in the first three columns are shown graphically in Figure V.

We wish to evaluate the dose of thermal neutrons in the Hurricane pulse, where the dose is the time integral of the flux over the duration of the pulse. We define flux to be mean velocity × density where the density is the total number of neutrons (of all thermal velocities) per unit volume.

The dose of instantaneous G.L.E.E.P. neutrons to give the same activity as was induced in the foil at Hurricane would be

$$\frac{V_G}{\lambda} \times \rho\ (\text{equivalent saturation})$$

where ρ (equivalent saturation) is the quantity given in the last column of the above table, i.e. the equivalent thermal neutron density which would produce, at saturation irradiation, the measured activity.

Here λ is the decay constant of the activity,

and $\overline{V}_G$ is the mean velocity of thermal neutrons in G.L.E.E.P.

The corresponding dose of Hurricane neutrons, by virtue of the $\frac{1}{V}$ absorption cross-section of the indium and silver foils at thermal velocities (See e.g. Ref (7) Appendix 3) is

$$\frac{\overline{V}_H}{\lambda} \times \rho \text{ (equivalent saturation)}$$

where $\overline{V}_H$ is the mean velocity of thermal neutrons at Hurricane.

$= 2\sqrt{\frac{2kT}{m\pi}}$ for a Maxwellian distributions at temperature T (degrees Absolute) where k = Boltzmann constant, m = neutron mass.

Taking the ambient temperature of about 100°F. to be the temperature of the distribution, the mean velocity of the Hurricane thermal neutrons is found to be 2.55×10^5 cm./sec.

Using this value of $\overline{V}_H$, the dose of thermal neutrons in the Hurricane pulse is evaluated as in Table VI, and shown graphically in Figure VI.

5.4 Neutron Penetration Into Concrete Cubicle Structure

Because of damage to the concrete structure, and of radioactive hazard, it was impossible to recover, (during October, 1952), the instruments located inside. It was hoped that these might be retrieved in May 1953, and again in November, 1953, when the islands were re-visited. Had recovery been possible, it seems certain that a counting rate adequate for accurate comparison with that of the exposed detectors at similar range would have been found. The latest attempt, however, was both unsuccessful and conclusive, and there is, consequently, no result for this measurement.

6. Discussion

The recovery of the various detectors after the event indicated that some features of the choice of materials, method of mounting, and estimation procedure were at fault.

The paraffin wax cylinder instruments proved to be quite robust, and, in fact, only one out of twelve was lost, the copper activity(12.88 hour half-life) having decayed considerably by the time the instrument was recovered.

The other types of detector - viz. the small chemical fast neutron threshold detectors, and the indium and silver thermal neutron sensitive foils - suffered several casualties.

At three of the closest sites, in the range 1,200 - 1,700 ft, the detectors had been blown from the supports and lost, in the chemical detector case, and likewise some of the foils were missing in this range, though no site was entirely stripped. Much of what was hoped for in the case of the reactions leading to the isotopes As^{76} and Y^{90}, with half-lives of 26.8 hours, and 61 hours respectively, was lost in the delays of recovery and chemical treatment, which together were on the average about fourteen days for the short-lived activities.

However, sufficient samples of the relatively long-lived phospherous (from sulphur), indium and silver activities were obtained to give results over the range to be explored.

6.1 The results shown in Figure III show a fair agreement between the several materials. The relative values for each material, which are of course independent of the calibration, give an approximately exponential fall with distance, with a "decay" constant of about 400 ft.

We must consider the possibility that a considerable fraction of these neutrons may have reached the detector at resonance energies. The evidence from the uniform activity density experiment described in 4.1.1 indicates that there was no appreciable activation by resonance neutrons reaching the front edge of the foil directly, and it is known that the instrument is relatively insensitive to resonance neutrons impinging generally on the wax. Considering that the mean lifetime of resonance neutrons is very much smaller than that of thermal neutrons, and that the thermal contribution as measured by the cadmium difference was small, it seems clear that the fast neutrons recorded here were in fact largely fast as distinct from resonance neutrons. In that case they may be presumed to fall in the range of linear response of the wax detector.

6.2 The results for the neutrons of greater than sulphur (n, p) threshold energy are quite erratic, though there is of course a decrease with increased distance, and in the 2,000 - 3,000 ft. range, an approximate exponential fall. Because of the fact that the cross-section is by no means a constant from 1 to 3 Mev, the range in which the majority of the neutrons certainly arrive, there is a great deal of uncertainty in the absolute value of dose, and we should consider the result as being merely specific phosphorous activity by fast neutron irradiation of sulphur. One curious point is that the values of

$$\int_{\text{threshold}}^{\infty} F(E)\,\sigma(E)\,dE$$ for the sulphur (n, p) and zirconium (n,p) reactions,

at the only range measurable - 1900 ft. - are of the same order of magnitude (Zr 40% greater) while the cross-sections in the literature give the sulphur value about ninety times that of zirconium, and the threshold for the sulphur case is lower, at 1.0 Mev than for zirconium, at 1.8 Mev. If this measurement is even approximately true, then we must suppose that there is a steep rise in the zirconium cross-section above threshold, compared with sulphur, and that there are a great many neutrons with energy between 1.8 Mev and the energy at which the sulphur cross-section ceases to rise steeply - viz ~ Mev.

