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A METHOD OF DETERMINING THE INTERMEDIATE
ENERGY NEUTRON DOSE

D. E. Hankins

March 10, 1961

**PHILLIPS
PETROLEUM
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ATOMIC ENERGY DIVISION

**NATIONAL REACTOR TESTING STATION
US ATOMIC ENERGY COMMISSION**

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A METHOD OF DETERMINING THE INTERMEDIATE
ENERGY NEUTRON DOSE

by

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PETROLEUM
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PREFACE

The technique described in this report is being utilized at the MTR-ETR to determine the dose rate of intermediate energy neutrons. There are several parameters associated with the method which have not and in some cases can not be absolutely defined. These parameters are outlined later in this preface. Considerable interest has been expressed in this study hence this report is being submitted. This report indicates the type of approach being used as well as the present status of the investigation.

The total neutron dose rates determined by this technique are higher than previously accepted dose rates existing around these reactors due to the high intermediate energy dose rate.

An independent study with a similar instrument was conducted by Dr. T. W. Bonner of the Rice Institute¹¹. His technique used in the interpretation of data and the spectrum type are different from that described in this report. The intermediate energy dose rates determined by either study indicate the same magnitude of importance for intermediate neutrons. The interpretation made by Dr. Bonner divides the total spectrum into two energy divisions (Thermal and Intermediate) whereas this report assumes a third division (Fast). The techniques used in the interpretation of data vary to the extent that no effort will be made here to describe the procedure used by Dr. Bonner.

The parameters which are being investigated further are indicated below and should be considered in the use of the principles embodied in this report in any neutron monitoring program.

- (1) The assumption was made in this report that the spectrum of neutrons outside the reactors is similar to the type known to exist inside the reactors, i.e., a Maxwellian energy distribution of thermal neutrons, a $1/E$ energy distribution of intermediate neutrons, and a Watt or Maxwellian energy distribution of fast neutrons. This assumption was made because the majority of the

neutrons outside the reactor are known to come through beam holes in the reactor rather than through the shielding.

- (2) The size of crystal used in this study is not identical to that used in constructing the relative counting rates (See Fig. 2) and there may also exist a slight variation in the neutron response of our spheres. These effects are known to be small but have not been adequately determined to give a reportable value.
- (3) The difference in efficiency of isotropic, point, and broad beam sources on the detector is not known. Theoretical mathematical calculations indicate this effect should be small. Present studies are designed to investigate this effect.
- (4) The average efficiency over the intermediate energy range can not be definitely determined. The technique used in this report to determine this efficiency may be in error. The magnitude of this error can not as yet be determined. This error is due primarily to the uncertainty associated with the extrapolations in Fig. 2. An effort may be made to replace these extrapolations with actual data.
- (5) The RPG value for fast neutrons was taken to be that of a monoenergetic source at 0.6 Mev. When the actual spectrum is determined (1) a re-evaluation of the RPG based on this spectrum will be made.

D. E. H.

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ABSTRACT

The intermediate energy neutron flux existing outside the biological shielding of reactors has not been studied to any great extent previous to this time, due to the lack of an instrument capable of detecting neutrons in the intermediate energy range. The instrument used at the MTR for the present study utilizes polyethylene spheres of various sizes to give different amounts of moderation and absorption to the impinging neutrons. A procedure for the approximate determination of the relative number of intermediate energy and fast neutrons is given.

By graphical methods the following information is obtained: (1) fraction of intermediate neutrons, (2) fraction of fast neutrons and (3) the approximate average energy of the fast neutrons. Since the instrument described can be used to determine the thermal neutron flux independent of intermediate and fast fluxes, only one instrument is required to determine the neutron flux in all three energy ranges. Dose calculations indicate the intermediate range neutrons give a dose greater than the dose delivered by fast neutrons around the MTR-ETR reactors under normal operating conditions.

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INTRODUCTION

Instruments capable of determining the flux of thermal and fast neutrons have been perfected to a fairly high degree.⁽¹⁻⁷⁾ The neutrons in the intermediate energy range (Cd cut-off to 100 kev) are not detectable by the thermal counters and are only partially detectable by the high energy instruments.⁽⁸⁾ Thus, there exists a large intermediate energy region in which the neutron flux has not been adequately determined.

The Radiation Protection Guide (RPG) for neutrons in the various energy ranges as given in Handbook #63⁽⁹⁾ are reproduced in Fig. 1. It will be noted that the RPGs range from 50 n/cm²/sec at high energies to 1750 n/cm²/sec at 5 kev. RPGs for neutrons having energies less than 5 kev begin a gradual decline as the neutron energies decrease, to a level of around 1500 n/cm²/sec at 100 kev. The RPG for thermal neutrons is 2000 n/cm²/sec.

The Health Physicist cannot make a good determination of the dose delivered to personnel in the vicinity of a neutron source unless he has a fair knowledge of the neutron spectrum.^(9,10) The study of the neutron energy spectrum present outside a reactor has not progressed to a degree commensurate with the health hazards involved. The assumption has been made in the past that the limitations and restrictions imposed by the β and γ activity are greater than the hazard due to neutrons. As a result, little progress in intermediate neutron dosimetry has been made.

