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SORTING OF LUMP MANGANESE ORES

Feasibility Study

(Amdel Report No 465)

by

J.E.A. Gooden.

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* of the Australian Mineral Development Laboratories, Adelaide.

Introduction

Sorting by hand picking from a belt has been used to separate iron rich lumps from screened manganese ore for many years in Western Australia. In Queensland, natural radioactivity of ore lumps at Mary Kathleen was used as the basis of a mechanical sorter, and elsewhere in the world sorters have been developed which depend on various natural properties of the ore and waste lumps.

It was considered possible that induced radioactivity might be used as the basis of a sorter for the manganese ores of Western Australia. The investigation reported examines this possibility and reaches the conclusion that it should be technically feasible to do so, though the cost of the operation may be too high for commercial application of the process.

The report has been included in the Bureau's Record series so that it may enjoy the wider distribution offered by the "Open File" system. It has not been altered in any way.

BUREAU OF MINERAL RESOURCES

Amdel Report

No. 465

SORTING OF LUMP MANGANESE ORES

Feasibility Study

by

J. E. A. Gooden

Investigated by: Metallurgy Section
Officer in Charge: P. K. Hosking

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THE AUSTRALIAN MINERAL DEVELOPMENT LABORATORIES
Adelaide South Australia

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SUMMARY

A method of sorting lumps of ore and gangue has been proposed in which the lumps are irradiated with neutrons while in motion. Certain elements will be made quite radioactive in even a brief irradiation, and the lumps then pass a detector which actuates a sorting mechanism.

The feasibility of using this technique for sorting manganese ore from gangue has been examined. Two methods have been considered, namely, thermal neutron irradiation, which activates manganese in the ore, and fast neutron irradiation, which activates silicon in the gangue. Laboratory tests were carried out using a plonium-beryllium neutron source and staionary samples of powered minerals. Samples were also sent to the USA for irradiation with 14.5 Mev neutrons. Approximate calculations based on this laboratory work lead to the conclusion that 4-inch cubes of 40% Mn ore should be separable from similar cubes of 50% Mn ore at a target cost of $A1.2 per ton of material treated. The efficiency of separation and the economics are markedly improved if the lump size is larger.

The work reported is a feasibility study only, and work should now be extended firstly to the use of a moving belt and secondly to the irradiation and counting of irregular lumps of ore.

1. INTRODUCTION

Hand picking or sorting has long been applied to coarse material for recovery of a high-grade fraction or removal of waste material. Labourers are stationed beside a moving belt which constantly presents new material, and from which they remove the wanted or unwanted lumps. Mechanical pickers or sorters have been devised which depend on the natural radioactivity of one of the constituents, e. g., the "Lapointe picker" (Lapointe and Wilmot, 1952) the radiometric sorters used at Mary Kathleen, Queensland, and at Beaverlodge, Canada (Colborne, 1963) and that described by Corral (1963). Sorters are also available which depend on differences in the light reflectance of the constituents, e. g., the Kelly and Hutter Sorter at Amdel built by Electronic Associates for Rio Tinto, the machine developed by Gromax Inc. (Slotemaker, 1964) and Gunson's "Sortex" machines which treat material in the range $\frac{1}{8}$-$\frac{3}{4}$ inch. Another possible means is to utilize X-ray absorption (Belash et al, 1962, 1964; Shumilovskii, et al, 1964) or fluorescence. A detector actuates via an electron circuit some mechanical device for diverting wanted or unwanted lumps. Other physical properties such as electrical conductivity may control a sorting operation.

The idea of sorting or "picking" by means of artificial radioactivity is potentially of much wider scope than the use of natural radioactivity. Two means have been proposed for tagging the desired constituent of an ore:

a. Selective adsorption of a suitable radioactive isotope from solution (Senftle and Gaudin, 1951; Gaudin, Senftle and Freyberger, 1952).

b. Irradiation of the lumps with neutrons or gamma rays to induce radioactivity (Halfawy and Senftle, 1957; Rudanovskii, 1960; Fuerstenau and Gaudin, 1961; Gaudin and Ramdohr, 1962; Arkhipov, 1963; Ostapov and Filippov, 1964).

One constituent having been made radioactive by either of these means, a separation can be effected by means of a detector and picking device in the same way as a separation based on natural radioactivity. It is important that this radioactivity be short-lived so that there is no hazard associated with the sorted product. This is generally a corollary of successful separation by method "b", as only isotopes with a short half-life will be produced in sufficient activity in a short irradiation. This method is considered in this report for the beneficiation of lump manganese ore.

Two approaches have been tried:

a. activation of manganese using slow neutrons

b. activation of silicon with fast neutrons.

In the former system the radioactive lumps would be accepted; in the latter case they would be rejected.

The main object of this first stage of work has been to establish whether the method has sufficient sensitivity to sort manganese ore from gangue. Calculations made before the commencement of work indicated that slow-neutron irradiation should produce sufficient manganese-56 activity for sorting, but an actual irradiation followed by measurement of the induced radioactivity in the best trial.

This work has therefore consisted of irradiation trials on stationary aggregates of powdered ore to enable calculations to be made for the case of lumps of ore moving on a belt.

2. THEORETICAL PRINCIPLES

2.1 Nuclear Reactions

Radioactive isotopes can be produced from stable isotopes by a variety of reactions, the most useful of which is slow neutron capture,

e.g. $^{23}Na + {}^{1}n \longrightarrow {}^{24}Na + \gamma$

which is an (n, γ) reaction

(^{24}Na then decays: $^{24}Na \xrightarrow[t_{1/2} = 14.8\ hr]{\beta} {}^{24}Mg$)

"Slow" or thermal neutrons are neutrons with energies in the range 0.01-0.1 ev.

In a very few cases slow neutrons give rise to (n, p) reactions

e.g. $^{14}N + {}^{1}n \longrightarrow {}^{14}C + p$

but generally "fast" neutrons are required.

Other reactions produced by fast neutrons are:

(n, α)

(n, n)

(n, 2n)

Deuteron bombardment leads to (d, p), (d, 2n), (d, n) and (d, α) reactions It is proposed to discuss only bombardment with neutrons in this report.

2.2 Sources of Neutrons

The three common sources of neutrons are:

a. nuclear reactors

b. isotope neutron sources

c. particle accelerators

A uranium pile such as BEPO which uses a graphite moderator gives a flux of the order of 10^{12} neutrons per cm^2 per second. Most of the neutrons have thermal velocities except for a proportion near the uranium rods which have not been sufficiently slowed down (Cook and Duncan, 1952).

Isotope sources utilise an (α, n) or (γ, n) reaction. The radium-beryllium source is an intimate mixture of beryllium powder and a radium salt. The alpha particles from radium eject neutrons from beryllium nuclei. A polonium-210-beryllium source was used in this work. Polonium 210 has the advantage of emitting only a minute proportion of γ-rays and hence is safer than radium, though of shorter life (half-life 138 days). The α particles emitted by Polonium-210 react:

$$^{9}_{4}Be + ^{4}_{2}He \longrightarrow ^{12}_{6}C + ^{1}_{0}n$$

The primary neutrons emitted from such a source have a wide range of energies. Figure 1 shows calculated spectra of neutron energies from a ^{210}Po-Be source, and Figure 2 the results of measurements by various workers.

Other isotope sources such as ^{210}Pb-Be, ^{227}Ac-Be, ^{228}Th-Be, and ^{124}Sb-Be are also available.

Particle accelerators are generally required for neutron outputs much above 10^8 neutrons per second. The most promising are low-voltage positive ion accelerators using the d-t reaction $^{3}H(d,n)^{4}He$. A disc-like target consisting of tritium occluded in a thin layer of titanium is bombarded with deuterons. The Texas Nuclear Corporation in June, 1964, quoted a price of $US20,900 for their Model 9400, which uses a 1.0 ma deuteron beam and is capable of a total 4π output of 1×10^{11} neutrons per second. A 3-5 curie per square inch target costing $A80 has a 4 to 6 hour half-life when continuously bombarded by a 1 ma deuteron beam.

The emitted neutrons are monoenergetic and their spatial distribution nearly isotropic (Texas Nuclear Corporation, published information and personal communication).

2.3 Nuclear Reactions Produced in Manganese Ore

The common constituents of manganese ores are manganese oxides, iron oxides and silica. On irradiation with thermal neutrons the reactions shown in Table 1 will occur. Table 2 shows the reactions which would be produced by irradiating such a manganese ore with fast (14.5 Mev) neutrons.

2.4 Growth of Radioactivity

Radiochemical yields are given by:

$$R = \frac{\phi A \sigma f}{W} (1 - e^{-0.693t/T_{1/2}}) \quad \ldots \quad (1)$$

where R = disintegration per second per gram of the whole element in the sample

ϕ = neutron flux (neutrons per cm^2 per second)

A = Avogadro's Number 6.02×10^{23}

σ = capture cross-section of the target isotope in cm^2 10^{-24} cm^2 = 1 barn

f = abundance of the target isotope expressed as a fraction

W = atomic weight

t = time of irradiation

$T_{1/2}$ = half-life of radioactive product same units as "t"

For short irradiations where $t < 1/10\ T_{1/2}$ say,

the above expression reduces to

$$R = \frac{\phi A \sigma f}{W} \quad \frac{(0.693t)}{T_{1/2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

On this basis the activity R produced by 0.1 second irradiation in a flux of 10^9 neutrons per cm^2 per second has been calculated and is shown in Tables 1 and 2. In the case of Table 1 the flux is 10^9 thermal neutrons per cm^2 per second, in Table 2 it is 10^9 fast (14.5 Mev) neutrons per cm^2 per second.

2.5 Radioactive Decay

Having produced a certain number of radioactive atoms by the brief neutron irradiation, these radioactive atoms proceed to decay at a rate characteristic of the particular isotope. The rate equation for radioactive decay is

$$\frac{dN}{dt} = -\lambda N \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where N = number of radioactive atoms

t = time

λ = disintegration constant characteristic of the isotope considered. $\lambda = \frac{0.693}{\text{half-life}}$

A given radioactive isotope may decay by one scheme or by several schemes simultaneously.

3. MATERIALS

Manganese dioxide (Sample W)	May and Baker Laboratory Reagent grade
Quartz sand (Sample Z)	Screened and purified beach sand
Synthetic manganese ore (Sample X)	A mixture of Samples W and Z in the ratio 77.5:22.5 by weight
Manganese ore (Sample Y)	A representative sample from the Peak Hill, W.A. Material held by Amdel

The chemical analyses appear in Table 3.

A suite of lump specimens of manganese ore from MC's 24P and 26P situated at Horseshoe in the Peak Hill Goldfield of Western Australia was despatched to Amdel. These specimens were stated to represent the full range of lump material encountered in quarrying the deposits, unconsolidated surface loam and basal river sand being excluded These samples have been stored for use in lump-sorting trials if required.

4. EQUIPMENT

Neutron Source	Polonium-beryllium PDN 1C emitting 2.5×10^6 neutrons/sec on 14.2.64. Half-life of Polonium-210: 138 days.
Detector	Thallium-activated sodium iodide crystal, 2 inch dia x 1 inch, with photomultiplier, mounted in a lead castle.
Scaler	Ekco automatic

5. EXPERIMENTAL PROCEDURE AND RESULTS

5.1 Laboratory Activation of Manganese with Slow Neutrons

5.1.1 Activation

For preliminary work it was necessary to use a manganese sample of known composition and suitable shape. This was obtained by packing manganese dioxide into a plastic container (Fig. 3) of internal dimensions 2-in. dia by $\frac{1}{2}$ inch height. The bottom and the removable lid were both of $\frac{1}{16}$ inch perspex.

To simulate proposed plant practice the container was separated from the neutron source by a sample of $\frac{3}{8}$-inch thick conveyor belting. The arrangements used are shown in Figure 4 (a, b, and c). A fresh sample of manganese dioxide was used for irradiation in each of the three arrangements and the time of irradiation was 10 minutes in each case. The same face of the container was presented to both the neutron source and the scintillation crystal.

5.1.2 Detection

The radioactivity induced in the sample was measured using a 2-inch diameter by 1-inch crystal, as shown in Figure 5. The distance from the sample to the crystal corresponds to the thickness of the conveyor belting. The activities measured are given in Table 4.

As a check on the activity being measured the sample irradiated in "a" was counted several times in the course of an hour and a half. The half-life of the activity was found to be 2.7 hours (see Fig. 6) which confirms it as manganese-56 (2.59 hours). There may also be a short-lived activity present ($T_{1/2}$ = several minutes), but this has not been followed up.