The activity level in the Cl^{35} (n, α) P^{32} reaction seems of a reasonable order, but without a detailed knowledge of cross-section, the flux cannot be evaluated.

It is clear that much has been lost by inadequate mounting arrangements at the close sites, and delays in recovery and chemical treatment.

6.3 The results shown in Figure VI for thermal neutron dose are consistent apart from two points which are inexplicably high. The one result for silver, which is of course completely independent, agrees well with the indium figures. The variation with distance is an approximate exponential with a decay constant of about 0.0023 ft^{-1}. We can compare the reciprocal - 430 ft., with the capture mean free path of thermal neutrons in air, viz 500 ft. ca.

Because of the differences in the activation conditions of the foils at Hurricane, and in the G.L.E.E.P. calibration, the results would be more reliably quoted as "dose to give an activity in a foil of a certain size (0.005 in. thick, 0.86 in. diameter) in which a certain activity results from irradiation in a known thermal neutron density."

A point of some interest is that we may deduce from these thermal flux results, in conjunction with the wax fast neutron figures, a value for the efficiency of the wax instrument for thermal neutrons. Over the middle of the range studied we find that the fast dose is approximately constant at three times the thermal value, and the thermal/fast activation ratio (Table III) when plotted against distance for all the materials is similarly about constant, with some discrepancies, at about 10 per cent. These two figures indicate an efficiency for thermal neutrons of 30 per cent relative to the fast neutron value, and the value obtained from some previous work with a similar wax system was about 20 per cent. As the wax fast neutron and foil thermal neutron measurements are, of course, quite independent, this seems quite fair agreement.

7. Conclusion

We may deduce an estimate of lethal range in air for fast and slow neutrons together, using the published figures (8) of 10^{11} and 5×10^{11} per square centimeter for fast and slow respectively, and counting all the neutrons above thermal energies as fast. We find, in fact, that the thermal contribution is negligible, and that the lethal range for fast neutrons is approximately 2,600 ft. from ground zero.

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Team R.M.2

W. J. Moyce (Team Leader).
A. D. McRonald - All general details of Hurricane and calibration work.
P. M. Harris - Assistance in erecting instruments and counting work after recovery. Recovery mainly his responsibility.

Team R.C.2.

D. G. Vallis - Chemistry and estimation of activity induced in "threshold" fast neutron detectors.

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TABLE I

Substance	Reaction Studied	Neutron Energy Threshold (Mev) - Where Appropriate	(Isotopic) Reaction Cross-Section (Barns) [at 0.025 ev for Thermal Neutron Reactions]	Resulting Activity		
				Half-Life	Emission Energy (Mev)	
					β	γ
Gold	Au^{197} (th n, γ)Au^{198}	-	96 ± 10 [4]	2.69d	0.97	0.41
Tantalum	Ta^{181} (th n, γ)Ta^{182}	-	21 ± 7 [4]	117d	0.53	Many
Copper	Cu^{63} (th n, γ)Cu^{64}	-	3.9 ± 0.8 [4]	12.88h	0.57 0.66	1.3
Antimony	Sb^{121} (th n, γ)Sb^{122} Sb^{123} (th n, γ) Sb^{124}	- -	5.7 ± 0.5 [4] 3.9 ± 0.3 [4]	2.8d 60d	1.94 1.36 Many	0.57 Many
Sulphur	S^{32}(n, p) P^{32}	1 - 3 1.0	0.3 [2] 0.285 [3]	14.3d	1.7	None
Selenium	Se^{76}(n, p)As^{76}	2.3	0.0165 [3]	26.8h	Many	Many
Zirconium	Zr^{90}(n, p)Y^{90}	1.8	0.0031 [3]	61h	2.2	None
Oxychloride	Cl(n, α)P^{32}		.017 at 3 Mev	14.3d	1.7	None
Indium	In^{113}(th n, γ)In^{114}	-	56 ± 12 [4]	50.d	2.05	
Silver	Ag^{109} (th n, γ)Ag^{110}	-	2.8 ± 0.5 [4]	270d	Many	Many

All the figures in Table I are from NBS Circular 499 unless otherwise indicated.