Work on an intermediate energy neutron detector at the MTR was started during the summer of 1959 by Professor George LeBaron of the College of Southern Utah, who conducted an extensive literature review to find a possible solution to this problem. Several approaches were considered and calculations were made on some of these. His search indicated that an instrument developed by Dr. T. W. Bonner of Rice Institute might be suited for this study.⁽¹¹⁾

EQUIPMENT

The actual neutron detector is a lithium iodide crystal, 8 mm in diameter and 2 mm thick, which is 80% "black" for thermal neutrons. The crystal is coupled to an RCA 6655A photomultiplier tube by means of a 1/2 inch outside diameter light pipe, which is wrapped in aluminum foil to limit light loss

and taped with Scotch #33 tape. The system is enclosed in a hollow brass tube which gives mechanical support and acts as a light shield. The output of the photomultiplier tube is fed through an Al preamplifier and amplifier to a scaler. Circuitry and details of construction were obtained from Dr. Bonner at the Rice Institute.

The detector system is made particularly appropriate to the present problem through the use of five polyethylene spheres, with diameters of 2 inches, 3 inches, 5 inches, 8 inches, and 12 inches, which are placed in turn on the light pipe so that the lithium iodide crystal is at the center of the sphere. (See plates 1, 2, and 3.) The detection of neutrons of higher than thermal energies is accomplished by the moderation of the neutrons in the polyethylene. The 2 inch sphere gives only a small amount of moderation to the neutrons and is thus most sensitive at low neutron energies. The 12 inch sphere offers maximum moderation and a large degree of absorption; consequently, the higher energy neutrons are counted at a higher sensitivity than the lower energies which are largely absorbed before reaching the crystal. Thermal neutrons are removed by a shield of cadmium placed over the sphere and detector.

The spheres have been calibrated by Dr. Bonner through the use of some 200 monoenergetic neutron sources. Graphs of the relative counting rates versus energy are shown in Fig. 2. The curves shown in Fig. 2 are for a 4 mm diameter and 4 mm thick crystal. The crystal we are using varies slightly from the curves shown by less than 0.1 on the arbitrary scale.

In a monoenergetic neutron field a different count rate is observed with each of the 5 spheres. The ratios of these 5 count rates could be determined prior to counting by analysis of Fig. 2 at the energy of the monoenergetic neutron field. Conversely, if an unknown monoenergetic neutron field were used, the ratios obtained should enable one to find an energy in Fig. 2 that would give the same ratio as obtained experimentally. The extension of this principle across the entire energy spectrum is the basis for the use of this instrument to measure the intermediate neutron energy spectrum. The fact that the relative counting rates in Fig. 2 vary over a wide range and have no consistent similarity enables us to describe an intermediate energy neutron spectrum within reasonable limits. For a particular set of count rates observed with each of the five spheres, a spectrum could be drawn that would give, when integrated together with the relative counting rate curves of Fig. 2, the same ratios as obtained experimentally. All other spectral curves would give ratios that vary from the experimental data to some degree depending on how well the assumed spectrum approximates the actual spectrum.

The assumption is made here that the intermediate energy neutron spectrum outside a reactor is a smooth curve with no sharp spikes. This assumption is probably valid, since the cross sections of nitrogen, oxygen, hydrogen, and carbon are nearly constant over this region.⁽¹²⁾ These cross sections imply a constant gradual loss of energy for neutrons in the intermediate energy region, which would tend to smooth out any irregularities which might have existed in the original source spectrum. This assumption simplifies the determination of the neutron spectrum from experimental data.

As an approximation to the neutron energy distribution in the high energy range, it was assumed that the neutrons could be averaged into a monoenergetic spectrum.⁽¹³⁾ The simplification of an energy spectrum to a monoenergetic spectrum with the energy located at the average energy of the fast neutron spectrum is not a serious simplification for a source with a gaussian distribution or a spectrum containing only one major peak. If the source is complex the instrument will indicate an average energy which may not be accurate.

PRELIMINARY MATHEMATICAL APPROACHES

The first attempt to determine the intermediate neutron spectrum, which proved to be unsuccessful, was to reconstruct the neutron spectrum by solving a set of simultaneous equations in the experimental counting rates and neutron flux as a function of energy. The details of this procedure are described in Appendix A.

The second attempt to determine the intermediate neutron spectrum consisted of assuming several types of intermediate spectra and computing the counting ratios to be expected for each. See Appendix B. This investigation indicated that in most cases the neutrons being detected by the instrument on the main reactor floor of the MTR consisted largely of $1/E$ (Energy) spectrum neutrons. It was found that as the instrument was moved closer to the experimental holes in the reactor, a progressive change in counting ratios resulted, indicating that a pure $1/E$ spectrum did not exist around these experimental holes. Data taken at the ETR indicated that a pure $1/E$ spectrum did not exist at any of the locations selected there.

EXPERIMENTAL METHOD

To minimize the error in the counting ratios resulting from long term changes in the neutron flux, several series of two-minute counts with each sphere were taken at each location. The count rate for each sphere is then computed. Count rates obtained in this work vary considerably depending on the location of the instrument with respect to the reactor and beam holes. Table 1 lists the count rates obtained at 25 locations around the MTR, ETR, and EBR-I* reactors. (See Fig. 3.) The count rates for the spheres being used are totaled to obtain "total count". The "percent of the total count" for each sphere is then determined. The "percent of the total count" assigned to each sphere is, by definition, the experimental counting ratio for that sphere.

The first step in analysis of the experimental data was to examine the validity of the assumption that the ratios obtained from several counting locations at a considerable distance from the MTR reactor corresponded to a $1/E$ spectrum with few if any fast neutrons. The experimental ratios varied somewhat from the expected ratios computed from the relative counting rate curves (Fig. 2) for a $1/E$ spectrum. This variation from the

* EBR-I and ZPR III are operated by Argonne National Laboratories. The author wishes to thank the Argonne personnel for their cooperation in the use of these facilities.

