W0 4139

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REACTORS—RESEARCH AND TESTING

LOS ALAMOS SCIENTIFIC LABORATORY

of

THE UNIVERSITY OF CALIFORNIA

December 15, 1950

LA-1192

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NEUTRON ENERGY DISTRIBUTIONS INSIDE THE FAST REACTOR

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REACTORS

CLASSIFICATION CANCELLED
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For The Atomic Energy Commission
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Abstract

This report presents results of nuclear plate work carried out to determine the neutron energy distribution inside the Los Alamos fast reactor. Most of the distributions which were investigated are valid over the energy region from 0.4 to 6 Mev. The results show that at the center of the reactor pot about 65% of the neutrons are located below 1 Mev in a rather narrow energy region which has a maximum in the neighborhood of 0.5 to 0.6 Mev. Above 2 Mev the energy distribution is similar to that of a plutonium fission neutron spectrum, i.e. the spectrum decreases exponentially, diminishing by a factor of 10 in intensity over an energy range of about 4 Mev. The loading geometry of the reactor pot does not seem to appreciably affect the spectrum at the center of the pot. However, spectra determined outside the pot can be significantly altered by the particular viewing geometry employed to examine the neutrons coming from the center of the reactor.

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NEUTRON ENERGY DISTRIBUTIONS INSIDE THE FAST REACTOR

I. INTRODUCTION

The experiments described in this report represent various experimental methods which have been used to determine the neutron energy distribution inside the fast reactor. All of the experiments involve techniques which can be used with nuclear plates. Nuclear plates were used as detectors on account of their small size which enabled them to be fit into the reactor confines without disturbing the reactivity or neutron spectrum.

The first experiments consisted of placing nuclear plates in contact with threshold fission foils at the center of the pot containing the reactive material. This method has the desirable properties of being simple and of providing data which is certain to be representative of the neutron spectrum at the center of the reactor. However, since only three fissionable elements having suitable thresholds could be found, the spectral information provided is quite meager. A second method involved collimating the neutrons from the center through a hole emerging from the top of the pot through the shielding of the reactor. The spectrum of the collimated neutrons was determined by measuring the forward proton recoils produced in nuclear plates placed in this neutron beam. This method accurately records the continuous neutron spectrum (above 0.4 Mev) which exists in the collimator tube. However, the question arising in connection with this method is whether or not this collimated spectrum is representative of the spectrum at the center of the reactor. Various pot loadings and center slug arrangements were used in an attempt to answer this question. A third method consisted of calculating the neutron spectrum from a measurement of the proton recoil spectrum produced in a nuclear plate placed at the center of the reactor. This method ought to give the best answer to the continuous neutron energy distribution at the center. The nuclear plate technique involved in this measurement is lengthy and had not been used previously. Investigations of the reliability of the method are still being continued.

The report has been divided into two sections. The first part describes results obtained by collimating the neutrons from the pot and the second part presents results obtained from experiments carried out directly at the center of the pot.

Between the time of doing these experiments (August 1948 to February 1949) and the writing of this report (summer 1950), the service or operating loading of the reactor was changed from a peripheral loading geometry containing both plutonium and normal uranium to a uniform

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loading geometry containing only plutonium. This latter loading is not represented in any of the experiments described here. However, since all of the three pot loadings which were tried yielded approximately the same neutron spectra, it is anticipated that the present service loading would behave similarly.

II. ENERGY INVESTIGATIONS OF COLLIMATED NEUTRONS FROM REACTOR POT

A. Experimental Arrangement.

The experimental arrangement is shown in Fig. 1. The center hole leading from the pot through the upper tamper and shielding is the mercury outlet hole. During preliminary experiments when the reactor was run at low power, no mercury was employed and this exit hole was used as a collimator for neutrons emerging from the center pot. In order to determine the spectrum of these collimated neutrons nuclear plates were placed in this tube with their emulsion surfaces parallel to the neutron beam. The plates were placed inside a 1/32 inch cadmium liner so as to prevent thermal neutrons, produced in the boron plastic and masonite shielding, from entering and producing an n,p reaction with the nitrogen in the emulsion. A 1/64 inch thick light tight aluminum container was used to hold the cadmium liner and plates in the neutron beam. The plates were placed in the collimation hole at a distance of either 63 cm or 73 cm above the top of the pot; the above collimation permitted incoming neutrons to make a maximum angle of $\approx 1^\circ$ with the emulsion surface.

The question continually arose as to what loading the center slug position of the pot should have so as to secure a collimated neutron spectrum similar to that of the pot spectrum. If the center position was occupied by a slug of reactive material (plutonium), most of the collimated neutrons would consist of neutrons produced by fission in this center slug. In order to eliminate the above possibility, an open center hole or center hole loaded with non-reactive material was considered the best loading. A disadvantage of the latter loading is that the collimated beam consists mainly of scattered neutrons from the pot. However, the solid angle subtended by the plates is such that it includes some material about the center slug position. In the second pot loading geometry to be described, the material adjacent to the center slug consists of reactive material, so that here the beam will also possess a certain fraction of neutrons emerging directly from the fissionable material. However, in any case, with the open center hole, the ratio of scattered neutrons to primary fission neutrons would be expected to be larger in the collimated beam than at the center of the pot.

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Fig 1 Experimental arrangement

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Since a plutonium loaded center hole greatly emphasizes the primary neutrons coming directly from the plutonium and an open center hole would seem to exaggerate the scattered neutrons existing in the pot spectrum, it is evident that neither of the above center hole loading methods gives the desired result. Both types of center hole loadings were tried for various pot loading geometries. First, in the case of the peripheral loading geometry, the center hole was loaded with normal uranium; second, in the aluminum cage loading geometry with only plutonium, the center hole was empty and third, in the central loading geometry, the center hole contained plutonium.

A background experiment was carried out to be certain that the collimated neutron beam consisted of neutrons from the pot. Two cylindrical rods consisting of steel and boron plastic were inserted to fill the collimating tube between the top of the pot and the nuclear plates. Since the steel and boron plastic shielding plug reduces the open tube neutron intensity to practically zero, any neutrons recorded would reach the plates by other means than through the plugged collimating tube.

B. Nuclear Plate Analysis

Either Ilford type C2 or Eastman type NTA plates, 100 microns thick, were usually used in the present experiments. The plates were cut into sections of $1/2" \times 1"$ for exposure in the center of the $7/8"$ diameter collimating tube. The following processing procedure was used for both plate types.

1. Soak in water for 10 minutes.
 2. Develop in D-19 (diluted 1:4) for 30 minutes. Agitate.
 3. Fix in acid hypo (diluted 1:1) for about 2 hours. Agitate.
 4. Wash at least one hour and dry.
- (all solutions were at 68 F).

The above plates were analyzed by the method of measuring proton recoils about a small angle of the forward neutron direction. This is the same technique which has been used in several experiments^{1,2,3}. Therefore, for details the reader will be referred back to these earlier reports and only the brief essentials of the method will be given here.

The proton recoil method of analyzing neutron spectra is practical since $E_p = E_n \cos^2 \theta$ where E_p and E_n are the energy of the proton

1. N. Nereson and F. Reines, LADC-748 (1950) or Rev. Sci. Inst. 21, 534 (1950).
2. N. Nereson, LA-1078 (1950).
3. N. Nereson, LA-1123 (1950).

recoil and incident neutron respectively and θ is the angle between the neutron and proton directions. Thus, if θ is made small, $E_p \approx E_n$, or more accurately, E_p is only a few percent less than E_n and only a small correction on the measured quantity E_p is required to determine E_n .

In using the above technique, it is necessary that the neutron mean free path in the emulsion be large compared to the analyzed emulsion volume. (See Section III for actual figures). The above conditions must be satisfied in order to make certain that (1), a neutron produces only one proton recoil in the analyzed volume and (2), the incoming neutron spectrum is not altered as it proceeds through the emulsion. In the actual analysis the swath length was restricted to a length of 1 cm⁴ as measured from the neutron entrance end of the plate; the width of the analysis region is quite immaterial but this was also usually restricted to 1 cm.

The plates were analyzed by measuring proton recoils in the processed emulsion which possessed less than a 10° angle with the beam or forward neutron direction. Therefore, from any point in the processed emulsion all acceptable proton recoils lay within a rectangular pyramid having half-angles of 10° in the horizontal and vertical planes of the emulsion. Since this angular criteria was applied to the processed emulsion and since the emulsion thickness shrinks vertically by about a factor 2.5 upon processing, acceptable proton recoils in the unprocessed emulsion lay within a rectangular pyramid of half-angle 10° in the horizontal plane and half-angle 25° in the vertical or azimuthal plane. The plate exposures were usually such that between 1 and 2 forward proton recoil tracks were contained in the entire emulsion thickness for each microscope field (see Table II). It has been found that the above track density should not be exceeded for accurate analysis of short tracks¹. However, in the case of the central loading geometry this track density was exceeded, the number of forward recoils being between 3 and 4 per field, and poor agreement exists between different microscopists results in the low energy region.

4. Since the mean free path of a 0.5 Mev neutron in the nuclear emulsion is about 2 cm, it would have been more desirable to use about 0.5 cm long swaths or less in order to be more certain of meeting the above conditions. However, in actual practice the average path length of incoming neutrons within the analyzed emulsion volume is less than 0.5 cm. The reason for this is that most of the neutrons will enter the plate at small angles (1° or 2°) on account of (1), the inability to align the emulsion surfaces to any greater precision than about 1° in the collimating tube and (2), the neutron collimation at the plate is within 1°.

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The energy resolution resulting from the above angular criteria is 13% at 0.4 Mev and 6% at 2 Mev¹. Energy resolution is defined as the energy half-width of the proton recoil distribution obtained from neutrons of energy E_n divided by E_n . This means that neutron peaks possessing half-widths (at half-maximum) equal to 50 kev can be resolved at 0.4 Mev and 120 kev at 2 Mev. This is sufficient resolution for the spectral curves obtained in the present experiments.

Analysis of the plates was carried out on Leitz microscopes using 10X or 12X compensating eyepieces and 90X or 95X oil immersion objectives. One of the eyepieces contained a 20° angle with bisecting line and the other eyepiece contained a suitable scale for measuring the length of the proton recoil tracks. The 20° angle with center line was used to judge whether or not tracks were within the limiting horizontal angle of 10°. The depth of focus of the microscope (about 3/4 of a micron) was used to ascertain if tracks were within the maximum vertical or azimuthal angle of 10°. Practically, this means that 5 microns or more of the beginning of the track must be in focus to be within the 10° dip angle. The depth of focus sets a limit on the reliability of determining the correct number of tracks for track lengths below about 5 microns or 0.5 Mev. Below 5 microns, the tracks must appear to be in complete focus or show no dip in order to be within the 10° azimuthal angle. This criteria would permit more tracks to be measured within the 10° azimuthal angle than actually exist. However, straggling and missing grain phenomena also greatly influence the determination of the number of tracks below 0.5 Mev, and investigation shows that the number of measured tracks are always less than the correct number in this energy region. The above problems are discussed fully in another report¹ and the findings of this previous work have been applied to the results obtained in the present experiments.