Table II

Neutron Resonance Activation Data

Substance	Isotope of Interest	(Isotopic) Activation Cross-Section(4) for Thermal (0.025 ev) Neutron (Barns)	Resonance Activation			Ratio of Resonance Integral to Thermal Cross-Section
			Resonance Energy(5) (ev)	"Strength" (5) of Resonance $\int_{\sigma_0}^{2}$ [Barns (ev)^2]	Resonance Integral (6) $I = \int_{Cd}^{\infty} \frac{\sigma_a(E)dE}{E}$	
Gold	Au^{197}	96 ± 10	4.87	638	1300	13.6 ± 1.4
Tantalum	Ta^{181}	21 ± 7	6.1 10.3 13.6 20 24 35 39	 44 9 9 35 97 197	517	24.6 ± 8.2
Antimony	Sb^{121}, Sb^{123}	5.7 ± 0.5 (Sb^{121}) 3.9 ± 0.3 (Sb^{123})	5.8 15 21	~ 12 ~ 35 ~ 35	(Sb^{121}) 147 (Sb^{123}) 125	25.8 ± 2.3 32.1 ± 2.5
Copper	Cu^{63}	3.9 ± 0.8	-	-	3.8	1.0 ± 0.2

TABLE III

Activities in Foils Inside Wax Cylinders

Foil	Range (ft.)	Measured half-life used in extrapolation.	Equivalent Initial ct./min.	% Thermal/Fast Activation, i.e. Incident Energy Discrimination
Gold	1300	2.69 ± 0.3% days from observation over ten half-lives.	5.97×10^7 ± 3% *	20.7 ± 5.1
	2050		1.35×10^7	10.9 ± 4.2
	2700		1.24×10^6	8.54 ± 4.2
Copper	2600	12.88 ± 0.4% Hours from observation over eight half-lives.	2.22×10^5 ± 3%	9.0 ± 6.2
	3200		4.34×10^4	(1.9)
Tantalum	1700	114.7 ± 1.4% days from observation over three half-lives.	4.06×10^4 ± 3%	11.1 ± 4.2
	2300		9.89×10^3	(1.7)
Antimony (Sb^{122} Isotope)	2250	2.70 ± 0.04 days Standard deviation eight foils over six half-lives each.	7.74×10^5 ± 3%	36.0 ± 5.0
	2950		1.89×10^5	13.9 ± 4.4
(Sb^{124} Isotope)	2250	57.4 ± 1.6 days Standard deviation on seven foil results over three half-lives.	8.87×10^3 ± 3%	13.3 ± 4.4
	2950		2.16×10^3	9.9 ± 4.2

* These errors are an estimate of uncertainties in Geiger counter stability, dead time correction applied, and extrapolation to zero time.

TABLE IV

Fast Neutron Dose Values at Different Ranges

Using Various Materials as Detectors

Substance Used as Detector		Range from Ground Zero (ft.)	Fast Neutron Dose ($n./cm^2$) All Neutrons Above Cadmium Cut-off Energy Included.
Gold	(1)	1300	$1.94 \times 10^{12} \pm 4.8\%$
	(2)	2050	$4.39 \times 10^{11} \pm 4.8\%$
	(3)	2700	$4.03 \times 10^{10} \pm 4.8\%$
Copper	(1)	2600	$8.41 \times 10^{10} \pm 7.2\%$
	(2)	3200	$1.65 \times 10^{10} \pm 7.2\%$
Tantalum	(1)	1700	$6.90 \times 10^{11} \pm 8.1\%$
	(2)	2300	$1.68 \times 10^{11} \pm 8.1\%$
Antimony (Sb^{122})	(1)	2250	$2.11 \times 10^{11} \pm 19.1\%$
	(2)	2950	$5.14 \times 10^{10} \pm 19.1\%$
Antimony (Sb^{124})	(1)	2250	$2.63 \times 10^{11} \pm 21.1\%$
	(2)	2950	$6.39 \times 10^{10} \pm 21.1\%$

TABLE V

Dose of Fast Neutrons with Energy z ~ 3 Mev
(i.e. Effective S (n,p) P Threshold)

Range (ft.)	$\int_{\text{Sulphur Threshold}}^{\infty} F(E)\sigma_s(E)dE$	Fast Neutron Dose ($cm.^{-2}$)
1900	$1.59 \times 10^{9} \pm 5.0\%$	$5.30 \times 10^{9} \pm 5.9\%$
2300	$3.79 \times 10^{8} \pm 14.0\%$	$1.26 \times 10^{9} \pm 14.0\%$
2500 (1)	$1.22 \times 10^{8} \pm 15.2\%$	$4.07 \times 10^{8} \pm 15.2\%$
2500 (2)	$5.17 \times 10^{7} \pm 29.9\%$	$1.72 \times 10^{8} \pm 29.9\%$
2850	$2.71 \times 10^{7} \pm 41.7\%$	$9.03 \times 10^{7} \pm 41.7\%$
3150 (1)	$1.16 \times 10^{8} \pm 29.1\%$	$3.87 \times 10^{8} \pm 29.1\%$
3150 (2)	$5.19 \times 10^{7} \pm 26.9\%$	$1.73 \times 10^{8} \pm 26.9\%$
3350	$2.88 \times 10^{8} \pm 13.9\%$	$9.60 \times 10^{8} \pm 13.9\%$
3700 (1)	$2.03 \times 10^{8} \pm 9.0\%$	$6.77 \times 10^{8} \pm 9.0\%$
3700 (2)	$1.90 \times 10^{8} \pm 31.6\%$	$6.33 \times 10^{8} \pm 31.6\%$
4050	$6.12 \times 10^{7} \pm 41.6\%$	$2.04 \times 10^{8} \pm 41.6\%$
4900	$2.95 \times 10^{7} \pm 83.6\%$	$9.83 \quad 10^{7} \pm 83.6\%$