Table I
Experimental Data.

#	Reactor	2"		3"		8"		Total CPM	% of Total CPM		
		CPM	t min	CPM	t min	CPM	t min		2"	3"	8"
1	EBR-I	918.0	5	1465.2	4	552.4	5	2935.6	31.3	49.9	18.8
2	MTR	151.0	47	243.3	20	97.4	54	491.7	30.7	49.5	19.8
3	MTR	884.7	13	1409.2	12	560.2	11	2854.1	31.0	49.4	19.6
4	MTR	907.8	8	1456.3	8	602.1	8	2966.2	30.6	49.1	20.3
5	MTR	690.5	8	1136.9	8	487.8	8	2315.2	29.8	49.1	21.1
6	MTR	508.5	8	830.1	8	359.9	8	1698.5	29.9	48.9	21.2
7	MTR	181.0	8	295.6	8	134.5	8	611.1	29.6	48.4	22.0
8	MTR	289.4	8	474.5	8	218.0	8	981.9	29.5	48.3	22.2
9	MTR	1600.5	6	2670.7	6	1267.8	6	5539.0	28.9	48.2	22.9
10	MTR	192.9	16	318.9	9	151.1	7	662.9	29.1	48.1	22.8
11	MTR	1680.3	8	2739.3	8	1281.0	8	5700.6	29.5	48.0	22.5
12	MTR	2185.0	8	3644.6	8	1773.7	9	7603.3	28.7	47.9	23.3
13	MTR	1809.6	9	2955.0	8	1420.5	8	6185.1	29.3	47.8	23.0
14	MTR	798.0	6	1281.3	6	615.3	6	2694.6	29.6	47.6	22.8
15	MTR	901.1	14	1479.9	14	735.3	14	3116.3	28.9	47.5	23.6
16	MTR	2532.8	6	4203.5	6	2140.8	8	8877.1	28.5	47.4	24.1
17	MTR	603.2	25	985.7	15	494.5	17	2083.4	29.0	47.3	23.7
18	MTR	733.6	15	1220.0	15	627.8	15	2581.4	28.4	47.3	24.3
19	MTR	457.8	50	770.4	15	399.6	46	1627.8	28.1	47.3	24.6
20	MTR	1366.4	13	2269.7	7	1212.0	12	4848.1	28.2	46.8	25.0
21	ETR	30.8	6	51.8	6	28.7	9	111.3	27.7	46.5	25.8
22	MTR	421.0	10	690.5	13	383.3	10	1494.8	28.2	46.2	25.6
23	MTR	1172.0	23	2017.4	10	1238.5	11	4427.9	26.5	45.6	28.0
24	ETR	51.8	6	89.0	6	58.4	10	199.2	26.0	44.7	29.3
25	ETR	52.7	12	92.7	12	65.5	12	210.9	25.0	44.0	31.1

computed $1/E$ spectrum consisted of data points which indicated that the $1/E$ spectrum would have to be cut off at an energy much lower than the average fission neutron energy of 0.7 Mev. However, the experimental results are probably a better representation of the $1/E$ spectrum than the ratios obtained by integration of Fig. 2. Relative counting rate curves were prepared by the author using slightly different extrapolations which resulted in a much closer agreement between experimental and computed ratios. A further modification of the extrapolations could result in the ratio obtained experimentally.

The assumption was made that around the MTR reactor the neutron spectrum consisted of $1/E$ neutrons and neutrons that are the same as the fission spectrum with an energy of approximately 0.7 Mev. Graphs with percent of total count (counting ratios) vs fraction of counts from fast neutrons were prepared by joining with straight lines the counting ratios for a pure $1/E$ spectrum (i.e., no source of fast neutrons present) and the ratios expected for a monoenergetic source of fast neutrons. The latter ratios were taken directly from Fig. 2. Since it was not possible to be certain that any of the experimentally observed spectra actually had a true $1/E$ energy dependence, the $1/E$ counting ratios, i.e., the points of intersection of the straight lines with the y-axis, were determined by inspection of the several sets of experimental points lying nearest to that axis. The resulting graphs then indicate the change in counting ratios to be expected as the spectrum varies from a pure $1/E$ spectrum at the left side of the graph to a pure monoenergetic spectrum at the right. Four such graphs were prepared, assuming monoenergetic energies of 0.4 Mev, 0.5 Mev, 0.6 Mev, and 0.7 Mev (Figures 4-7).

The counting ratios expected for a combination of $1/E$ neutrons and fast neutrons of a particular energy and relative abundance are given by the points of intersection of a vertical line with the counting ratio curves on a graph of the above type. Similarly, when experimental data lie on a vertical line we may conclude that the ratios were obtained from a spectrum having the fast fraction and energy indicated by the graph. Statistical fluctuations in counting rates and long term variations in the neutron flux result in experimental data which fluctuates about a vertical alignment. Some fluctuation may result from changes in the ratio of fast to intermediate energy neutrons. This change in ratio is assumed to be small and of a statistical nature. The degree of deviation from a vertical alignment is dependent on counting rate, counting time, and, in some cases to be explained in detail later, on location with respect to the reactor.