The track data was accumulated by taking successive swaths on the plate (about 0.2 mm apart) along the axis of the neutron beam direction. Consecutive fields were examined along every swath; using this method, every acceptable track originating in the swath would be measured. In order to minimize the number of tracks leaving the emulsion surfaces, a thickness of 5 microns was skipped from the top and bottom surfaces of the emulsion thickness, i.e. tracks originating within the above volumes were ignored. However, correction factors for tracks leaving the emulsion surfaces are still required and these have been calculated in another report². A table of these correction factors are shown in Table I and a graph is shown in Fig. 2.

The track data was tabulated in proton recoil energy intervals of 0.1 Mev as this is a practical energy interval close to the resolution of the method. After observing the curve shape, the above small intervals were kept if the curve necessitated this resolution but, if not, the data was grouped into larger intervals (about 0.5 Mev) and averaged.

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T(b.p.) T(a.p.) T (a.)		100 microns 40 " 30 "		87.5 microns 35 " 25 "		75 microns 30 " 20 "		50 microns 20 " 10 "	
E_p	l_p	P	C	P	C	P	C	P	C
1.65 Mev	30 microns	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
2.00	40	0.02	1.02	0.02	1.02	0.02	1.02	0.03	1.03
2.31	50	0.04	1.04	0.04	1.04	0.05	1.05	0.07	1.07
2.60	60	0.06	1.06	0.06	1.07	0.075	1.08	0.12	1.14
2.90	71	0.08	1.09	0.09	1.10	0.11	1.125	0.21	1.26
3.13	80	0.10	1.13	0.12	1.14	0.14	1.165	0.27	1.37
3.35	90	0.12	1.14	0.14	1.16	0.17	1.21	0.34	1.51
3.56	100	0.155	1.175	0.17	1.20	0.21	1.27	0.41	1.66
4.00	120.5	0.195	1.24	0.23	1.29	0.30	1.42	0.51	2.02
4.58	150	0.28	1.38	0.33	1.50	0.41	1.69	0.59	2.56
5.47	200	0.41	1.70	0.49	1.96	0.56	2.25	0.71	3.45
6.27	250	0.53	2.13	0.59	2.46	0.65	2.85	0.77	4.35
6.93	300	0.61	2.53	0.66	2.94	0.71	3.39	0.80	5.08

Legend: T(b.p.) = Emulsion thickness before processing.
T(a.p.) = Emulsion thickness after processing.
T (a.) = Emulsion thickness analyzed for tracks.
 E_p = Energy of proton recoil.
 l_p = Length of proton recoil track.
 P = Probability of proton recoil track of length l_p leaving emulsion surfaces when originating in T(a.) and proceeding within angular limits of $0^\circ \pm 10^\circ$.
C = Correction factor to be applied to data in order to adjust for tracks leaving emulsion surfaces.

Table I Correction factors for proton recoil tracks leaving emulsion surfaces. Tracks originate within a thickness T(a.) and are contained within angular limits of $0^\circ \pm 10^\circ$ in the processed emulsion. (Shrinkage factor of 2.5 assumed in processing emulsion).

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Fig 2 Proton energy versus correction factor for proton recoil tracks leaving emulsion surfaces.

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The number of tracks observed is proportional to the collision cross section of hydrogen, σ_p , and to the neutron flux. Therefore, the data must be corrected for the variation of σ_p with E . L. Goldstein's calculation⁵ has been used for the values of $\sigma_p(E)$ and a curve of σ_p vs. E is shown in Fig. 3. The quantity obtained after correcting the number of tracks for σ_p and for tracks leaving the emulsion surfaces is proportional to the neutron flux. The latter figure is proportional to the neutron flux existing at the neutron energy value corresponding to the midpoint of the E_p interval. The conversion of E_p to E_n is described in a previous report¹. Briefly, the peak or maximum of a proton recoil distribution obtained by the present measurement technique from a monochromatic neutron source is located about 5% below the neutron bombarding energy. The center of gravity of such a distribution is located about 7% below the neutron energy. A 5% energy correction has been applied to the present spectral curves on account of their "peaked" shape. Perhaps the 7% correction would be more correct in the flat region of the spectral curves; however the difference in the two corrections is quite small, being only 0.12 Mev at 6 Mev⁰.

The neutron spectrum for each loading was usually determined from a total of about 3000 tracks measured by two different microscopists. Since the personal element enters into this method of nuclear plate analysis, the results are more conclusive if agreement is obtained between data from two people working independently. Therefore, comparison graphs showing the data from two different microscopists are shown in the results section; a comparison of these two sets of data gives an idea over what energy region the combined spectral results are reliable

5. L. Goldstein, LA-702 (1948).
6. Since the writing of the report referred to in reference 1, it has been discovered that the above corrections are slightly inaccurate. The inaccuracy arises from neglecting the fact that the horizontal projection of the tracks are measured rather than their true length. The energy decrease (which is the larger effect) due to the measurement technique was considered but the track length decrease was ignored or overlooked. If the latter fact is taken into account, a calculation shows that the maximum of a proton recoil distribution from a monochromatic neutron source is shifted 7% below the neutron energy; the center of gravity of the distribution is shifted by 9%. Actually, the difference between 7% and 5% is too small to detect in the low energy region (0.3 Mev to 1.5 Mev) where the experimental and calculated curves of this investigation were compared. Since most of the tables and figures of this report had been prepared when this small inaccuracy was noted, they contain the 5% correction. However, the last figure, Fig. 13, has been drawn using the 7% energy correction.

Fig. 3 Neutron-proton scattering cross section versus energy.

and free of personal error.

A summary of general information concerning the analysis of the above plates is given in Table II. The original experimental details dealing with the exposure of the plates in the fast reactor is recorded in LA notebook #2178, pages 62 to 77. A list of plate numbers, their purpose, the microscopist and the LA notebooks in which the original track data is recorded is given below.

Plate number in LA notebooks	Plate purpose	Microscopist	LA notebook numbers
I64	Collimated neutron spectrum from peripheral loading geometry.	E.A.	2833, 2909
I64		J.E.	2793
I37	Collimated neutron spectrum from aluminum cage loading geometry with only plutonium.	E.A.	2909
I37		J.E.	2675
37		J.E.	2580, 2675
Il45	Collimated neutron spectrum from central loading geometry.	D.S.	2910
Il45		E.A.	2909
Il45		J.E.	2793, 2996
45		J.E.	2675
I66	Background data for colli- mated neutron spectrum with peripheral loading geometry.	E.A.	2909
I66		J.E.	2996
I66		D.S.	2910

C. Results

1. Collimated neutron spectrum from peripheral loading.

The peripheral loading scheme is shown in the inset in Fig. 5. This loading geometry is the loading which was used during service operation of the reactor. In the present experiment the center slug consisted of two 2 1/2" pieces of normal uranium: the plutonium slug normally occupying the center was moved to an adjacent position. The plates were exposed to the collimated beam at 63 cm above the top of the pot for 200 watt-minutes. A background run was also taken for this loading. In the latter case, the collimating tube was plugged with a neutron shield consisting of 43 cm of steel and 20 cm of boron plastic and the plates exposed for 200 watt-minutes.

The data and calculations on the above plates are shown in Tables III and IV. A graph illustrating a comparison of two microscopists results on the data and background plates is shown in Fig. 4. The ratio

Plate Number in LA Notebook	Plate Purpose	Exposure	Plate Type	Microscopist	Measured Average Emulsion Thickness		Processed Emulsion Thickness Analyzed	Number of Fields	Microscope Field Area in Square Microns	Number of Measured Tracks Above 0.4 Mev	Processed Emulsion Volume Analyzed (Units of 10^{-4} cm ³)	Number of Tracks Leaving Emulsion Surfaces
					Unprocessed	Processed						
I64	Data plates for peripheral loading geometry.	200 watt-min. at 64 cm. above top of pot.	Ilford C2 100 microns	E. A.	90 microns	10 microns	30 microns	1810	8660	2706	4.8	0
I64			"	J. E.	"	36 "	26 "	1113	8600	881	2.5	2
Combined I64 data			"	E. A. and J. E.						3587	7.3	2
I66	Background plates for peripheral loading geometry.	200 watt-min. at 64 cm. above top of pot.	Ilford C2 100 microns	E. A.	90 microns	37 microns	27 microns	1108	8660	130	2.6	0
I66			"	J. E.	"	35 "	25 "	1475	8600	156	3.1	0
Combined I66 data			"	E. A. and J. E.						286	5.7	0
I37	Data plates for aluminum cage loading geometry with only plutonium.	300 watt-min. at 73 cm. above top of pot.	Ilford C2 100 microns	J. E.	100 microns	39 microns	29 microns	468	8600	440	1.16	1
I37			"	E. A.	"	40 "	30 "	520	8660	885	1.38	0
Combined I37 data			"	J. E. and E. A.						1325	2.6	1
37			Eastman NTA 100 microns	J. E.	80 "	33 "	23 "	1049	8600	1580	2.1	6
I45	Data plates for central loading geometry.	500 watt-min. at 73 cm. above top of pot.	Ilford C2 100 microns	D. S.	90 microns	34 microns	24 microns	516	9161	1831	1.1	8
I45			"	J. E.	"	37 "	27 "	628	8600	1986	1.2	14
45			Eastman NTA 75 microns	J. E.	50 "	20 "	10 "	443	8600	832	0.4	30

TABLE II. General Information on Analysis of Plates Exposed in Collimated Neutron Beam from Reactor Pot.

Plate Number in LA Notebooks	Plate Purpose	Exposure	Plate Type	Microscopist	Measured Average Emulsion Thickness		Processed Emulsion Thickness Analyzed	Number of Fields	Microscope Field Area	Number of Measured Tracks Above 4 Microns	Dry Emulsion Volume Analyzed (Units of 10^{-4} cm ³)	Number of Tracks Leaving Emulsion Surfaces
					Unprocessed	Processed						
33	Data plates for continuous neutron spectrum at center of reactor.	0.2 watt-sec. Eastman NTA at center of reactor pot with central loading.	Eastman NTA 100 microns	E. A.	90 microns	47 microns	47 microns	521	60 μ x 60 μ (3600 μ^2)	1861	1.70	286
30			"	S.S.	90 "	37 "	37 "	96	80 μ x 80 μ (6400 μ^2)	457	0.55	108
I30(I4)			Ilford EI 100 microns	E. A.	90 "	35 "	35 "	505	60 μ x 60 μ (3600 μ^2)	1903	1.64	231

TABLE VIII. General Information on Analysis of Proton Recoil Plates Exposed at Center of Reactor Pot.

