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Kelly, John J., Jr.; Clements, Neal W.

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DETERMINATION OF THERMAL NEUTRON FLUX BY ACTIVATION OF A PURE TARGET WITH KNOWN CROSS SECTION

JOHN J. KELLY, JR.
and
NEAL W. CLEMENTS

UNITED STATES
NAVAL POSTGRADUATE SCHOOL

THESIS

DETERMINATION OF THERMAL NEUTRON FLUX

BY ACTIVATION OF A PURE TARGET

WITH KNOWN CROSS SECTION

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by

John J. Kelly, Jr.
Lieutenant Colonel, Corps of Engineers, United States Army

and

Neal W. Clements
Lieutenant Commander, Civil Engineer Corps, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
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Monterey, California

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This work is accepted as fulfilling
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ABSTRACT

The thermal neutron flux in a reactor may be determined by activation of a pure target of known cross section. Gold foils were irradiated in the core of the AGN-201 reactor and from the absolute disintegration rate the thermal flux at the core center was determined to be 5.31×10^6 neutrons per square centimeter per second, maximum, at a nominal power level of 100 milliwatts.

The previous determination of the thermal flux by the manufacturer using a comparison method and a polonium-beryllium neutron source gave a value of 4.5×10^6 neutrons per square centimeter per second at the same power level.

The writers wish to express their appreciation to Professor William W. Hawes of the U. S. Naval Postgraduate School for his assistance and encouragement during this investigation.

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LIST OF ILLUSTRATIONS

1. INTRODUCTION

Methods of absolute flux determination by activation of pure targets with known cross section are described by Raffle (1), Greenfield (2) and Sanford and Nicoll (3) using both gold and indium foils. Flux determinations have also been made by a comparison method using foils which were irradiated in a known flux. The accuracy of this latter method depends primarily on how well the known flux can be established.

Greenfield counted the induced beta activity in indium foils and claims a precision of 5%. Although indium has a number of characteristics which make it suitable for use as a target material such as a large thermal cross section, a large and uncertain self-absorption correction is necessary for a foil of sufficient thickness. Both Raffle, and Sanford and Nicoll used beta-gamma coincidence counting with gold foils and claim precisions of 1% and 3% respectively.

Gold is an excellent target material and was chosen for this investigation for the following reasons:

a. It has a single isotope with a large thermal cross section.

b. The cross section varies closely as 1/v in the range of thermal energies.

c. It has a simple decay scheme and lends itself well to gamma radiation counting.

d. It is readily available in pure form and is chemically stable.

e. The produced activity decays with a half life of 2.7 days permitting reasonable counting times and decay corrections.

With gamma counting, as compared to beta counting, no large self-absorption correction enters; moreover, through the employment of a

scintillation detector with appropriate counting technique, estimation of absolute detection efficiency is possible from the geometry of the sample-phosphor arrangement.

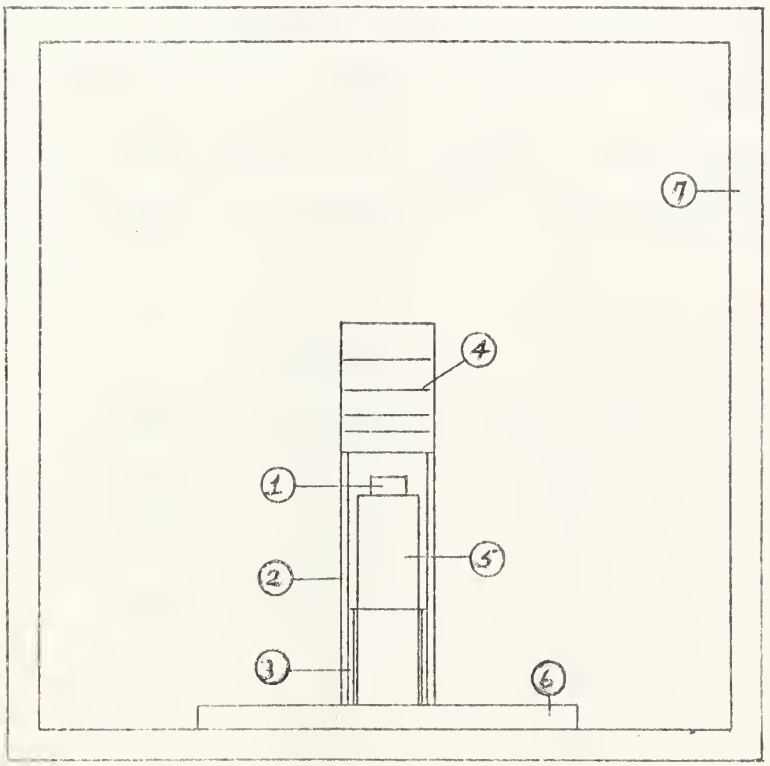
2. EXPERIMENTAL

Circular gold foils with an average thickness of 11.5 mils and diameter of $\frac{1}{2}$ inch were irradiated at the center of the core of the AGN-201 reactor. By using a sample-carrier rod, each foil was introduced at the same position in the core with a placement accuracy of 1 millimeter. The core is homogeneous and is 25 centimeters in diameter. The foil was introduced after the reactor had reached full power and removed under the same condition. Each foil was irradiated at the same power level to within an accuracy of 2%. Time was measured to within an accuracy of 1 minute for a nominal 4 hour irradiation time.