Data obtained from twenty-five locations around the MTR, ETR, and EBR-I (See Table 1) were drawn on each of these graphs. Since the 5" sphere yielded an insignificant slope on the graphs and was consequently of little value in establishing a point along the curve, this sphere was eliminated in the following work. The 12" sphere was eliminated at the same time due to the low counting rate obtained in its use. In subsequent work only the 2", 3", and 8" spheres were used, and only data obtained with these three spheres are presented here. Since the fraction of fast

neutrons never exceeded 32% in the present series of observations, the scale of the abscissa of Figs. 4-7 has been expanded to present the data in greater detail.

The data of Table 1 exhibit the best vertical alignment when plotted in the graph of Fig. 6. Therefore, 0.6 Mev is considered to be the most probable average energy of the fast neutrons coming through the shielding and holes in the shielding of these reactors.

Of special interest are the points of intersection of the counting ratio curves with the y-axis in Fig. 6, which represent the ratios for a pure $1/E$ spectrum together with an assumed 0.6 Mev source. No data have been found to date which lie to the left of the y-axis. If data should be found which lie farther to the left, the positions of the points of intersection on the y-axis would, of course, have to be readjusted. Data have been obtained from as many locations around the reactors as time permitted to find a pure $1/E$ spectrum. It is believed that the set of data obtained at EBR-I, with ≈ 9 feet of concrete shielding between the reactor and detector, is the best representation of a $1/E$ spectrum, since the ratios obtained in this measurement fall at the extreme left side of the graph.

A determination of the $1/E$ ratios by moderation of a Po-Be neutron source was attempted. Due to the absorption of neutrons within the source housing, the low counting rates posed a problem as did the distortion of the spectrum resulting from lead, steel, U^{238} , and other materials with irregular cross sections in the intermediate or fast range. Since in the interpretation of our data we are using counting ratios from a $1/E$ spectrum and counting ratios of a fast spectrum assumed to be gaussian; any change from a $1/E$ spectrum to some other type results in data to which the present technique is not applicable. The effects of distorting the $1/E$ spectrum by these materials when the present method of interpretation is applied are (1) an apparent lower energy fast neutron spectrum and (2) relatively more of the neutrons in the fast spectrum. This results in an overestimate of the dose at that location. This effect was noticed in all data taken within six feet of either the reactor or any shielding materials containing lead. All data taken in these locations were found to be in disagreement with data taken in other locations. Such data were therefore eliminated from consideration at this time. It is believed that a reactor containing considerable U^{238} would require at least the use of graphs with modified $1/E$ ratios. Because of disagreement between measurements made at the sub-pile room at the ETR before and after the installation of six tons of U^{238} as shielding material, it is questioned whether the modification of the $1/E$ spectrum due to the high peaks in the U^{238} cross section in the intermediate energy range is not so severe as to render the present technique invalid in the presence of large quantities of this material.

The relative number of high energy neutrons present in a $1/E$ spectrum depends on the original energy of the source. Since the spheres' counting rates vary with neutron energy, one would expect a difference in $1/E$

spectrum ratios for sources of different energies. Assuming the 0.6 Mev $1/E$ spectrum ratios to be correct, the $1/E$ spectrum ratios for sources of other energies were adjusted by computing from the relative counting rate curves (Fig. 2) the loss or gain in counting rate that would result from a change in energy of the fast source. This was done by assuming, first, that the $1/E$ spectrum found to exist around the reactor was continuous from Cd cut-off to 0.6 Mev, where it ends abruptly. The addition or subtraction of counting rate was then based on the average relative counting rates taken from Fig. 2. This adjustment could not be made with a great deal of accuracy, but the result is undoubtedly more accurate than to assume the 0.6 Mev $1/E$ spectrum ratios for all fast source energies.

Fig. 8 shows the change in counting ratios expected as the neutron flux is varied from a pure $1/E$ spectrum to a pure fast spectrum, for fast neutron energies of 3.0 Mev, 1.0 Mev, 0.6 Mev, 0.4 Mev, and 0.1 Mev. The points lying on the y-axis represent the ratios obtained by calculating the change in the $1/E$ spectrum ratios as described above for each of the five energies selected. Points plotted on the right side of the graph indicate the ratios expected for monoenergetic sources of the same energies. Fig. 8 thus displays five families of curves, one for each selected energy. The abscissa gives the fraction of counts from high energy neutrons over the full range of 0 to 1.0.

RESULTS

To use Fig. 8 to determine the energy of the neutrons in a given source and the fraction of fast neutrons from this source at a given location, the counting rate for each of the 3 spheres is determined experimentally. The "percent of total count" for each sphere is calculated and plotted on the appropriate member of each of the families of curves in the figure. The set of points plotted on the family of curves for one energy will give a better vertical alignment than those plotted on any of the other families of energy curves. For example, if a 3.0 Mev source were used the points on the 3.0 Mev energy curves would give a better vertical alignment than those on the 1.0 Mev, 0.6 Mev, etc., curves. The value of the abscissa at which the experimental points align themselves on the 3.0 Mev energy curve indicates the fraction of counts from neutrons in the fast (3.0 Mev in this case) neutron energy range. The fraction of intermediate neutrons is determined by subtracting this figure from unity. We have thus obtained (1) fraction of counts from $1/E$ neutrons; (2) fraction of counts from fast neutrons; and (3) the approximate energy of the fast neutrons.

Fig. 9 illustrates the above technique applied to one set of data taken at the ETR. The experimental counting ratios for the spheres were: 2", 26.0%; 3", 44.7%; 8", 29.3%. These values are shown as connected circles on each family of curves. The circles on the 0.6 Mev energy lines give the best vertical alignment, at a value of about 0.20 on the abscissa. Thus the fraction of counts from fast neutrons is 0.20, the fraction of counts from intermediate neutrons is 0.80, and the average energy of the fast

neutrons is 0.6 Mev. Accurate data are necessary to determine the fast neutron energy of an unknown source. It is well to use several independent sets of data.