TABLE VI

Total Dose of Thermal Neutrons

Range (ft.)	Total Dose of Thermal Neutrons/cm^2.	
	Indium	Silver
1300	$9.28 \times 10^{11} \pm 7.5\%$	$6.54 \times 10^{11} \pm 10.1\%$
1600	$2.89 \times 10^{12} \pm 7.8\%$	
1850	$2.78 \times 10^{11} \pm 7.1\%$	
2100	$1.47 \times 10^{11} \pm 7.9\%$	
2300	$7.09 \times 10^{10} \pm 7.8\%$	
2500	$6.25 \times 10^{10} \pm 7.8\%$	
2850	$2.32 \times 10^{10} \pm 8.6\%$	
3150	$1.81 \times 10^{10} \pm 8.6\%$	
3700	$4.36 \times 10^{10} \pm 9.6\%$	
4050	$3.18 \times 10^{9} \pm 27\%$	

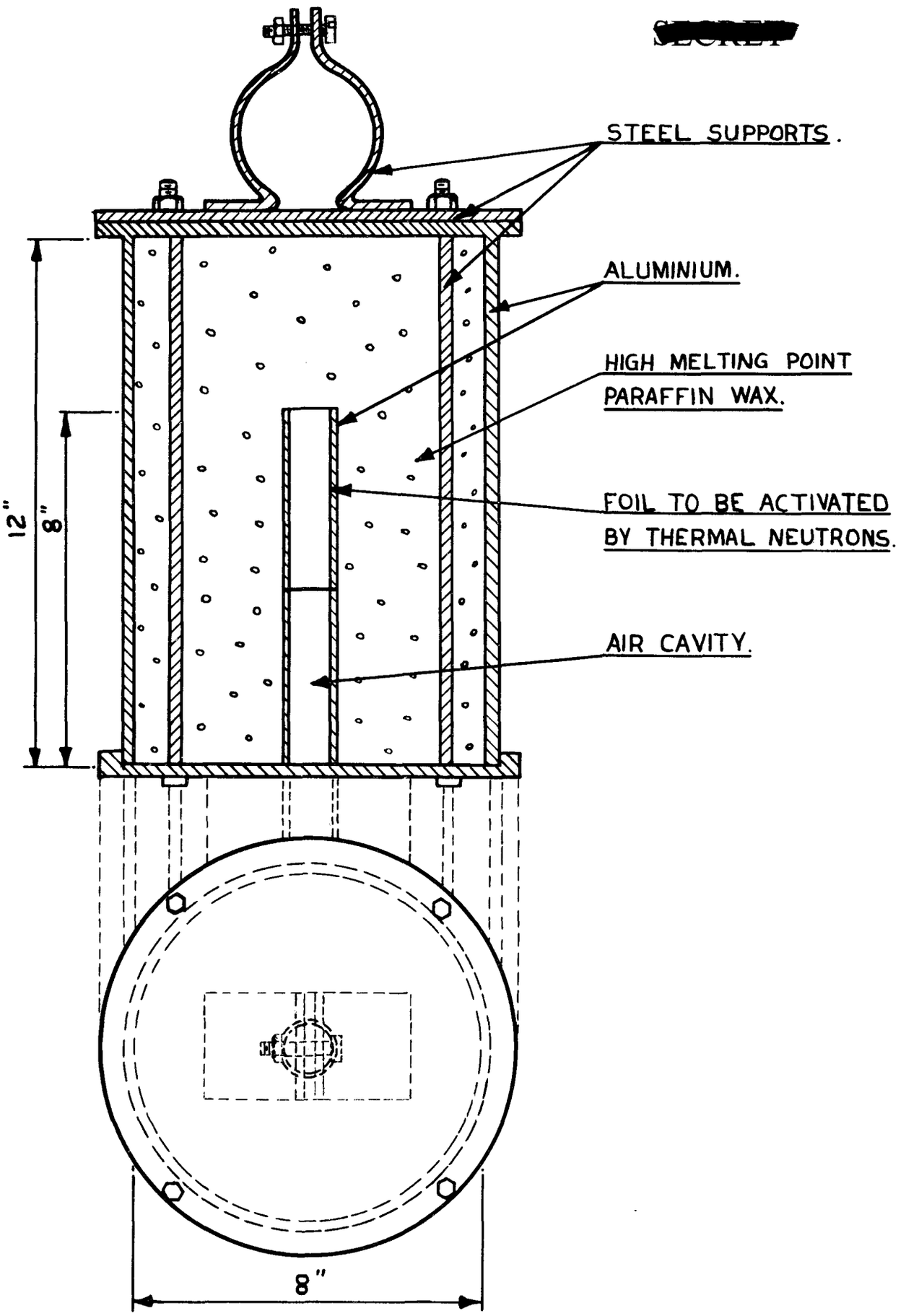

FIGURE 1. DIAGRAM OF PARAFFIN WAX UNIT.