The results in Table 4 show the effect of surrounding the sample with water which slows the fast neutrons from the source to thermal velocities

and scatters a considerable number back through the sample. Configuration "b" appears to be the best, the ½ inch of water between the source and belting in "c" only decreasing the geometrical efficiency.

5.1.3 Calculation of Induced Activity

It is not feasible to calculate theoretically the slow neutron flux to which the sample is exposed. Only a fraction of the neutrons emitted by the source have energies in the thermal region (see Fig. 2) but more energetic neutrons are slowed down by the moderator, which scatters neutrons back through the sample.

The only satisfactory method of determining induced activity is to carry out an irradiation and calculations will therefore be based on the measurements described in Section 5.1.2. The isotope source was emitting, at the time of the experimental work, 1.6×10^6 neutrons per second. If this neutron source in arrangement "b" were replaced by a more powerful source of the same type emitting 5×10^{10} neutrons per second, and irradiation carried out for 1 second, the count rate due to Mn^{56} would be:

$$(73\text{-}5) \times \frac{5 \times 10^{10}}{1.6 \times 10^6} \times \frac{1}{60 \times 10} = 3400 \text{ counts per second.}$$

The volume of this sample is 20 ml and the weight 51 g so that the bulk density is 2.5 whereas massive pyrolusite has a specific gravity of approximately 5.0. This sample of manganese dioxide was found by analysis to contain 54.2% Mn, so that it contains 27.6 g manganese. If this weight of manganese were present as pure pyrolusite crystals (43.7 g) occupying 8.7 ml in a 20 ml disc of siliceous rock, the remainder of the volume being quartz of sp gr 2.65, the analysis of the disc of rock would be:

Mn	37.5%
SiO_2	40.6%

These results are used in Appendix B to derive the count expected from a cube of ore irradiated and counted in motion.

5.2 Laboratory Activation of Silicon with Fast Neutrons

5.2.1 Procedure

The plastic container used previously, of internal dimensions 2 inches diameter by ½-inch height, was filled with silica sand and a piece of ⅜-inch conveyor belting laid on top. Upon this was placed a disc of 1-mm cadmium sheet to absorb thermal neutrons and the neutrons source positioned centrally on this. In one test the sample was irradiated for 11.5 minutes before counting under a 2-inch scintillation crystal, as before.

5.2.2 Results

Weight of silica sand,	g	41.2
Time of irradiation,	min	11.5

Time fron end of irradiation, min and sec:			Count Rate (counts/100 sec)
0.43	to	2.23	1275
2.30	to	4.10	1025
4.27	to	6.07	811
6.30	to	8.10	725
8.25	to	10.05	675

Mean background: counts per sec. 5.6

By graphing the net count-rate against time (Fig. 7) the half-life of the activity produced is found to be 2.55 minutes, corresponding to ^{28}Al (2.3 minutes). The net activity of the sample of silica sand extrapolated to the end of the irradiation is 12 counts per second.

The geometrical efficiency of the irradiation arrangement would be approximately 25%, and it is assumed that 18% (Fig. 2) of the 1.26×10^6 neutrons per second emitted by the source (at the date of the experimental work) had energies in excess of the 7 Mev required for the (np) reaction (Fig. 8). Moderation by the belting is ignored.

If the isotope source were replaced by a neutron generator emitting 5×10^{10} fast neutrons per second, and irradiation confined to 1 second, the expected count rate due to silicon would be -

$$12 \times \frac{5 \times 10^{10}}{0.18 \times 1.26 \times 10^6} \times \frac{1 - \exp\left(-\frac{0.693}{2.27 \times 60}\right)}{1 - \exp\left(-\frac{0.693 \times 11.5}{2.27}\right)}$$

$$= \frac{12 \times 5 \times 10^{10} \times 0.005}{0.18 \times 1.26 \times 10^6 \times 0.97}$$

$$= 1.4 \times 10^4$$

5.3 Activation of Amdel Samples with Fast Neutrons in the USA

Since a suitable fast-neutron generator was not available in Australia, Samples W, X, Y and Z were sent to the Texas Nuclear Corporation, Austin, Texas, through their Australian agents, Astronic Imports. Appendix A, which is Texas Nuclear Corporation's report on these samples, describes in detail the procedure used.

Samples weighing 7-10 g in polyethylene containers 1 inch in diameter by ½-inch deep were irradiated in a 14.5 Mev neutron flux of approximately 2.25×10^9 neutrons per cm^2 per second for a period of 2 minutes. The samples were then counted with a 3-inch by 3-inch thallium-activated sodium iodide crystal and a decay curve plotted for each (Fig. 9 and 10).

These results, and similar measurements made on standard samples, after normalising to neutron flux and correcting for Compton background and analyser dead-time, were used by Texas Nuclear Corporation to calculate the analytical results shown in Table 5.

Since the detailed data necessary to carry out the corrections on the measured count-rates are not available to Amdel, the activity produced by a

given irradiation has been estimated by taking the sample weight as 10 g, the 14.5 Mev neutron flux as 2.25×10^9 neutrons per cm^2 per second and extrapolating the decay curves in Figures 9 and 10 to t=0 (i.e. termination of irradiation).

The extrapolated count-rates are shown in Table 6.

These results are graphed in Figure 11.

For a 41.2 g sample of silica sand irradiated for 1 second the count rate would be approximately -

$$5.83 \times 10^4 \times 2 \times \frac{0.005}{0.46}$$

(increase due to 5 x larger sample, approx.) (time factor)

$= 1.3 \times 10^3$ counts/sec.

This result is a factor of 10 smaller than that deduced in Section 5.2.2. The difference is ascribable to gating of the analyser (see Appendix A).

6. DISCUSSION

6.1 Irradiation and Counting of a Moving Lump

In Appendix B an approximate expression has been derived for the count-rate expected from a cube of ore in passing in turn over a neutron source and a scintillation crystal. The count-rate obtained in actual laboratory irradiation tests has been used to obtain the constants in the expression so that the actual count expected can be estimated.

The scintillation crystal should be located at a sufficient distance from the neutron generator to allow the ^{16}N activity (from oxides present) to decay before the lump is counted.

6.2 Sorting Based on Manganese Content

The total count expected from 4-inch (10 cm) cubes of homogeneous manganese ore spaced at 10-inch (25 cm) centres can be calculated from expressions derived in Appendix B, and is as follows:

$$C = \frac{6 \times 10^{-7} \times M \times N \times 23.03}{v^2}$$

For M = 1.38 g Mn/cc, $N = 5 \times 10^{10}$ n/sec, v = 80 ft/min
C = 600 counts

Figure 12 shows the recorded count due to manganese -56 plotted against manganese content of the lumps. This value holds for neutrons from a ^{210}Po-Be source submerged in water. In practice a neutron generator using the (d-t) reactor would be used, and both the lump and the neutron source would be submerged in water to produce the maximum flux of thermal neutrons.

The counts expected for 4-inch cubes of 40% Mn and 50% Mn ore have been derived and the frequency distributions of the observed counts drawn in Figure 13. To these counts will be added a background due to activation

of siliceous gangue by fast neutrons (and, in practice, activation of other gangue elements) as well as that due to environmental radioactivity and cosmic rays. Much of the γ-ray background would be of sufficiently different energy for some separation to be made (^{28}Al(from Si), 1.78 Mev; ^{56}Mn, 0.85 Mev; etc), so that there is a reasonable chance of a sorting process. Metallurgical grade manganese ore normally assays approximately 48% Mn.

6.3 Sorting Based on Silica Content

From equation 7, Appendix B, and the count-rates obtained by Texas Nuclear Inc., $k\,k' = 3 \times 10^{-7}$, and a 4-inch cube of pure quartz would be expected to give 263 counts at a belt speed of 80 ft per minute. This is probably a conservative estimate, as the analyser was gated (see Appendix A) and a considerable number of counts were apparently lost.

The expected activity due to silica is also shown in Figure 12.

6.4 Sorting of Larger Lumps

The count recorded will be proportional to the length of the lumps, but lump width and thickness will only slightly increase the count.

6.5 Cost of Sorting

Based on the prices given in Section 2.2, the cost of running a 5×10^{10} neutron per second generator would be approximately \$A20 per hour for target alone. If 4-inch cubes of specific gravity 4.0 were spaced at 10-inch centres on an 80 ft per minute belt, the treatment rate would be 17 tons per hour, making the cost for targets \$A1.2 per ton. With 6-inch lumps the cost would be reduced to \$A0.2 per ton.

6.6 Sorting Based on X-ray Fluorescence

The principles of x-ray fluorescence analysis have been applied to the analysis of flowing streams of ore pulp at several copper concentration plants, viz. Anaconda (Lucy et al, 1963) and Palabora (Hewett-Emmett and Price, 1965, Anon, 1965). It has also been applied to the monitoring of the thickness of the tin coating on tinplate, and in a portable instrument recently developed by Hilger and Watts, to metal ore prospecting.

Apart from mechanical difficulties of presenting lumps to the sensing head, the main disadvantage of this method for controlling a lump-sorting operation is the limited penetration of the soft x-rays used. The x-ray beam would only "see" a small area of the surface and only penetrate a fraction of a millimetre so that unless each lump was very homogeneous, quite erroneous decisions would be made.

7. CONCLUSIONS

This method appears technically and economically feasible for separating manganese ore in cubes from 4 inches upwards, on the basis of manganese content. Sorting based on silica content may also be possible if the gangue is predominantly siliceous.

Following this preliminary study with stationary samples, a small belt (approximately 10 ft between pulleys) with a variable speed drive should be set up to actually convey lumps of manganese ore in turn over a neutron source and a scintillation crystal. A source similar to that used in the present work but with a greater neutron output should be used.

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APPENDIX A

REPORT ON ANALYSIS OF MANGANESE ORE SAMPLES

by Texas Nuclear Corporation, Austin, Texas
7th December, 1964

ABSTRACT

Fast neutron activation analysis techniques were employed to assay the silicon content of manganese ores. Fifteen Mev neutrons were produced by bombarding a tritium-zirconium target with 150 kev deuterons accelerated in a Texas Nuclear Corporation Model 9400 neutron generator. Representative samples weighing from 7 to 10 g each were prepared from the bulk material supplied. These samples were irradiated for 2 minutes in a flux of approximately 2×10^9 neutrons per cm^2 per second and the activity produced was compared to the activity in standard samples prepared at this laboratory. Adequate sensitivity was obtained for the silicon measurements.

TECHNICAL DISCUSSION

Samples W, X, Y and Z of manganese ores were analysed for silicon content.

The following procedure was used for the measurements. Prepared standards and portions of each ore sample were packed into polyethylene containers approximately 1 inch in diameter by ½-inch deep. The samples weighed from 7 to 10 grams each. The samples and standards were each irradiated in a fast neutron flux of approximately 2.25×10^9 neutrons per cm^2 per second for a period of 2 minutes. The neutron flux was monitored with a ½-inch x ½-inch plastic scintillator optically coupled to a 2-inch photomultiplier tube.

Instead of collecting the entire spectrum the analyser was gated to accept only pulses corresponding to the Al^{28} 1.78 Mev gamma ray. The radioisotope Al^{28} (half-life 2.3 minutes) is formed by activation of Si^{28} ($Si^{28}(n, p)Al^{28}$). The samples and standards were each activated for 2 minutes and after a 3-minute delay the 1.78 Mev activity was sequentially counted for 6-second intervals using a 3-inch x 3-inch NaI (Tl) crystal, storing each count in a different channel of the RIDL 400 channel analyser. In this manner a decay curve was obtained. The counting rate at the same time after irradiation normalized to neutron flux was taken as a quantitative measure of the silicon in each sample. Results are presented in Table A-1. Results are low due to the very high gamma ray activity of the samples. This causes a gain change in the photomultiplier tube which moves the pulses corresponding to the 1.78 Mev gamma ray past the upper level of the gate, resulting in an incorrect count. They could be corrected by using smaller samples or shorter irradiation times.

TABLE A-1

Ore Sample	% Silicon	
	Activation	Assay (Carried out by Amdel)
W	1.67	1.75
X	10.42	11.61
Y	3.79	4.22
Z	35.9	45.6

CONCLUSIONS

The silicon determinations in Samples W, X, Y and Z contain substantial errors due to the very high counting rates produced. Precision could have been improved by shorter irradiations, longer waiting periods before counting, lower neutron fluxes, or smaller samples.

APPENDIX B

IRRADIATION AND COUNTING OF A LUMP OF ORE

Consider a 1 cm cube of homogeneous manganese ore situated at any point (x, y) on a flat belt above a neutron source P which radiates isotropically[a] N neutrons per second (see Fig. B-1).