The activity of the irradiated foils was determined by measurement of gamma emission over a spectrum of energies from 0 to 1.6 Mev. The detector employed was a $1\frac{1}{2}$-inch x 1-inch NaI(Tl) scintillation crystal mounted on a Dumont #6292 photomultiplier tube, both of which were encased in a plastic holder and sample mount. The photomultiplier tube was operated at 1250 volts for an overall gain of 1.8×10^6. The foils were supported by a 0.032-inch-thick plastic sample holder. The holder was of adequate thickness to attenuate beta radiation to an insignificant level. Positions were provided to permit a variation of sample to detector distance ranging from 3 to 10 centimeters. The entire assembly was placed centrally inside a 2-inch lined lead shield which had inside dimensions of 14 x 14 x 20 inches. Figure 1 shows diagramatically the detector assembly and shield. For this arrangement, there was a backscatter peak at 144 Kev. The contribution of this backscatter to the total count rate was approximately 1.5%, a value low enough that significant error was not introduced in photopeak

KEY

1. $1\frac{1}{2}$" x 1" NaI(Tl) Scintillation Crystal
2. 4" Plastic Tubing
3. 3" Plastic Tubing
4. Sample Holder Shelves
5. Photomultiplier Tube
6. 12" x 12" x 1" Plastic Base
7. 14" x 14" x 20" Lead Shield with $\frac{1}{4}$" Brass and Aluminum Liners



Front Section

PLASTIC SAMPLE HOLDER AND SHIELD

Figure 1

estimation.

The output of the photomultiplier tube became the input to a Tracerlab RLP-6 Stepwise Scanning Spectrometer in which the range of energies from 0 to 1.6 Mev was divided into 50 equal increments. The response of the spectrometer was determined by calibration with samples of Co-60, Zn-65, Cs-137 and Au-198 at their principal photopeaks. Calibration data are contained in Table 1 and shown graphically in Figure 2. The proportional response of the spectrometer is shown by the linearity of the calibration curve. The slope of the curve in Figure 2 is aribitrary and was chosen to insure good delineation of the high energy portion of the spectrum. By using Cs-137 and Au-198 just prior to each foil measurement, calibration was checked for drift. It was determined experimentally that optimum response was obtained at the 3-centimeter source to detector distance. Accordingly, this position was used throughout this work.

Table 1

Sample	Energy(Mev)	Channel No.
Au-198	0.411	13.0
Cs-137	0.662	20.8
Zn-65	1.114	35.1
Co-60	1.17	36.8
Co-60	1.33	41.9

The absolute gamma emission rate, Ra, is obtained from the following expression:

$$(1)\quad Ra = \frac{Np}{P \cdot E_t \cdot F_s \cdot F_{ic}}$$ in which

Np = number of events per unit time under the photopeak

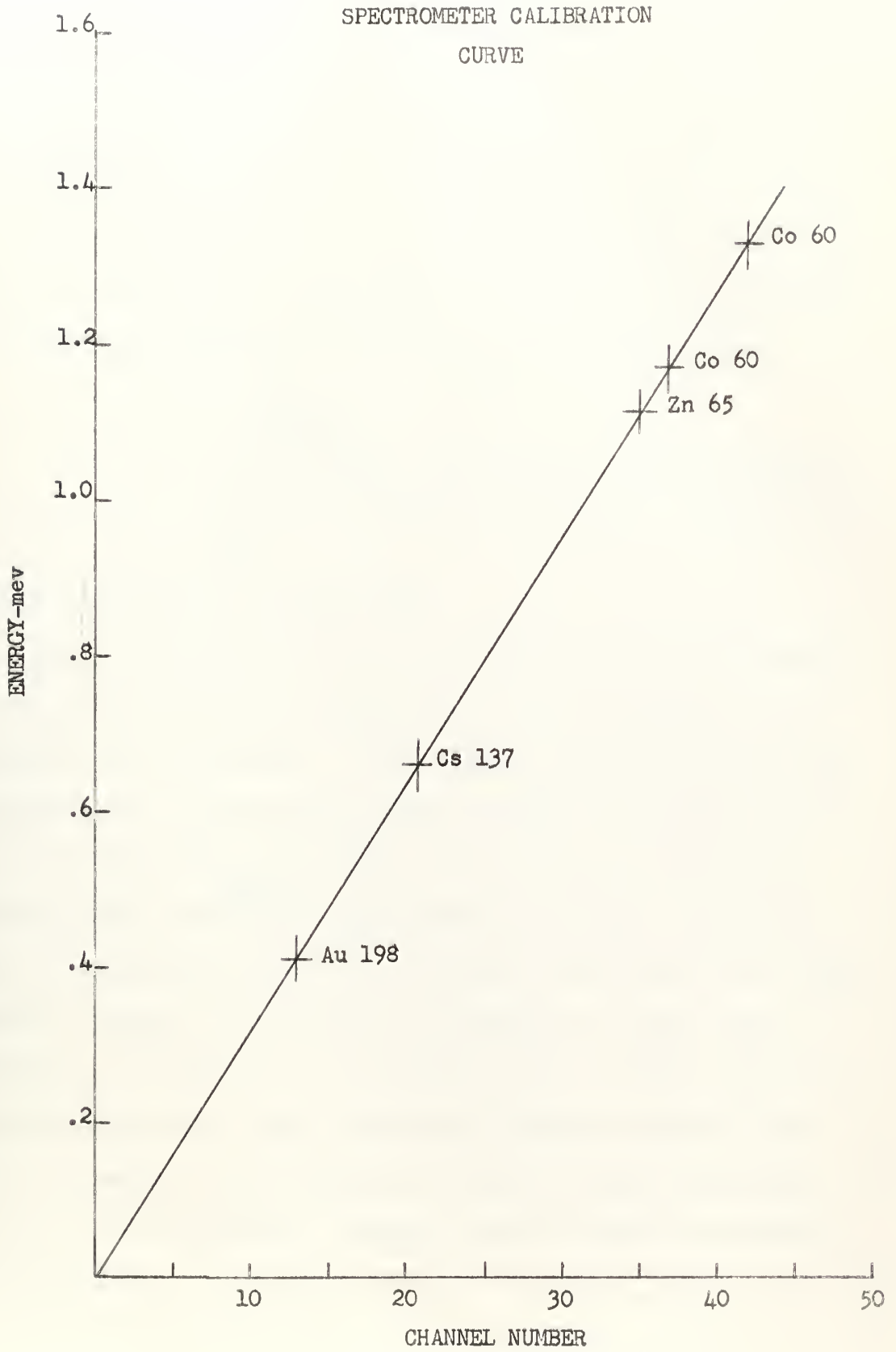

SPECTROMETER CALIBRATION
CURVE
1.6
1.4
1.2
1.0
.8
.6
.4
.2
ENERGY-mev
Co 60
Co 60
Zn 65
Cs 137
Au 198
10
20
30
40
50
CHANNEL NUMBER

Figure 2

P = peak-to-total ratio

E_t = absolute crystal detection efficiency

F_s = correction factor for gamma self-absorption

F_{ic} = correction factor for internal conversion

The value of the absolute crystal detection efficiency which was used was obtained from Heath (4) and is 0.0328. The correction factor for internal conversion is 0.96 as given by Raffle (1). The correction for gamma self-absorption in the foil is given by the formula:

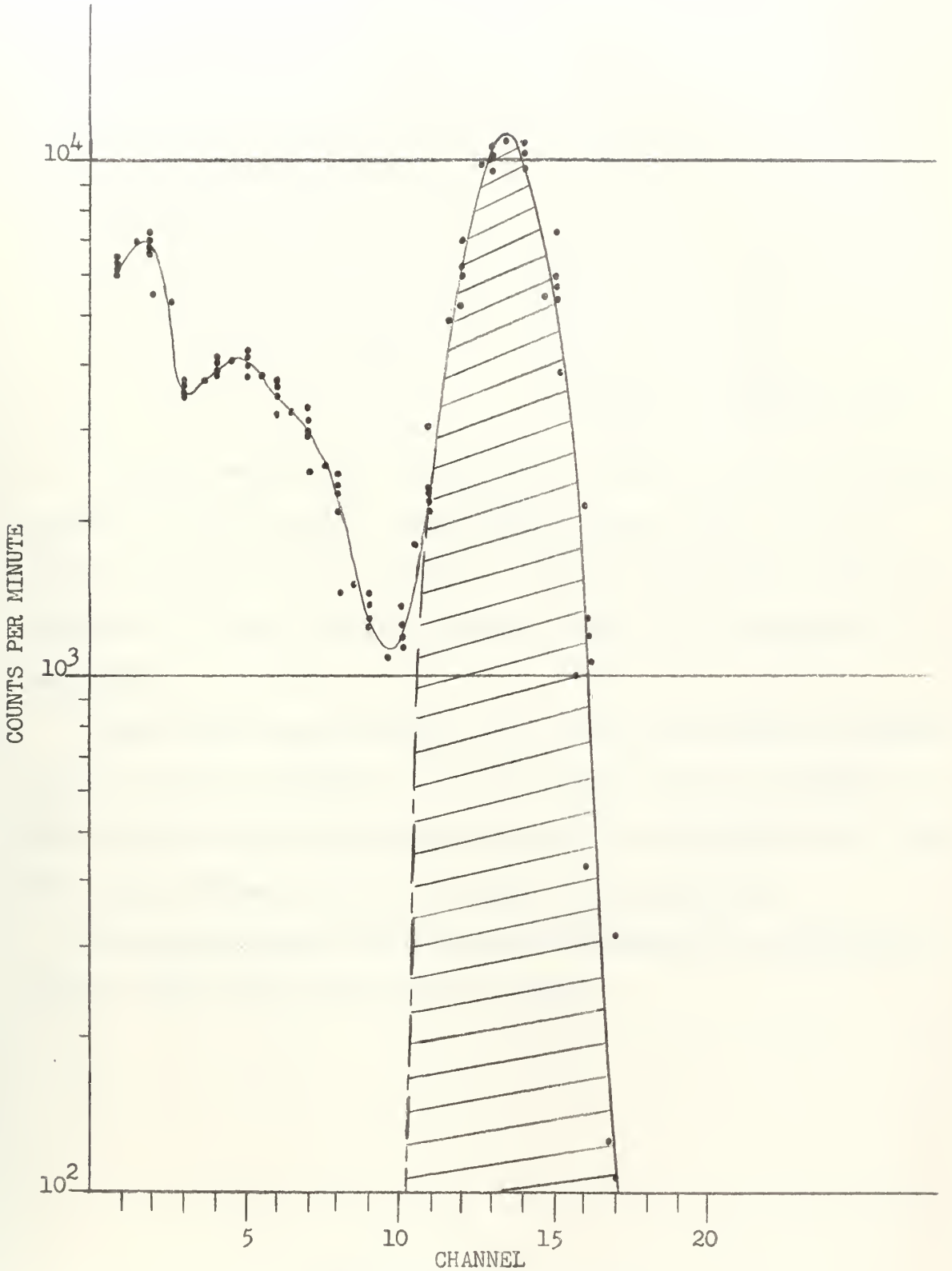
$$F_s = \frac{\mu t}{1 - \exp(-\mu t)}$$ in which

t = foil thickness, 0.475 grams per square centimeter

μ = absorption coefficient, 0.19 square centimeters per gram

The calculated value of F_s is 0.955.

The peak-to-total ratio, P, is the fraction of the total number of events which fall in the photopeak. This was estimated by the methods given by Heath (5). It was assumed that the activity in the neighborhood of the photopeak follows a Gaussian distribution given by the formula $f(x) = \frac{1}{\sqrt{2\pi}} \exp(-\frac{1}{2}x^2)$, $-\infty < x < \infty$. On a semi-logarithmic plot, the Gaussian shape becomes a parabola. By fitting the theoretical parabolic shape to the high energy side of the experimental photopeak and determining the parameters of this curve, an estimation is permitted for the maximum number of events under the photoelectric peak. Figure 3 shows the normalized spectrum taken from six samples. From these data, the peak-to-total ratios given in Table 2 were determined. Complete supporting data are contained in Appendix I.



GAMMA SPECTRUM 2.7d Au-198

Figure 3

Table 2

Sample	Peak Count	Total Count	Ratio
1	33,500	72,647	0.461
2	25,700	58,200	0.442
3	26,400	55,459	0.476
4	34,650	71,655	0.484
5	5,450	12,073	0.451
6	36,900	84,962	0.434
		Mean =	0.458 ± 0.008 s.e.

The above value may be compared with a value of 0.510 as determined by Bell (6) for a 1½-inch x 1-inch NaI(Tl) crystal with a source to detector distance of 2.5 centimeters. Heath (7) determined a peak-to-total ratio of 0.565 using the same size crystal and a distance of 1 centimeter.

Twelve foils were irradiated, six of which were encased in cadmium covers to permit calculation of the epithermal flux; the remaining six were irradiated bare and provided the basis for calculation of the total flux. The difference yields the thermal flux (Appendix I).

The absolute gamma emission rate was determined from expression (1) and the results are listed in Table 3 below.