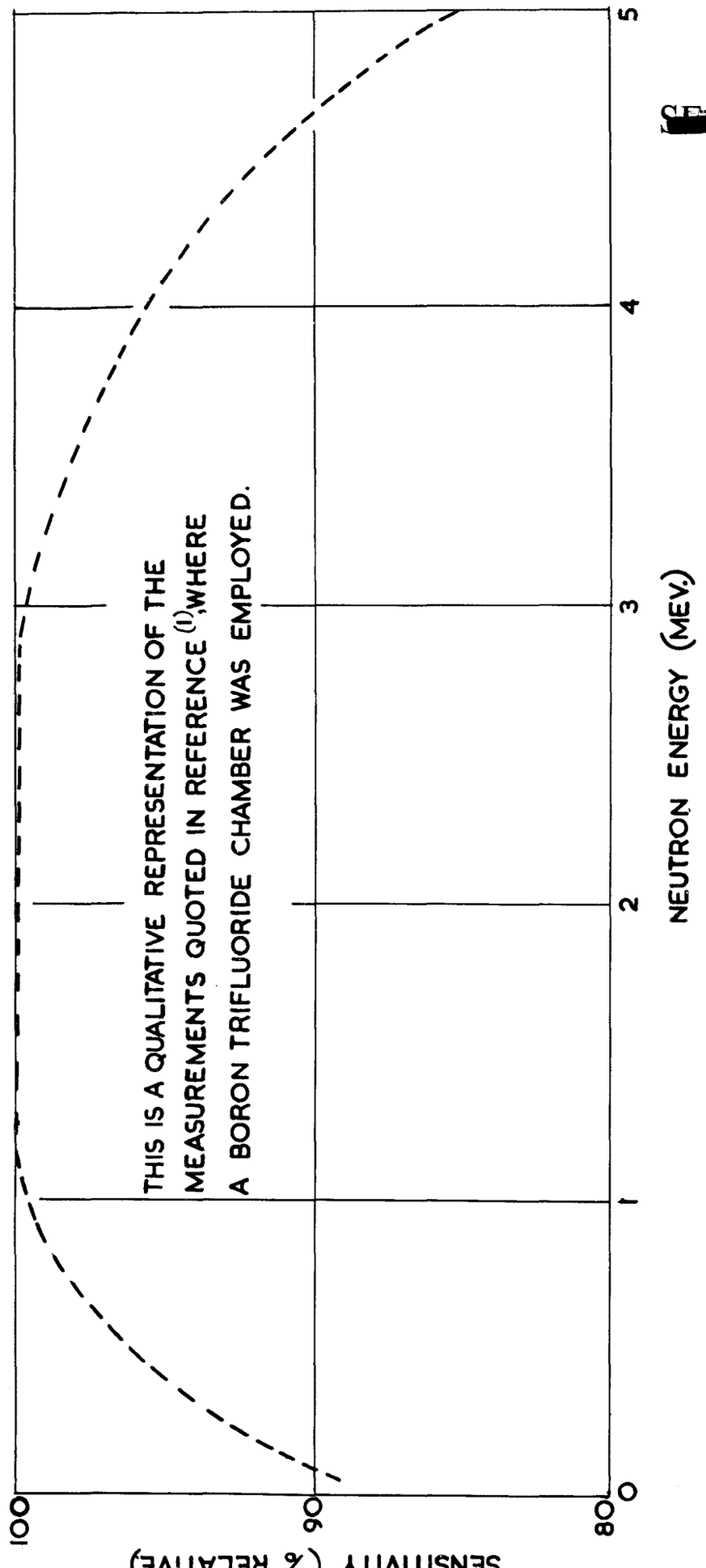

FIGURE II- RELATIVE RESPONSE OF PARAFFIN WAX UNIT FOR NEUTRONS OF DIFFERENT INCIDENT ENERGY.