Proton Recoil Energy Interval in Mev	Number of Tracks per 0.1 Mev		Energy in Mev Associated with Averaged Tracks		σ in Barns at E_n	Relative Neutron Flux. Average Tracks per 0.1 Mev/ $\sigma_p \times 10^{24}$		
	Plate I66 by E.A.	Plate I66 by J.E.	E_p Interval in Mev	Average E_n in Mev		Plate I66 by E.A.	Plate I66 by J.E.	Combined I66 Plates
0.3 - 0.4	12	11	0.3 - 0.4	0.37	7.25	1.7 ± 0.5	1.5 ± 0.5	3.2 ± 0.7
0.4 - 0.5	32	30	0.4 - 0.5	0.47	6.30	5.1 ± 0.9	4.7 ± 0.9	9.8 ± 1.3
0.5 - 0.6	26	59	0.5 - 0.6	0.58	5.65	4.6 ± 0.9	10.3 ± 1.3	14.9 ± 1.6
0.6 - 0.7	21	22	0.6 - 0.7	0.68	5.25	4.0 ± 0.9	4.2 ± 0.9	8.2 ± 1.3
0.7 - 0.8	3	17	0.7 - 0.8	0.79	4.90	0.6 ± 0.4	3.5 ± 0.8	4.1 ± 0.9
0.8 - 0.9	9	8	0.8 - 0.9	0.89	4.52	2.0 ± 0.7	1.8 ± 0.6	3.8 ± 0.9
0.9 - 1.0	9	5	0.9 - 1.1	1.05	4.30	1.7 ± 0.5	1.1 ± 0.4	2.8 ± 0.6
1.0 - 1.1	6	4						
1.1 - 1.2	5	1	1.1 - 1.3	1.21	3.92	1.1 ± 0.4	0.8 ± 0.3	1.9 ± 0.5
1.2 - 1.3	4	5						
1.3 - 1.4	1	0	1.3 - 1.5	1.47	3.50	0.6 ± 0.3	0.3 ± 0.2	0.9 ± 0.4
1.4 - 1.5	3	2						
1.5 - 1.6	4	1	1.5 - 2.0	1.84	3.05	0.4 ± 0.2	0.1 ± 0.1	0.5 ± 0.2
1.6 - 1.7	1	1						
1.7 - 1.8	1	0						
1.8 - 1.9	0	0						
1.9 - 2.0	0	0						
2.0 - 2.1	1	0	2.0 - 2.5	2.36	2.65	0.3 ± 0.2	0.1 ± 0.1	0.4 ± 0.2
2.1 - 2.2	2	1						
2.2 - 2.3	1	0						
2.3 - 2.4	1	0						
2.4 - 2.5	0	0						

TABLE III Data and Calculations on Nuclear Plates Exposed in Fast Reactor
for Background Effect with Peripheral Loading.

Proton Recoil Energy Interval in Mev	Number of Tracks per 0.1 Mev		Energy in Mev Associated with Averaged Tracks		σ_p in Barns at E_n	Correction Factor for Tracks Leaving Emulsion Surfaces		Relative Neutron Flux, Corrected Average Tracks per 0.1 Mev/ $\sigma_p \times 10^{24}$		
	Plate I64 by E.A.	Plate I64 by J.E.	Ep Interval in Mev	Average E_n in Mev		I64 by E.A. $T(a.p.) = 40\mu$	I64 by J.E. $T(a.p.) = 36\mu$	Plate I64 by E.A.	Plate I64 by J.E.	Combined I64 Plates
0.3 - 0.4	295	97	0.3 - 0.4	0.37	7.25	1.0	1.0	40.7 ± 2.4	13.4 ± 1.3	54.1 ± 2.8
0.4 - 0.5	532	85	0.4 - 0.5	0.47	6.30	1.0	1.0	64.4 ± 3.7	13.5 ± 1.5	97.9 ± 3.9
0.5 - 0.6	454	182	0.5 - 0.6	0.58	5.65	1.0	1.0	80.3 ± 3.8	32.2 ± 2.4	112.5 ± 4.5
0.6 - 0.7	518	141	0.6 - 0.7	0.68	5.25	1.0	1.0	98.6 ± 4.4	26.9 ± 2.3	125.5 ± 4.9
0.7 - 0.8	208	123	0.7 - 0.8	0.79	4.90	1.0	1.0	42.4 ± 2.9	25.1 ± 2.3	67.5 ± 3.7
0.8 - 0.9	213	67	0.8 - 0.9	0.89	4.52	1.0	1.0	47.1 ± 3.2	14.8 ± 1.8	61.9 ± 3.7
0.9 - 1.0	169	50	0.9 - 1.1	1.05	4.30	1.0	1.0	28.1 ± 1.8	9.1 ± 1.0	37.2 ± 2.1
1.0 - 1.1	72	29								
1.1 - 1.2	87	24	1.1 - 1.3	1.21	3.92	1.0	1.0	18.4 ± 1.6	6.7 ± 0.9	25.1 ± 1.8
1.2 - 1.3	56	28								
1.3 - 1.4	53	13	1.3 - 1.5	1.47	3.50	1.0	1.0	13.9 ± 1.4	4.4 ± 0.8	18.3 ± 1.6
1.4 - 1.5	44	18								
1.5 - 1.6	49	17	1.5 - 2.0	1.84	3.05	1.0	1.0	9.2 ± 0.8	4.1 ± 0.5	13.3 ± 0.9
1.6 - 1.7	26	9								
1.7 - 1.8	27	15								
1.8 - 1.9	24	8								
1.9 - 2.0	15	13								
2.0 - 2.1	11	16	2.0 - 2.5	2.36	2.65	1.03	1.03	4.9 ± 0.6	2.7 ± 0.5	7.6 ± 0.8
2.1 - 2.2	16	1								
2.2 - 2.3	11	8								
2.3 - 2.4	14	5								
2.4 - 2.5	11	4								
2.5 - 2.6	11	4	2.5 - 3.0	2.69	2.35	1.07	1.08	3.4 ± 0.6	0.9 ± 0.3	4.3 ± 0.6
2.6 - 2.7	4	0								
2.7 - 2.8	11	1								
2.8 - 2.9	2	0								
2.9 - 3.0	5	5								
3.0 - 3.1	6	2	3.0 - 3.5	3.41	2.10	1.12	1.14	3.0 ± 0.6	0.8 ± 0.3	3.8 ± 0.6
3.1 - 3.2	6	2								
3.2 - 3.3	3	2								
3.3 - 3.4	6	1								
3.4 - 3.5	8	0								
3.5 - 3.6	2	1	3.5 - 4.0	3.94	1.95	1.20	1.22	1.5 ± 0.4	0.3 ± 0.2	1.8 ± 0.5
3.6 - 3.7	2	0								
3.7 - 3.8	4	1								
3.8 - 3.9	4	0								
3.9 - 4.0	0	0								
4.0 - 4.1	4	2	4.0 - 4.5	4.46	1.75	1.29	1.35	1.4 ± 0.5	0.8 ± 0.3	2.2 ± 0.6
4.1 - 4.2	1	0								
4.2 - 4.3	2	2								
4.3 - 4.4	2	1								
4.4 - 4.5	0	0								
4.5 - 4.6	2	0	4.5 - 5.0	4.99	1.60	1.43	1.55	1.0 ± 0.5	0.4 ± 0.4	1.4 ± 0.6
4.6 - 4.7	1	0								
4.7 - 4.8	2	0								
4.8 - 4.9	0	0								
4.9 - 5.0	1	1								
5.0 - 5.1	0	0	5.0 - 5.5	5.51	1.50	1.61	1.78	0	0	0
5.1 - 5.2	0	0								
5.2 - 5.3	0	0								
5.3 - 5.4	0	0								
5.4 - 5.5	0	0								
5.5 - 5.6	0	0	5.5 - 6.0	6.04	1.43	1.84	2.06	0.8 ± 0.5	0	0.8 ± 0.5
5.6 - 5.7	2	0								
5.7 - 5.8	0	0								
5.8 - 5.9	0	0								
5.9 - 6.0	1	0								
Tracks > 6 Mev	2	0								

TABLE IV Data and Calculations on Nuclear Plates Exposed in Fast Reactor with Peripheral Loading Geometry.

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of emulsion volumes analyzed should provide the best figure for correlating absolute track intensities between the results of two different microscopists. Unfortunately, there is a chance for rather large errors to enter into emulsion volume determinations. The largest error seems to arise from microscope instrumental inaccuracy in determining emulsion thickness - different microscopes may differ by as much as 4 or 5 microns in measuring an emulsion thickness of 40 microns. Another source of emulsion volume error due either to personal or instrumental cause is involved in the measurement of the 5 micron emulsion thickness skipped from the surfaces of the emulsion. Therefore, the ordinate scale ratio for the two sets of results has been adjusted to correspond to the average of the emulsion volume ratio and the ratio of the number of tracks measured by each of the microscopists. The ratio of the number of tracks above 0.4 Mev usually agrees approximately with the emulsion volume ratio; however, in cases of disagreement the average of these ratios has been chosen as the ordinate scale ratio for these comparison graphs.

In Fig. 4 the agreement of the two sets of data as to the general shape of the spectrum curve is quite good. Only the points at 0.47 and 0.68 Mev are in poor agreement; in both of these cases one point seems unusually high and the other one unusually low. The comparison of the two sets of results indicates that the combined data could be trusted for reliability above 0.5 Mev and used with reservations between 0.3 and 0.5 Mev. The ordinate scale for the background run has also been approximately adjusted so that equal volumes of data and background plates are compared on the graph. Agreement between the two sets of background data is satisfactory except for the 0.58 Mev point.

The combined results from the data and background results are plotted in Fig. 5. Previous investigation¹ has shown that the 0.3 - 0.4 and 0.4 - 0.5 Mev proton recoil energy intervals must be increased by $75 \pm 10\%$ and $10 \pm 2\%$ respectively in order to provide correct values for the neutron flux. These corrections have been made on the combined results both for the regular data and the background data. The solid curve is the neutron spectrum obtained from the corrected data points while the dashed curve represents that obtained by subtracting the background data points. Since the above curves differ at most by 10% in height, the background is not a serious effect in this experiment. The fact that the background curve has roughly the same shape as the data curve suggests that the background neutrons have the same source and a similar transmission to that of the pot neutrons. The most obvious mechanism is that these background neutrons arise from the reactor pot and reach the nuclear plates by proceeding upward through some of the adjacent open experimental holes. Some of these holes are only a few inches distant from the collimating tube and it is possible for neutrons to diffuse through the separating material and enter the

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Fig. 5 Combined results on collimated neutron spectrum and background effect for peripheral loading.

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nuclear plates.

2. Collimated neutron spectrum from aluminum cage loading with only plutonium.

The pot loading for this experiment is shown in the inset in Fig. 7. The center slug position is empty. In this respect, the loading is somewhat similar to that of the previous experiment in that no reactive material was placed at the center; however, the loading of the plutonium in this case is more uniform than in the peripheral geometry. Another difference is that here aluminum replaces the mercury in the interspaces between the slugs. (The substitution of aluminum for mercury was tried chiefly for the information of the Argonne Laboratory, the idea being to simulate their sodium-potassium cooling mixture and to obtain preliminary information on properties of such a mixture). The plates were exposed to the collimated beam at 73 cm above the top of the pot for 300 watt-minutes.