Table 3

Run No.	Irradiation Time(min)	Foil Weight(gm)	Ra(c/m)
	Bare Foils		
1	356	0.60	2.81×10^6
2	356	0.60	2.54×10^6
3	328	0.61	2.58×10^6
4	328	0.61	2.56×10^6
5	274	0.61	1.98×10^6
6	274	0.61	2.17×10^6
	Cadmium Covered Foils		
1	252	0.60	3.96×10^5
2	236	0.61	3.28×10^5
3	270	0.61	3.77×10^5
4	252	0.61	3.69×10^5
5	252	0.61	3.54×10^5
6	252	0.61	3.59×10^5

Flux calculations were made from the absolute gamma emission rate, Ra, by means of the following expression:

$$(2)\quad \phi = \frac{Ra \cdot W}{No \cdot \sigma a \cdot m \cdot 1-\exp(-\lambda T) \cdot \exp(-\lambda t)}$$

in which W = atomic weight of the foil

No = Avogadro's Number

σa = average thermal cross section of the foil, $\sigma_o \frac{\sqrt{\pi}}{2}$

m = mass of the foil

T = irradiation time

t = elapsed time between irradiation and counting

λ = decay constant for Au-198

The value of the thermal cross section, σ_o, which was used is 98 barns as quoted by Hughes and Harvey (8). The decay constant for Au-198 is 1.73×10^{-4} per minute derived from data of Strominger, Hollander and Seaborg (9). The values of total and epithermal flux as calculated from expression (2) are listed in column 2 of Tables 4 and 5.

Table 4

Total Flux, neutrons per square centimeter per second

Run No.	Calculated Value	Corrected Value
1	4.87×10^6	6.85×10^6
2	4.41×10^6	6.22×10^6
3	4.75×10^6	6.70×10^6
4	4.73×10^6	6.67×10^6
5	4.31×10^6	6.08×10^6
6	4.73×10^6	6.67×10^6
		Mean = 6.53×10^6 $\pm$ 0.05 s.e.

Table 5

Epithermal Flux, neutrons per square centimeter per second

Run No.	Calculated Value	Corrected Value
1	0.945×10^6	1.33×10^6
2	0.831×10^6	1.17×10^6
3	0.839×10^6	1.18×10^6
4	0.880×10^6	1.24×10^6
5	0.845×10^6	1.19×10^6
6	0.862×10^6	1.21×10^6
		Mean = 1.22×10^6 $\pm$ 0.024 s.e.

In order to obtain the true value of the thermal flux in the reactor, the value calculated from expression (2) must be corrected. A major correction to be considered is the flux perturbation due to the absorption of neutrons by the foil and the self shielding of the internal layers of the foil by the outer layers. The flux in the neighborhood of the foil will be depressed due to the absorption of neutrons by the foil; therefore, the flux seen at the surface will be less than the unperturbed flux in the reactor. In this respect, the foil may be thought of as a sink for thermal neutrons. The flux will be further depressed within the foil itself due to the absorption of neutrons by each layer, and the flux at any depth within the foil will be less than that seen at the surface. The determination of the correction factor for flux perturbation is contained in Appendix II and follows the method of Bothe (10) as modified by Tittle (11, 12).[1] The corrected values of the flux are listed in column 3 of Tables 4 and 5.

Another correction to the calculated flux which was considered is that due to the attenuation of epithermal neutrons by the cadmium cover. Experimental results determined by Martin (14) with a 0.40 inch cadmium cover gave a correction factor of 2% for the attenuation of eqithermal neutrons. Martin gives data for relative activity versus cadmium thickness. Using these data, the correction factor was determined to be less than 1% for the 0.20 inch cadmium cover used in this determination. This may be neglected in comparison with inherent errors. The cadmium ratio obtained was 5.36.

[1]Measurements of flux perturbation in gold foils in graphite have been made by Sola (13) and the results are in very good agreement with the values calculated by Bothe's method.

The value of the thermal flux calculated with the corrections and data above was 5.31×10^6 neutrons per square centimeter per second.

3. DISCUSSION OF RESULTS

The known relationship between induced activity and neutron flux provides a dependable and accurate basis for the determination of the flux in a reactor provided the corrections discussed in the previous section are made to the calculated values. Of these corrections, that due to perturbation of the flux by the presence of the foil has the greatest magnitude. The 11.5 mil foils used in this investigation are quite thick and gave a correction factor of 29%. The use of thinner foils, less than 5 mils thick, would cause less perturbation and would reduce this correction factor to approximately 5%. Even more important, since the theoretical correction is more reliable the smaller it is, the use of foils of half the thickness would permit more reliance to be placed on this perturbation correction.

The data collected from the various samples are in good agreement. Based on a standard error of 0.05 for the total flux and 0.024 for the epithermal flux, a standard error of 2.1% has been calculated for the reported thermal flux. Any error in the theoretical correction calculated for flux depression is not included in this standard error.

4. SUMMARY

Procedures have been developed for measurement of the thermal flux in the Naval Postgraduate School reactor by employing gold foils and determining the absolute activity through measurement of gamma radiation. The maximum flux at a power level of 100 milliwatts was found to be $(5.31 \pm 0.11) \times 10^6$ neutrons per square centimeter per second.