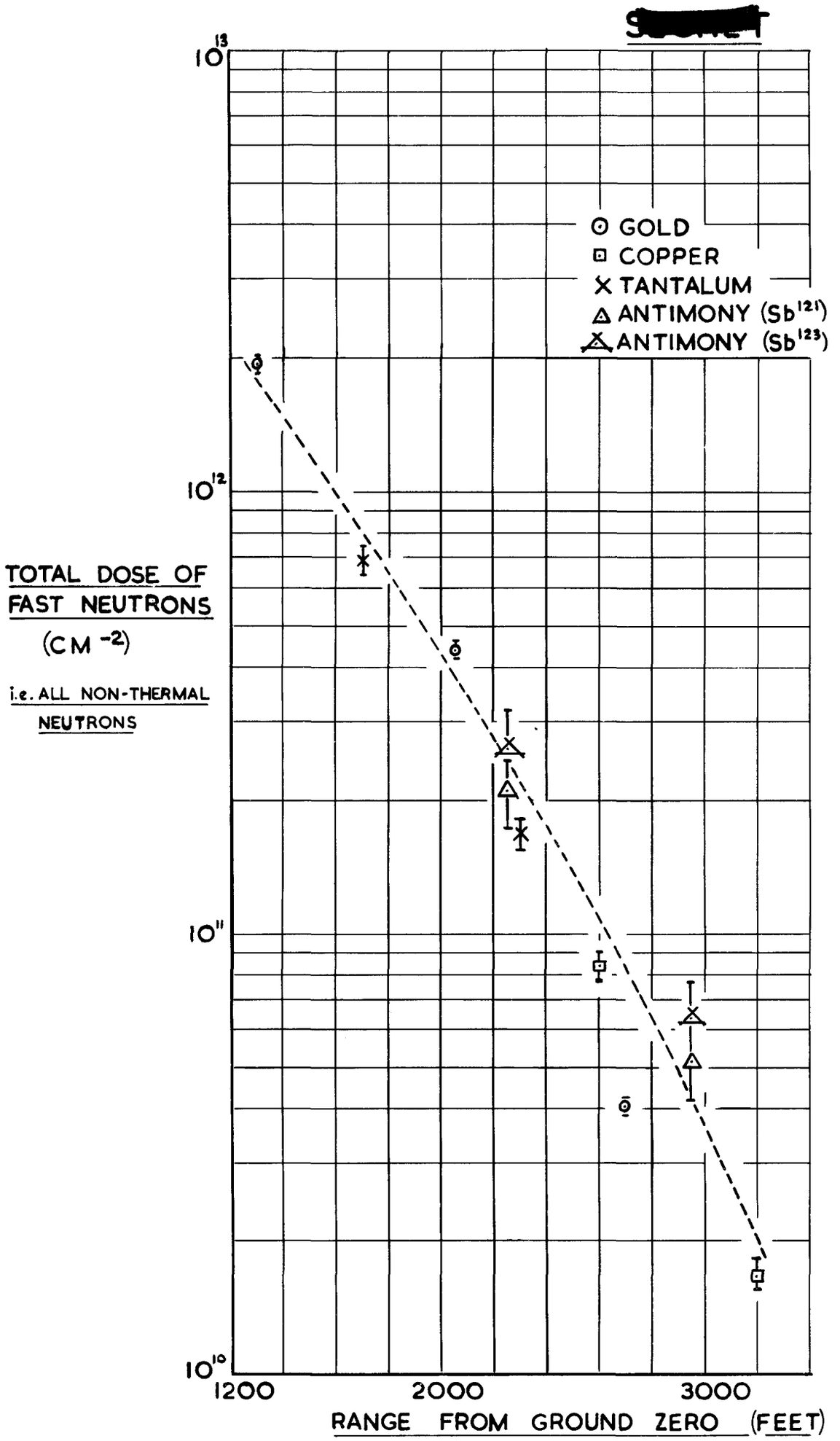

FIGURE III. VARIATION OF FAST NEUTRON DOSE WITH RANGE.