The data and calculations relating to this experiment are shown in Table V. A graph comparing data taken by two microscopists is illustrated in Fig. 6. As before, the ordinate scales for the two sets of data have been adjusted so that approximately equal volumes of analyzed emulsion are compared on the graph. Satisfactory agreement exists between the two sets of data except for the low energy point at 0.37 Mev. Therefore, the combined data curve can be expected to be quite free of personal observation error above about 0.4 Mev.

The combined data are plotted in Fig. 7. Approximate corrections plate inefficiency have again been made for the 0.3 - 0.4 and 0.4 - 0.5 Mev proton recoil energy intervals. No background experiment was performed for this loading geometry but, as previously shown, the background exerts a small effect on the spectral curve.

3. Collimated neutron spectrum from central loading.

The loading geometry in this experiment is shown in the inset diagram in Fig. 9. This loading differed chiefly from the previous two loadings in that the center slug position consisted of reactive material or plutonium. The pot itself was identical to that used in the peripheral loading and mercury filled all interspaces between the plutonium and uranium slugs. The plates were located at a distance of 73 cm above the surface of the pot and were exposed for 500 watt-minutes.

Data and calculations for the above plate exposure are shown in Table VI. A comparison of the results of two microscopists is shown in Fig. 8. Satisfactory agreement as to the general shape of the curve

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Proton Recoil Energy Interval in Mev	Number of Tracks per 0.1 Mev			Energy in Mev Associated with Averaged Tracks		σ_p in Barns at E_n	Correction Factor for Tracks Leaving Emulsion Surfaces		Relative Neutron Flux, Corrected Average Tracks per 0.1 Mev/ $\sigma_p \times 10^{24}$		
	Plate 37 by J.E.	Plate 137 by J.E.	Plate 137 by E.A.	E_p Interval in Mev	Average E_n in Mev		Plate 37 T(a.p.)= 33.4	Plate 137 T(a.p.)= 40.4	Plate 37 by J.E.	Plate 137 by E.A.	Plates 37 and 137
0.2 - 0.3	170	13	39	0.2 - 0.3	0.26	8.55	1.0	1.0	19.8 ± 1.5	6.1 ± 0.85	25.9 ± 1.7
0.3 - 0.4	254	47	72	0.3 - 0.4	0.37	7.25	1.0	1.0	35.0 ± 2.2	16.4 ± 1.5	51.4 ± 2.7
0.4 - 0.5	366	95	134	0.4 - 0.5	0.47	6.30	1.0	1.0	58.0 ± 3.0	36.3 ± 2.4	94.3 ± 3.9
0.5 - 0.6	345	87	151	0.5 - 0.6	0.58	5.65	1.0	1.0	61.1 ± 3.3	42.1 ± 2.7	103.2 ± 4.2
0.6 - 0.7	219	57	105	0.6 - 0.7	0.68	5.25	1.0	1.0	41.7 ± 2.8	30.9 ± 2.4	72.6 ± 3.7
0.7 - 0.8	108	33	68	0.7 - 0.8	0.79	4.90	1.0	1.0	22.0 ± 2.1	20.6 ± 2.0	42.6 ± 2.9
0.8 - 0.9	98	29	78	0.8 - 1.0	0.95	4.45	1.0	1.0	19.4 ± 1.9	20.2 ± 1.5	39.6 ± 3.0
0.9 - 1.0	75	19	53								
1.0 - 1.1	54	13	51	1.0 - 1.3	1.21	3.95	1.0	1.0	12.4 ± 1.0	13.7 ± 1.1	26.2 ± 2.0
1.1 - 1.2	44	12	31								
1.2 - 1.3	50	17	39								
1.3 - 1.4	21	11	19	1.3 - 1.6	1.52	3.48	1.0	1.0	6.4 ± 0.8	6.9 ± 0.8	13.3 ± 1.6
1.4 - 1.5	23	4	18								
1.5 - 1.6	23	6	14								
1.6 - 1.7	17	8	8	1.6 - 2.0	1.89	2.95	1.0	1.0	5.0 ± 0.7	6.4 ± 0.8	11.4 ± 1.3
1.7 - 1.8	8	6	15								
1.8 - 1.9	18	8	15								
1.9 - 2.0	16	7	9								
2.0 - 2.1	9	2	8	2.0 - 2.5	2.36	2.65	1.03	1.03	3.2 ± 0.5	4.4 ± 0.6	7.6 ± 1.0
2.1 - 2.2	10	3	11								
2.2 - 2.3	7	0	4								
2.3 - 2.4	9	4	8								
2.4 - 2.5	6	2	13								
2.5 - 2.6	7	0	3	2.5 - 3.0	2.89	2.35	1.09	1.07	2.2 ± 0.5	2.3 ± 0.5	4.5 ± 0.9
2.6 - 2.7	6	3	2								
2.7 - 2.8	3	3	3								
2.8 - 2.9	3	3	4								
2.9 - 3.0	4	2	2								
3.0 - 3.1	2	2	0	3.0 - 3.5	3.41	2.10	1.17	1.12	1.7 ± 0.4	1.1 ± 0.3	2.8 ± 0.8
3.1 - 3.2	2	0	3								
3.2 - 3.3	4	0	4								
3.3 - 3.4	6	1	0								
3.4 - 3.5	1	0	2								
3.5 - 3.6	1	0	1	3.5 - 4.0	3.94	1.95	1.27	1.20	0.5 ± 0.2	0.6 ± 0.3	1.1 ± 0.6
3.6 - 3.7	0	0	1								
3.7 - 3.8	2	0	1								
3.8 - 3.9	1	0	0								
3.9 - 4.0	1	0	2								
4.0 - 4.1	1	1	1	4.0 - 4.5	4.46	1.75	1.44	1.29	0.7 ± 0.3	0.6 ± 0.3	1.3 ± 0.7
4.1 - 4.2	0	0	0								
4.2 - 4.3	1	0	1								
4.3 - 4.4	1	1	0								
4.4 - 4.5	1	0	0								
4.5 - 4.6	0	0	1	4.5 - 5.0	4.99	1.60	1.67	1.43	0.2 ± 0.2	0.5 ± 0.3	0.7 ± 0.5
4.6 - 4.7	0	0	0								
4.7 - 4.8	0	0	1								
4.8 - 4.9	0	1	0								
4.9 - 5.0	0	0	0								
5.0 - 5.1	0	0	0	5.0 - 5.5	5.51	1.50	1.95	1.61	0	0	0
5.1 - 5.2	0	0	0								
5.2 - 5.3	0	0	0								
5.3 - 5.4	0	0	0								
5.4 - 5.5	0	0	0								
5.5 - 5.6	1	0	0	5.5 - 6.0	6.04	1.43	2.25	1.84	0.9 ± 0.6	0.3 ± 0.3	1.2 ± 0.6
5.6 - 5.7	1	0	1								
5.7 - 5.8	0	0	0								
5.8 - 5.9	1	0	0								
5.9 - 6.0	0	0	0								
Tracks > 6 Mev	3	0	0								

TABLE V. Data and Calculations on Nuclear Plates Exposed in Fast Reactor Having Aluminum Cage Loading Geometry with Only Plutonium.

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Fig. 6 Comparison of two sets of results on collimated neutron spectrum from aluminum cage loading with only plutonium

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Fig. 7 Combined results on collimated neutron spectrum from aluminum cage loading with only plutonium.

exists above 0.8 Mev but results vary widely in the region from 0.3 to 0.8 Mev. The poor agreement between the data at low energies was caused by poor plate quality and by too great a track density (see Table II). Both of the above factors increase the difficulties encountered in correctly analyzing the short tracks. The combined data from these three sets can probably be considered free of observational error above 0.8 Mev. In the combined data graph of Fig. 9 a dotted line has been drawn for the spectral curve below 0.8 Mev to show that the data is uncertain in this region. Since this spectral curve is more similar to the normal fission spectrum than the curves of the previous two experiments, a comparison has been made with the Pu²³⁹ or U²³⁵ fission spectrum^{2,7}.

D. Discussion

The spectral curves obtained from the collimated neutron beam in the first two experiments are very similar. A comparison of these two spectra is shown in Fig. 10. The curves have identical shape above 2 Mev⁸ and differ only slightly below 2 Mev; the spectrum from the peripheral loading has a maximum at 0.6 Mev and the aluminum cage loading spectrum has a maximum at 0.5 Mev. The greater neutron degradation in the case of the latter curve may be due to neutrons losing more energy per collision in the aluminum pot than in the peripheral loaded pot having mercury in the interspaces.

Both of the spectra in Fig. 10 were obtained with approximately the same center slug conditions, i.e. no plutonium in the center position. However, the geometry of the rest of these loadings is quite different in the two experiments, being peripheral in the first experiment and centralized or uniform in the second experiment. This indicates that the loading geometry does not appreciably influence the neutron spectra above 0.4 Mev inside the pot. This conclusion is also supported by the fission foil experiments⁹ at the center of the pot and by the experiment⁹ which consists of a calculation of the neutron spectrum from a plate exposed at the center of the pot with central loading. The neutron spectrum derived from this latter experiment has been plotted as a dashed curve in Fig. 10; the points were arbitrarily normalized to the high energy region of the two collimated spectra. It is observed that this calculated spectrum for the central loading geometry is a similarly shaped curve, i.e. the curve rises rapidly at energies