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APPENDIX I

DATA FOR

PEAK TO TOTAL RATIO

Sample 1 8 Feb 1960

Channel Number	Number of Counts	Counting Time (min)	Channel Number	Number of Counts	Counting Time (min)
1	6149	1.00	26	10	1.00
2	6497	1.00	27	8	1.00
3	3500	1.00	28	15	1.00
4	4087	1.00	29	11	1.00
5	4141	1.00	30	8	1.00
6	3537	1.00	31	3	1.00
7	3010	1.00	32	3	1.00
8	2179	1.00	33	4	1.00
9	1225	1.00	34	5	1.00
10	1397	1.00	35	6	1.00
11	3186	1.00	36	10	1.00
12	7017	1.00	37	8	1.00
13	10047	1.00	38	5	1.00
14	9860	1.00	39	5	1.00
15	5277	1.00	40	2	1.00
16	1194	1.00	41	2	1.00
17	124	1.00	42	1	1.00
18	59	1.00	43	1	1.00
19	34	1.00	44	2	1.00
20	29	1.00	45	4	1.00
21	32	1.00	46	0	1.00
22	44	1.00	47	1	1.00
23	52	1.00	48	0	1.00
24	38	1.00	49	0	1.00
25	18	1.00	50	0	1.00

Sample 2 9 Feb 1960

Channel Number	Number of Counts	Counting Time (min)	Channel Number	Number of Counts	Counting Time (min)
1	28697	5.00	26	48	5.00
2	24768	5.00	27	38	5.00
3	15131	5.00	28	32	5.00
4	17619	5.00	29	43	5.00
5	16719	5.00	30	26	5.00
6	14185	5.00	31	27	5.00
7	11204	5.00	32	33	5.00
8	6720	5.00	33	26	5.00
9	5737	5.00	34	36	5.00
10	5068	5.00	35	31	5.00
11	9598	5.00	36	33	5.00
12	27189	5.00	37	22	5.00
13	44622	5.00	38	15	5.00
14	42447	5.00	39	12	5.00
15	17442	5.00	40	8	5.00
16	1987	5.00	41	11	5.00
17	283	5.00	42	10	5.00
18	229	5.00	43	6	5.00
19	196	5.00	44	10	5.00
20	228	5.00	45	3	5.00
21	255	5.00	46	4	5.00
22	245	5.00	47	2	5.00
23	166	5.00	48	8	5.00
24	101	5.00	49	1	5.00
25	64	5.00	50	3	5.00

Sample 3 9 Feb 1960

Channel Number	Number of Counts	Counting Time (min)	Channel Number	Number of Counts	Counting Time (min)
1	6039	1.00	26	5	1.00
2	4456	1.00	27	4	1.00
3	3009	1.00	28	10	1.00
4	3473	1.00	29	7	1.00
5	3329	1.00	30	6	1.00
6	2678	1.00	31	3	1.00
7	2171	1.00	32	7	1.00
8	1297	1.00	33	4	1.00
9	923	1.00	34	11	1.00
10	1535	1.00	35	5	1.00
11	4071	1.00	36	4	1.00
12	8366	1.00	37	1	1.00
13	8512	1.00	38	2	1.00
14	4499	1.00	39	1	1.00
15	856	1.00	40	1	1.00
16	72	1.00	41	1	1.00
17	45	1.00	42	1	1.00
18	46	1.00	43	0	1.00
19	55	1.00	44	1	1.00
20	36	1.00	45	2	1.00
21	36	1.00	46	1	1.00
22	25	1.00	47	0	1.00
23	21	1.00	48	0	1.00
24	11	1.00	49	1	1.00
25	20	1.00	50	0	1.00

Sample 4 11 Feb 1960

Channel Number	Number of Counts	Counting Time (min)	Channel Number	Number of Counts	Counting Time (min)
1	6096	1.00	26	8	1.00
2	6718	1.00	27	10	1.00
3	3448	1.00	28	5	1.00
4	3920	1.00	29	13	1.00
5	4039	1.00	30	5	1.00
6	3481	1.00	31	4	1.00
7	3131	1.00	32	5	1.00
8	2181	1.00	33	5	1.00
9	1265	1.00	34	5	1.00
10	1188	1.00	35	6	1.00
11	2196	1.00	36	11	1.00
12	5847	1.00	37	7	1.00
13	10091	1.00	38	4	1.00
14	10535	1.00	39	2	1.00
15	5846	1.00	40	1	1.00
16	1273	1.00	41	4	1.00
17	123	1.00	42	2	1.00
18	69	1.00	43	1	1.00
19	40	1.00	44	5	1.00
20	55	1.00	45	1	1.00
21	54	1.00	46	1	1.00
22	52	1.00	47	4	1.00
23	49	1.00	48	0	1.00
24	34	1.00	49	1	1.00
25	14	1.00	50	0	1.00