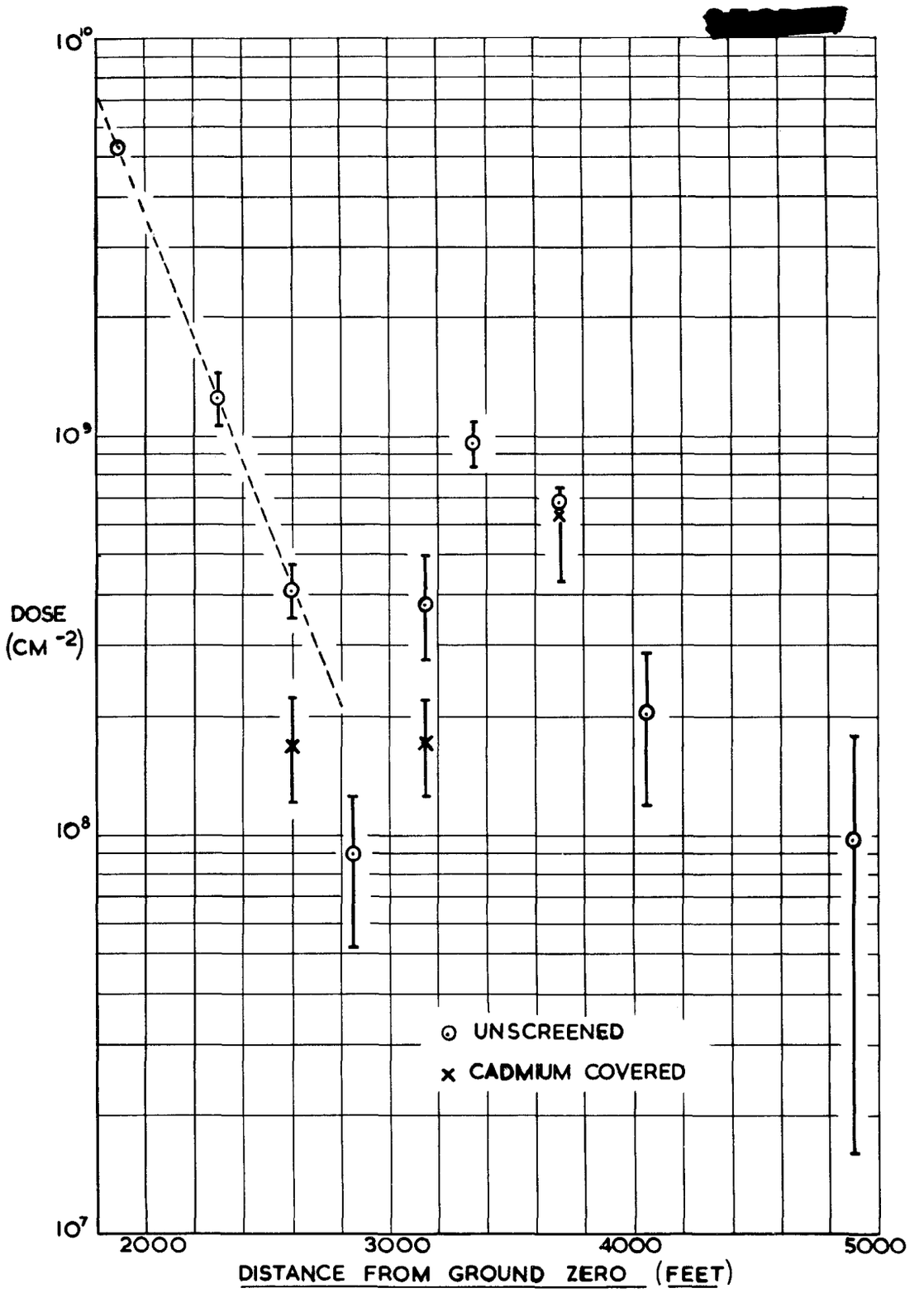

FIGURE IV. DOSE OF (VERY) FAST NEUTRONS

[i.e. OF ENERGY > S (n,p) P THRESHOLD]