The neutron flux at the centre of the 1 cm cube is given by

$$\phi = \frac{N}{4\pi(x^2 + Y^2 + 2^2)} \text{ neutrons/cm}^2\text{/sec} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Now the manganese -56 activity induced

$$a = kM\phi\Delta t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where M = g of manganese present in 1 cm cube

and Δt is the time spent by the cube in any given position provided this is small in comparison with the half-life of manganese -56.

IRRADIATION OF MOVING CUBE

The total manganese -56 activity induced in the cube while it is carried on a fast-moving belt over the neutron source is effectively.

$$a = \int_0^\infty kM\phi \; dt \quad \text{disintegrations/second}$$

$$v \text{ (belt speed)} = \frac{dx}{dt} \text{ (cm/sec)}$$

$$a = \frac{kM}{v} \int_{-\infty}^{\infty} \phi \; dx$$

$$\frac{kMN}{4\pi v} \int_{-\infty}^{\infty} \frac{dx}{x^2 + (y^2 + 4)}$$

(a) This flux distribution for the case of fast neutron irradiation is assumed for slow neutron distribution. The difference (see Cook and Duncan, 1952, Fig. 5.1, p 203) will not appreciably affect the final results of these calculations.

$$= \frac{kMN}{4\pi v\sqrt{y^2+4}} \left[\tan^{-1}\left(\frac{x}{\sqrt{y^2+4}}\right)\right]_{-\infty}^{\infty}$$

$$= \frac{kMN}{4\pi v\sqrt{y^2+4}} \left[\frac{\pi}{2} + \frac{\pi}{2}\right]$$

$$= \frac{kMN}{4v\sqrt{y^2+4}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Values of $\frac{1}{4\sqrt{y^2+4}}$ are graphed in Figure B-3, which thus presents the distribution of activity across the width of a 1 cm-thick slab of ore after passing over the neutron source.

COUNTING OF A MOVING CUBE

The count-rate expected from the cube at any instant in passing over a scintillation crystal further along the belt is given by

$$C = k' a E \text{ counts per second} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where E is the geometrical efficiency, i. e. the fraction of the gamma-rays emitted by the cube which pass through the crystal. The arrangement is shown in Figure B-2. E was estimated as a function of horizontal distance from the centre of a 3-inch scintillation crystal by means of a geometrical construction. In principle, the elliptical cone of rays reaching the crystal face from a point source at the centre of the cube was approximated by a circular cone, and the geometrical efficiency calculated as the ratio of the volume of the cone to the volume of the whole sphere of rays. Values of E are graphed in Figure B-4.

If the cube is counted over a belt displacement of $2x_1$ cm (x_1 cm on either side of the centre of the crystal) the total count will be

$$C = \int_{t_1}^{t_2} c \, dt \quad \text{counts}$$

$$v = \frac{dx}{dt}$$

$$C = \int_{-x}^{+x_1} \frac{c}{v}\, dx$$

$$= \int_{-x_1}^{+x_1} \frac{k' a E}{v}\, dx$$

$$= \frac{k' k MN}{\left\{4\sqrt{y^2 + 4}\right\} v^2} \int_{-x_1}^{x_1} E\, dx \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

This must be integrated graphically and Figure B-5 shows, for integral values of x and y

i. in the upper l.h. quadrant - values of the horizontal distance from the centre of the crystal

ii. in the upper r.h. quadrant - values of 10^3 E

iii. in the lower l.h. quadrant - values of $\frac{10^4 E}{4\sqrt{y^2 + 4}}$

For a given value of y the integral $\frac{1}{4\sqrt{y^2 + 4}} \int_{-x_1}^{x} E\, dx$

can be found from the point-values shown in Figure B-5. The volume under the surface is then obtained by integrating the "slices" graphically in the y-direction.

Considering 10 cm cubes of homogeneous ore spaced at 25 cm centres, the scaler being re-set and restarted as the leading edge of one cube crosses the line at $-x_1$ in Figure B-5, and the trailing edge of the preceding cube crosses the line $+x_1$, the count registered in the distance $2x_1$ is obtained as follows:

y =	± 5	± 4	± 3	± 2	± 1	0
Column Sum ($-x_1$ to x_1)	712	1039	1711	2606	3690	4222
x10 cm	7120	10390	17110	26060	36900	42220

These are the cross-sectional areas of vertical slices parallel to the x-axis. The volume under the surface is now found by means of Simpson's rule to be 230, 250 cm^3, and on multiplication by 10^{-4} to restore the decimal point, 23.03 cm^3.

STATIONARY DISC OF ORE

For a stationary disc of ore 1 cm thick, irradiated directly over the source for t seconds, the activity induced in a 1 cm cube is given by equations (1) and (2).

i.e. $$a = \frac{kMN}{4\pi (x^2 + y^2 + 2^2)} \Delta t$$

putting $y = 0$ $$a = \frac{kMN}{4\pi (x^2 + 4)} \Delta t$$

The count-rate obtained is given by

$$C = k' a E \text{ counts per second}$$

$$= \frac{k\, k'MN\, E}{4\pi (x^2 + 4)} \Delta t \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The count-rate obtained from the whole disc is given by the volume of revolution swept out by the curve

$$C = \frac{k\, k'MN}{4\pi} \frac{E}{(x^2 + 4)}$$ multiplied by the time of irradiation

From Figure B-6

$$\text{Volume} = 1.034$$

$$\therefore \text{Count-rate} = \frac{k\, k'MN.1.03.t}{4\pi} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

For the laboratory experiment described in Section 5.1.2.

$$M = 1.38 \text{ g/cm}^3$$

$$N = 1.6 \times 10^6 \text{ (with characteristic } ^{210}\text{Po-Be spectrum)}$$