Sample 5 12 Feb 1960

Channel Number	Number of Counts	Counting Time (min)	Channel Number	Number of Counts	Counting Time (min)
1	2055	2.00	26	11	2.00
2	2286	2.00	27	9	2.00
3	1186	2.00	28	4	2.00
4	1359	2.00	29	11	2.00
5	1389	2.00	30	11	2.00
6	1217	2.00	31	13	2.00
7	1091	2.00	32	7	2.00
8	797	2.00	33	5	2.00
9	454	2.00	34	3	2.00
10	394	2.00	35	2	2.00
11	707	2.00	36	12	2.00
12	1666	2.00	37	8	2.00
13	2935	2.00	38	6	2.00
14	3485	2.00	39	11	2.00
15	2375	2.00	40	1	2.00
16	698	2.00	41	2	2.00
17	105	2.00	42	6	2.00
18	43	2.00	43	4	2.00
19	25	2.00	44	5	2.00
20	27	2.00	45	3	2.00
21	27	2.00	46	2	2.00
22	17	2.00	47	3	2.00
23	21	2.00	48	2	2.00
24	30	2.00	49	0	2.00
25	14	2.00	50	2	2.00

Sample 6 29 Feb 1960

Channel Number	Number of Counts	Counting Time (min)	Channel Number	Number of Counts	Counting Time (min)
1	6946	1.00	26	12	1.00
2	8554	1.00	27	14	1.00
3	4032	1.00	28	8	1.00
4	4530	1.00	29	11	1.00
5	4914	1.00	30	4	1.00
6	4294	1.00	31	5	1.00
7	3625	1.00	32	5	1.00
8	2781	1.00	33	7	1.00
9	1686	1.00	34	4	1.00
10	1351	1.00	35	7	1.00
11	2464	1.00	36	7	1.00
12	6831	1.00	37	13	1.00
13	11677	1.00	38	8	1.00
14	12645	1.00	39	4	1.00
15	6942	1.00	40	5	1.00
16	1216	1.00	41	2	1.00
17	118	1.00	42	3	1.00
18	75	1.00	43	0	1.00
19	62	1.00	44	0	1.00
20	72	1.00	45	0	1.00
21	62	1.00	46	0	1.00
22	55	1.00	47	0	1.00
23	58	1.00	48	0	1.00
24	35	1.00	49	0	1.00
25	17	1.00	50	1	1.00

DATA FOR

FLUX DETERMINATION

Without Cadmium

Channel Number	Number of Counts	Counting Time (min)
	Run 1 29 Feb 1960	
10	1598	1.00
11	3998	1.00
12	8935	1.00
13	13165	1.00
14	10177	1.00
15	3222	1.00
16	342	1.00
17	114	1.00
18	64	1.00
	Run 2 29 Feb 1960	
8	2245	1.00
9	1375	1.00
10	1767	1.00
11	4291	1.00
12	9909	1.00
13	13070	1.00
14	9599	1.00
15	2800	1.00
16	220	1.00
17	79	1.00
	Run 3 15 Mar 1960	
7	3198	1.00
8	1929	1.00
9	1389	1.00
10	2429	1.00
11	6002	1.00
12	12491	1.00
13	12128	1.00
14	6438	1.00
15	1003	1.00
16	103	1.00
17	76	1.00

Without Cadmium

Channel Number	Number of Counts	Counting Time (min)
	Run 4 15 Mar 1960	
7	3429	1.00
8	2473	1.00
9	1432	1.00
10	1364	1.00
11	2691	1.00
12	6340	1.00
13	12197	1.00
14	11639	1.00
15	4705	1.00
16	611	1.00
17	95	1.00
	Run 5 18 Mar 1960	
7	2716	1.00
8	1719	1.00
9	1138	1.00
10	1021	1.00
11	1503	1.00
12	4234	1.00
13	8450	1.00
14	10025	1.00
15	5191	1.00
16	687	1.00
17	88	1.00
	Run 6 18 Mar 1960	
7	2898	1.00
8	2056	1.00
9	1226	1.00
10	999	1.00
11	1876	1.00
12	5308	1.00
13	9706	1.00
14	7589	1.00
15	4372	1.00
16	699	1.00
17	58	1.00

With Cadmium

Channel Number	Number of Counts	Counting Time (min)
	Run 1 12 Feb 1960	
7	1091	2.00
8	797	2.00
9	454	2.00
10	394	2.00
11	707	2.00
12	1666	2.00
13	2935	2.00
14	3485	2.00
15	2375	2.00
16	698	2.00
17	105	2.00
	Run 2 7 Mar 1960	
8	702	2.00
9	481	2.00
10	340	2.00
11	512	2.00
12	1069	2.00
13	2173	2.00
14	2904	2.00
15	2790	2.00
16	1424	2.00
17	295	2.00
18	41	2.00
	Run 3 10 Mar 1960	
7	1159	2.00
8	834	2.00
9	518	2.00
10	756	2.00
11	1765	2.00
12	2392	2.00
13	3420	2.00
14	3465	2.00
15	1566	2.00
16	175	2.00
17	37	2.00