7. E. Watt, LA-718 (1948).

8. See Fig. 13 for better comparison of these two spectra in high energy region.

9. Described in Section III of this report.

Proton Recoil Energy Interval in Mev	Number of Tracks per 0.1 Mev			Energy in Mev Associated with Averaged Tracks		σ_p in Barns at E_n	Correction Factor for Tracks Leaving Emulsion Surfaces			Relative Neutron Flux. Corrected Average Tracks per 0.1 Mev / $\sigma_p \times 10^{-24}$			
	Plate I45 by D.S.	Plate I45 by J.E.	Plate 45 by J.E.	E_p Interval	Average E_n		I45 by D.S. $T(a.p.) = 34\%$	I45 by J.E. $T(a.p.) = 37\%$	45 by J.E. $T(a.p.) = 29\%$	Plate I45 by D.S.	Plate I45 by J.E.	Plate 45 by J.E.	Plates I45 + 45
0.3 - 0.4	168	34	24	0.3 - 0.4	0.37	7.25	1.0	1.0	1.0	23.2 ± 1.8	4.7 ± 0.8	3.3 ± 0.7	31.2 ± 2.1
0.4 - 0.5	339	42	33	0.4 - 0.5	0.47	6.30	1.0	1.0	1.0	53.8 ± 2.9	6.7 ± 1.0	5.2 ± 0.9	65.7 ± 3.2
0.5 - 0.6	211	122	70	0.5 - 0.6	0.58	5.65	1.0	1.0	1.0	37.3 ± 2.6	21.6 ± 2.0	12.4 ± 1.5	71.3 ± 3.6
0.6 - 0.7	247	154	85	0.6 - 0.7	0.68	5.25	1.0	1.0	1.0	47.0 ± 3.0	29.3 ± 2.4	16.2 ± 1.7	92.5 ± 4.2
0.7 - 0.8	123	206	84	0.7 - 0.8	0.79	4.90	1.0	1.0	1.0	25.1 ± 2.3	42.0 ± 2.9	17.1 ± 1.9	84.2 ± 4.1
0.8 - 0.9	134	152	45	0.8 - 1.0	0.95	4.45	1.0	1.0	1.0	25.6 ± 1.7	33.5 ± 1.9	10.8 ± 1.1	69.9 ± 2.8
0.9 - 1.0	93	146	51										
1.0 - 1.1	98	108	37	1.0 - 1.3	1.21	3.95	1.0	1.0	1.0	18.2 ± 1.2	28.4 ± 1.5	11.1 ± 1.0	57.7 ± 2.2
1.1 - 1.2	68	100	62										
1.2 - 1.3	49	129	33										
1.3 - 1.4	62	85	33	1.3 - 1.6	1.52	3.48	1.0	1.0	1.0	14.9 ± 1.2	20.7 ± 1.4	9.7 ± 1.0	45.3 ± 2.1
1.4 - 1.5	36	70	40										
1.5 - 1.6	58	61	28										
1.6 - 1.7	42	63	18	1.6 - 2.0	1.89	2.95	1.0	1.0	1.01	10.2 ± 0.9	16.8 ± 1.2	7.1 ± 0.8	34.1 ± 1.7
1.7 - 1.8	44	33	26										
1.8 - 1.9	17	56	21										
1.9 - 2.0	18	44	18										
2.0 - 2.1	24	38	15	2.0 - 2.5	2.36	2.65	1.03	1.03	1.06	7.4 ± 0.8	12.5 ± 1.0	5.8 ± 0.6	25.7 ± 1.4
2.1 - 2.2	28	30	10										
2.2 - 2.3	22	46	23										
2.3 - 2.4	9	26	12										
2.4 - 2.5	11	21	12										
2.5 - 2.6	13	28	8	2.5 - 3.0	2.89	2.35	1.08	1.07	1.18	4.1 ± 0.6	8.8 ± 1.0	3.8 ± 0.4	16.7 ± 1.2
2.6 - 2.7	11	19	4										
2.7 - 2.8	12	21	10										
2.8 - 2.9	3	18	8										
2.9 - 3.0	6	11	8										
3.0 - 3.1	2	15	4	3.0 - 3.5	3.41	2.10	1.16	1.13	1.44	2.6 ± 0.5	5.8 ± 0.8	2.1 ± 0.5	10.5 ± 1.1
3.1 - 3.2	8	11	7										
3.2 - 3.3	7	14	3										
3.3 - 3.4	5	7	1										
3.4 - 3.5	2	7	0										
3.5 - 3.6	5	8	1	3.5 - 4.0	3.94	1.95	1.25	1.22	1.82	1.7 ± 0.5	3.2 ± 0.6	2.1 ± 0.7	7.0 ± 1.0
3.6 - 3.7	5	7	6										
3.7 - 3.8	1	4	2										
3.8 - 3.9	2	4	2										
3.9 - 4.0	0	3	0										
4.0 - 4.1	2	7	1	4.0 - 4.5	4.46	1.75	1.41	1.34	2.24	1.1 ± 0.4	3.5 ± 0.7	1.8 ± 0.7	6.4 ± 1.1
4.1 - 4.2	2	3	3										
4.2 - 4.3	1	6	1										
4.3 - 4.4	1	4	1										
4.4 - 4.5	1	3	1										
4.5 - 4.6	0	2	3	4.5 - 5.0	4.99	1.60	1.62	1.50	2.70	0.8 - 0.4	2.1 ± 0.6	1.3 ± 0.7	4.2 ± 1.0
4.6 - 4.7	1	3	0										
4.7 - 4.8	0	3	0										
4.8 - 4.9	3	0	0										
4.9 - 5.0	0	3	1										
5.0 - 5.1	0	0	0	5.0 - 5.5	5.51	1.50	1.90	1.75	3.18	0.8 - 0.4	0.9 ± 0.5	0 ± 0	1.7 ± 0.6
5.2 - 5.3	1	1	0										
5.3 - 5.4	1	1	0										
5.4 - 5.5	1	1	0										
5.5 - 5.6	0	2	0	5.5 - 6.0	6.04	1.43	2.2	2.0	3.70	0.6 - 0.4	1.4 ± 0.6	0.5 ± 0.5	2.5 ± 1.0
5.6 - 5.7	0	1	1										
5.7 - 5.8	0	1	0										
5.8 - 5.9	1	1	0										
5.9 - 6.0	1	0	0										
Tracks > 6 Mev	1	1	0										

TABLE VI. Data and Calculations on Nuclear Plates Exposed in Fast Reactor with Central Loading Geometry.

Fig. 8 Comparison of results on collimated neutron spectrum from central loading

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Fig 9 Combined results on collimated neutron spectrum from central loading

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Fig. 10 Comparison of collimated neutron spectra obtained with peripheral and aluminum cage loading geometries. Inset: present results compared with Rosen's results for peripheral loading.

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below 1 Mev and decreases slowly at energies above 2 Mev.

The inset graph of Fig. 10 shows a comparison of Rosen's results¹⁰ with the present results for the case of the peripheral loading geometry. The loading geometry was identical in these two experiments but the method of collimation differed. Rosen used a special 1 1/8" i.d. collimator made up of a section of tamped boron powder 6" long and a section of cold rolled steel 24" long. This 6" o.d. collimator was inserted into the reactor to replace the center removable tamper and shield can. A nuclear plate camera was placed at the top or steel end of the collimator to detect the emerging neutrons. The two sets of results are in excellent agreement above 0.5 Mev. It is interesting to note that these two different types of collimators do not influence the neutron spectrum.

The collimated spectrum obtained from the central loading geometry shown in Fig. 9 is quite different from the curve shapes shown in Fig. 10. The most noticeable difference is the larger ratio of neutron flux above 1 Mev to that below 1 Mev. Evidently, this difference in the collimated spectra for the central loading geometry is due to the center slug being plutonium. The nuclear plates detect mainly the neutron flux emerging from the center slug position and therefore, one might expect a plutonium fission spectrum superimposed on the spectrum emerging from the reactor pot through the center plutonium rod. The curve in Fig. 9 seems to substantiate the above reasoning, viz. the high energy region resembles a fission spectrum since the pot spectrum contributes very little here; the low energy region is much higher than the fission spectrum since here the pot spectrum adds greatly to the fission spectrum.

As will be shown later in Section III, the neutron spectrum calculated from the plate exposed at the center of the pot with the central loading provides the most accurate representation (above 0.6 Mev) of the neutron spectrum existing at the center of the pot (see Fig. 13). From a comparison of the collimated spectra with this calculated spectrum (see Fig. 10 and Fig. 13), one concludes that the collimation method using an empty center hole or a non-reactive slug in the center hole is an approximate method for roughly determining the shape of the neutron spectrum inside the pot. At least the above collimation geometry is much better than that of using a reactive slug at the center of the pot.

The disagreement which does exist between the first two collimated spectra and the calculated spectrum obtained for the center of the pot

10. L. Rosen, LAMS-915 (1949).

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is probably not due to the difference in loading geometry but rather to the different experimental arrangements used in the two cases. As mentioned earlier in the report, one expects the plates in the collimated beam to see a larger fraction of scattered neutrons than a detector at the center of the pot. If the curves from the two methods are matched in the high energy region as in Fig. 10, the collimated spectra curves show a greater flux around the 1 - 2 Mev region. However, a better understanding is secured by observing in the inset graph of Fig. 13 that the spectra from collimation and the spectrum at the pot center possess different slopes in the high energy region. Therefore, it is more satisfactory to match the spectra in the 1 - 2 Mev region as has been done in Fig. 13. The comparison in the inset graph in Fig. 13 emphasizes the main difference of the collimated spectra as showing a smaller neutron flux in the high energy region than the spectrum at the pot center. In brief, the reason for this discrepancy seems to be that the collimated neutrons reach the detector chiefly through elastic scattering processes. Since the elastic scattering cross section decreases with increasing energy, it would be expected that the number of neutrons in the collimated beam would show a faster decrease with energy than those at the center of the pot. More detailed discussion on this matter is presented at the end of Section III.

III. NEUTRON ENERGY INVESTIGATIONS AT CENTER OF REACTOR POT

A. Threshold Fission Foil Method.

1. Experimental procedure.

The experimental arrangement is the same as that shown in Fig. 1. Threshold fission foils were placed against Eastman NTC plates and exposed at the center of the reactor pot. A detail of the exposure geometry is shown in the left inset diagram in Fig. 1. Except in the case of the aluminum cage loading geometry, all of the exposures were made with the plates and foils placed between two 2 1/2" sections of normal uranium; in the aluminum cage loading the plates were situated between two 2 1/2" sections of U²³⁵ metal. In all cases, the exposure assembly occupied the center slug position.

Foils containing U²³⁵, Np²³⁷, and U²³⁸ were employed. The effective fission thresholds of the latter two foils for the reactor spectrum are approximately 0.5 and 1.4 Mev respectively. A coating of about 0.01 mg/cm² of metal was used for the U²³⁵ and Np²³⁷ foils and about 0.1 mg/cm² of metal for the U²³⁸ foil. Exposures were made at 100 or 200 watt-minutes. In some pot loadings, the U²³⁵ foil and plate were wrapped in cadmium to determine if any neutrons existed below the cadmium cut-off.

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The plates were analyzed by merely averaging the number of fission tracks per microscope field over the region of the foil (1/2" x 1"). The spacing of swaths and fields varied but the counting was always performed over the entire foil area in order to average out irregularities in the foil coating. Each plate was usually counted to an accuracy of about 3% and the average of two or more separate foils was used to obtain a result. The original experimental details on the above experiments are recorded in LA notebook #2178, pages 34 to 77.

2. Results and discussion.

The results of the experiment are tabulated in Table VII. The final foil and nuclear plate results have been presented in terms of tracks/watt-minute/atom of fissionable metal. During these preliminary reactor experiments, the reactor power was not determined accurately and the absolute number of tracks per watt-minute of exposure may be in error by $\pm 20\%$. This is evident from a comparison of results obtained with the central loading geometry during the July-Oct. 1948 period and during Dec. 1948. Therefore, instead of comparing the absolute number of tracks, a better comparison criteria is to compare the ratios existing between the different foils. All of the listed errors are standard statistical errors. Other systematic errors that may be present are foil coating ($\pm 2\%$) and microscope field area ($\pm 4\%$).