$$C = 73-5 = 68 \text{ counts/sec}$$

$$t = 10 \text{ min}$$

i.e. $$\frac{k.k'.1.6 \times 10^6.1.38.1.03.10.60}{4\pi} = 68$$

Hence $$k\, k' = 6 \times 10^{-7}$$

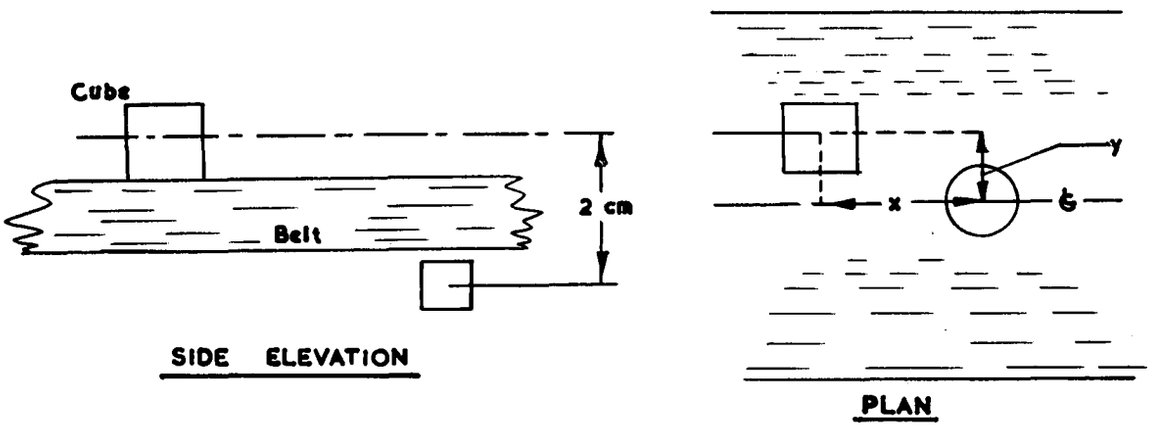


FIG. B-1: IRRADIATION OF MOVING 1 cm CUBE
Diagrammatic

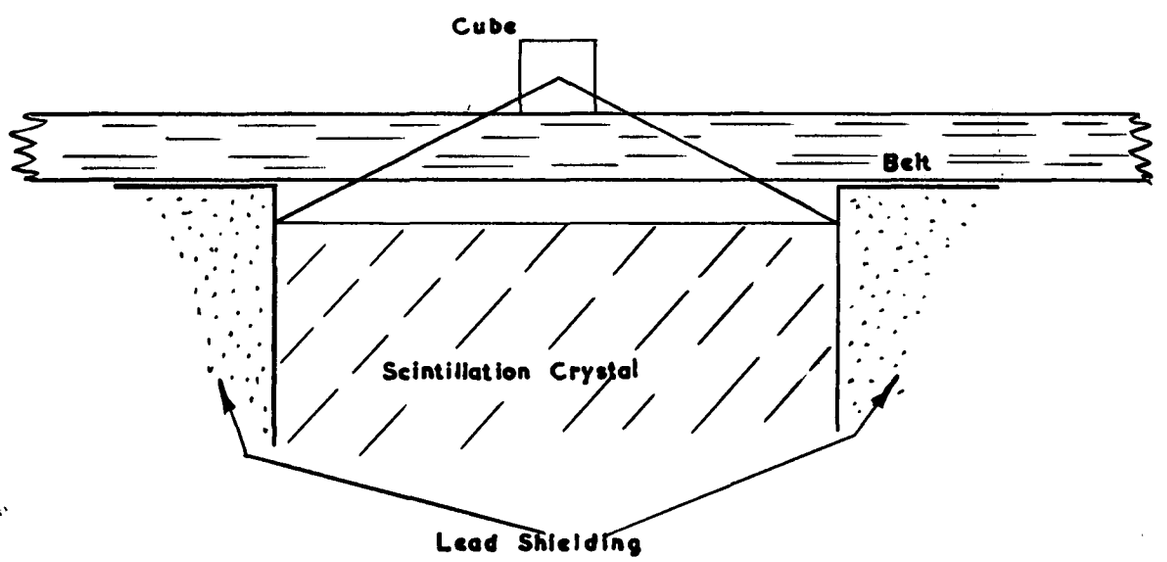


FIG. B-2: COUNTING OF MOVING 1 cm CUBE
Diagrammatic

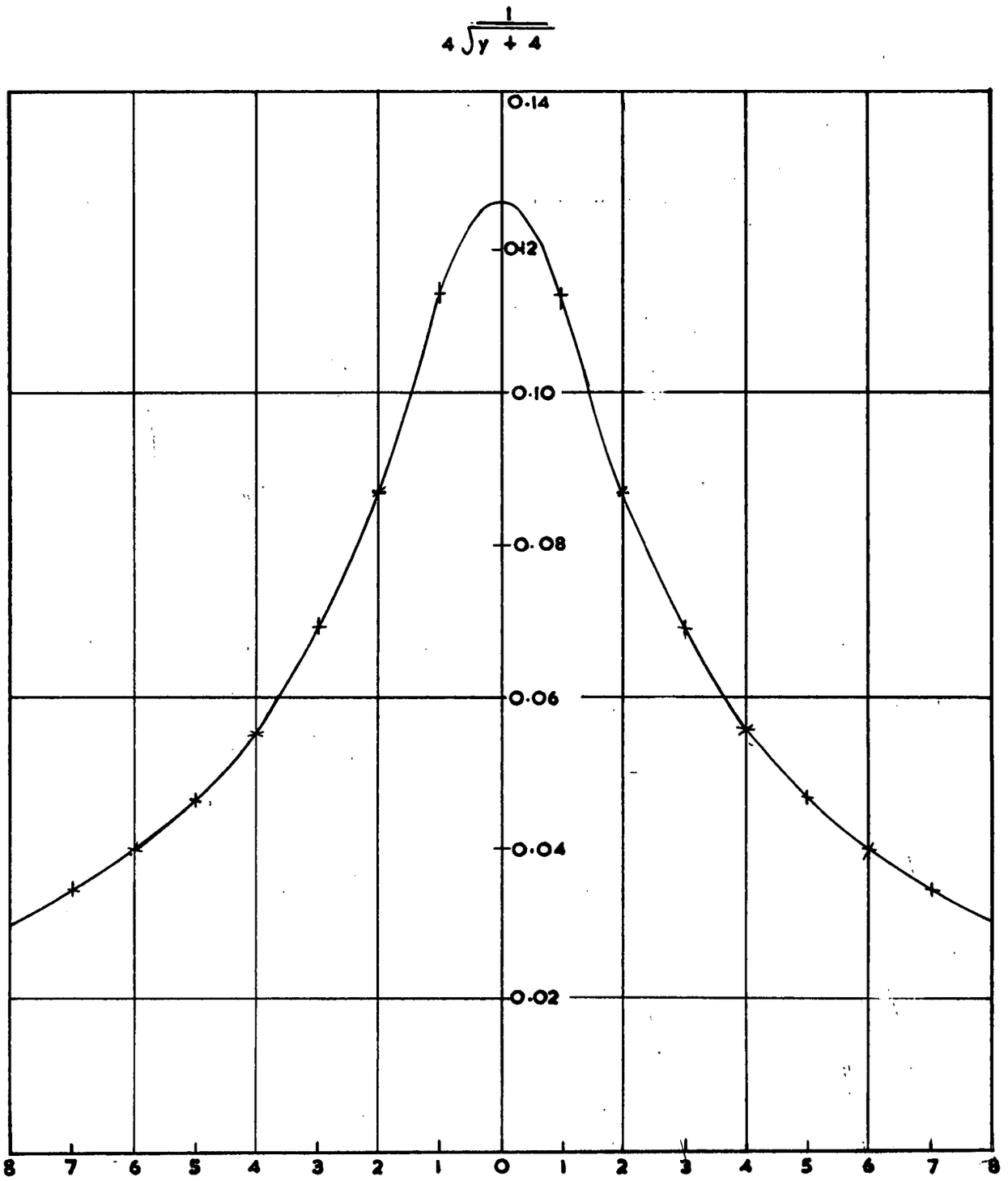


FIG. B-3: GRAPH OF $\frac{1}{4\sqrt{y^2+4}}$ AS A FUNCTION OF y

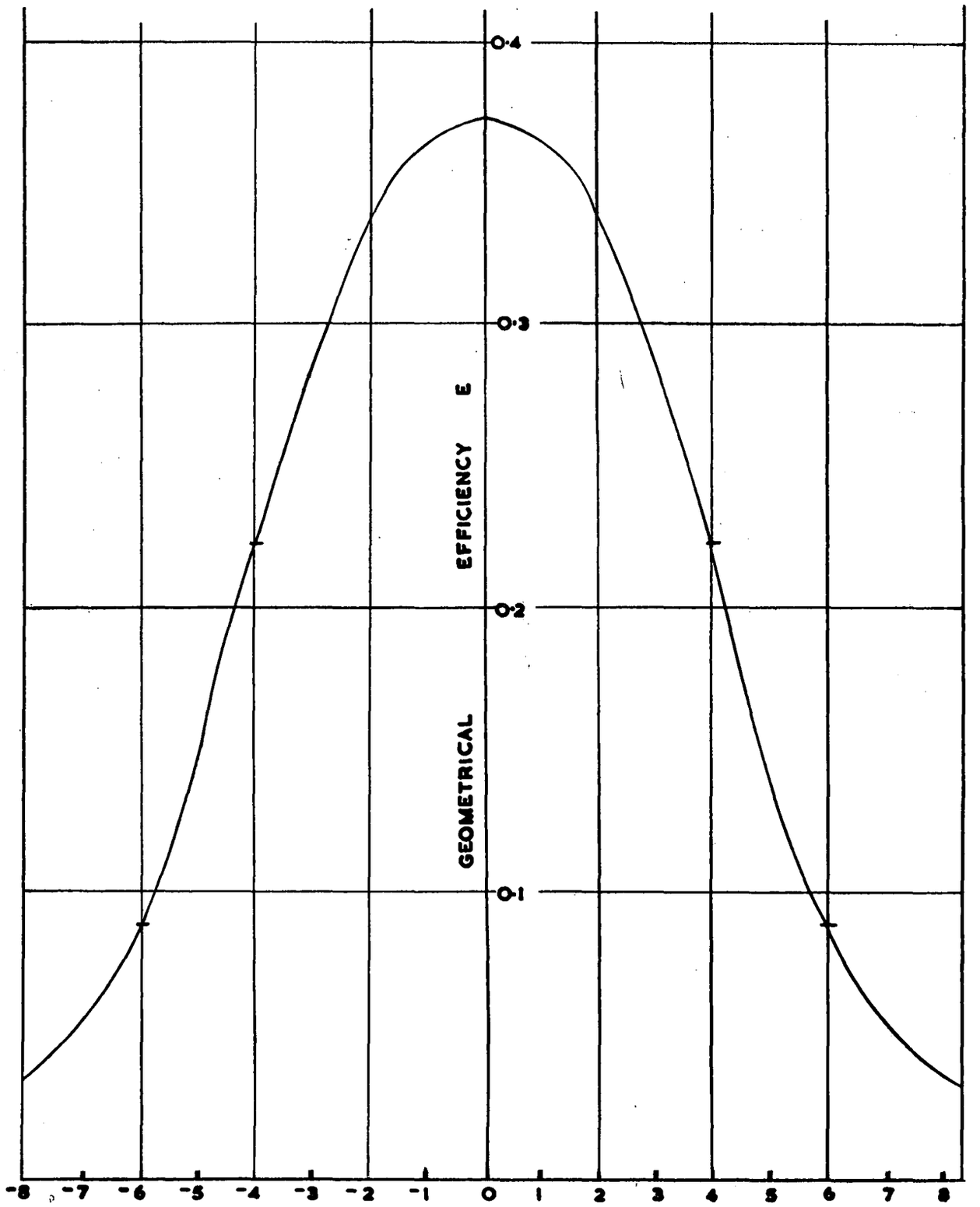


FIG. B-4: GEOMETRICAL EFFICIENCY

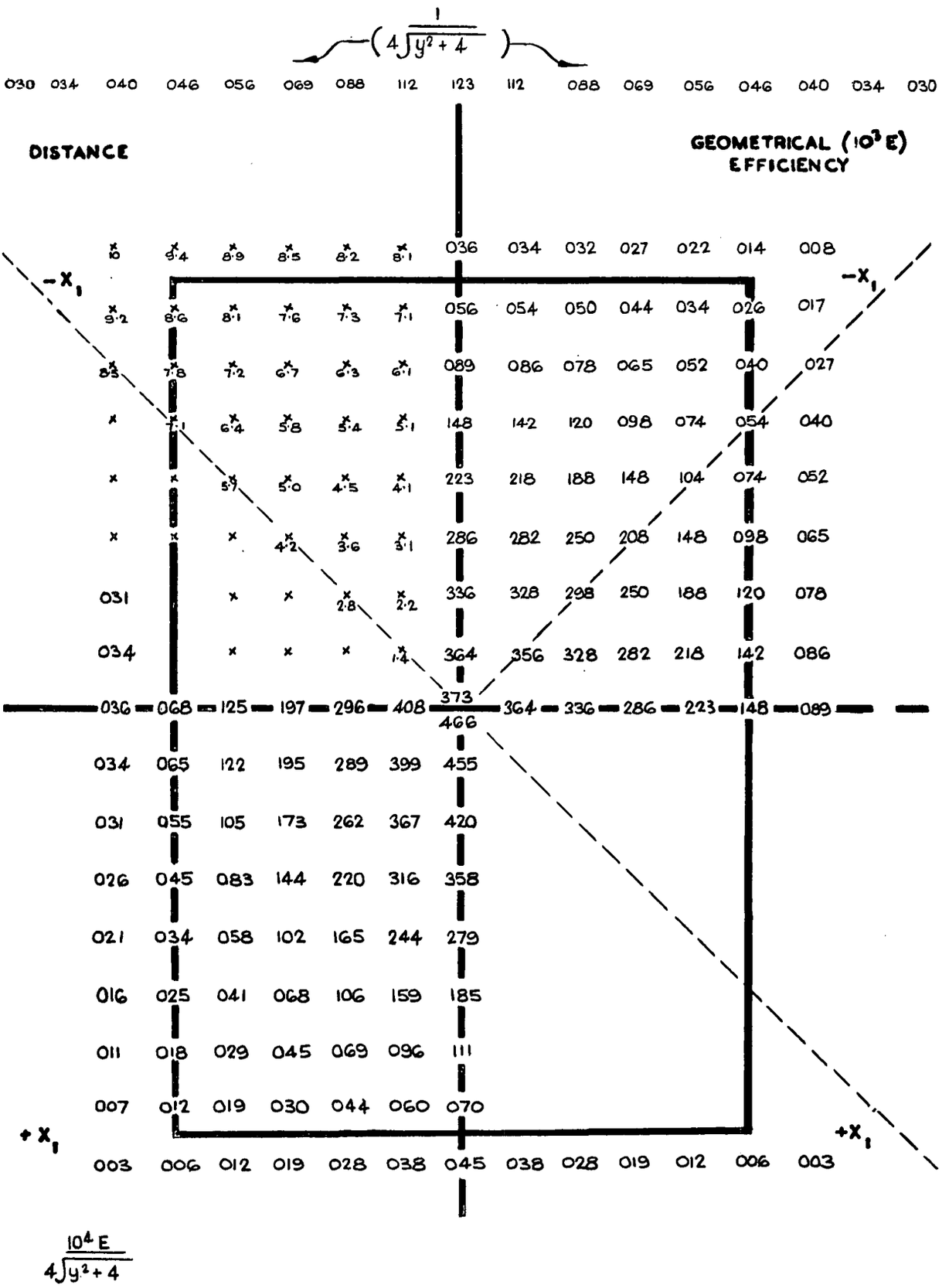


FIG. B-5: COUNTING OF IRRADIATED CUBE IN MOTION

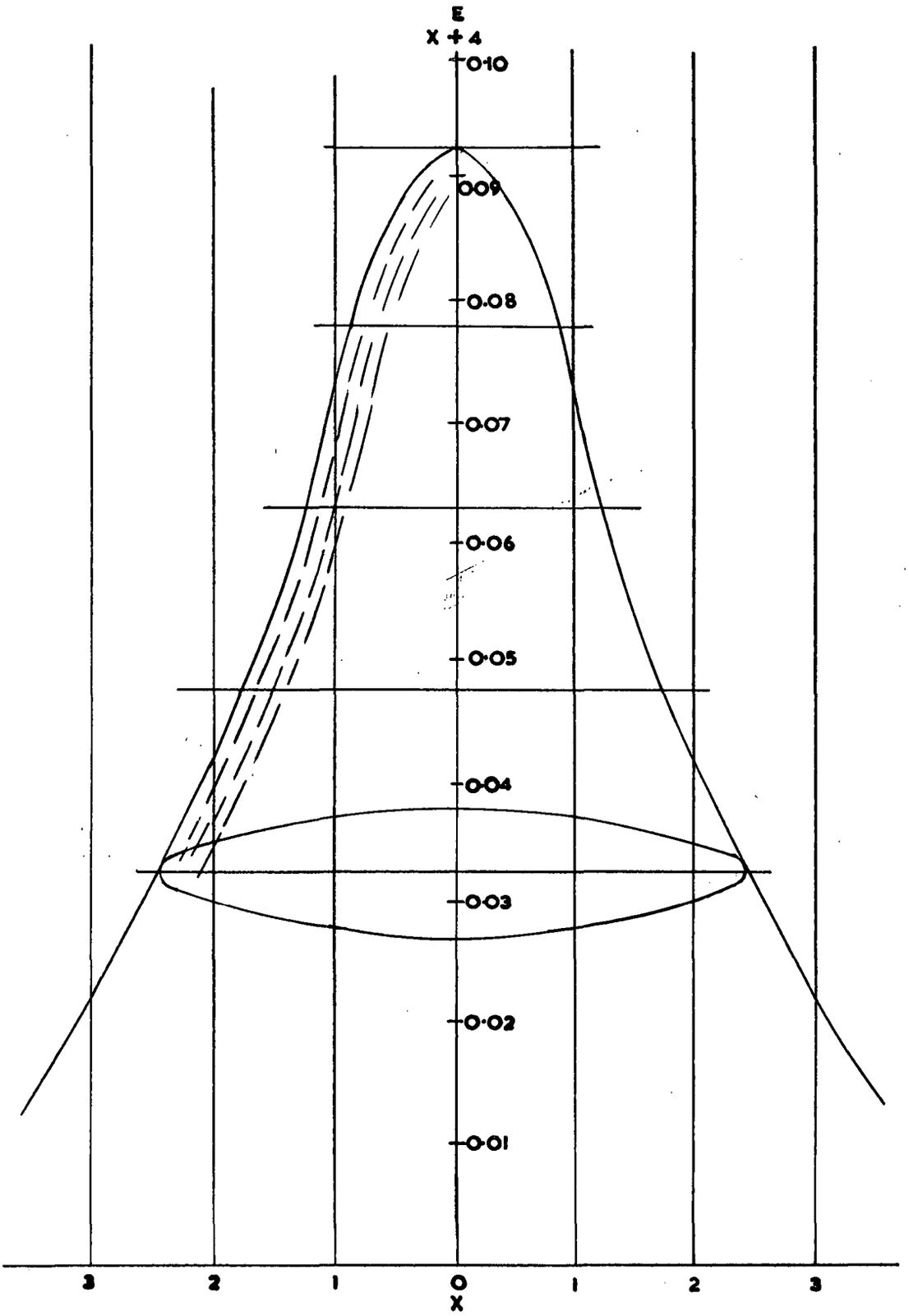


FIG. B-6: GRAPH OF $\frac{E}{x^2 + 4}$

TABLES 1 TO 6

FIGURES 1 TO 13

TABLE 1: NUCLEAR REACTIONS PRODUCED IN MANGANESE ORE BY THERMAL NEUTRONS
Derived, in part, from Taylor, D. (1964)

Reaction	Isotopic Capture Cross Section σ barns	% Abundance F	Half-life $T_{1/2}$	Activity(a) Produced	Gamma Radiation Mev	Other Radiation Mev
$^{30}Si(n,\gamma)^{31}Si$	0.110	3.13	2.62 hr	0.56	1.26 (0.07%)	β^- 1.4 (100%)
$^{55}Mn(n,\gamma)^{56}Mn$	13.3	100	2.58 hr	1090	0.845 (99%) 1.81 (24%) 2.12 (15%) 2.52, 2.66, 2.96, and 3.39 (all weak)	β^- 0.33 (1%) 0.75 (15%) 1.05 (24%) 2.86 (60%)
$^{54}Fe(n,\gamma)^{55}Fe$	2.5	5.81	2.60 yr	0.013	0.0059 Mn x-rays	100% E.C.