With Cadmium

Channel Number	Number of Counts	Counting Time (min)
	Run 4 17 Mar 1960	
7	465	1.00
8	306	1.00
9	202	1.00
10	197	1.00
11	380	1.00
12	937	1.00
13	1760	1.00
14	1464	1.00
15	519	1.00
16	53	1.00
17	15	1.00
	Run 5 17 Mar 1960	
9	352	1.00
10	189	1.00
11	156	1.00
12	587	1.00
13	894	1.00
14	1183	1.00
15	1518	1.00
16	1247	1.00
17	403	1.00
18	80	1.00
19	13	1.00
	Run 6 17 Mar 1960	
9	677	2.00
10	411	2.00
11	501	2.00
12	1006	2.00
13	1377	2.00
14	1966	2.00
15	2861	2.00
16	2521	2.00
17	1009	2.00
18	151	2.00
19	27	2.00

APPENDIX II

CALCULATION OF FLUX PERTURBATION

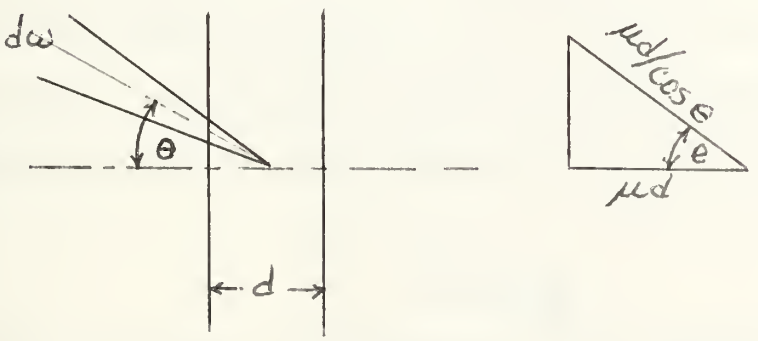
In order to determine the flux depression due to the presence of the foil, Bothe first considered the case of a neutron flux with intensity K and uniform velocity v impinging on the foil. The intensity of neutrons striking the foil through the solid angle dw is Kdw. K will generally depend on the direction of dw. The density of neutrons striking the foil will then be

$$n = 1/v \int K dw$$

If a foil of thickness d and absorption coefficient μ is placed in an isotropic flux, then the absorption of neutrons by the foil is given by the following expression:

$$dA = K \left|\cos \Theta\right| \left(1 - e^{-\mu d / \left|\cos \Theta\right|}\right) dw$$

where Θ is the angle of incidence.



Integrating the above expression over all space, Bothe arrived at the value of the absorption

$$A = \tfrac{1}{2} v n \left[1 - e^{-\mu d} (1 - \mu d) - \mu^2 d^2 E(-\mu d)\right] \quad (1)$$

which is the probability of absorption of a neutron in an isotropic flux by a layer of thickness d . $E(-\mu d)$ is the exponential integral function. For a foil of no thickness, that is, $ud \ll 1$, Equation (1) becomes

$$A = v \mu d n \quad (2)$$

If Equation (1) is divided by Equation (2), the result is the ratio of the absorption by a foil of thickness d to the absorption by a foil of no thickness. This ratio is the correction factor for flux depression within the foil and is designated G. Then making the substitution $x = \mu d$,

$$G = \frac{1 - e^{-x}(1 - x) - x^2 E(x)}{2x} \tag{3}$$

in which x is the ratio of the foil thickness to the mean free path of the foil and $E(x) = \int_x^\infty \frac{e^{-s} ds}{s}$

The neutron absorption mean free path in gold is 0.17 centimeters, as given by Sola (13). For a foil of thickness 0.0294 centimeters, Equation (3) gives a value of G equal to 0.765.

Bothe derived an expression for the flux depression outside the foil due to absorption in the foil based on a sphere. Tittle (12) showed by experiment that Bothe's expression could be applied to a disk foil provided the transport mean free path of the diffusing medium is used in lieu of the scattering mean free path given by Bothe. The expression for the flux depression outside the foil, H, is given by:

$$H = \frac{1}{1 + 0.34 \frac{aR}{\lambda}} \tag{4}$$

in which a is equal to the numerator of the expression for G, R is the radius of the foil and λ is the transport mean free path of the diffusion medium. The transport mean free path may be determined from the relation:

$$\lambda_{tr} = \frac{\lambda_s}{1 - \overline{\mu}_o} \tag{5}$$

in which:

λ_s = the scattering mean free path

$\overline{\mu}_o$ = the average value of the cosine of the scattering angle of the neutron in the laboratory system.

For a foil of radius 0.63 centimeters and transport mean free path of 0.73 centimeters calculated for the polyethylene core, $H = 0.92_7$. It may be noted that H is a function of both the material of the foil and the diffusing medium whereas G is a function of the foil material only.

The total flux perturbation, F, is equal to GH. Its value is 0.71 for the present case.