The N_p^{237}/U^{238} ratio is the same within experimental error for all of the loadings. Therefore, for all three loading geometries, the relative neutron spectrum at the pot center is the same above 0.5 Mev. The three fission foil ratios for the central and aluminum cage loadings indicate that these two loadings possess similar neutron spectra over the entire energy region. The ratios involving U^{235} for the peripheral loading show that this loading geometry possesses either neutrons of a lower energy (< 0.3 Mev) or relatively greater numbers of similar low energy neutrons than the other two loadings. This effect is most likely due to the primary fissionable material being around the edge of the pot and, therefore, the neutrons must proceed through more material and become more degraded before reaching the foils at the center of the pot. This effect would be more pronounced for neutrons of low energy since collision cross sections are higher at low energies. Evidently the reason for the low values of tracks/watt-minute/atom in the case of the peripheral loading is due to the geometric neutron distribution which this loading produces. The other two loadings produce neutron distributions with an intensity maximum at the center of the pot whereas the peripheral loading distribution would have a dip at the center.

Rough spectrum curves can be derived by considering the various energy regions over which the threshold fission foils are activated.

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Fission foil metal	Tracks/watt-minute/atom of metal x 10 ¹⁵			
	Peripheral loading (Jan. 1949)	Aluminum cage loading (Nov. 1948)	Central loading (Aug.- Oct. 1948)	Central loading (Dec. 1948)
${}_{92}\text{U}^{235}$	27.5 ± 0.5	38 ± 0.4	50 ± 1	66 ± 1
${}_{93}\text{Np}^{237}$	15.0 ± 0.3	31 ± 0.5	38 ± 1	56 ± 1
${}_{92}\text{U}^{238}$	2.6 ± 0.1	5.4 ± 0.2	7.2 ± 0.2	9.8 ± 0.3

Fission foil metals	Fission foil ratios			
	Peripheral loading (Jan. 1949)	Aluminum cage loading (Nov. 1948)	Central loading (Aug.- Oct. 1948)	Central loading (Dec. 1948)
$\text{Np}^{237}/\text{U}^{238}$	5.8 ± 0.3	5.7 ± 0.3	5.3 ± 0.2	5.7 ± 0.2
$\text{U}^{235}/\text{U}^{238}$	10.6 ± 0.5	7.0 ± 0.3	6.9 ± 0.3	6.7 ± 0.2
$\text{U}^{235}/\text{Np}^{237}$	1.8 ± 0.05	1.2 ± 0.05	1.3 ± 0.05	1.2 ± 0.05

TABLE VII. Results from Threshold Fission Foils on NTC Plates Exposed at Center of Reactor Pot with Three Different Loadings.

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In this way, a band or step spectrum can be obtained. This has previously been done for the central loading geometry¹¹. However, since the curves obtained are only approximate and the main purpose of this report is to present continuous spectra, the fission foil results have been only presented in ratio form and used mainly for comparison and check purposes with the continuous spectral determinations.

The foil ratio U^{235} (with cadmium)/ U^{235} (without cadmium) turned out to be 1.00 ± 0.01 for the central and aluminum cage loading geometries. If any pot neutrons exist which have energies below the cadmium cut-off, they must be less than about 1% of the total number.

B. Proton Recoil Plate Method.

1. Description of method and plate analysis.

The idea of this experiment was to derive a continuous neutron spectrum from a proton recoil spectrum obtained at the center of the pot. For this purpose, proton recording nuclear plates were inserted between two 2 1/2" sections of normal uranium and this assembly placed in the center slug position of the reactor pot (see Fig. 1). The plates were exposed for approximately 0.2 watt-second in the central loading geometry. The experiment was not performed for other loading geometries. The neutron spectrum or flux, $N_p(E)$, can be derived from the measured proton recoil spectrum, $M_p(E)$, by use of the equation¹²

$$N_n(E) = \frac{-d(CM_p(E_p))}{dE_p} \times \frac{E \lambda(E)}{V_e Q} = \frac{-\Delta \left[CM_p(l_p) \Delta l_p / \Delta E_p \right]}{\Delta E_p} \times \frac{E}{\sigma_p(E) n_p V_e Q}$$

where

C is a geometry correction factor for proton recoil tracks leaving the emulsion surfaces.

$\lambda(E)$ is the mean free path of the neutron in the emulsion,

Q is the exposure quantity given to the plate,

V is the emulsion volume.

It is practical to employ the following measurement units for use in the equation given in the last form.

11. J. Hall, LAMD-125 (1948).
12. F. Reines, Phys. Rev. 74, 1565 (1948).

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- $N_n(E)$ = number of neutrons/Mev/cm²/watt-minute at energy E,
 $M_p(l_p)$ = number of proton recoils per micron interval measured at proton range, l_p , corresponding to energy E_p .
 $\Delta l_p/\Delta E_p$ = number of microns of proton range per Mev interval at energy E_p ,
 n_p = number of protons per cm³ of unprocessed or dry emulsion,
 V_e = total volume in cm³ of dry nuclear emulsion analyzed,
 Q = exposure in watt-minutes,
 $\sigma_p(E)$ = n-p collision cross section in cm² units at energy E.

The above equation is appropriate only if the mean free path, $\lambda(E)$, for a neutron-proton collision in the emulsion is large compared to the average dimension of the emulsion volume, i.e. a neutron entering the emulsion volume should produce only one proton recoil. A calculation shows that $\lambda = 1.4$ cm at 0.1 Mev, 2.7 cm at 1 Mev and 8.0 cm at 10 Mev. Since the emulsions used were at most 100 microns thick and the area covered for an analysis was about 0.2 x 0.2 cm, the above condition is fulfilled. Another condition to be satisfied is that the neutron flux be isotropic. It has been assumed that the neutron flux at the reactor center is isotropic. The geometry factor, C, has the following form¹³ for an isotropic proton recoil distribution:

$$C = 2t/(2t - l_p) \quad \text{for } l_p < t$$
$$C = 2l_p/t \quad \text{for } l_p > t$$

where t is the thickness of the unprocessed or dry emulsion.

The plate analysis was carried out on the same microscopes described in Section II. One of the eyepieces was equipped with a net reticule for defining a field area and the other one with a scale for measuring the track lengths. Usually an area of about 25 fields wide x 25 fields long was mapped out for analysis on a plate. Since it was necessary to scan every field within the above area, the tracks in each field were diagramed so as to keep an account of the measured tracks and the exact location of the fields. In order that the same area be measured for all track lengths, the tracks crossing the perimeter of the above area were measured on two sides of the area while on the other two sides these tracks were not measured.

The plate was analyzed by measuring the total length of every proton recoil track contained within the surfaces of the emulsion. The

13. The calculation of these correction factors as well as the derivation of the previous equation will be presented in a future report.

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total track length was obtained by measurement of the horizontal projection of the track and the vertical distance between the ends of the track. In calculating the true length in dry emulsion from the above two measured quantities, the vertical distance was multiplied by a factor of 2.5 ± 0.1 to compensate for emulsion shrinkage. This vertical measurement is subject to considerable error. For depths > 10 microns, the microscope facility, human judgement, and shrinkage uncertainty, introduce a depth measurement error of about 10%. For depths < 10 microns, the error is proportionately larger since the microscope can measure depths to only about ± 1 micron. For short tracks, this depth uncertainty can cause a large error in the true length. For example, a track whose horizontal projection measures 4 microns and whose dip measures 2 ± 1 microns has an error of about 30% associated with its total length of 6.4 ± 1.8 microns. Since the tracks can be located in any position whatsoever, the short track problem is more difficult in the present analysis than in the forward direction type of track analysis.

A total of about 5000 proton recoil tracks were measured for this analysis by two microscopists from two Eastman NTA plates and an Ilford El plate¹⁴. General information concerning the analysis of these plates is given in Table VIII (same page as Table II) and the actual data obtained is tabulated in Table IX. Since the range of a proton in an Ilford El plate is 3% less than in an NTA type plate, the tracks from the El plate were increased by 3% in order to be able to compare and add them to the NTA plate results. The data from the two microscopists on plates 33 and 30 agree satisfactorily when the difference in the number of tracks and analyzed emulsion volume is taken into account. A comparison graph, not illustrated, shows good agreement above 4 microns. The agreement between the NTA plate and El plate results, shown in Fig. 11, is satisfactory above 5 microns. A large disagreement occurs in the 4 - 5 micron interval; the NTA data seems unusually high and the El data quite low. The reason for the disagreement is probably connected with the uncertainty of correctly observing and accurately measuring these short tracks. However, the fact that two microscopists agreed on the 4.5 micron point for the NTA plate may indicate that the NTA plate was somehow responsible. From the above comparisons of results, one would expect the combined data to be reasonably free of observational error above 5 microns. The combined data on plates 33, 30, and I30 presented in Table IX has been used to determine the final proton recoil spectrum drawn in Fig. 12.

14. This El plate was loaded with normal lithium. A search was made to see if any Li^6 disintegrations could be observed in the emulsion from reactor neutrons. The attempt was unsuccessful since not enough Li^6 was contained in the emulsion.