(a) Activity, calculated using equation (2) and expressed as disintegrations per second per gram of the whole element in the sample, produced by 0.1 second irradiation in a flux of 10^9 thermal neutrons per cm^2 per second.

TABLE 2: NUCLEAR REACTIONS PRODUCED IN MANGANESE ORE BY 14.5 Mev NEUTRONS
Derived, in part, from Gillespie and Hill (1961)

Reaction	Isotopic Capture Cross Section barns	% Abundance[a] F	Half-life $T_{1/2}$	Activity[b] Produced	Gamma Radiation Mev	Other Radiation Mev
^{16}O (n, p)^{16}N	0.09	99.76	7.3 sec	32,080	6.13, 7.13	β^- 10.4 (28%) 4.39 (54%) 3.32 (18%)
^{28}Si (n, p)^{28}Al	0.22 ± 0.05	92.16	2.27 min	2,210	1.78 (100%)	β^- 2.87 (100%)
^{29}Si (n, p)^{29}Al	0.10 ± 0.03	4.71	6.56 min	17.8	2.43 (15%) 1.28 (85%)	β^- 2.5 (70%) 1.4 (30%)
^{30}Si (n, α)^{27}Mg	0.080± 0.016	3.13	9.45 min	6.56	0.843(70%) 1.015(30%)	β^- 1.75 (58%) 1.59 (42%)
^{55}Mn(n, α)^{52}V	0.030± 0.012	100	3.76 min	101	1.43 (100%)	β^- 2.47 (100%)
^{56}Fe(n, p)^{56}Mn	0.110± 0.010	91.64	2.58 hr	8.11	0.085, 1.81, 2.13	β^- 2.81 (50%) 1.04 (30%) 0.65 (20%)

(a) After Taylor (1964).

(b) Activity, calculated using equation (2) and expressed as disintegrations per second per gram of the whole element in the sample, produced by 0.1 second irradiation in a flux of 10^9, 14.5-Mev neutrons per cm^2 per second.

TABLE 3: CHEMICAL ANALYSES

		Sample			
		W	X	Y	Z
Manganese	Mn	54.2	42.0	30.0	nd[a]
Iron	Fe	0.74	0.6	19.2	nd
Silica	SiO_2	3.74	24.9	9.05	97.8
Aluminium oxide	Al_2O_3	nd	nd	3.9	nd
Calcium oxide	CaO	nd	nd	0.085	nd
Magnesium oxide	MgO	nd	nd	0.03	nd
Phosphorus pentoxide	P_2O_5	nd	nd	0.12	nd

(a) nd - Not determined.

TABLE 4: MEASUREMENT OF INDUCED ACTIVITY

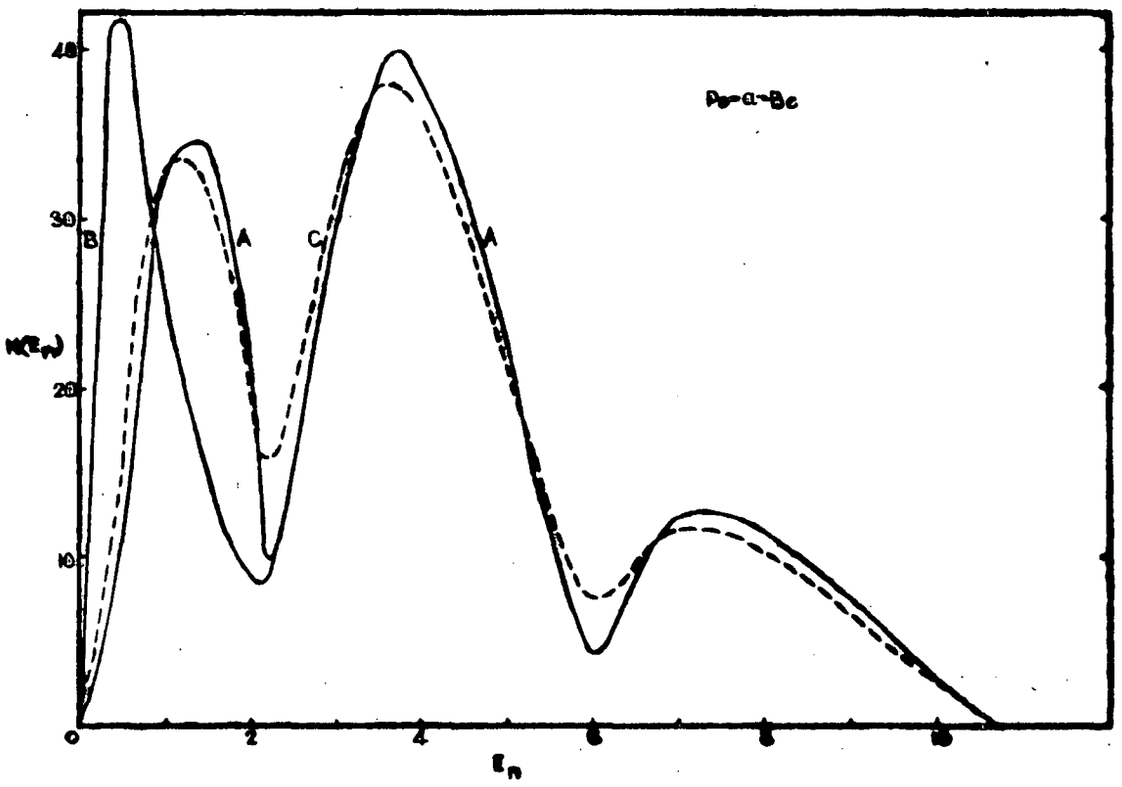
	Irradiation Arrangement (Fig. 4)		
	a.	b.	c.
Weight of manganese dioxide, g	48	51	51
Time interval between end of 10 minutes' irradiation and commencement of counting, min	5	2	4
Counts recorded in 300 sec	5199	21,555	18,748
Counts per second	17.3	71.9	62.5
Background, counts/sec	5.1	4.9	4.9
Gross count rate at end of irradiation (by extrapolation), counts/sec	18	73	64

TABLE 5: RESULTS OF ACTIVATION ANALYSIS
Using 14.5 Mev Neutrons

Sample	% Silicon	
	Activation Analysis	Assay
W	1.67	1.75
X	10.42	11.61
Y	3.79	4.22
Z	35.9	45.6

TABLE 6: ACTIVATION OF SILICON WITH 14.5 Mev NEUTRONS
Extrapolated Count-Rates

Sample	Si Content	Count-Rate Extrapolated to t = O	
	%	cpm	cps
W	1.75	1.75×10^5	2,900
X	11.61	1.13×10^6	18,800
Y	4.22	4.1×10^5	6,850
Z	45.6	3.5×10^6	58,300

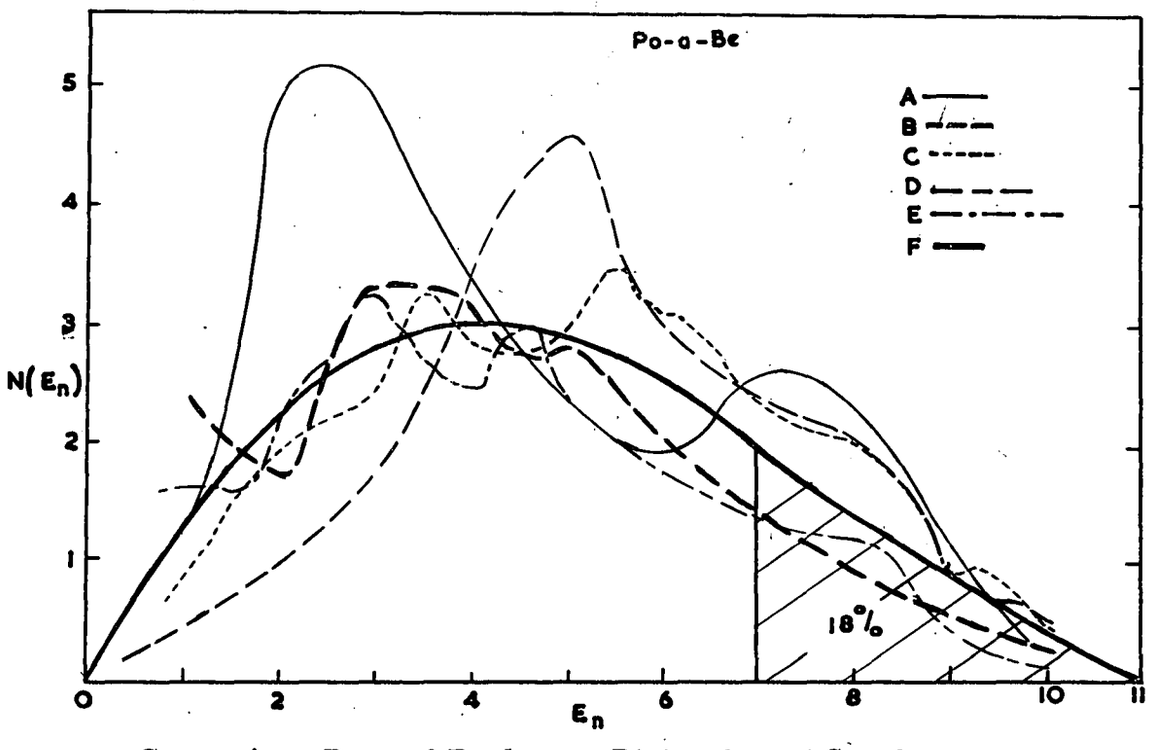


Curve A. Calculated spectrum assuming C^{12} energy levels of 0 Mev, 4.43 Mev and 7.65 Mev enter into the reaction.

Curve B. Calculated spectrum assuming C^{12} energy levels of 0 Mev and 4.43 Mev and also three-body break-up of C^{13} enter into the reaction.

Curve C. Calculated spectrum using assumptions of Curve A as modified by neutron scattering in the source.