A Po-Be neutron source (with an average energy of 3 Mev) was used to check the accuracy of Fig. 8. The moderation of the neutrons from the source was varied by using several geometries: (1) the source as far away from reflectors as possible; (2) the source against a paraffin wall; (3) various amounts of moderator (polyethylene) between the source and the counter. Each set of data gave an alignment on the 3 Mev curve as indicated in Fig. 10.

An Sb-Be source was also obtained to check the accuracy of Fig. 8, but the results were questionable due to the high gamma flux associated with the source (150 mr/hr at the detector). The effect of gamma radiation was then investigated to determine the error introduced in the results obtained from Fig. 8.

To check the gamma sensitivity of this technique, a Po-Be source was used first with no gamma field and then in a strong gamma field (50 mr/hr from a 10 mg radium source). Since the detector is somewhat gamma sensitive, an increase in counting rate was observed for each of the spheres. The information obtained from Fig. 8 then indicated (1) that a higher energy neutron source had been used, and (2) that a larger fraction of the neutrons was in the intermediate range. The second effect is serious from the point of view of personnel safety, since the intermediate energy neutrons have a much lower RPG than fast neutrons and the dose will consequently be underestimated. The increased dose estimate due to the increase in count rate does not compensate for the lowering of the estimated dose resulting from the shift of counts from the fast spectrum into the intermediate energy spectrum.

It is therefore concluded that the instrument must be used in reasonably low gamma fields, or else a correction for the gamma sensitivity must be applied. In applications where higher neutron fluxes are available, pulse height discrimination may be used to eliminate most of the gamma radiation although this results in some loss of neutron sensitivity; or the voltage applied to the photomultiplier may be decreased with the same effect. The pulse height discriminator level used in this work gave the most sensitive neutron response with as little gamma response as possible consistent with this high neutron sensitivity.

Instrument noise will cause the same effect as a gamma background. Fortunately this effect could be reduced, by adjustment of the discriminator setting, to a level of about six counts per minute or less.

Four Pu²⁴⁰ fuel plates* for ZPR-III were used in the same manner as the Po-Be source referred to previously. The results, which are shown in Fig. 11, are similar to those obtained with the Po-Be source, indicating that this technique can be applied to more than one energy neutron source.

* These fuel plates were Pu²³⁹ enriched 4 1/2% by Pu²⁴⁰. The neutrons observed were principally from the Pu²⁴⁰.

The procedure for taking data requires long counting times to reduce the statistical error in counting. The smaller the statistical error the more accurately the graph can be used to determine the neutron spectrum. The flux must remain constant during the counting, no major changes in moderating material in the room must be made during the counting time, the instrument must remain in the same location, and the high voltage must remain constant during the taking of a complete set of data. If any of the above experimental conditions change, the results will be in error. Fortunately a relatively small change in source strength or moderator geometry during a series of measurements is immediately detectable in the interpretation of the data, usually because of a failure of the points to align on Fig. 8.

In the situation where only one energy source of neutrons will be encountered, a graph can be drawn with only that particular set of energy curves. This would be the case around the MTR and ETR reactors. Fig. 12 was prepared for use at the MTR and ETR. The use of only one set of energy curves would permit the determination of the fraction of intermediate range neutrons more conveniently, since the energy of the high energy neutrons is already established.

A graph such as that of Fig. 12 mentioned in the preceding paragraph must be used with care. It has been found in all cases where the instrument was moved to within six feet of the reactor or lead shielding around experiments, that the spectrum can not be determined by this method because the irregular absorption cross sections of these materials distort the $1/E$ spectrum.

DOSE CALCULATION

The instrument was calibrated for dose measurement through the use of a Pu-Be neutron source (average neutron energy of 4.5 Mev) supplied by Monsanto Chemical Company. On the basis of the manufacturer's calibration of the source strength (8.52×10^6 neutrons/sec) the detection efficiency for the 8" sphere using point source geometry was found to be 0.124%. The efficiency of any sphere at a given energy can then be determined from Fig. 2, which represents the relative efficiencies of the spheres as a function of energy determined by the technique of Dr. Bonner. In particular, the efficiency of the 8" sphere at 0.6 Mev is 0.129%. The efficiency for the $1/E$ spectrum cannot be obtained from Fig. 2, as explained previously in this report, due to the uncertainty in extrapolations over the range from thermal to 0.6 kev.

The efficiency used for the $1/E$ spectrum was arrived at in the following manner. A visual inspection of Fig. 2 indicates the 2" sphere has an average relative counting rate from Cd cut off (.4 ev) to 0.6 Mev of about 3.1 on the arbitrary scale of the figure. It is believed by the author that the extrapolation of this 2" curve is probably the most accurate of the three curves being used, since the 2" sphere offers little moderation and absorption to impinging neutrons and thus would not alter greatly the instrument's response to lower energy neutrons. The instrument responds predominantly to slow neutrons, and thus has a response curve somewhat similar to the one shown in Fig. 2 with the exception of the slight rise

around 0.4 ev which would be due to the effect of the sphere. The counting ratio for the 2" sphere for the 1/E spectrum originating from a 0.6 Mev source was established previously in this report to be 31.3 when the 2", 3" and 8" spheres are used. By comparing this experimental 1/E spectrum counting ratio for the 2" sphere with its average relative counting rate from Fig. 2, one arrives at a normalizing factor by means of which the average relative counting rates of the other spheres may be obtained from their measured 1/E counting ratios, without reference to the extrapolations of Fig. 2. The average relative counting rates for the three spheres are then, on the scale of Fig. 2: 8", 1.88; 3", 4.99; and 2", 3.13. The 1/E spectrum detection efficiency of the 8" sphere was then calculated to be 0.025%. The uncertainty inherent in the above normalization procedure can be eliminated when the extrapolations of Fig. 2 are replaced by measured values. At present the necessary equipment and techniques for obtaining monoenergetic neutrons in the intermediate range have not become available.