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Proton recoil track length interval in microns	Number of tracks					Track length interval for averaged tracks	Average number of tracks per micron interval				
	Plate E33 by E.A.	Plate E30 by S.S.	Plates E33 + E30 by E.A. and S.S.	Plate I30 by E.A.	Plates E33 + E30 + I30		Plate E33	Plate E30	Plates E33 + E30	Plate I30	Plates E33 + E30 + I30
0 - 1	0	0	0	0	0	0 - 1	0 * 0	0 * 0	0 * 0	0 * 0	0 * 0
1 - 2	12	134	146	6	152	1 - 2	12 * 3.5	134 * 11.6	146 * 12.1	6 * 2.4	152 * 12.3
2 - 3	584	251	835	40	875	2 - 3	584 * 24.2	251 * 15.8	835 * 28.8	40 * 6.3	875 * 29.6
3 - 4	482	84	566	461	1027	3 - 4	482 * 22.0	84 * 9.2	566 * 23.8	461 * 21.5	1027 * 31.0
4 - 5	497	179	676	343	1219	4 - 5	497 * 26.4	179 * 13.4	676 * 29.6	343 * 18.5	1219 * 34.9
5 - 6	292	68	360	433	793	5 - 6	292 * 17.1	68 * 8.2	360 * 19.0	433 * 20.8	793 * 28.2
6 - 7	155	36	191	295	486	6 - 7	155 * 12.4	36 * 6.0	191 * 13.8	295 * 17.2	486 * 22.0
7 - 8	70	27	97	175	272	7 - 8	70 * 8.4	27 * 5.2	97 * 9.8	175 * 13.2	272 * 16.5
8 - 9	74	15	89	91	180	8 - 9	74 * 5.3	15 * 2.5	89 * 5.9	91 * 8.5	180 * 8.6
9 - 10	41	9	50	64	114	10 - 12	46 * 4.8	12.5 * 2.5	58.5 * 5.4	44.0 * 4.7	102.5 * 7.2
10 - 11	50	16	66	62	128						
11 - 12	42	9	51	26	77	12 - 14	28.5 * 3.7	8.0 * 2.0	36.5 * 4.2	29.5 * 3.9	66 * 5.7
12 - 13	27	10	37	33	70	14 - 16	22.0 * 3.3	5.5 * 1.7	27.5 * 3.7	23.5 * 3.5	51 * 5.0
13 - 14	30	6	36	26	62						
14 - 15	23	3	26	16	42	16 - 20	16.3 * 2.03	5.3 * 1.2	21.5 * 2.3	18.8 * 2.2	40.3 * 3.2
15 - 16	21	8	29	31	60						
16 - 17	18	7	25	16	41	20 - 25	11.8 * 1.6	2.6 * 0.7	14.4 * 1.7	10.6 * 1.5	25 * 2.2
17 - 18	17	4	21	30	51						
18 - 19	20	5	25	11	36	25 - 30	9.6 * 1.4	1.8 * 0.6	11.4 * 1.5	9.8 * 1.4	21.2 * 2.1
19 - 20	10	5	18	18	33						
20 - 21	14	4	18	14	32	30 - 35	6.2 * 1.1	0.8 * 0.4	7.0 * 1.2	5.2 * 1.0	12.2 * 1.6
21 - 22	7	4	11	14	25						
22 - 23	16	1	17	9	26	35 - 40	5.0 * 1.0	0.4 * 0.3	5.4 * 1.0	4.4 * 0.9	9.8 * 1.4
23 - 24	9	3	12	5	17						
24 - 25	13	1	14	11	25	40 - 50	3.5 * 0.6	0.5 * 0.2	4.1 * 0.6	3.4 * 0.6	7.5 * 0.9
25 - 26	20	0	20	10	30						
26 - 27	10	1	11	12	23	50 - 60	2.3 * 0.5	0.2 * 0.2	2.5 * 0.5	1.1 * 0.3	3.6 * 0.6
27 - 28	5	5	10	10	20						
28 - 29	9	1	10	12	22	60 - 70	1.8 * 0.4	0.4 * 0.2	2.2 * 0.4	1.2 * 0.3	3.4 * 0.6
29 - 30	4	2	6	5	11						
30 - 35	31	4	35	26	61	70 - 80	1.2 * 0.4	0.2 * 0.1	1.4 * 0.4	0.9 * 0.3	2.3 * 0.5
35 - 40	25	2	27	22	49						
40 - 45	25	2	27	22	49	80 - 90	0.4 * 0.2	0.3 * 0.2	0.7 * 0.3	0.3 * 0.2	1.0 * 0.3
45 - 50	11	3	14	12	26						
50 - 55	13	1	14	6	17	90 - 100	0.3 * 0.2	0.1 * 0.1	0.4 * 0.2	0.4 * 0.2	0.8 * 0.3
55 - 60	10	1	11	5	16						
60 - 65	13	2	15	6	21	100 - 110	0.2 * 0.1	0.1 * 0.1	0.3 * 0.2	0.4 * 0.2	0.7 * 0.3
65 - 70	5	2	7	6	13						
70 - 75	8	0	8	6	14	110 - 120	0.2 * 0.1	0.1 * 0.1	0.3 * 0.2	0.1 * 0.1	0.4 * 0.2
75 - 80	4	2	6	3	9						
80 - 85	2	1	3	1	4	120 - 130	0.2 * 0.1	0	0.2 * 0.1	0.2 * 0.1	0.4 * 0.2
85 - 90	2	2	4	2	6						
90 - 95	2	1	3	1	4	130 - 140	0.1 * 0.1	0	0.1 * 0.1	0.1 * 0.1	0.2 * 0.1
95 - 100	1	0	1	3	4						
100 - 110	2	1	3	4	7	140 - 150	0.15 * 0.09	0	0.15 * 0.09	0.05 * 0.05	0.2 * 0.1
110 - 120	2	1	3	1	4						
120 - 130	2	0	2	2	4	150 - 160	0	0	0	0	0
130 - 140	1	0	1	1	2						
140 - 150	0	0	0	0	0	160 - 170	0	0	0	0	0
150 - 160	3	0	1	1	4						
160 - 170	0	0	0	0	0	170 - 180	0	0	0	0	0
170 - 180	0	0	0	0	0						
180 - 190	0	0	0	0	0	180 - 200	0.05 * 0.05	0	0.05 * 0.05	0	0.05 * 0.05
190 - 200	1	0	0	0	1						
200 - 210	0	0	0	1	1	200 - 220	0	0	0	0.05 * 0.05	0.05 * 0.05
210 - 220	0	0	0	0	0						
220 - 230	0	0	0	0	0	220 - 240	0.05 * 0.05	0	0.05 * 0.05	0	0.05 * 0.05
230 - 240	1	0	0	0	1						
240 - 250	0	0	0	0	0	240 - 260	0	0	0	0	0
250 - 260	0	0	0	0	0						
260 - 270	0	0	0	0	0	260 - 280	0.05 * 0.05	0	0	0	0.05 * 0.05
270 - 280	1	0	0	0	1						

TABLE IX. Data from Proton Recoil Plates Exposed at Center of Reactor Pot with Central Loading.

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Fig 11 Comparison of two sets of data from proton recoil plates exposed at center of reactor pot with central loading

Fig 12 Proton recoil spectrum measured from plates exposed at center of reactor pot with central loading Upper inset calculated neutron spectrum

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The original details concerning the exposure of the above plates are recorded in LA notebook #2178, page 51. The original track measurements are found in the following notebooks.

<u>Plate number</u>	<u>LA notebooks</u>
33	#2454, #2668, #2764
30	#2085
I30 (Li)	#2668

Considering everything which could influence the proton recoil curve in Fig. 12, it is felt that the region of the curve below 6 microns is uncertain at the present time. This uncertainty is exclusive of statistical errors and is largely due to the fact that no complete investigation has been made of the reliability or corrections to be applied on an emulsion measurement of an isotropic proton recoil track distribution. It is not possible for the curve below 6 microns to possess the shape indicated by the original data points O_3 , O_2 , and O_1 as these points indicate a maximum and then a decrease in the number of protons. Two limiting proton recoil spectra have been drawn for this region as based upon two bracketing sets of correction factors. The lower curve has been drawn through points corrected slightly more than that used for forward direction tracks within $\pm 10^{01}$. Also, for this lower limit curve, the O_2 data point has been lowered to an assumed value of O'_2 since the original point is probably made unusually high by the NTA plate data (see Fig. 11). The upper curve is based upon points corrected slightly less than those obtained from an investigation¹⁵ of measuring all proton recoil tracks from a unidirectional neutron beam of energy 1.8 Mev. In the first case, all of the short tracks are practically horizontal and relatively easy to observe and measure; in the second case, all of the short tracks are at large angles and dip steeply. Correction factors in the second case are larger due to the greater difficulty of observing and measuring the tracks. The actual correction factors for the isotropic proton recoil distribution lie somewhere between the above two bracketing cases. The following table summarizes the attempt to obtain limiting conditions on the proton recoil curve below 6 microns.

15. Details of this investigation are not presented here since the work will soon be published in the same report referred to in footnote #12.

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Percentage increase applied to data for correction

Proton recoil length or energy	Forward direction recoils from unidirectional neutrons. ($E_n = E_p$)	Lower limit corrections to proton recoil spectrum.	Upper limit corrections to proton recoil spectrum.	Recoils in all directions from unidirectional neutrons. ($E_n = 1.8$ Mev)
3.5 μ or 0.35 Mev	75%	100%	135%	200%
4.5 μ or 0.43 Mev	15%	15%	20%	35%
5.5 μ or 0.50 Mev	none	none	5%	10%
6.5 μ or 0.57 Mev	none	none	none	none

2. Results and discussion.

The calculation of the neutron spectrum from the proton recoil spectrum is tabulated in Table X. The values of $M_p(\rho_p)$ were obtained from the curves in Fig. 12. The values of $\Delta/p/\Delta E_p$, microns of proton range per Mev, were obtained from a smoothed curve of $\Delta/p/\Delta E_p$ vs. E_p . Values of Q_p were read from curve 1 of Fig. 3. Constants used are listed below.

$$\begin{aligned}
 n_p &= 0.034 \times 10^{24} = \text{number of protons per cm}^3 \text{ of dry emulsion,} \\
 V_e &= 3.9 \times 10^{-4} \text{ cm}^3 = \text{dry emulsion volume analyzed,} \\
 Q &= 0.2 \text{ watt-second or } 3.33 \times 10^{-3} \text{ watt-minutes of exposure.}
 \end{aligned}$$

The derived neutron spectrum is shown in the upper inset in Fig. 12. The absolute units given for the ordinate scale are estimated to be accurate to only $\pm 30\%$. This is due mainly to the uncertainty regarding analyzed emulsion volume ($\pm 20\%$) and exposure quantity ($\pm 20\%$). From a comparison of the two limiting neutron spectra below 0.6 Mev, it is evident that the calculated neutron spectrum is quite sensitive to the short track correction factors. Until this method of determining neutron spectra is further investigated, the question as to the correct number of short proton recoil tracks causes the derived neutron spectrum to be uncertain below 0.6 Mev. Further investigation should extend the reliability of the neutron spectrum to about 0.4 Mev.

The fission foil results for the central loading geometry are very useful for approximating the low energy region and checking the neutron spectrum in Fig. 12. Since the proton recoil plates were exposed during

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E_p (in Mev)	l_p (in microns)	$M_p(l_p)$ (at E_p)	Correction factor = C (at E_p)	$\Delta l_p / \Delta E_p$ (at E_p)	$CM_p(l_p) \frac{\Delta l_p}{\Delta E_p}$ = $CM_p(E_p)$	$\Delta CM_p / \Delta E_p$ (at E)	E (in Mev)	σ_p in barns (at E)	$\frac{E}{\sigma_p}$	$N_n(E) =$ $\frac{\Delta CM_p}{\Delta E_p} \times \frac{E}{\sigma_p n_p V_{eq}}$
0.3	2.85		1.014	11.8			0.35	7.5	0.047	(Multiply results by 10^9)
0.4	4.1	1800; 1310	1.023	13.2	24,350; 17,700	118,300; 66,800	0.45	6.5	0.069	185; 104 * 5.5
0.5	5.5	830; 730	1.032	14.6	12,520; 11,020	66,800; 51,800	0.55	5.85	0.094	141; 109 * 7.4
0.6	7.0	350	1.041	16.0	5,840	27,650	0.65	5.35	0.121	75.2 * 5.6
0.7	8.7	168	1.051	17.4	3,075	9,255	0.75	5.00	0.150	31.2 * 2.7
0.8	10.5	108	1.063	18.7	2,146	5,716	0.85	4.75	0.178	22.8 * 2.4
0.9	12.5	74	1.075	19.8	1,575	3,530	0.95	4.45	0.213	16.9 * 2.1
1.0	14.5	54	1.088	20.8	1,222	1580	1.10	4.15	0.265	9.4 * 1.2
1.2	18.8	36	1.119	22.5	906	840	1.35	3.70	0.365	7.1 * 0.9
1.5	26.0	22	1.169	25.4	654	628	1.75	3.20	0.547	7.7 * 1.4
2.0	40.0	8.7	1.286	30.4	340	250	2.25	2.70	0.830	4.7 * 1.0
2.5	56.5	4.2	1.457	35.2	215	170	2.75	2.42	1.14	4.4 * 1.3
3.0	75.0	1.9	1.714	39.8	130	103	3.25	2.18	1.49	3.4 * 1.6
3.5	97.0	0.82	2.155	44.4	78.4	63.0	3.75	2.00	1.87	2.7 * 1.8
4.0	120.5	0.36	2.678	48.6	46.9	36.0	4.25	1.83	2.32	1.9 * 1.5
4.5	146.0	0.17	3.244	52.4	28.9	23.6	4.75	1.70	2.80	1.5 * 1.2
5.0	173.0	0.08	3.844	55.6	17.1	13.2	5.25	1.56	3.37	1.0 * 1.0
5.5	202.0	0.04	4.49	58.4	10.5	8.4	5.75	1.47	3.91	0.8 * 1.0
6.0	234.0	0.02	5.20	61.0	6.3					

TABLE X. Calculation of Neutron Spectrum, $N_n(E)$, from Measured Proton Recoil Spectrum, $M_p(l_p)$.
(At Center of Reactor Pot with Central Loading).