FIG. 1: CALCULATED NEUTRON ENERGY SPECTRUM FOR A Po-Be SOURCE
After Hess, 1957



Curve A. Data of Perlman, Richards and Speck
Curve B. Data of Cochran and Henry
Curve C. Data of Elliott, McGarry and Faust.
Curve D. Data of P. Demers
Curve E. Data of Whitmore and Baker
Curve F. Approximate smoothed mean of above results

FIG. 2: MEASURED NEUTRON ENERGY SPECTRA FOR A Po-Be SOURCE
After Hess, 1957

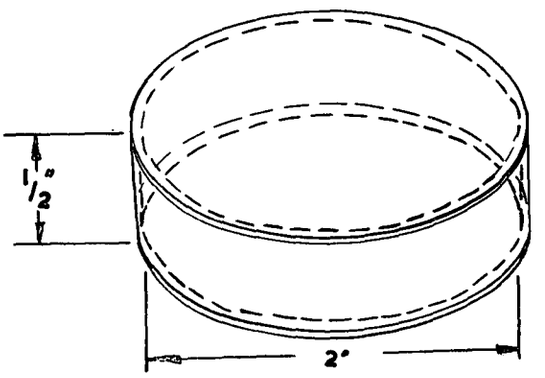


FIG. 3: SAMPLE CONTAINER
Actual Size

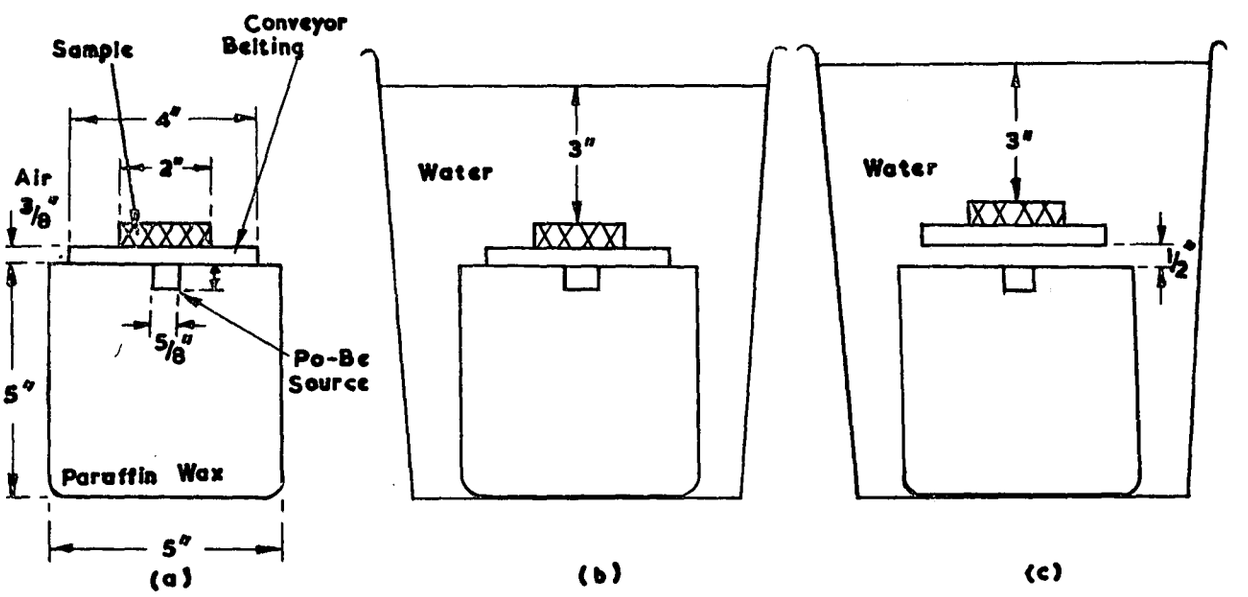


FIG. 4: IRRADIATION ARRANGEMENT
One-quarter Actual Size

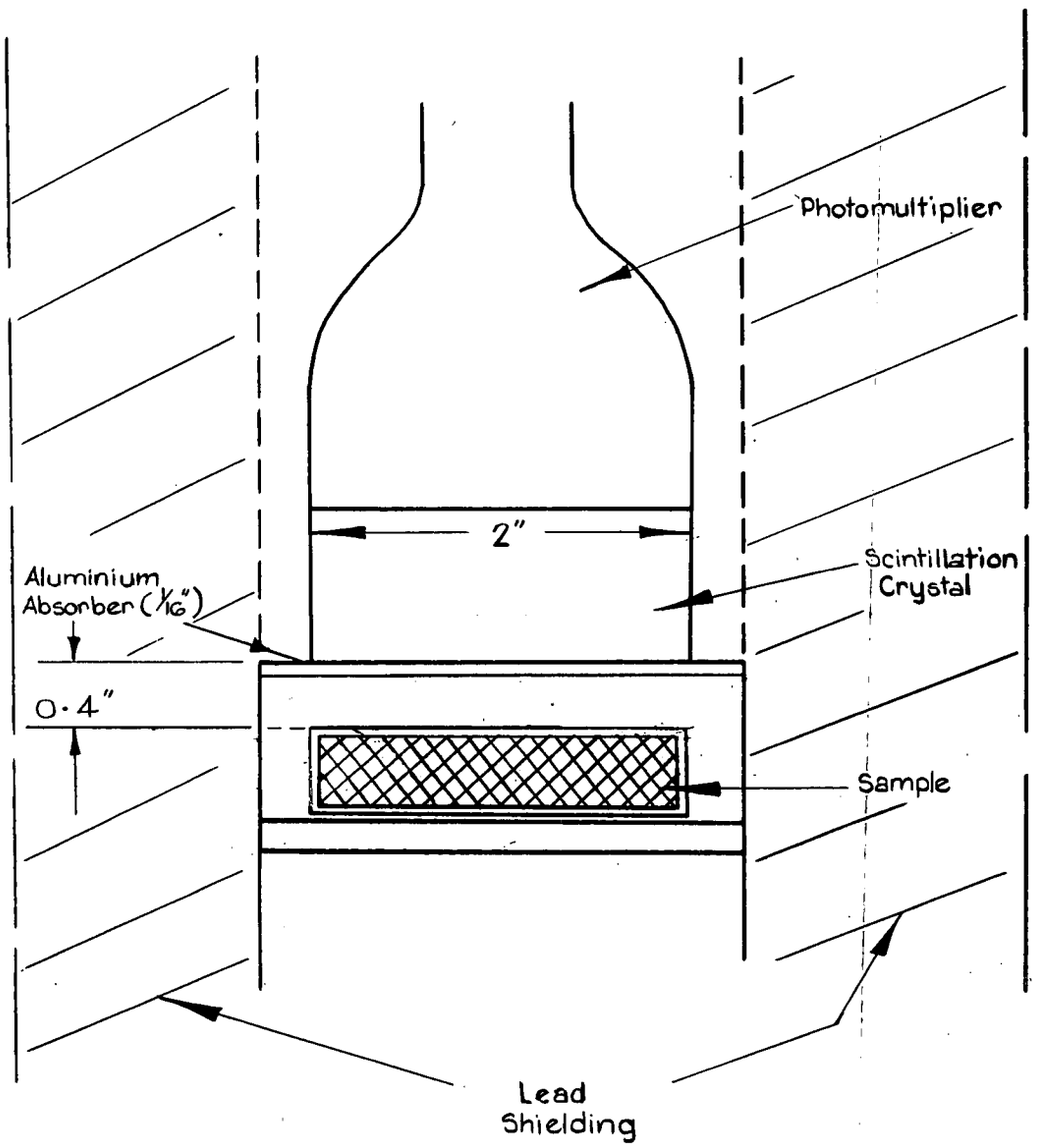


FIG. 5: DETECTION ARRANGEMENT
Actual Size

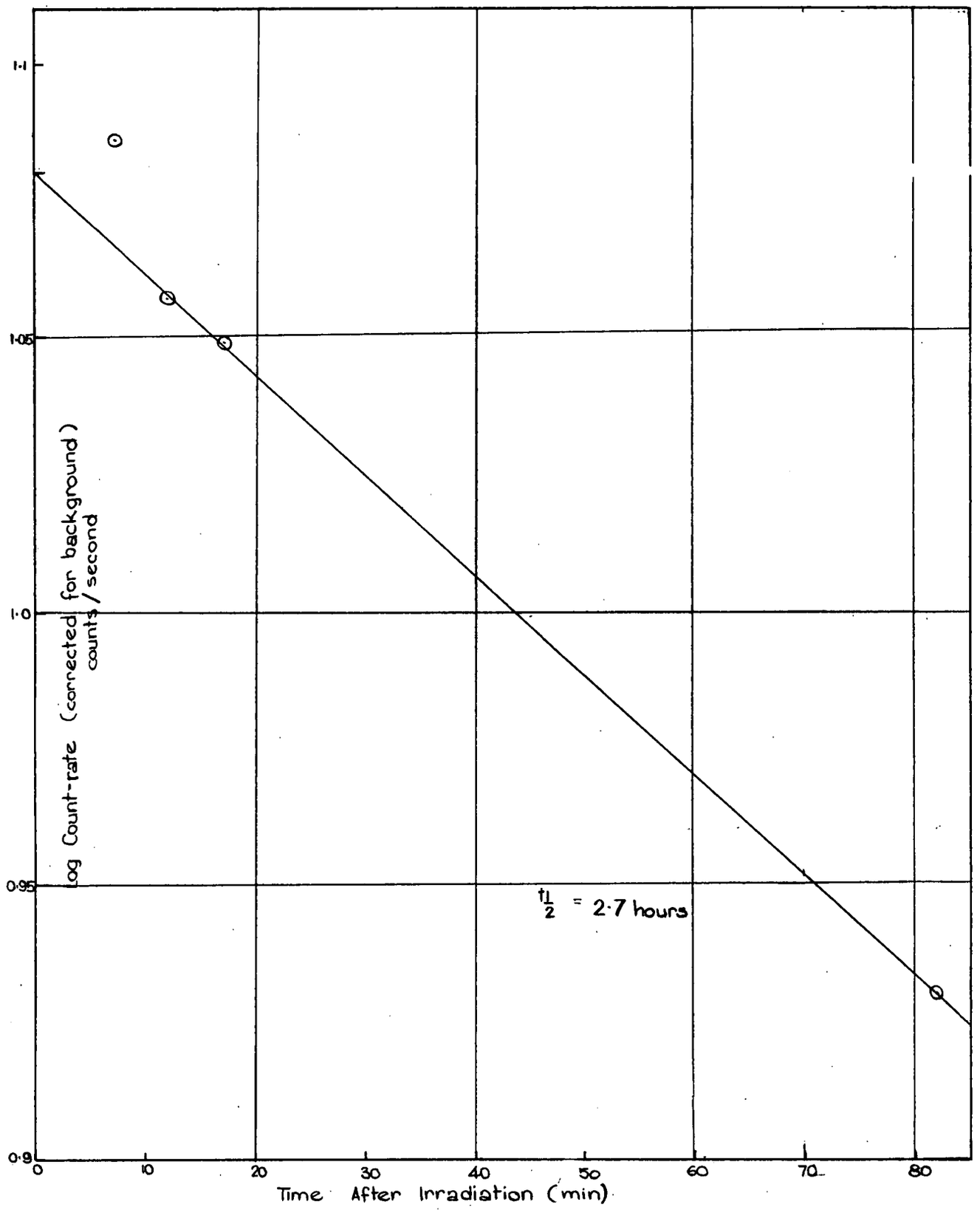


FIG. 6: DECAY CURVE OBTAINED FOR IRRADIATED MANGANESE DIOXIDE SAMPLE

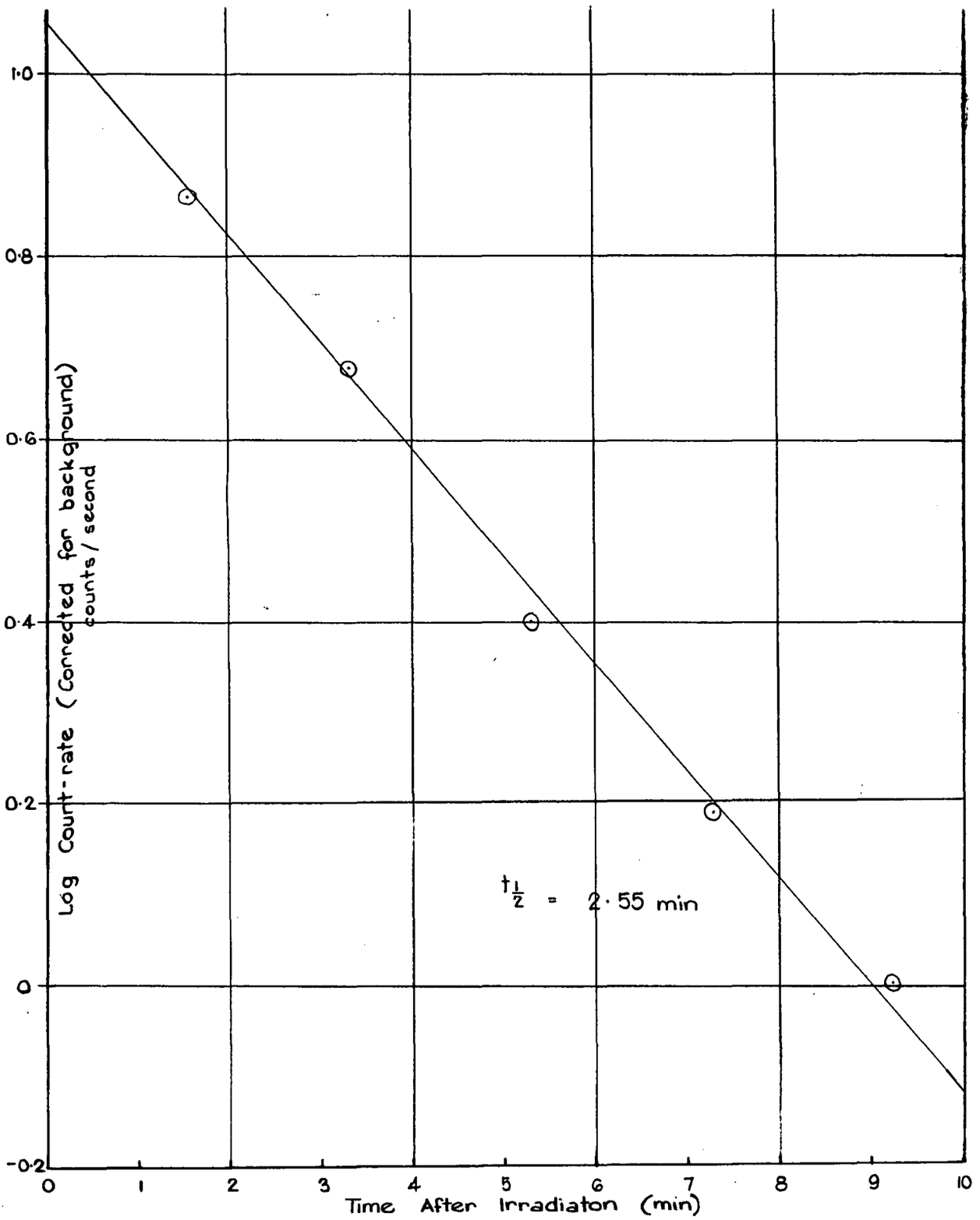


FIG. 7: DECAY CURVE OBTAINED FOR IRRADIATED SILICA SAND SAMPLE

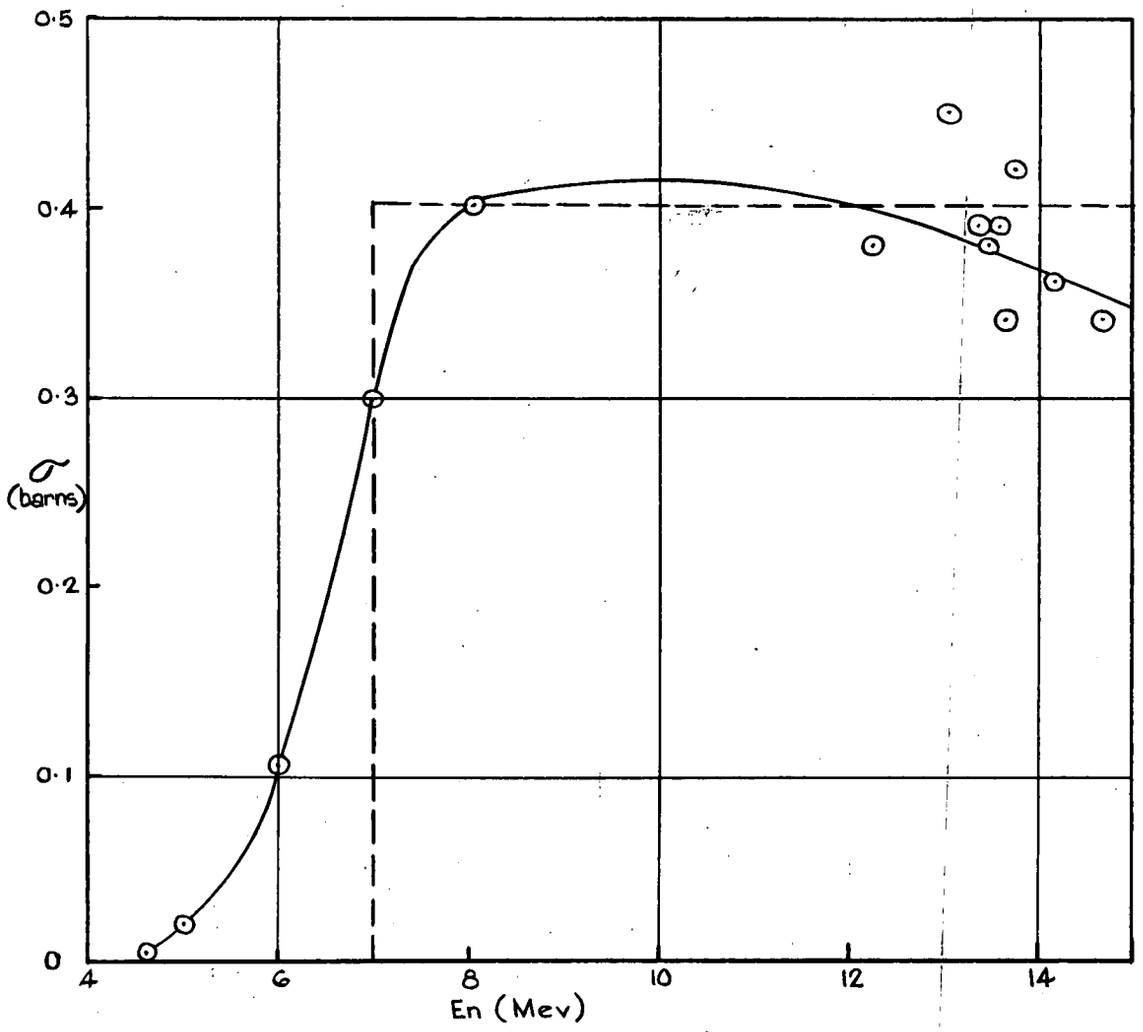


FIG. 8: REACTION CROSS-SECTION AS A FUNCTION OF NEUTRON ENERGY
Reaction: $_{14}Si^{28}$ (n, p) $_{13}Al^{28}$
Drawn from data of Howerton (1959)