Let the following quantities be explicitly defined:

N = count rate, in counts per minute, for the 8" sphere

α = fraction of count rate due to 0.6 Mev neutrons

$1-\alpha$ = fraction of count rate due to 1/E neutrons

A = effective area of the sphere = 324.3 cm^2

η = detection efficiency of the sphere for 0.6 Mev neutrons = 1.29×10^{-3}

ϵ = detection efficiency of the sphere for 1/E neutrons = 2.5×10^{-4}

RPG (fast) = neutron flux at 0.6 Mev giving a dose of 1 mrem/hr = $10 \text{ n/cm}^2/\text{sec}$

RPG (1/E) = neutron flux integrated from 0.4 ev to 0.6 Mev giving a dose of 1 mrem/hr = $77.7 \text{ n/cm}^2/\text{sec}$

Then the dose rates in mrem/hr for fast and 1/E spectrum neutrons are, respectively,

$$D(\text{fast}) = \frac{\alpha N / \eta}{60A} \cdot \frac{1}{\text{RPG}(\text{fast})},$$

$$D(1/E) = \frac{(1-\alpha)N / \epsilon}{60A} \cdot \frac{1}{\text{RPG}(1/E)},$$

The value of α for which these dose rates are equal depends upon the two detection efficiencies and RPG estimates. Using the current numerical values of these quantities, one finds that the fast and 1/E dose rates are equal when $\alpha = 0.4$. It is evident from Fig. 6 and the data of Table 2 that in the MTR-ETR area α is significantly less than 0.4 under normal reactor operating conditions, and that consequently the intermediate energy neutron dose rate exceeds the fast neutron dose rate. In most cases the

Table II
Observed Dose Rates

Date	Location	Dose Rate Fast mrem/hr	Dose Rate Intermediate mrem/hr	Total Dose Rate mrem/hr
MTR				
Feb. 29, 1960	# 17	1.0	6.6	7.6
Feb. 29, 1960	10	0.3	2.2	2.5
Mar. 14, 1960	20	3.0	15.8	18.8
Mar. 14, 1960	23	4.6	15.1	19.7
April 1, 1960	19	1.0	5.2	6.2
April 5, 1960	2	≈ 0	1.4	1.4
April 5, 1960	4	0.4	8.6	9.0
April 5, 1960	5	0.4	6.9	7.3
April 5, 1960	6	0.4	5.1	5.5
April 5, 1960	8	0.3	3.0	3.3
April 5, 1960	7	0.2	1.9	2.1
May 20, 1960	3	0.2	8.1	8.3
Nov. 22, 1960	15	1.4	9.8	11.2
Nov. 1, 1960	18	1.4	8.3	9.7
Dec. 2, 1960	12	0.6	4.4	5.0
Dec. 2, 1960	13	0.5	3.5	4.0
Dec. 2, 1960	9	0.4	3.3	3.7
Dec. 2, 1960	14	0.2	1.5	1.7
Dec. 2, 1960	22	0.2	0.9	1.1
Dec. 2, 1960	16	0.9	5.2	6.1
Dec. 2, 1960	11	0.4	3.2	3.6
ETR				
May 13, 1960	25	0.3	0.7	1.0
May 13, 1960	24	0.2	0.7	0.9
May 13, 1960	21	0.1	0.4	0.5
EBR-I				
Nov. 9, 1960	1	0.0	8.1	8.1

neutron dose rate is greater than that due to β and γ activities at the same location.

The ratio of doses contributed by 1/E spectrum neutrons and 0.6 Mev neutrons is

$$\frac{D(1/E)}{D(\text{fast})} = \frac{\text{RPG}(\text{fast})}{\text{RPG}(1/E)} \cdot \frac{1-\alpha}{\alpha} = 0.664 \frac{1-\alpha}{\alpha}$$

This ratio is shown as a function of α in Fig. 12. It ranges from about 4 to 10 for data recorded around the MTR-ETR.

The total dose rate is given by

$$D(\text{total}) = \frac{\alpha N/h}{60A} \cdot \frac{1}{\text{RPG}(\text{fast})} + \frac{(1-\alpha)N/\epsilon}{60A} \cdot \frac{1}{\text{RPG}(1/E)}$$

When the current numerical values for the 8" sphere are used, the total dose rate in mrem/hr becomes

$$D(\text{total}) = N \times 10^{-3} (2.65 + 1.34\alpha).$$

Figs. 12 and 13 have been prepared to reduce to a minimum the calculations required of the Health Physicist in determining the total dose rate and the ratio of intermediate to fast dose rates during routine use of this instrument and technique. When the counting ratios for the 2", 3", and 8" spheres are plotted on the corresponding straight lines of Fig. 12, a vertical line through the three points intersects the x-axis at the appropriate value of α . The intersection of the same vertical line with the dose rate curve indicates the ratio of intermediate to fast dose rates.