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Oct. 1948, the Aug.-Oct. 1948 fission foil results should agree best with the calculated neutron spectrum. One can compare the fission foil results with the continuous spectrum by numerically integrating

$$\int_{E=0}^{E=\infty} N_n(E) \sigma_f(E) dE$$
 over the curve. If this is done for the curve in

Fig. 12, the results are¹⁶

$$\int_0^{\infty} N_n \sigma_{25} dE = 90 \times 10^{-15} \text{ fissions/watt-minute/atom of } U^{235}$$

$$\int_0^{\infty} N_n \sigma_{37} dE = 48 \times 10^{-15} \text{ fissions/watt-minute/atom of } N_p^{237}$$

$$\int_0^{\infty} N_n \sigma_{28} dE = 8.3 \times 10^{-15} \text{ fissions/watt-minute/atom of } U^{238}$$

The ratios from these values are

$$N_p^{237}/U^{238} = 5.8, \quad U^{235}/U^{238} = 10.8, \quad U^{235}/N_p^{237} = 1.9$$

The above values of $\int_0^{\infty} N_n \sigma_f dE$ agree fairly satisfactorily (i.e. within 20%¹⁷) with the fission foil results from U^{238} and N_p^{237} but $\int_0^{\infty} N_n \sigma_{25} dE$

is about 80% higher than the U^{235} fission foil result. Obviously, the ratios show the same effect - the 37/28 ratio above is approximately in agreement with the corresponding fission foil ratio in Table VII while the ratios involving U^{235} , i.e. 25/28 and 25/37, are about 50% higher than the fission foil ratios. It is encouraging from the above comparisons that the trustworthy region of the calculated neutron spectrum, i.e. above 0.6 Mev, is in satisfactory agreement with the fission foil results. However, the low energy region below 0.6 Mev presents poor agreement in spite of attempts to draw the spectrum in this region (dashed line) so as to make $\int_0^{\infty} N_n \sigma_f dE$ for U^{235} as small as possible.

16. The contributing part of the integral from 6 Mev to ∞ has been estimated. (See following paragraph).
17. Although the uncertainty in exposure quantity is eliminated in this comparison, there still exists the * 20% uncertainty in emulsion volume which affects the absolute results.

Apparently, even the lower limit points on the proton recoil curve in Fig. 12 make the 0.45 and 0.55 Mev points on the calculated neutron spectrum too high. This discrepancy is not too surprising when one notes the large variations resulting in the neutron spectrum from the two limiting proton recoil curves in Fig. 12.

It is possible to draw the uncertain region of the neutron spectrum so as to obtain good agreement with the fission foil results. This is not a good method for determining the exact shape of the spectrum since agreement with the U^{235} foil can be obtained by either narrowing or lowering the peak at 0.5 Mev. Fortunately, $\int_0^\infty N_n \sigma_f dE$ for

N_p^{237} begins to make a significant contribution at the 0.45 Mev point. Since this integral is slightly high, the indicated procedure to obtain best agreement is to lower the maximum as narrowing the peak would not appreciably affect this integral. This has been done in Fig. 13 where the spectrum has been drawn through the reliable calculated points above 0.6 Mev but the 0.55 and 0.45 Mev points have been ignored, and the dashed curve has been drawn to agree with the N_p^{237} and U^{235} fission foil results. The following integrated results are obtained from the curve drawn in Fig. 13.

$$\int_0^{6 \text{ Mev}} N_n \sigma_{25} dE + \int_{6 \text{ Mev}}^{\infty} N_n \sigma_{25} dE = 60 \times 10^{-15} + 2 \times 10^{-15} = 62 \times 10^{-15}$$

$$\int_0^{6 \text{ Mev}} N_n \sigma_{37} dE + \int_{6 \text{ Mev}}^{\infty} N_n \sigma_{37} dE = 43 \times 10^{-15} + 2 \times 10^{-15} = 45 \times 10^{-15}$$

$$\int_0^{6 \text{ Mev}} N_n \sigma_{28} dE + \int_{6 \text{ Mev}}^{\infty} N_n \sigma_{28} dE = 7.0 \times 10^{-15} + 1.3 \times 10^{-15} = 8.3 \times 10^{-15}$$

As previously, the answers are in units of fissions/watt-minute/atom of metal. The contribution of the integral from 6 Mev to ∞ was estimated by extending the spectrum to higher energies with the same slope as before 6 Mev (see inset graph in Fig. 13). Ratios derived from the above integrated values are

$$N_p^{237}/U^{238} = 5.4, \quad U^{235}/U^{238} = 7.5, \quad \text{and} \quad U^{235}/N_p^{237} = 1.4.$$

A comparison with the Table VII results shows agreement within experimental error between the two sets of results. The above ratios involving U^{235} are still a little higher than the fission foil values; perfect agreement could be obtained by slightly shifting the dashed line in

Fig. 13 Low energy region of neutron spectrum at center of reactor pot drawn for agreement with fission foil results. Inset: semi-log plots of reactor neutron spectra.

Fig. 13 to the right, thereby narrowing the peak width of the curve. However, since this would cause the curve to deviate slightly from the lowest energy points of the collimated spectra, which were used as a guide in drawing the dashed curve, and since the two sets of results are within experimental error, the curve has been left in its present form.

Although the high energy region of the spectra presented in this report is not determined accurately, nevertheless it is interesting to observe the trend and approximate shape in this region. The semi-log plots in the inset graph of Fig. 13 emphasizes the high energy region of several spectra. The neutron spectrum at the center of the reactor pot possesses the same slope at high energies as the neutron fission spectrum of plutonium. It seems reasonable that a detector surrounded by fissionable material and immersed in a fission neutron flux bath would first of all record this primary fission spectrum. However, superimposed on this primary spectrum would be neutrons which reach the detector after having been scattered by the reactor pot metals or by the tamper. Apparently, the large increase of the reactor spectrum over that of the fission spectrum at energies below 1 Mev is due to inelastically scattered high energy neutrons which have been degraded to energies below 1 Mev. The reason is uncertain as to why these inelastically scattered neutrons are contained in such a narrow energy interval about the peak at 0.5 Mev.

The low energy region (< 1.5 Mev) of the spectrum at the pot center and the two collimated spectra are quite similar except for the peak heights which differ by 30%. Since the elastic scattering cross section predominates at low energies, the neutrons in the collimating tube evidently arrive at the nuclear plates chiefly by elastic scattering from the center uranium slug (peripheral loaded pot) or from the top of the uranium safety block (aluminum cage pot). However, as the energy increases above 2 Mev both of the collimated spectra curves decrease more rapidly with energy than the spectral curve at the center. Although the collimated spectra obtained from the central loading with a plutonium slug at the center is not plotted, its high energy slope lies between that of the other two collimated spectra and the plutonium fission spectrum. This is reasonable since the above spectrum is some combination of the two latter types of spectra. The actual slopes are given below.

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<u>Spectrum</u>	<u>High energy (2 to 6 Mev) slope.</u>
Plutonium fission neutron spectrum.	4.2 + 0.2 Mev per decade
Neutron spectrum at center of reactor pot with central loading.	4.2 + 0.2 " " "
Collimated neutron spectrum (central loading geometry).	3.3 + 0.1 " " "
Collimated neutron spectrum (peripheral and aluminum cage loading geometries).	2.8 + 0.1 " " "
Collimated neutron spectrum obtained by Rosen ¹⁰ (slope taken in 4-14 Mev region of spectrum for peripheral loading geometry).	3.0 " " "

Since the main process for the above high energy neutrons being recorded by the nuclear plates in the collimator is also elastic scattering, this faster intensity decrease of the collimated spectra must be due to the diminishing of the elastic cross section with energy¹⁸. The above argument does not seem entirely consistent with the fact that the low energy peaks of the collimated spectra are somewhat lower than that of the spectrum at the center. The fission foil results at the center of the pot indicate that the central and aluminum cage loadings possess the same relative spectrum throughout the entire energy range. Therefore, it would be expected that the collimated spectra from the aluminum cage loading would have at least as great a peak height as the central loading spectrum at the center, i.e. if the collimated beam consists chiefly of elastically scattered neutrons. It is true that the above effect is much smaller than that observed for the high energy region and other factors besides scattering may influence the collimated spectra to a larger extent at these low energies.

It is interesting to further examine the high energy region of the spectrum at the center of the pot and try to understand why its slope is similar to that of a fission spectrum. The low energy peak of this spectrum suggests that inelastic scattering certainly takes place inside the reactor pot. Since the inelastic cross section increases with energy one might ask why successively larger percentages of neutrons are not removed by this process as the energy increases, i.e. the argument is similar to that used in the previous paragraph where the large majority of neutrons arrived at the collimation detector via a scattering process. However, in the present case it would be expected that a detector at the center of the pot would see both primary fission neu-

18. Another way of stating this is to say that the inelastic cross section increases with energy since σ total for most heavy metals is approximately constant over the 1-10 Mev energy region.

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trons and scattered neutrons; therefore, the deviation from the regular fission spectrum high energy slope would not be expected to be as large in the present case as in the collimated spectra case. Since the spectrum at the center shows the same high energy slope¹⁹ as the regular fission spectrum, it must be true that the number of high energy scattered neutrons at the center of the pot is small compared to the number of primary fission neutrons. It is possible that this effect may be present only in this type of loading and detector position. As this loading produces a geometric neutron distribution with a maximum at the center of the pot, most of the fission neutrons are produced close to the center. Therefore, the majority of inelastic scattering events might take place on the average of a mean free path away (probably a few inches), i.e. near the edge of the pot or in the tamper. Once the neutrons have been inelastically scattered and degraded to a lower energy, the higher probability for elastic scattering at the lower energies might enable them to be scattered back into the pot and detected. Some of the neutrons present in the low energy peak at 0.5 Mev also arise from fission neutrons originating in the uranium tamper.

19. The statistical errors in this region of the spectrum are rather large and the expected effect on the slope due to scattering could be contained within the error limits. However, this possibility is made less likely by the agreement of the high energy section of this spectrum with the fission foil results.

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