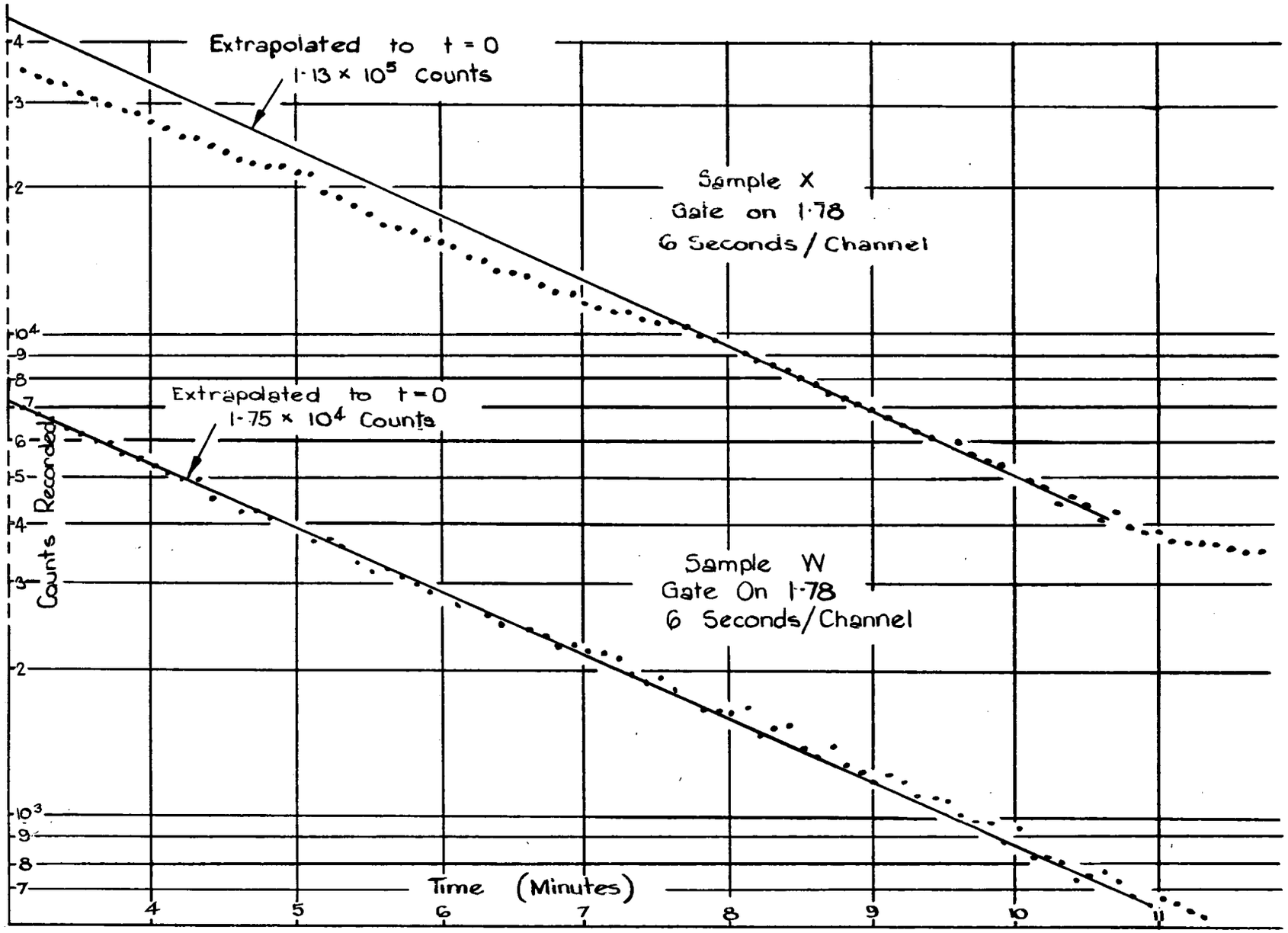


FIG. 9: SILICON TIME SPECTRA FOR SAMPLES W AND X

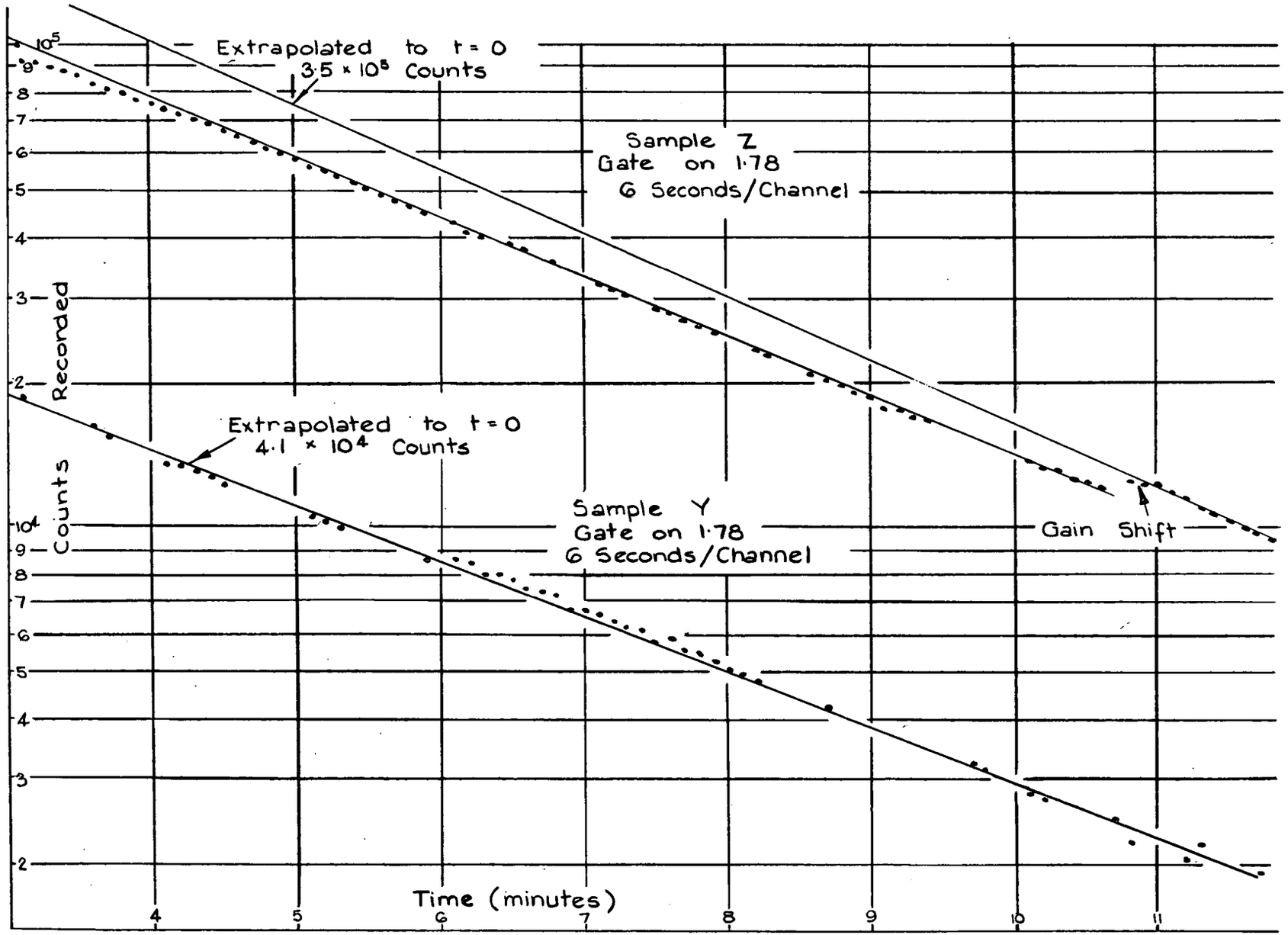


FIG. 10: SILICON TIME SPECTRA FOR SAMPLES Y AND Z

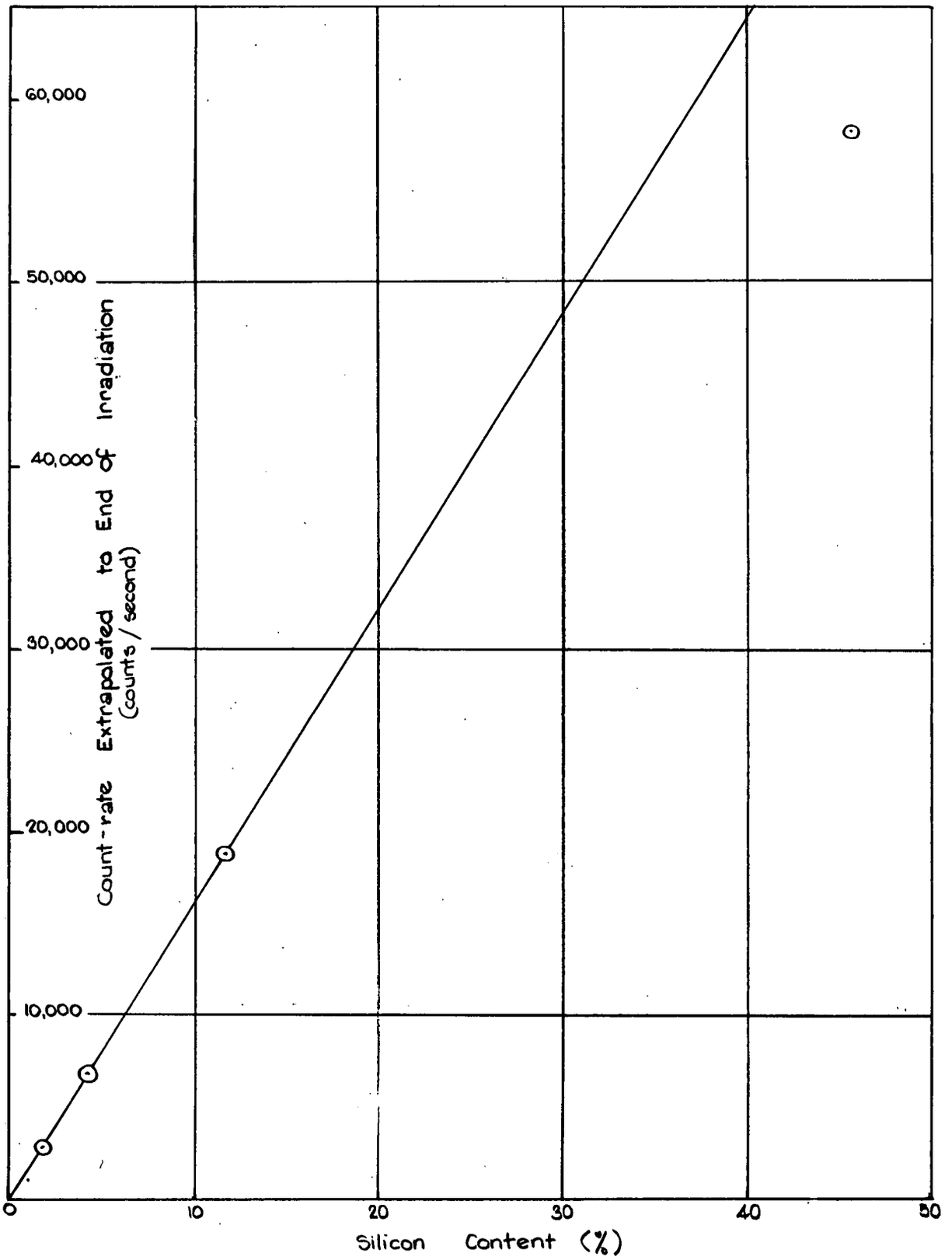


FIG. 11: ACTIVITY DUE TO SILICON INDUCED BY IRRADIATION WITH 14.5 Mev NEUTRONS

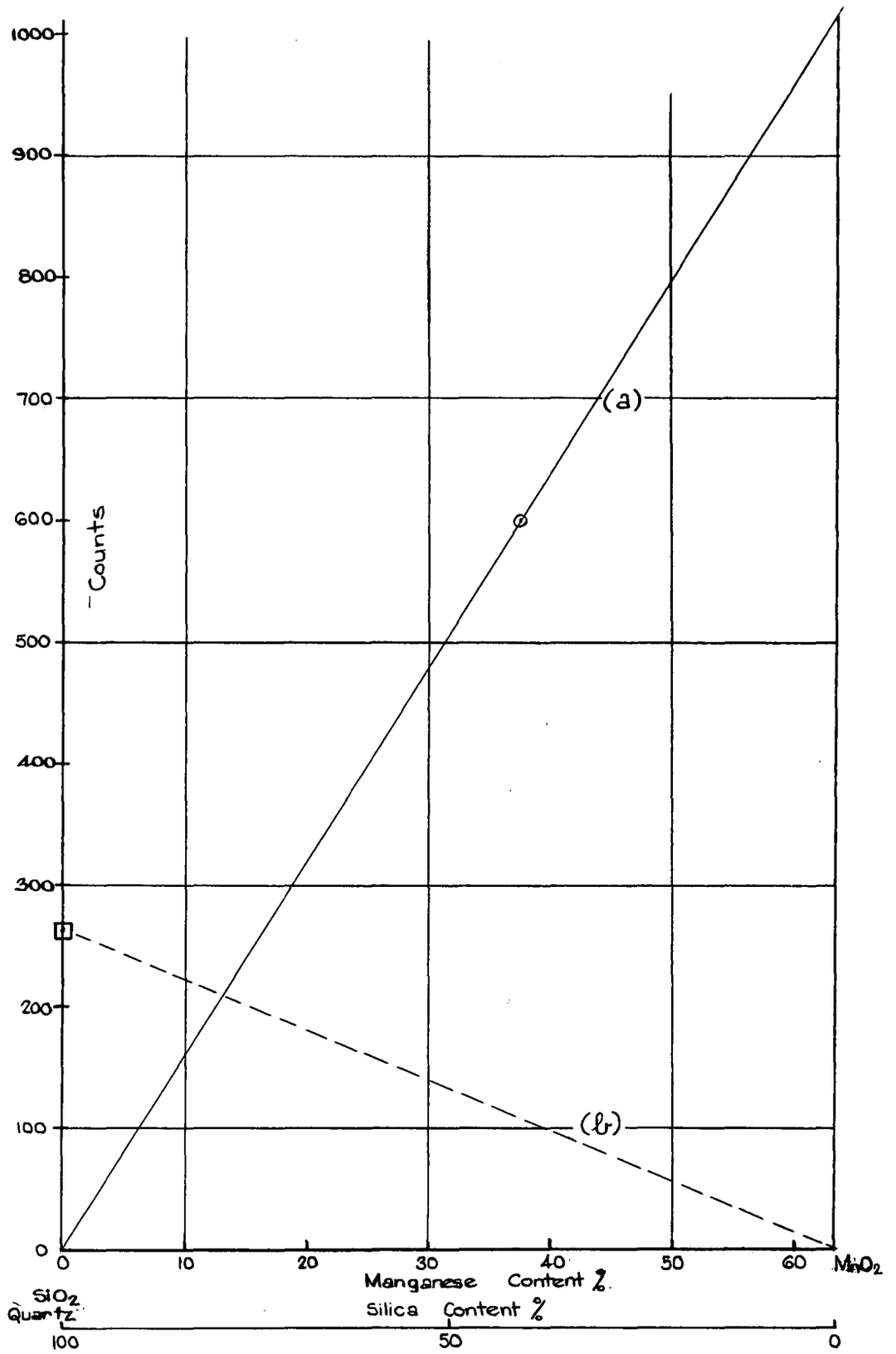


FIG. 12: COUNTS EXPECTED DUE TO:
a. MANGANESE CONTENT
b. SILICON CONTENT

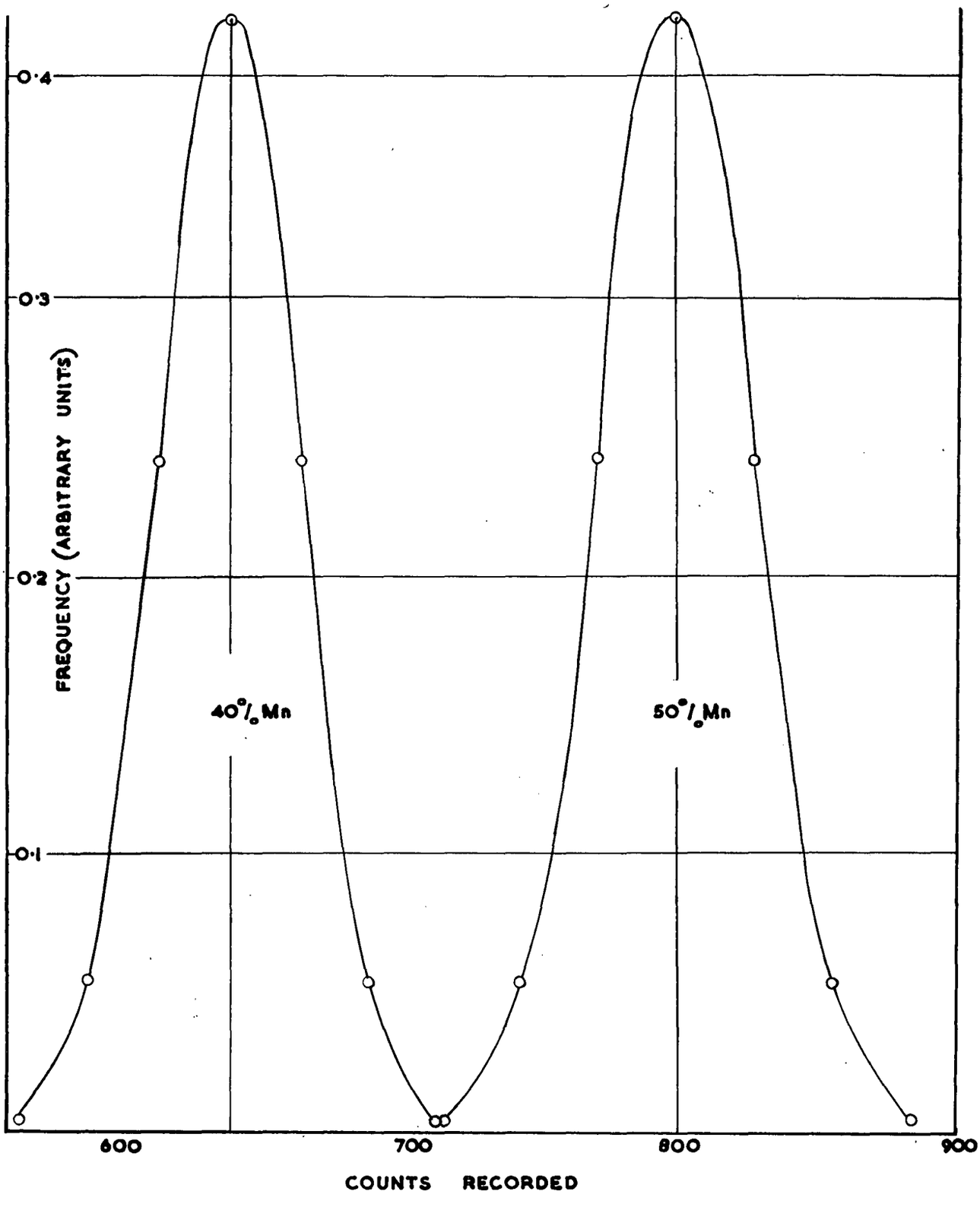


FIG. 13: FREQUENCY DISTRIBUTIONS OF EXPECTED COUNTS