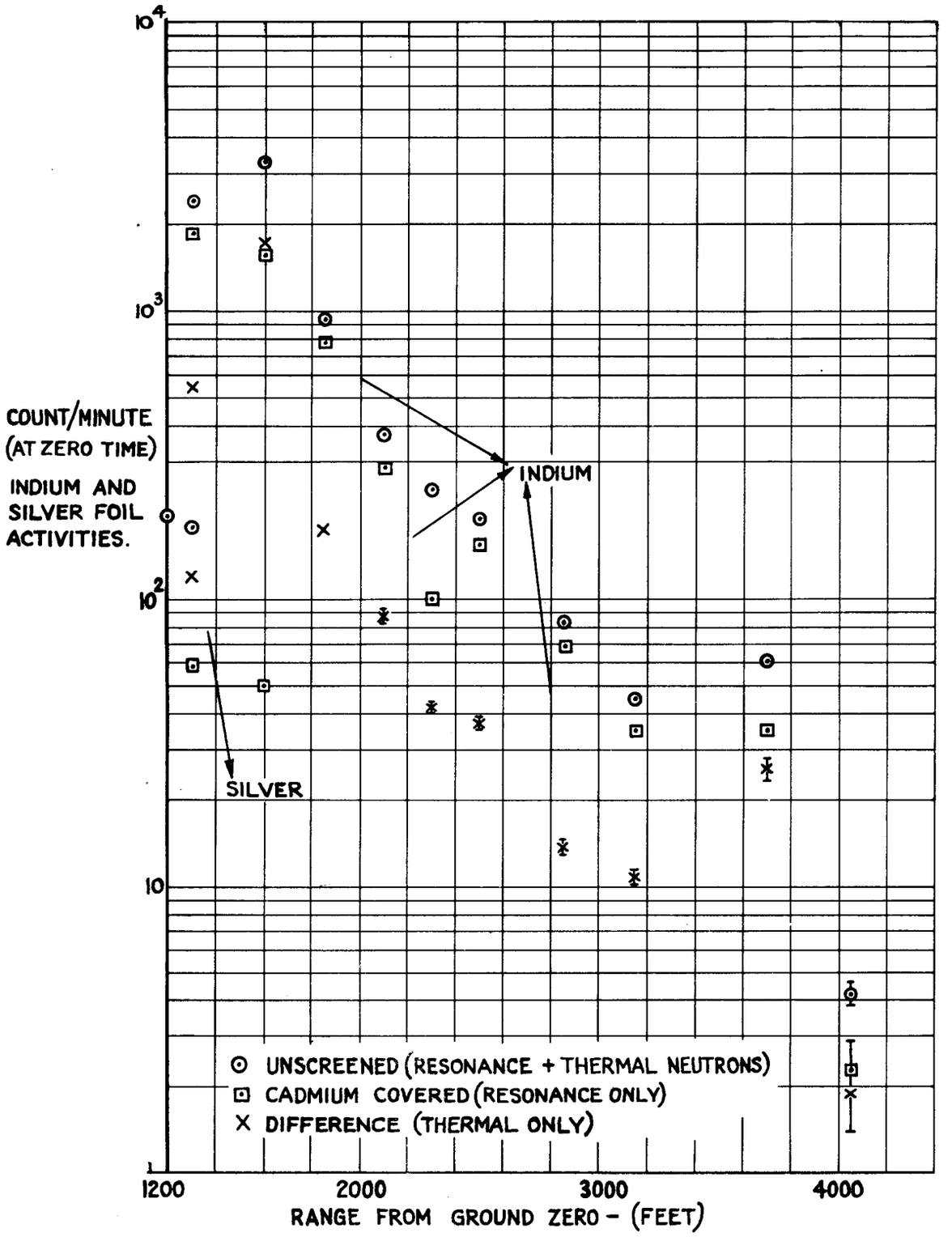

FIGURE V. TOTAL AND RESONANCE ACTIVITIES IN INDIUM AND SILVER FOILS.

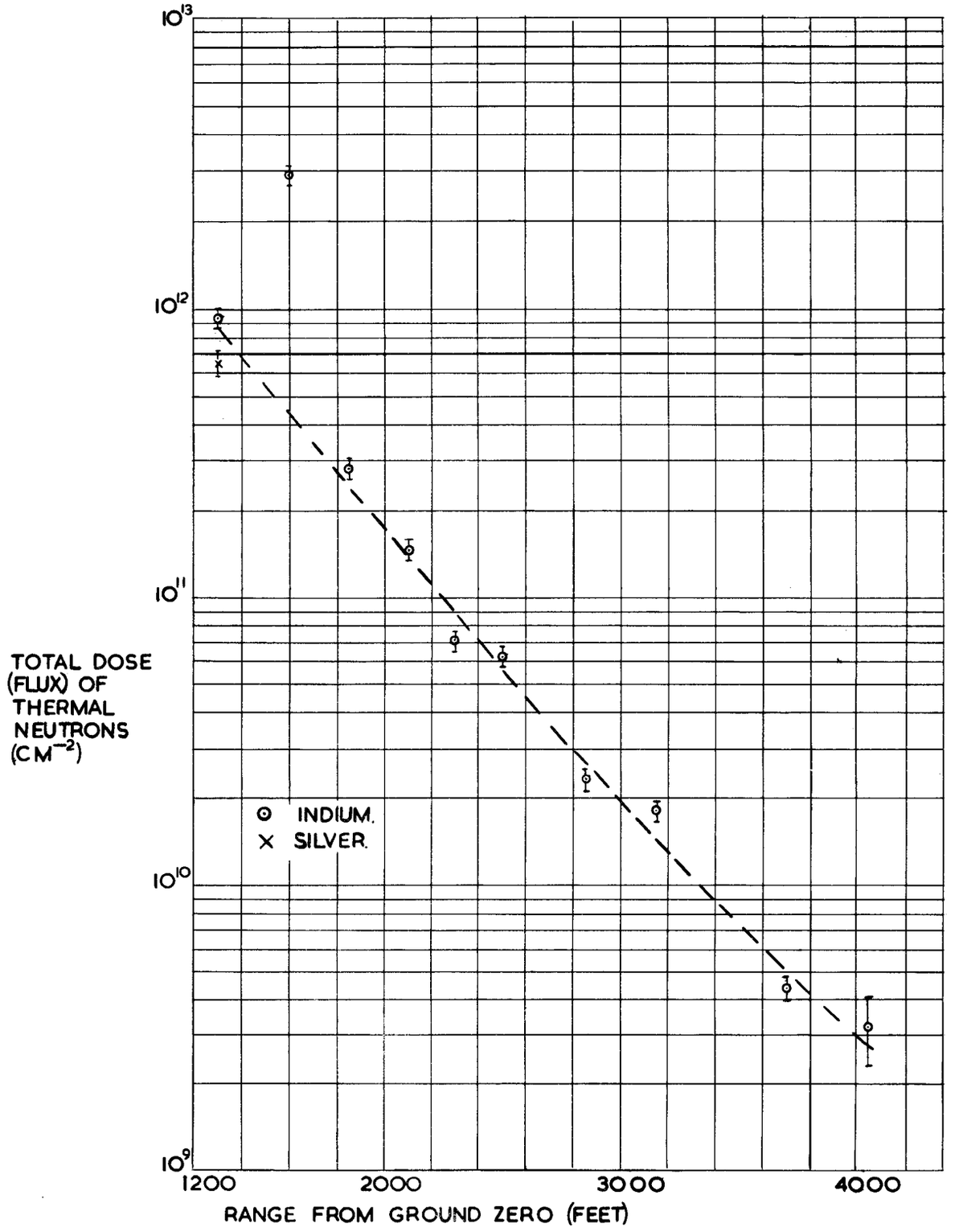

FIGURE VI - TOTAL DOSE OF THERMAL NEUTRONS