On the nomograph of Fig. 13, when a straight edge laid across the chart crosses the right hand scale at the value of α determined from Fig. 12 and crosses the left hand scale at the observed count rate of the 8" sphere, the total dose in mrem/hr is given by its intersection with the dose rate scale.

No neutrons were detected in the vicinity of the ETRC facility in the MTR building. At ZPR-III very few neutrons were found in the reactor console area, making statistically significant counting difficult. The estimated total dose rate at ZPR-III is < 0.1 mrem/hr. Dose rate measurements at ETR gave values from 0.5 to 1 mrem/hr, while measurements at MTR at various times and places ranged from 1 to 20 mrem/hr.

The thermal neutron flux is determined by using the probe with no sphere. The count rate is determined with the cadmium shield in place and with it removed. The observed count rate from a flux at the MTR reactor with the cadmium in place is less than half the flux with the cadmium shield removed. The difference between these counts is the thermal flux. This

phase of the study has not been completed at this writing. Preliminary data taken from six locations at the MTR indicate the relative dose rates from thermal, intermediate and fast neutrons shown in Table 3. These values are based on a thermal neutron RPG of $2000 \text{ n/cm}^2/\text{sec}$ and an efficiency having a value of 6.1 on Fig. 2 as reported by Bonner⁽¹¹⁾ for the bare probe. Of special interest are the dose rate ratios indicated in Table 3. If a constant relationship is found to exist, thermal and/or fast neutron detection instruments can be used to determine the total dose by applying a factor to the reading obtained from these instruments.

LIMITATIONS

All phases of this technique of determining the intermediate energy neutron flux have not yet been completely and thoroughly investigated. The procedure described in this report was developed to satisfy the need for an intermediate range instrument at the MTR-ETR area for Health Physics studies. Considerable study remains to be done on the validity of the method, as well as on possible applications of the instrument and procedure to other problems in neutron detection.

The gamma sensitivity problem requires extensive study, particularly to enable the determination of the neutron spectrum in an intense gamma field.

The effect of materials such as lead, steel and U^{238} , which change the counting ratios appreciably, requires more investigation.

The determination of the $1/E$ spectrum ratios for various source energies requires further refinement, although it is believed by the author that the values presently being used are within 1.0% of the actual ratios. Also, efficiency values of the spheres in the $1/E$ range must be determined by replacing the extrapolations of Fig. 2 by experimental data.

It is possible to determine the average energy of the source only within limits that vary depending on (1) the source energy and (2) the amount of moderation the neutrons have undergone before detection. The instrument is being used at present with only the 2", 3" and 8" spheres, which limits high energy determinations to energies below about 3.0 Mev. By utilizing the 12" sphere this limit could be raised slightly.

In routine use of the instrument, certain precautions must be observed in order to obtain valid results. With regard to the instrument itself: (1) The high voltage applied to the photomultiplier tube must remain constant. (2) The level of pulse height discrimination must conform to the conditions described in this report for the dose rate calibration. Concerning conditions under which measurements are made: (3) The flux of the source must not vary, and (4) The scattering material in the vicinity of the instrument must not be changed, during the course of the measurement. In order to obtain statistically significant results, (5) counting times must be such that at least 5000 - 10,000 counts are recorded with each sphere.

Table 3

Observed Dose Rate Ratios

#	Observed Counts/min			Counts/min			# of Neutrons/minute		
	2"	3"	8"	Inter	Fast	Therm	Inter	Fast	Thermal
A	877	1473	700	644	56	452	8090	134	1752
B	196	317	153	141	12	96	1660	27	351
C	778	1293	647	589	58	375	7400	138	1454
D	3518	5973	3108	2766	342	1305	34,740	816	5060
E	3482	5734	3064	2727	337	904	32,300	759	3300
F	557	925	470	418	52	257	4,950	117	938

#	Dose Rate mrem/hr				Dose Rate Ratio		
	Inter	Fast	Thermal	Total	Therm/ Total	Therm/ Inter	Fast/ Total
A	1.73	0.22	0.11	2.06	0.053	0.064	0.107
B	0.36	0.05	0.02	0.43	0.047	0.056	0.116
C	1.58	0.23	0.09	1.90	0.047	0.057	0.121
D	7.43	1.36	0.32	9.11	0.035	0.043	0.149
E	6.92	1.27	0.21	8.40	0.025	0.030	0.151
F	1.06	0.20	0.06	1.32	0.045	0.057	0.151

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Plate 1 Neutron Detection Instrument

Plate 2 Detection Unit

Plate 3 Detection Unit with Sphere in Place

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Figure 1

Radiation Protection Guide for Neutrons

Figure 2

Relative Counting Rate vs Energy for Moderating Spheres

Figure 3

Counting Locations at the MTR

FIG. 4

PPCo. - 8 - 3267

EXPERIMENTAL RESULTS ASSUMING $\frac{1}{E}$ SPECTRUM AND A 0.4 Mev SOURCE

FIG. 5

PPCo. - B - 3268

EXPERIMENTAL RESULTS ASSUMING $\frac{1}{E}$ SPECTRUM AND A 0.5 Mev SOURCE

FIG. 6

PPCo. - B - 3269

EXPERIMENTAL RESULTS ASSUMING $\frac{1}{E}$ SPECTRUM AND A 0.6 Mev SOURCE

FIG. 7

PPCo. - 8 - 3270

EXPERIMENTAL RESULTS ASSUMING $\frac{1}{E}$ SPECTRUM AND A 0.7 Mev SOURCE

FIG. 8

PPCo. - B-3271

CHANGE IN PERCENT OF TOTAL COUNT, $\frac{1}{E}$ SPECTRUM TO FAST SPECTRUM

FIG. 9

DETERMINATION OF AVERAGE ENERGY OF FAST NEUTRONS

PPCo. - B - 3272

FIG. 10

EXPERIMENTAL RESULTS, Po - Be SOURCE

PPCo. - B - 3273

FIG. II
 EXPERIMENTAL RESULTS, Pu^{240} FUEL PLATES

PPCo. - B - 3274

FIG. 12

PPCo. - 8 - 3275

GRAPH FOR DETERMINING THE FRACTION OF FAST NEUTRON COUNTS AND THE RATIO OF INTERMEDIATE TO FAST NEUTRON ENERGY DOSE RATES AT THE MTR - ETR

FIG. 13

NOMOGRAPH TO CONVERT RATIO AND COUNT RATE TO DOSE

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Appendix A

The first attempt to determine the intermediate neutron spectrum was based upon the use of a set of simultaneous equations expressing the experimental count rates as functions of the counting efficiencies and numbers of neutrons in specified energy ranges. The count rate for each sphere represents its response to neutrons of all energies. From the efficiency curves it is possible to establish, for a given sphere, its counting efficiency over any chosen energy range. The total count rate thus represents a sum of products of the number of neutrons in a given energy range incident on the sphere in a given time, and the average efficiency over that energy range. The total energy range was chosen to cover the entire spectrum from cadmium cut-off to infinity. Let the following quantities be defined:

C_r = the count obtained in a unit time using r^{th} sphere.

X_j = fraction of total neutrons that lie in j^{th} energy range.

a_{rj} = counting efficiency of the r^{th} sphere over j^{th} energy range.

N = number of neutrons per unit time impinging on sphere.

Then for the r^{th} sphere:

$$C_r = (a_{r1} X_1 + a_{r2} X_2 + \dots + a_{rj} X_j) N$$

The problem is to generate the intermediate energy neutron spectrum from observed values of C_r , where r ranges over the number of spheres used.

A set of five equations in five unknowns was set up in the form of a 5 x 5 matrix and constant vector for each set of experimental data. These equations were solved by the MTR IBM-650 computer for values of X_j . The values obtained were erratic, giving in some cases negative values. (14)

The next approach was to check the hypothesis that the neutron spectrum was a combination of $1/E$ spectrum neutrons and fission spectrum neutrons. (15-18) This was done by computing from Fig. 2 the ratio of counts which would be obtained from a $1/E$ spectrum and from a fission spectrum, and using them as the coefficients C on the left side of the following equations:

$$C_{\frac{1}{E},i} F + C_{F,i} f = C_{\text{EXP } i}$$

$$C_{\frac{1}{E},j} F + C_{F,j} f = C_{\text{EXP } j}$$

$C_{\frac{1}{E},i}$ = relative count rate for a $1/E$ spectrum for the i^{th} sphere.

$C_{F,i}$ = relative count rate for a fission spectrum for the i^{th} sphere.

F = fraction of $1/E$ neutrons in the observed spectrum.

f = fraction of fission neutrons in the observed spectrum.

$C_{\text{EXP } i}$ = relative count rate obtained experimentally for the i^{th} sphere.

Any two spheres could be used in these pairs of equations. All the spheres were used in this work giving 10 sets of equations. Again, negative results were obtained from some sets of experimental data.

It is believed that the erratic numerical results were due primarily to two sources of error, namely (1) the uncertainty in counting rates caused by poor statistics, possible fluctuations in the neutron flux and possible variation in fast neutron to intermediate energy neutron ratios; and (2) in accuracy in obtaining counting efficiencies from the relative counting rates graph with its lengthy extrapolations.

Appendix B

The following are the types of neutron energy spectra that were assumed in attempts to fit the experimental data.

- (1) The assumptions were made that the neutron spectrum consisted of (a) a $1/E$ spectrum plus additional neutrons added progressively as the neutron energy increased, and (b) a $1/E$ spectrum plus additional neutrons added progressively as the neutron energy decreased. A graph was plotted showing the ratios obtained by calculations for the various spectra assumed above. The counting ratios for these spectra were plotted as a function of spectra type. If the assumed neutron spectra had been the same as the actual spectra, the experimental data would have aligned vertically at points corresponding to the actual spectra. A fairly close alignment was found to exist; therefore several modifications of these spectra were investigated in a similar manner.
- (2) The assumption next was made that the neutron spectrum was one of the above plus some contribution due to a fission spectrum at higher energies.
- (3) The assumption was made that the spectrum consisted of a $1/E$ spectrum plus a larger number of neutrons at the lower energy end.
- (4) The assumption was made that the spectrum consisted of a $1/E$ spectrum and a fission spectrum.
- (5) The spectrum was assumed to consist of a $1/E$ spectrum with an excess of neutrons at 500 ev, 100 ev and 50 ev.
- (6) The spectrum was assumed to be a $1/E$ spectrum with a larger number of neutrons located in the lower energy region. The area to which the additional neutrons were added was from the lower limit to: 10 ev, 100 ev, 10^3 ev and 10^4 ev.
- (7) The spectrum was assumed to be a $1/E$ spectrum that was cut off sharply at different energies on the high energy end.

Of the various spectrum shapes enumerated above, the one on which the experimental data recorded at the MTR exhibited the best vertical alignment was the last one listed. Subsequent modifications are discussed in the body of this report.

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